An ultra-low phase noise microwave synthesizer for quantum sensing with cold atoms

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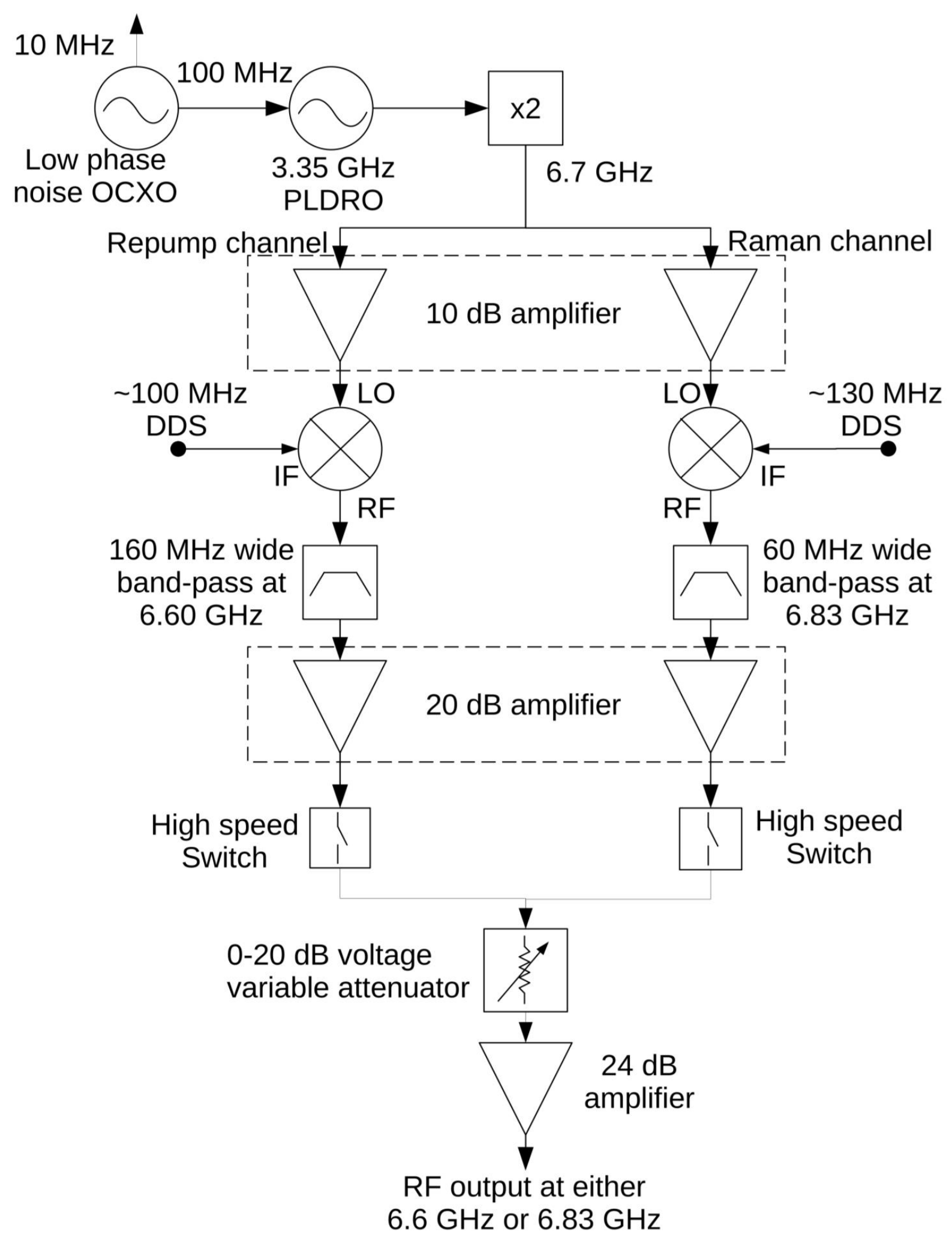
Abstract

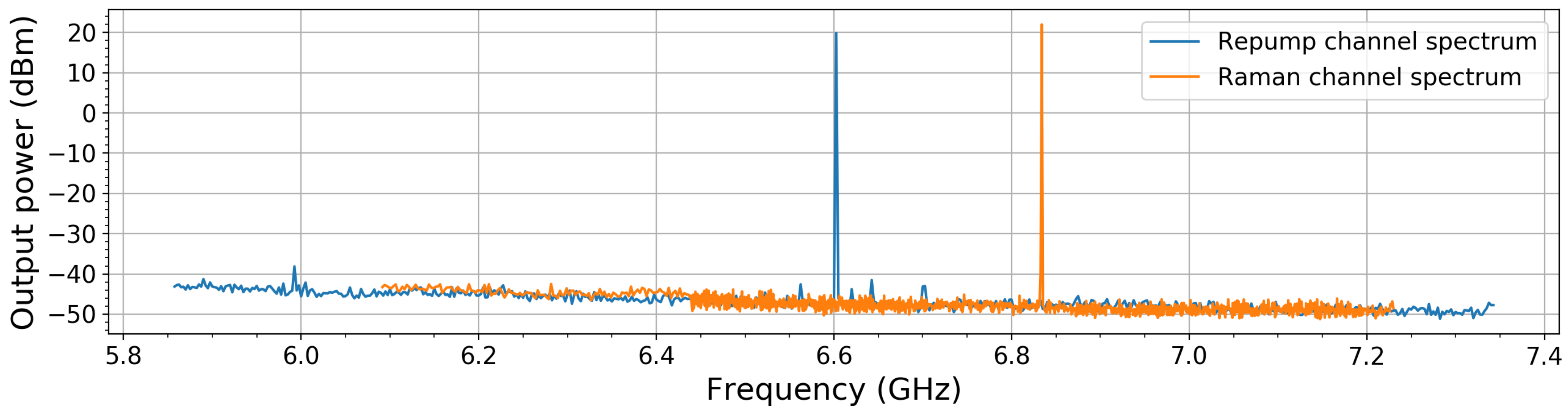
We present an ultra-low phase noise microwave synthesizer for high-precision quantum sensors based on cold-atom interferometry. The synthesizer is used both for laser cooling rubidium atoms and as momentum-transfer pulses in our atom interferometer. During these pulses, the phase of the laser is directly imprinted on the atomic wavefunction. Thus, for high-sensitivity quantum measurements, extremely low noise levels are required for the microwave signal phase. Two frequencies; one at 6.6 GHz acts as a repump for laser cooling, and one at 6.834 GHz for Raman transitions between hyperfine ground states. Sidebands in our 780 nm laser system are created using these frequencies. We present recent results of laser-cooling experiments in our combined 2D/3D magneto-optical trap.

Microwave Synthesizer – Design and Performance

Synthesizer Design

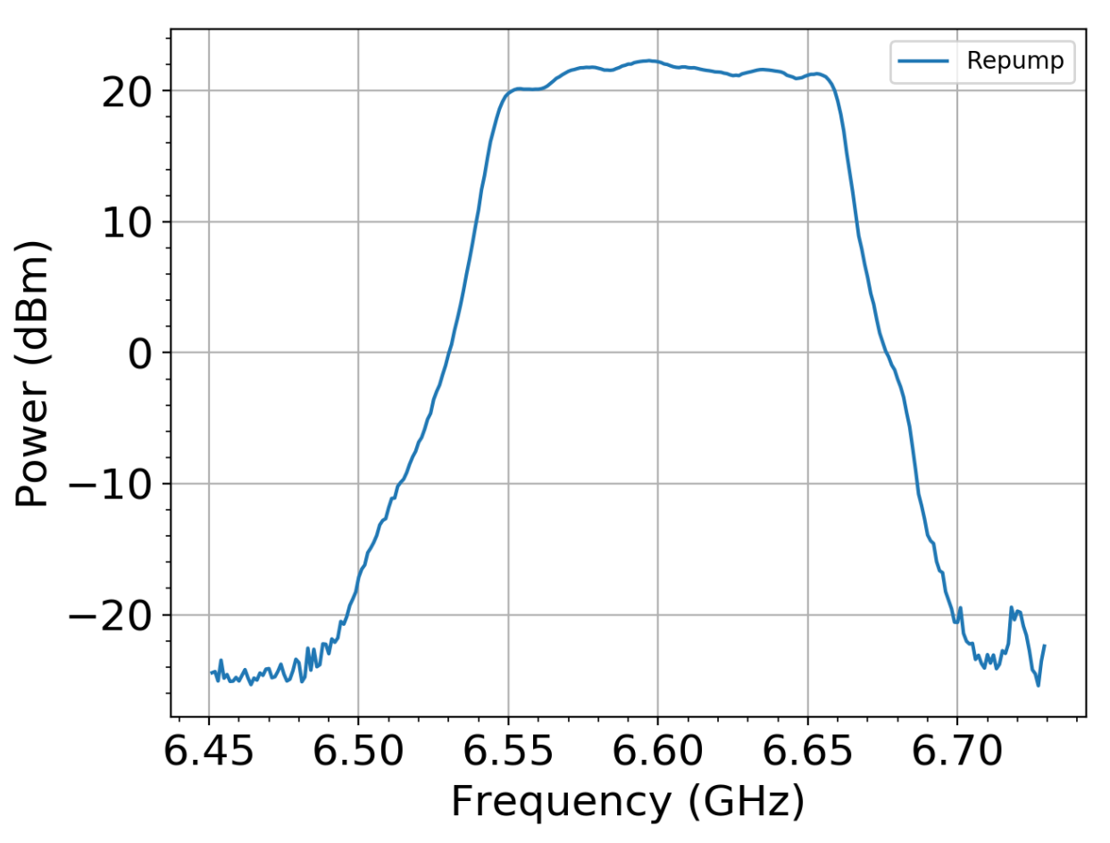
The microwave signal is derived from an ultra-low phase noise oven-controlled crystal oscillator (OCXO). A 100 MHz clock signal is sent to a single-loop phase locked dielectric resonator oscillator (PLDRO) and a frequency doubler to produce 6.7 GHz. This signal is power split into the Repump and Raman channels where they are then amplified and frequency mixed with 100 MHz and 134 MHz signals, respectively, derived from direct digital synthesis (DDS). These two channels are then filtered and further amplified. High speed TTL switches are used to independently control the output of each channel (switching time ~35 ns). The two channels are then recombined and attenuated using a voltage-controlled attenuator. A final amplification stage provides a maximum signal power to ~24 dBm.

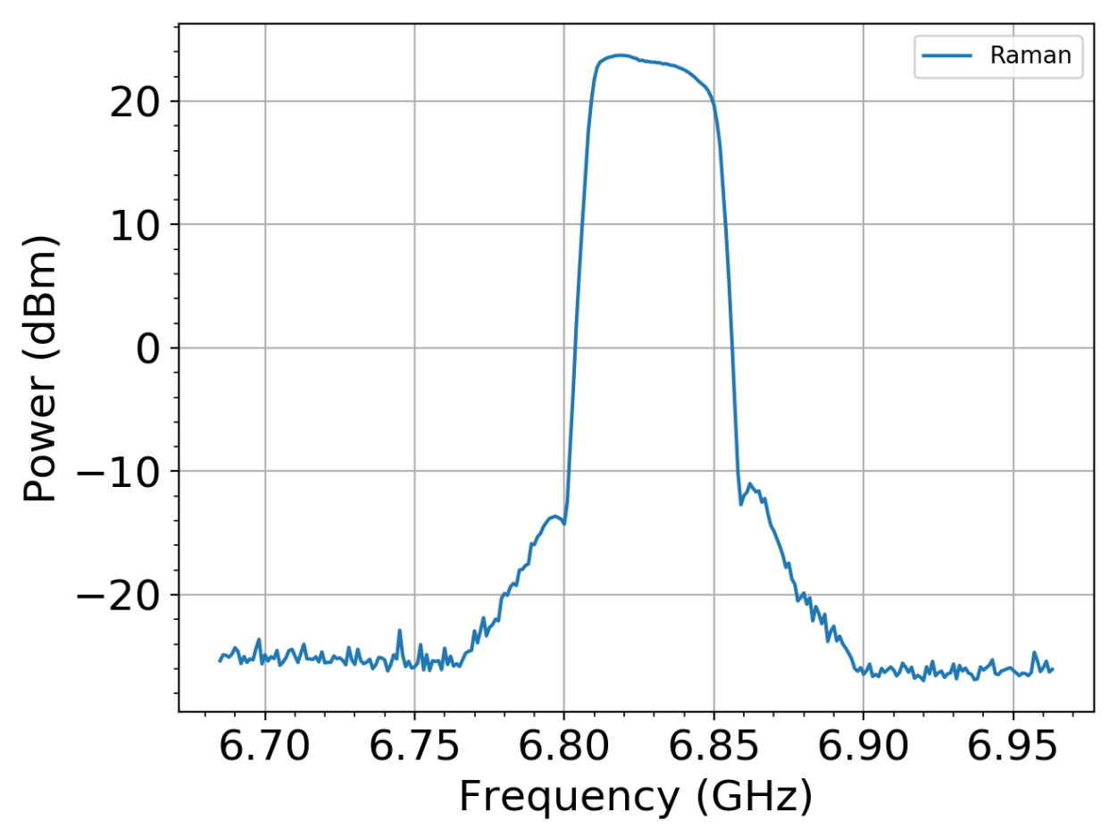


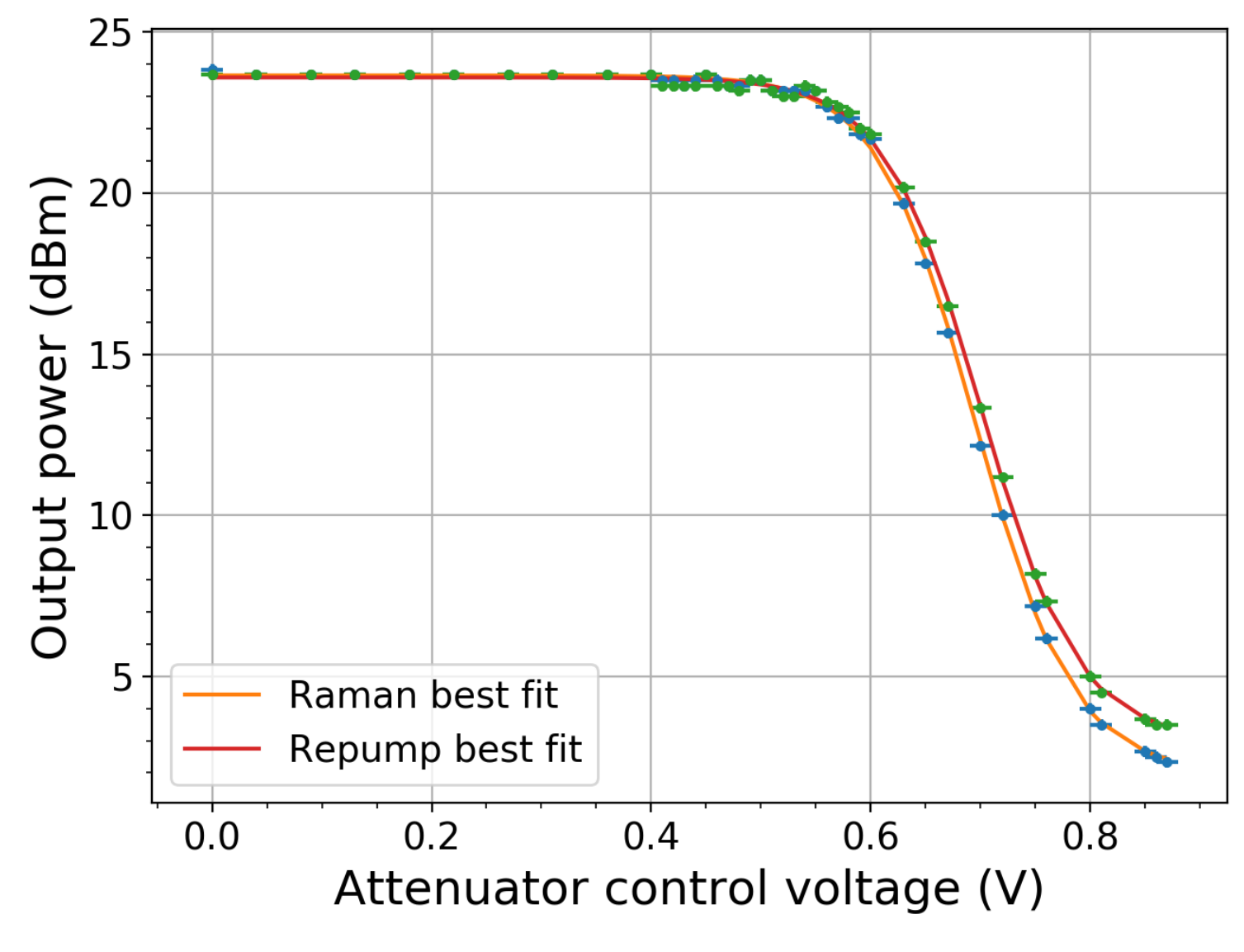


Cavity Bandpass Filters

Both channels employ strong cavity filters to remove spurious frequencies. The Repump channel uses a filter centered at 6.60 GHz with a -3 dB bandwidth of 112 MHz. The filter on the Raman channel is centered on 6.83 GHz with a -3 dB bandwidth of 41 MHz.







RF Power Control

The maximum output power achieved is (23.59 ± 0.03) dBm for the Repump signal and (23.66 ± 0.03) dBm for the Raman signal. We characterized the attenuator as a function of control voltage for both channels. This allows us to dynamically control the intensity of optical sidebands through the microwave signal power during experiments.

References and Acknowledgements

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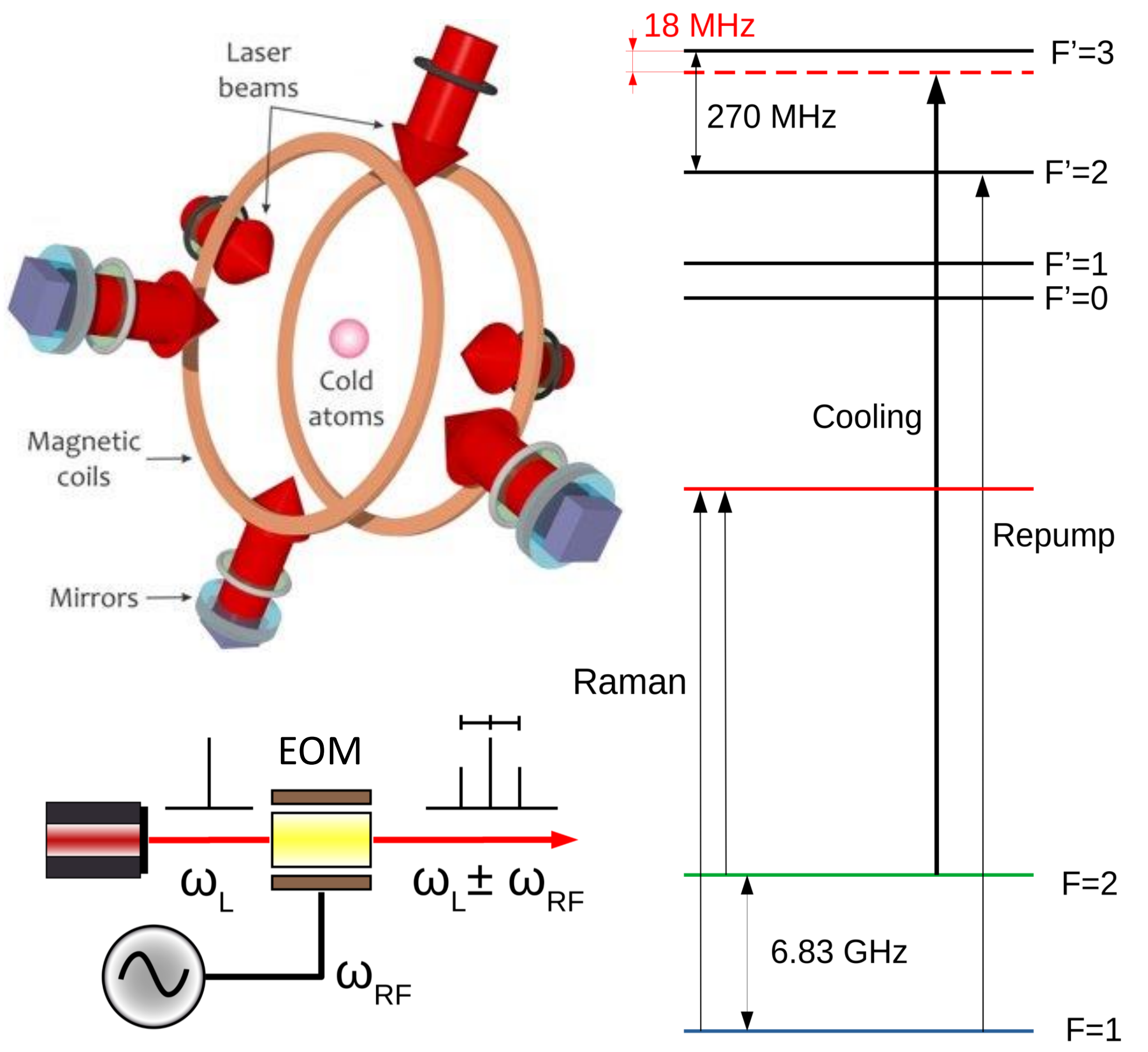
[4] This work is supported by NSERC, NBIF, and the CFI. We also thank Philippe Trottier and Torsten Reuschel of the UNB Space Physics lab for helpful discussions and assistance with electronics.

Laser Cooling and Atom Interferometry

Laser cooling of ^{87}Rb

The laser cooling process uses light red-detuned from the $F = 2$ to $F' = 3$ transition by ~18 MHz, capitalizing on Doppler shifts to decelerate atoms to ~10 cm/s through many absorption-emission cycles. Atoms that decay to the $F = 1$ ground state from $F' = 2$ are repumped by an additional laser frequency generated by an electro-optic modulator (EOM) operating at $\boldsymbol{\omega_{\mathrm{RF}}} = \mathbf{6.58}$ **GHz**.



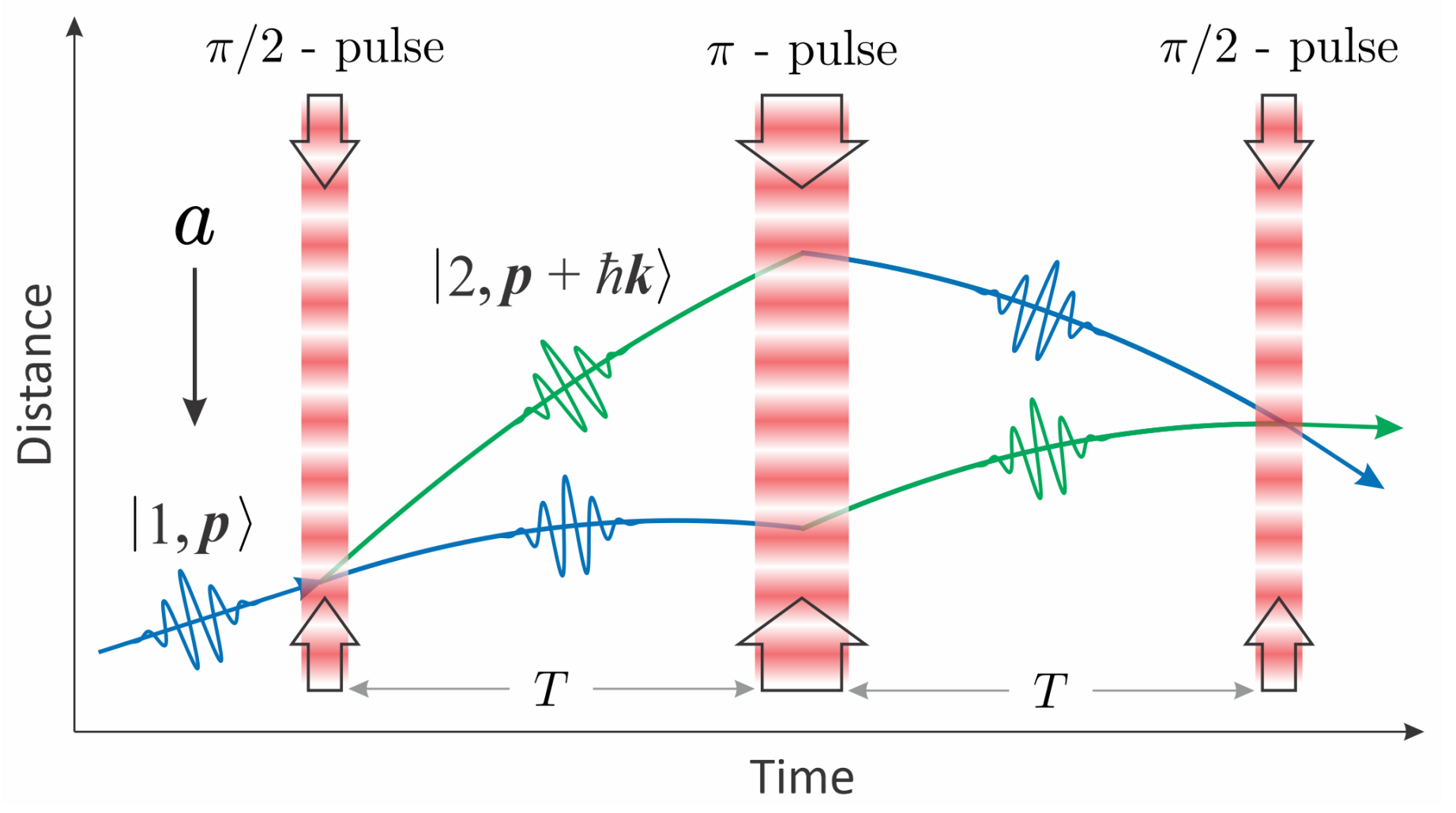
Raman interferometer

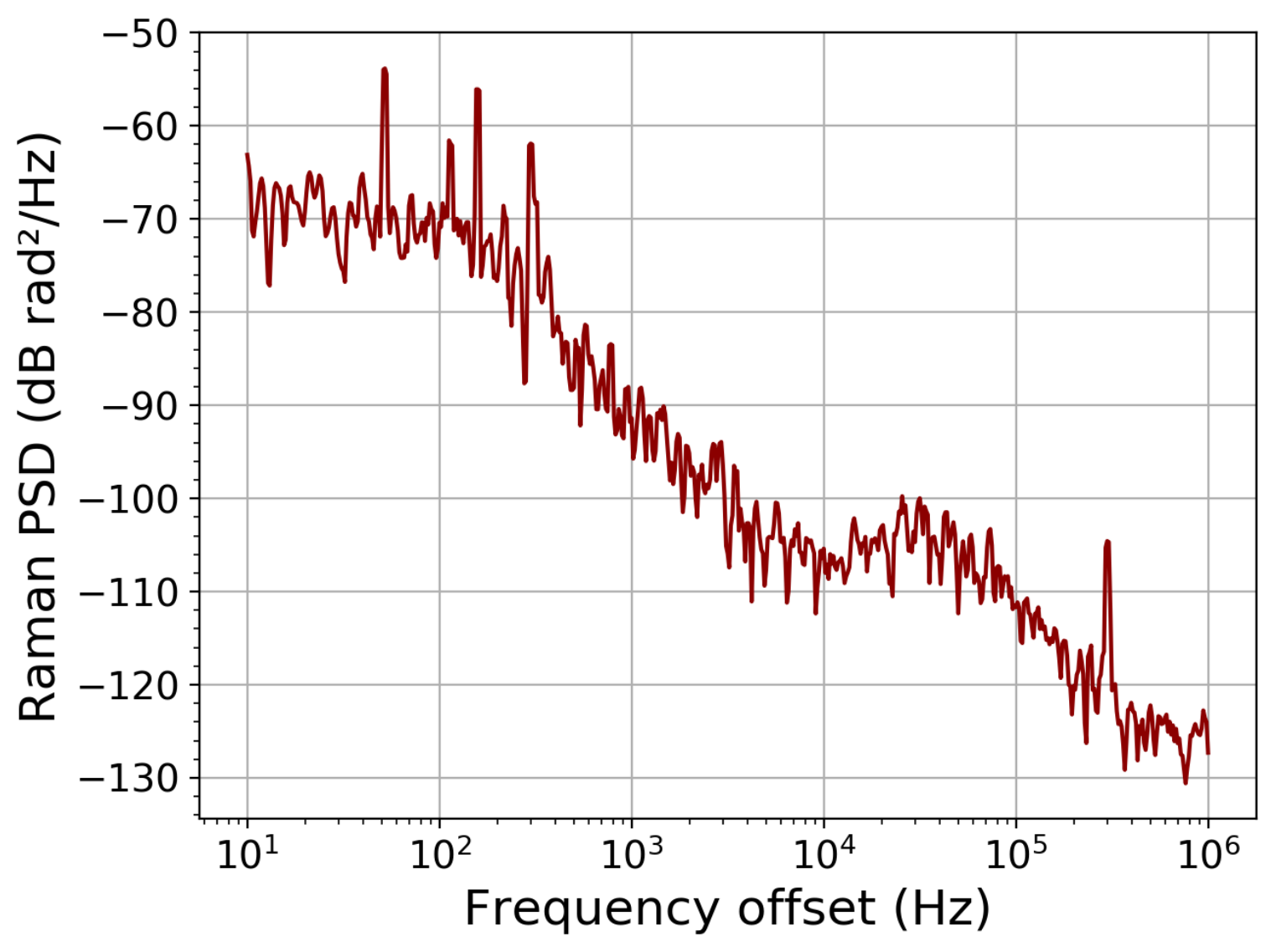
Our atom interferometer uses two-photon Raman transitions between the $F = 1$ and $F = 2$ ground states in ^{87}Rb. These two photons are separated by the hyperfine splitting $\boldsymbol{\omega_{\mathrm{RF}}} = \mathbf{6.834}$ **GHz** and are generated by driving the same EOM with our microwave synthesizer. The atom interferometer involves a sequence of three Raman pulses ($\pi/2 - \pi - \pi/2$) separated by a free-fall time T.

During each pulse, the phase of the Raman lasers $\phi_{i=1,2,3}$ is directly imprinted on the atomic wavepackets. The total phase shift at the output of the atom interferometer:

$$\Delta\Phi = \boldsymbol{k}_{\mathrm{eff}} \cdot \boldsymbol{a}\, T^2 + \phi_1 - 2\phi_2 + \phi_3$$

This phase is sensitive to the phase noise of the microwave signal.

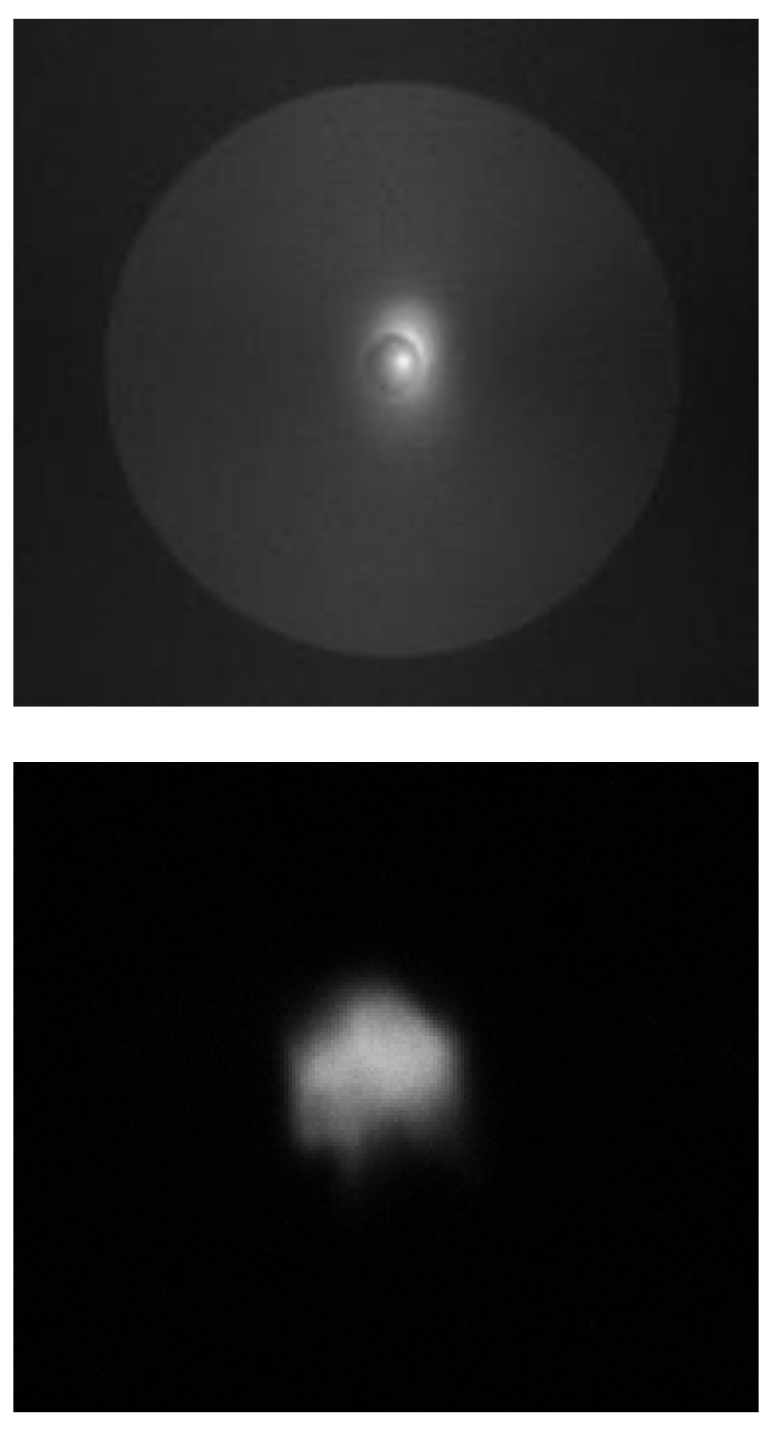




Influence of microwave phase noise

The power spectral density of the microwave phase noise at 6.8 GHz follows a $1/f$ trend with excellent performance, reaching -69 dB rad^2/Hz at 10 Hz frequency offset. The interferometric phase noise due to the synthesizer is estimated to be ~6.9 mrad at an interrogation time of $T = 100$ ms. This corresponds to a gravimeter sensitivity of $4.3 \times 10^{-9} g$ per shot.

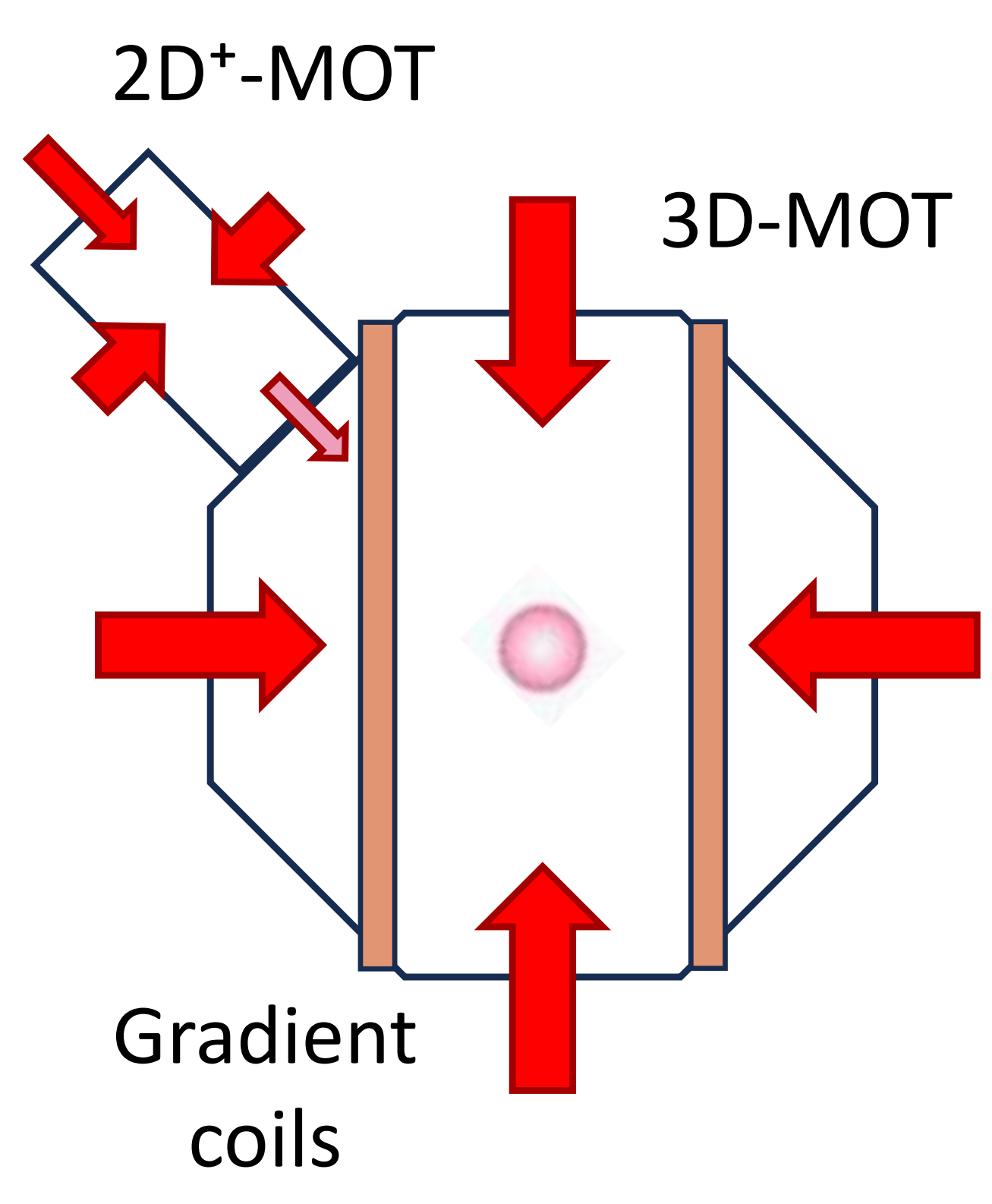
Cold Atom Source



Exposure times: 1.6 ms (top), 19 µs (bottom).

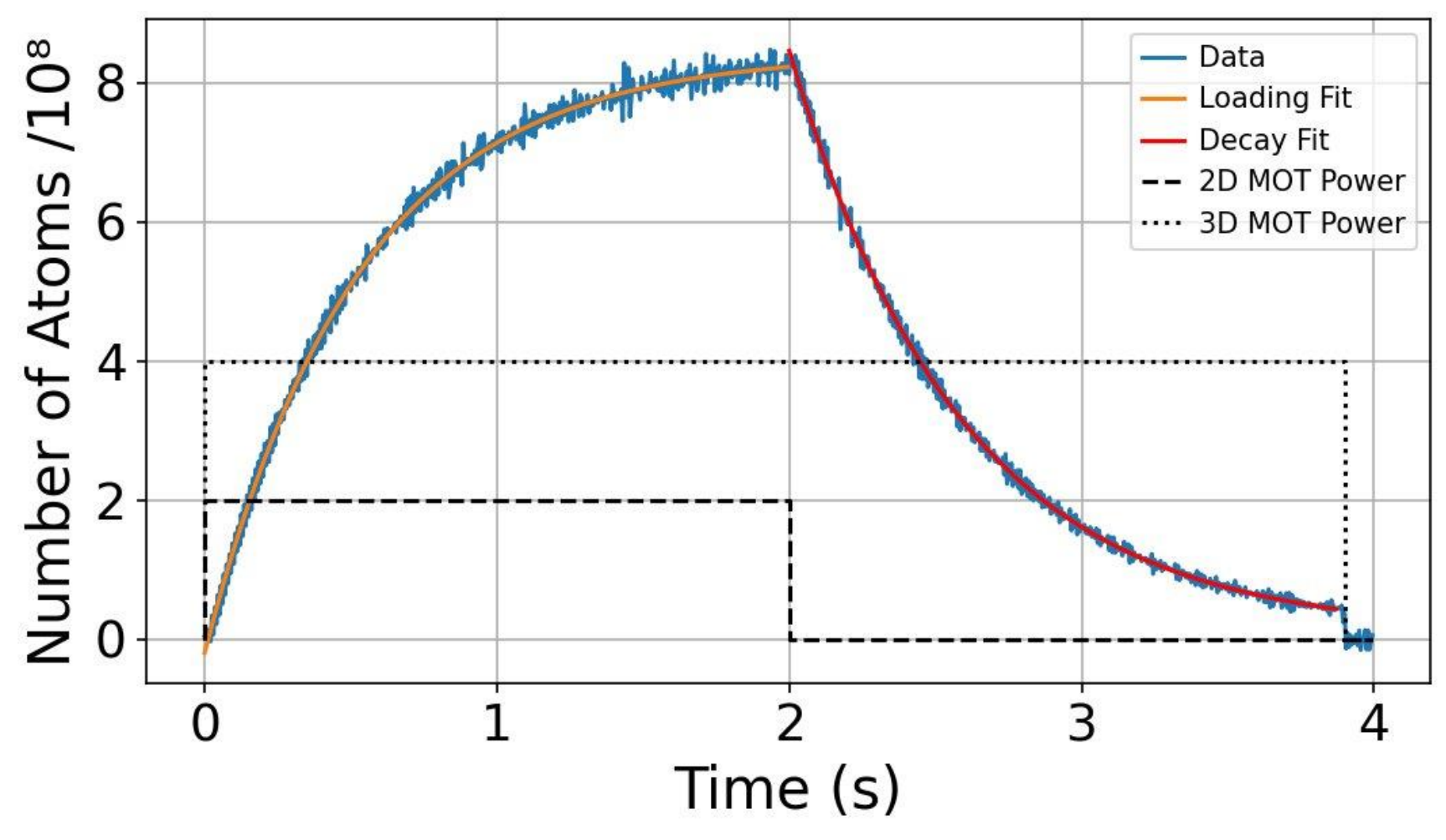
A compact 2D$^+$ / 3D MOT

Our compact cold atom source consists of a quartz vacuum cell that houses a 2D magneto-optical trap (2D-MOT) (top-left). A push beam forces transversely cooled atoms through a pinhole into a differentially-pumped region, where they are trapped and further cooled in a 3D-MOT (bottom-left). The main science chamber is a custom titanium design with excellent magnetic and vacuum properties.



MOT Loading and Decay

Fluorescence from the 3D-MOT with and without the 2D-MOT. The 2D-MOT provides an atomic flux of 1.6×10^9 atoms/s during the 3D-MOT loading. When the 2D-MOT is off, we measure a decay rate of $1.7\ \mathrm{s}^{-1}$ limited by background pressure (~5 nTorr).



Future Work

We are currently optimizing the atomic flux, atom number, and temperature of our cold atom source. This will lay the foundations for future quantum sensors based on cold-atom interferometry. We will conclude our study of the microwave synthesizer by directly measuring the phase noise of the atom interferometer.