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A Tunable Frequency-Offset-Locked Laser System For Cooling Neutral Atomic Gases

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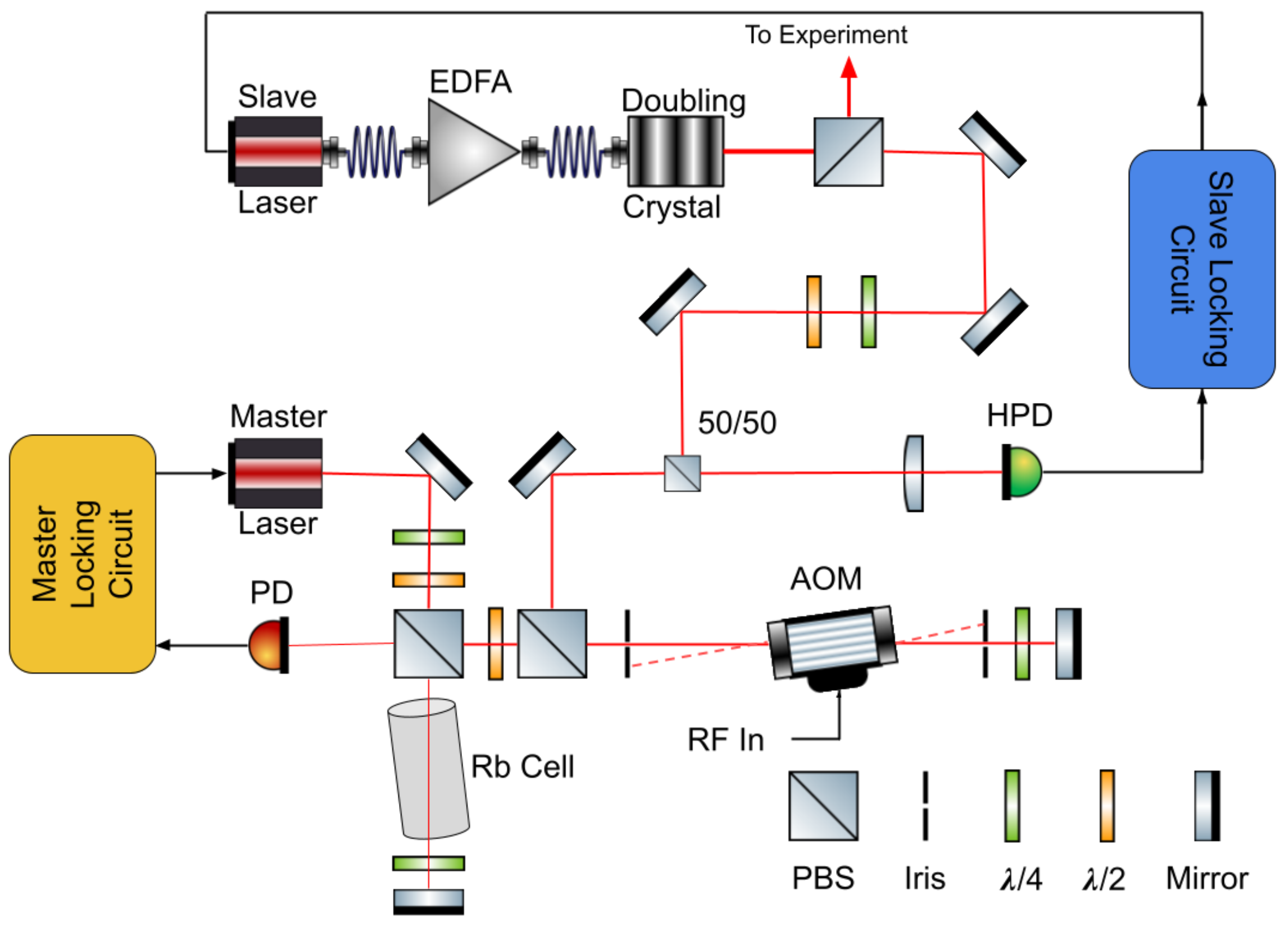
Abstract

We demonstrate a method for controlling a narrow-linewidth laser using a frequency-offset locking scheme using low-cost commercial electronics. We slave a diode laser to a stable master laser by measuring the optical beat note between the two lasers on a high-speed photodiode. This beat note is fed through **a broadband variable divider and a frequency-to-voltage converter [1] with a high degree of linearity**. An error signal is sent to an analog proportional-integrator controller that locks the slave's frequency to a reference point. This architecture allows for a large capture range (~1 GHz), with a fast response time (locking bandwidth ~5 kHz), which is ideal to laser cooling and optical manipulation of neutral atoms and molecules. With minor modifications, we will realize an **optical phase lock [2] for quantum sensing applications**.

Laser System and Locking Scheme

Quantum sensors based on atom interferometry can measure inertial effects such as accelerations and rotations with extreme precision. These instruments employ laser-cooled atoms at micro-Kelvin temperatures. In this work, we present progress toward constructing a 780 nm laser system based on a master-slave architecture. Here, the "master" laser serves as an ultra-stable optical reference to stabilize a "slave" laser to the desired frequency.

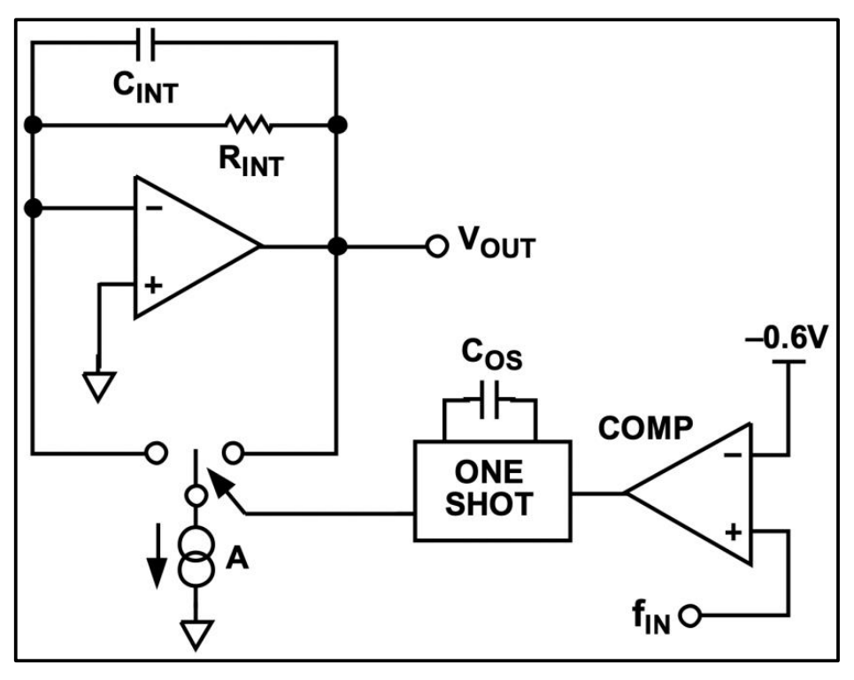
The master laser, a distributed-feedback diode laser **at 780 nm (~600 kHz linewidth)**, is stabilized using a standard saturated absorption setup. Its frequency is shifted by 180 MHz using a dual-pass acousto-optic modulator (AOM) before reaching the slave. The slave laser is an all-fibered diode **at 1560 nm (~150 kHz linewidth).** The slave light is amplified and converted to 780 nm using a frequency-doubling crystal. This light is then polarization matched and beat with the master light at a 50/50 beam splitter. The beat frequency is detected using a high-speed photodiode (~2 GHz bandwidth).

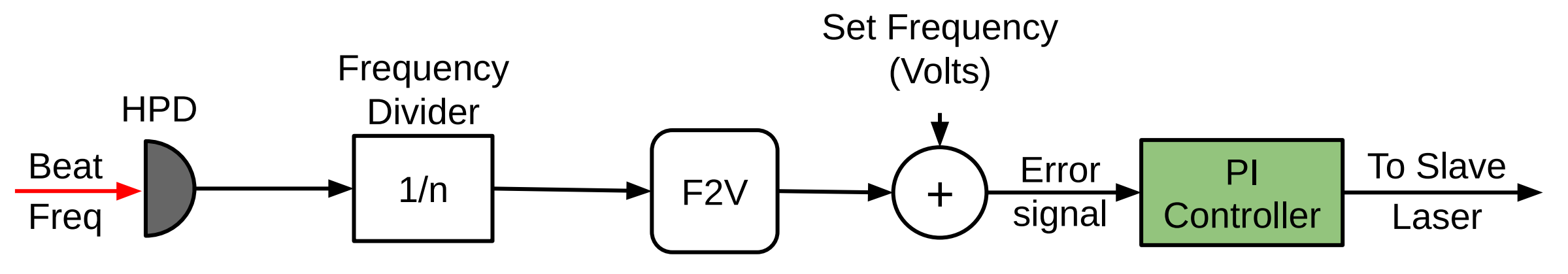


PD: Photodiode; HPD: High-speed Photodiode; AOM: Acousto-Optic Modulator; PBS: Polarizing Beam Splitter; 50/50: 50/50 Beam Splitter; $\lambda/4$: Quarter Waveplate; $\lambda/2$: Half Waveplate; Rb Cell: Rubidium Vapor Cell; EDFA: Er-doped Fiber Amplifier; RF In: radio-frequency signal (90 MHz).

The detected optical beat note ranges from 0.1 – 2.5 GHz. This signal is sent to a broadband programmable frequency divider [3] to match the sub-MHz range accepted by a frequency-to-voltage (F2V) converter [4]. The output of the F2V is low-pass filtered to obtain a **DC voltage proportional to the optical beat note with a high degree of linearity**. This filtered signal is summed with a control voltage (Set Frequency) that defines a setpoint for the slave laser.

This forms an error signal that is sent to an analog proportional-double-integrator (PI^2) controller and fed back to the slave. This feedback loop forces the error signal to zero; ensuring the slave reaches the desired optical frequency.

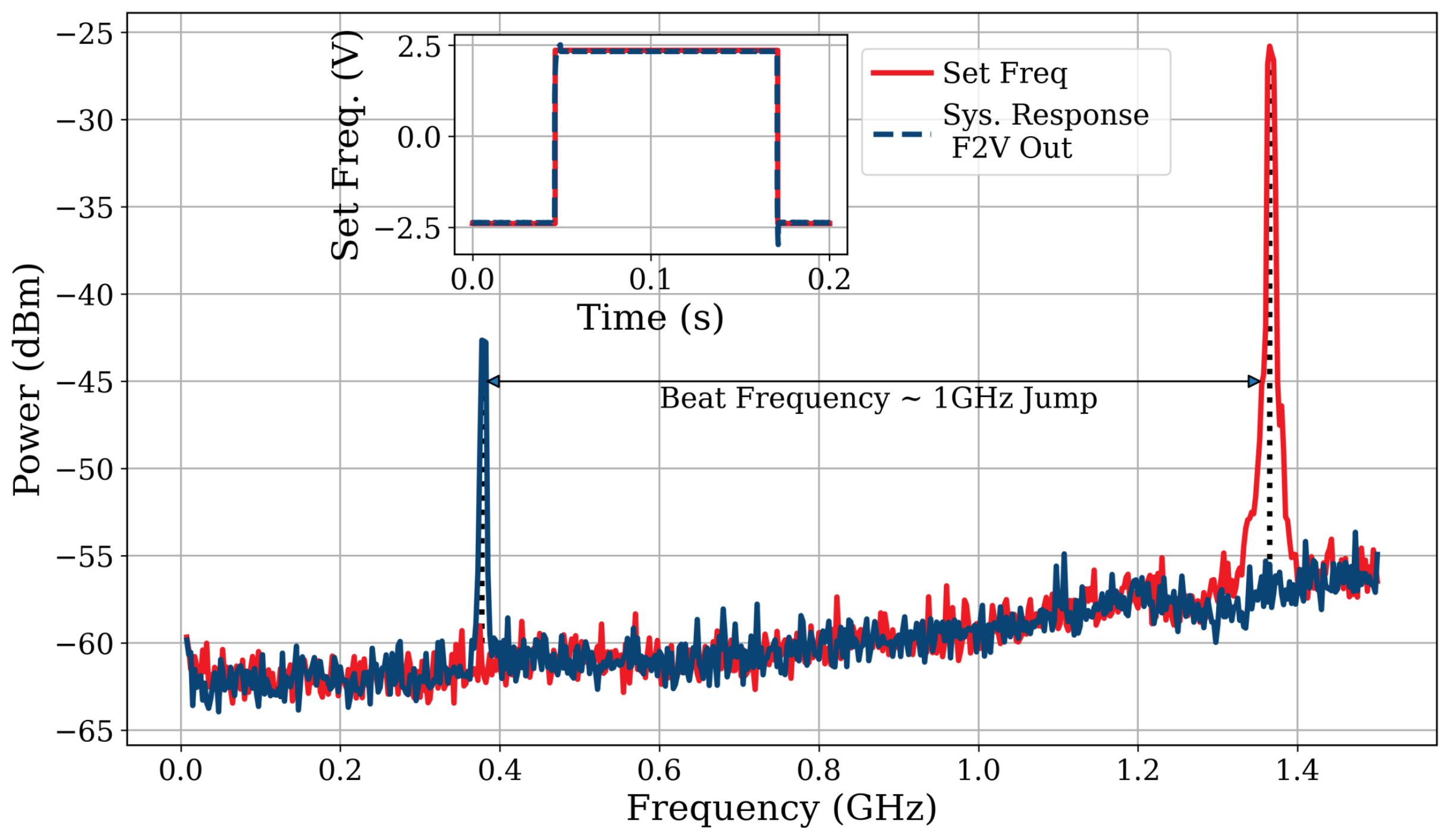




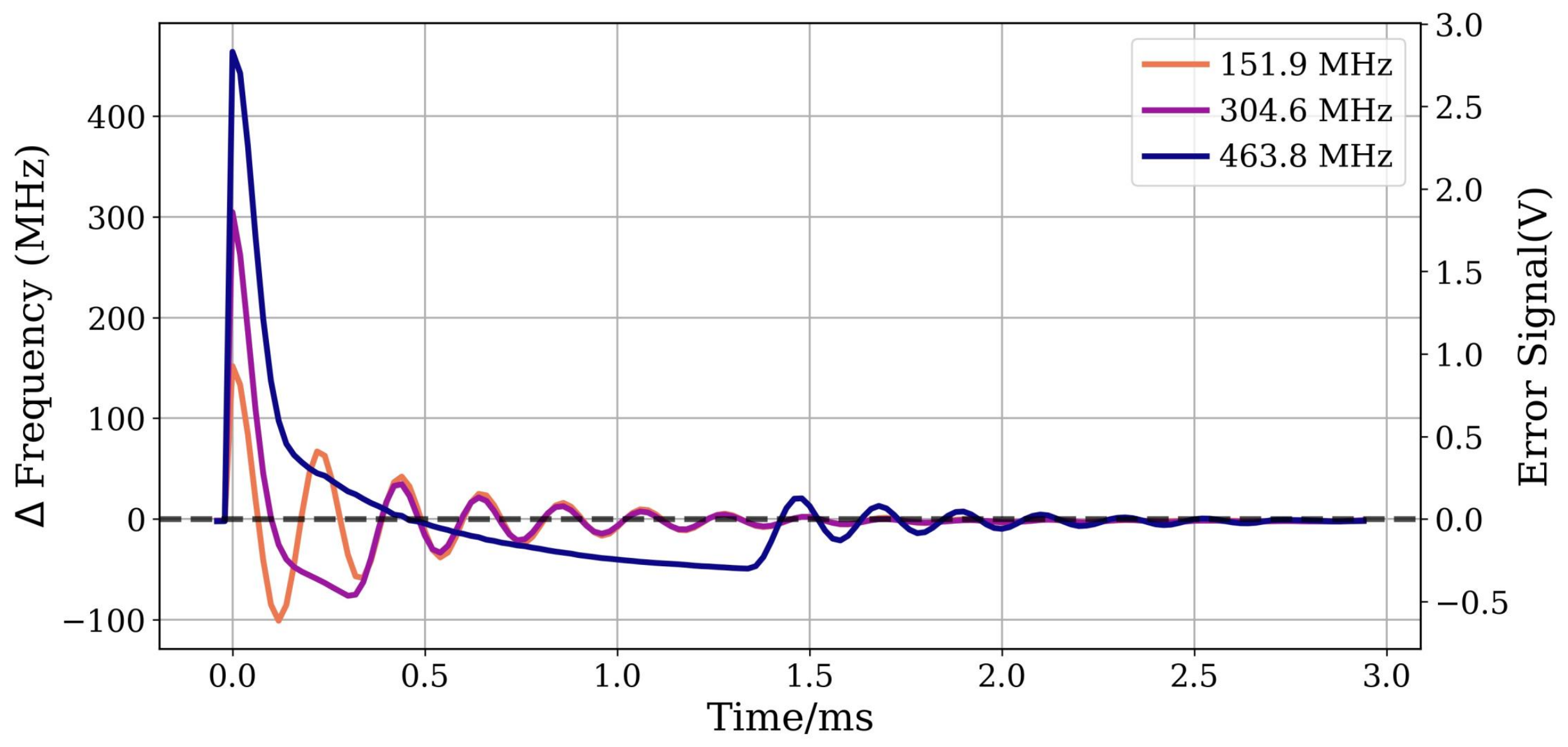
Frequency-Offset Lock Performance

Dynamic Range

We have tested the frequency-offset lock of the slave up to ~ 2 GHz (limited by the modulation range of our laser current controller). Below, we showcase an example of the dynamic range and response time of our lock. Here, we jump the set point by ~ 1 GHz using a square wave. The inset in this figure shows the "Set Frequency" input to the lock and the corresponding system response (F2V output).

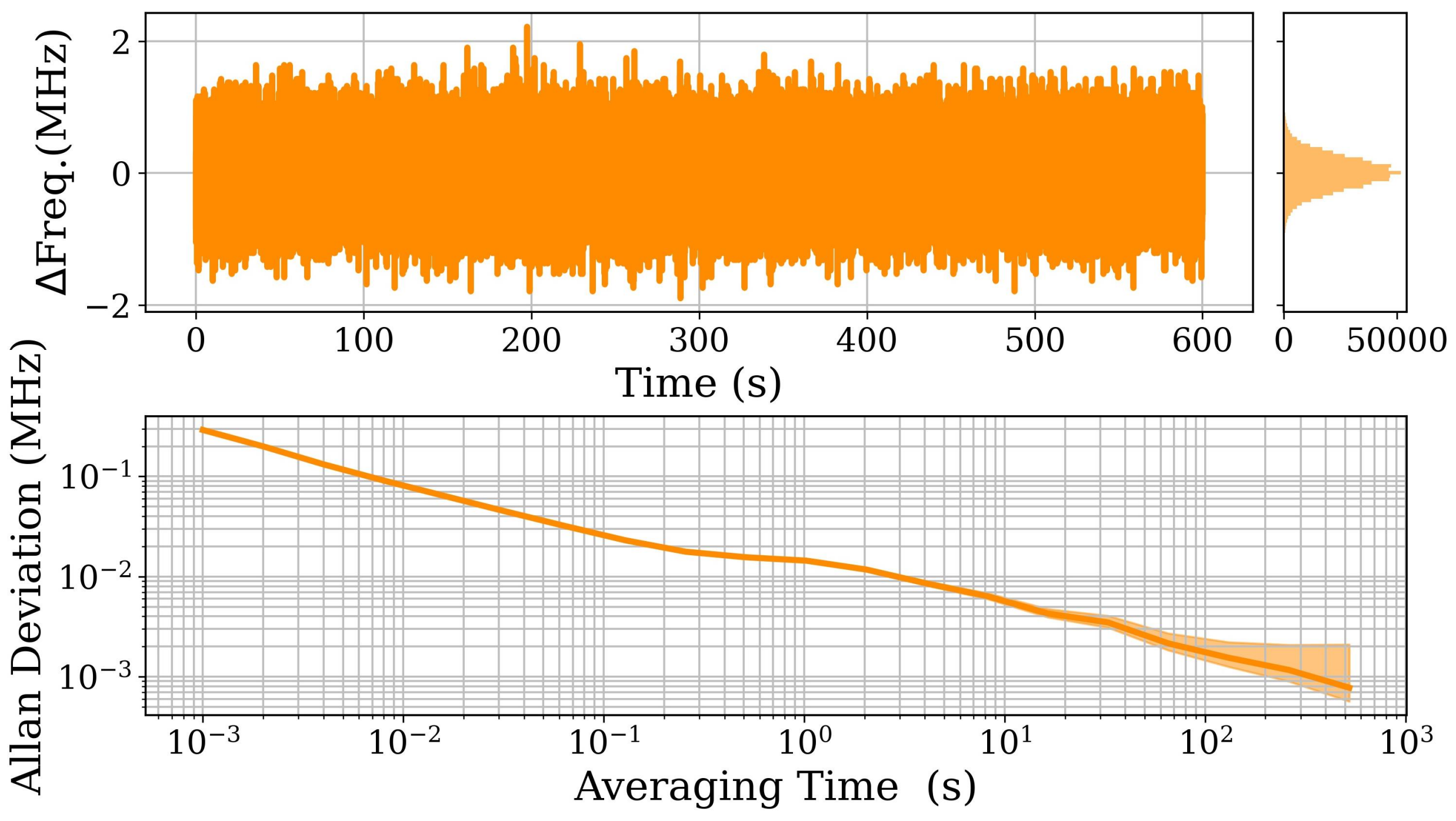


We optimize the stability and response time of the lock by measuring the impulse response of the system. With appropriate proportional and integrator gain settings, we achieve few millisecond response times. **For small frequency jumps (150 MHz) the system responds in < 1 ms, while larger jumps (460 MHz) take up to 2 ms.** The response time is limited by the 8 kHz filtering stage on the F2V.

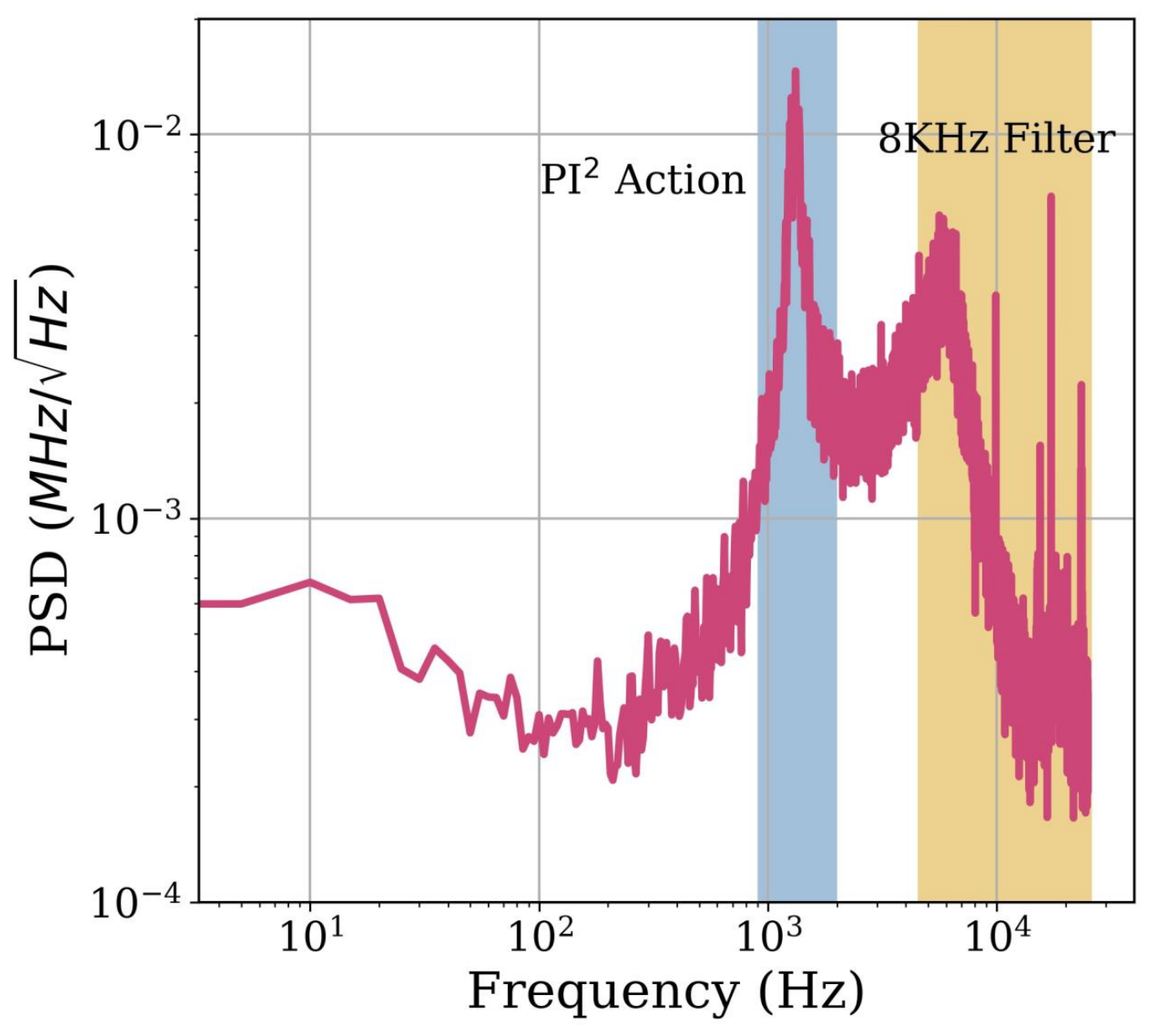


Laser Stability

The Allan deviation is a generalization of the standard error; providing a measure of frequency stability with averaging time τ. Lower values of the Allan deviation correspond to better stability. To illustrate the system's stability on short timescales, we locked the slave laser for 10 min. Below, we show (a) the time variation of the optical beat note and its noise distribution, and (b) the corresponding Allan deviation. **We reach a stability of ~15 kHz after 1 s of averaging.** This continues to decrease as $1/\sqrt{\tau}$, reaching < 1 kHz after 5 min.



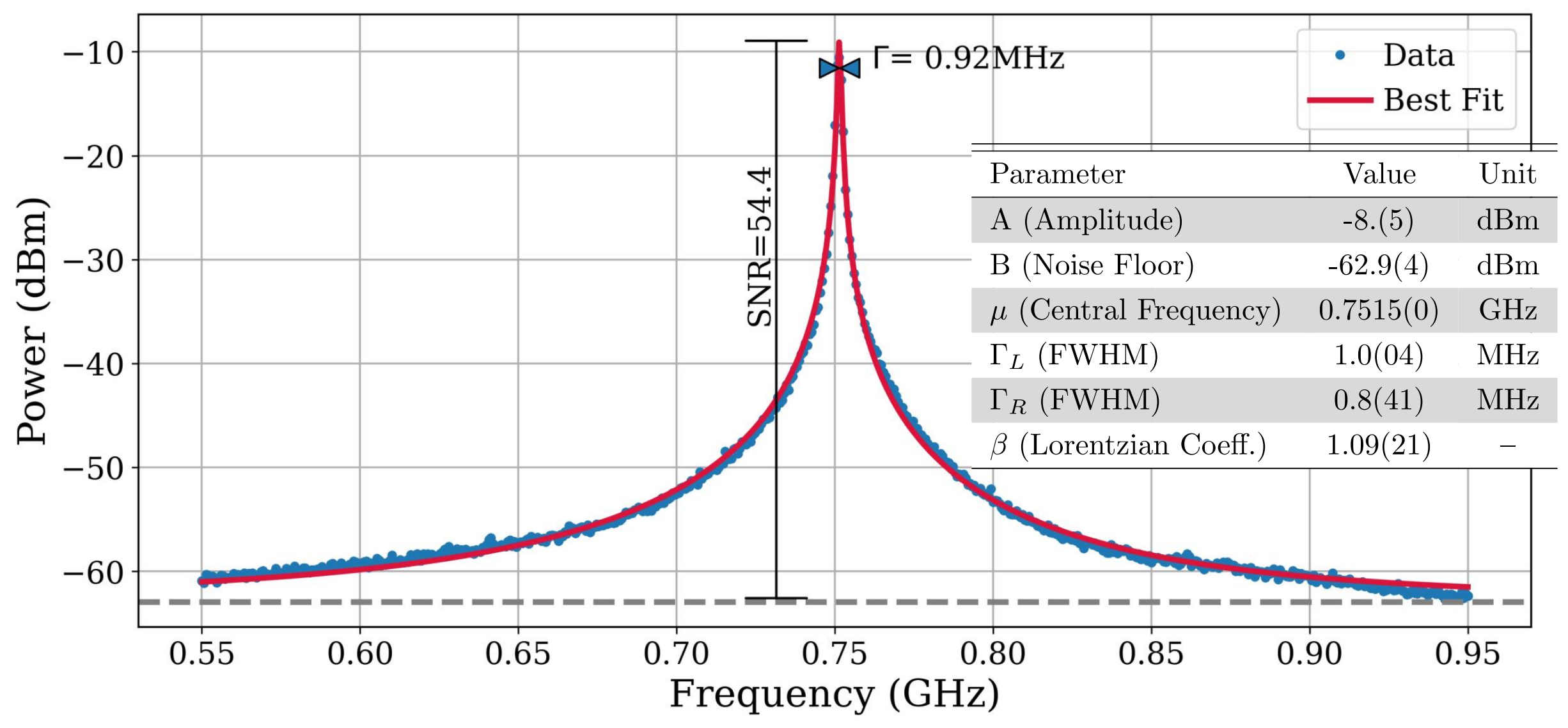
To identify noise sources, we analyze the power spectral density (PSD) of the error signal. The peak near 2 kHz results from the action of the PI^2 feedback. The broad peak near 8 kHz is due to the F2V filter stage. **We reach a noise floor of ~2 × 10^{-4} MHz/Hz$^{1/2}$**.



Laser System Characteristics

Beat Note Spectrum

To gain a deeper understanding of the laser system, **we analyze the master-slave beat note spectrum** (with the master free running). Below is the spectrum measured by our high-speed photodiode and the corresponding fit to our model. We found the distribution fits the logarithm of a skewed Lorentzian-beta function plus an additional term defining the noise floor of the spectrum analyzer (see below). Our in-house photodiode circuit yields an excellent signal-to-noise ratio of SNR = 54.4 dB.



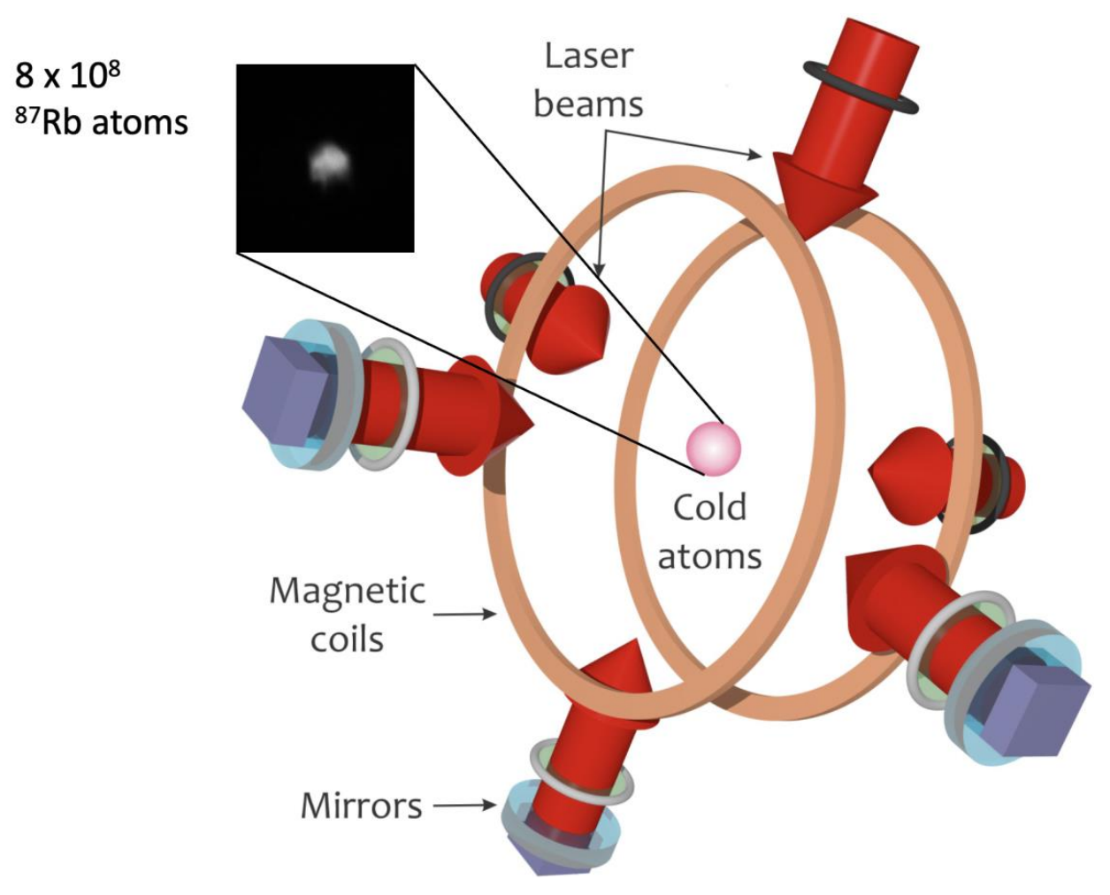
Parameter	Value	Unit
A (Amplitude)	-8.(5)	dBm
B (Noise Floor)	-62.9(4)	dBm
μ (Central Frequency)	0.7515(0)	GHz
Γ_L (FWHM)	1.0(04)	MHz
Γ_R (FWHM)	0.8(41)	MHz
β (Lorentzian Coeff.)	1.09(21)	–

$$P\ (\mathrm{dBm}) = 10\log_{10}\left(\frac{10^{A/10}}{[1 + C_{\mathrm{L}}\,(2(\omega-\mu)/\Gamma_{\mathrm{L}})^2 + C_{\mathrm{R}}\,(2(\omega-\mu)/\Gamma_{\mathrm{R}})^2]^{\beta}} + 10^{B/10}\right)$$

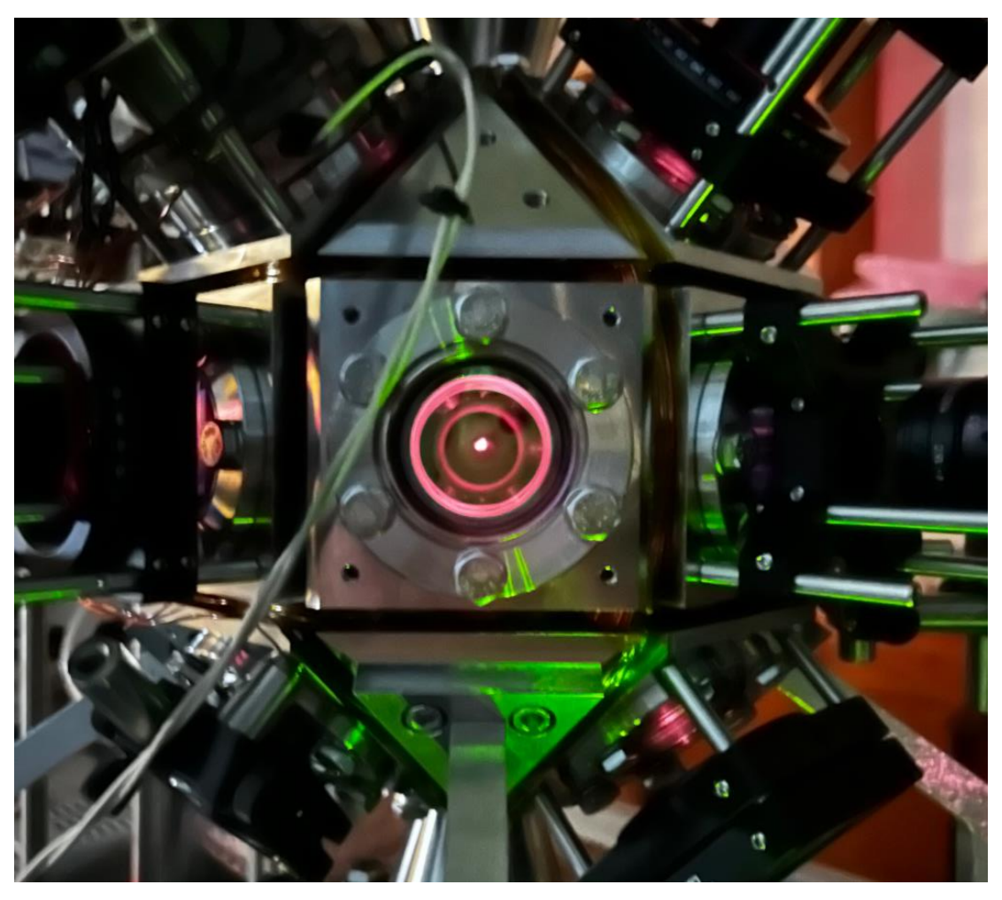
Here, C_{L} (C_{R}) is a coefficient equal to 1 on the left (right) of the peak and 0 on the right (left). This produces a skewed Lorentzian shape. The full-width at half-maximum $\Gamma = (\Gamma_{\mathrm{L}}+\Gamma_{\mathrm{R}})/2 = 0.92$ MHz is consistent with the sum of the laser linewidths: $\sim 0.6 + 2 \times 0.15 = 0.9$ MHz.

Cold Rubidium-87 Source

The narrow linewidth and high stability of our lasers allows us to fine tune the frequency required to achieve a 2D magneto-optical trap (MOT). The 2D MOT transversely cools the gas, creating an atomic beam that loads a 3D MOT (see below). This is the first step towards realizing a quantum gravimeter based on atom interferometry.



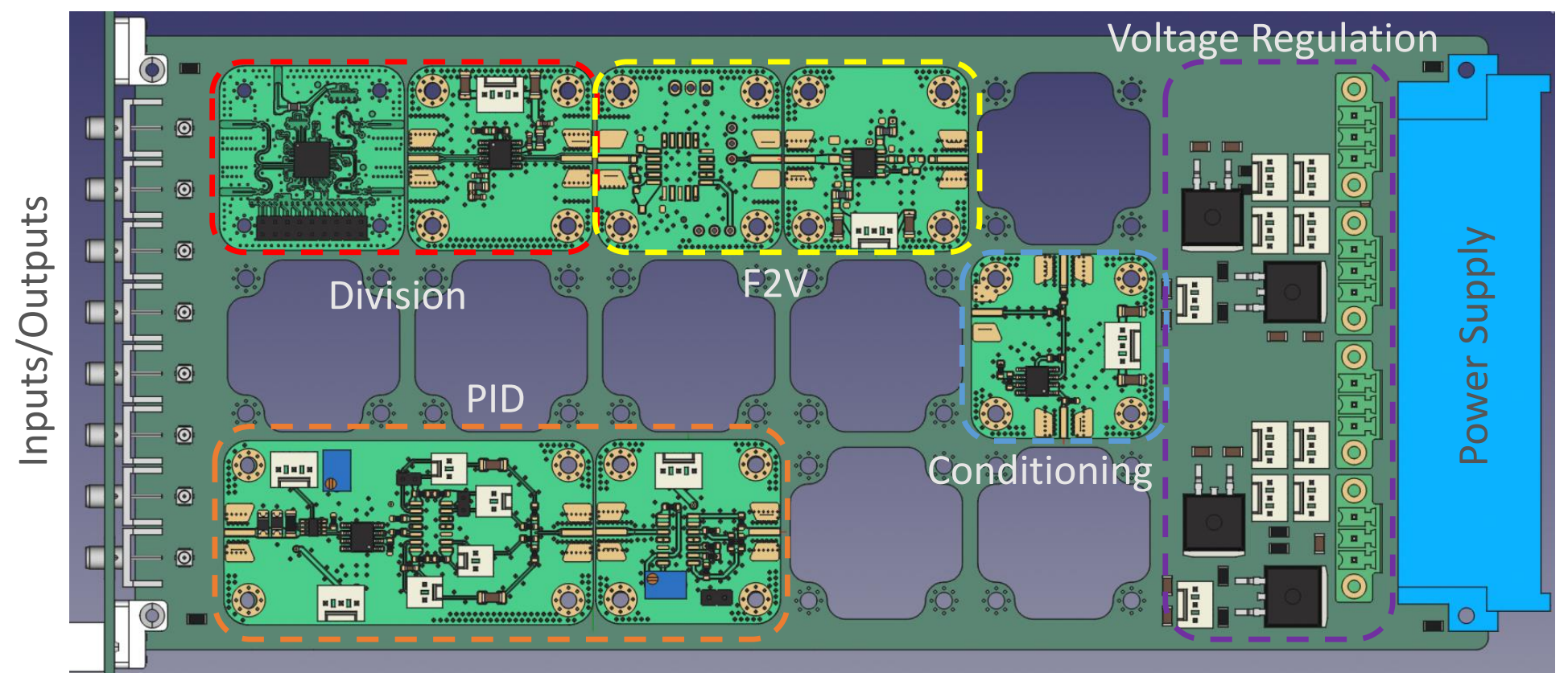
The schematic of a 3D MOT.
Inset: image of trapped ^{87}Rb atoms.



Our titanium science chamber with optics and 3D MOT inside.

Future Work

Future versions of the locking circuit will have a fully modulator design (see below). **We plan to increase the locking bandwidth to minimize the response time. We will also implement dynamic control of the frequency division factor** to optimize the frequency resolution at large beat frequencies.



This architecture is ideal for further **development of an optical phase-locked loop (OPPL) at 6.8 GHz** for our two slave lasers. This is required for a future Raman-based atom interferometer.

Acknowledgements and References

This work is supported by NSERC, NBIF, the CFI, and the Canadian DND through the IDEaS program. We also thank Torsten Reuschel and Dennis Tokaryk of UNB for helpful discussions.

[1] T. Stace et al, Meas. Sci. Technol. **9**, 1635 (1998).
[2] S. Lee et al, Curr. Appl. Phys. **51**, 29-33 (2023).
[3] Microsemi MX1DS10P broadband programmable divider.
[4] Analog Devices AD650 Frequency-to-Voltage Converter.