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Towards Spectral-Hole Burning at Dilution Temperatures for Ultra Frequency-Stable Lasers

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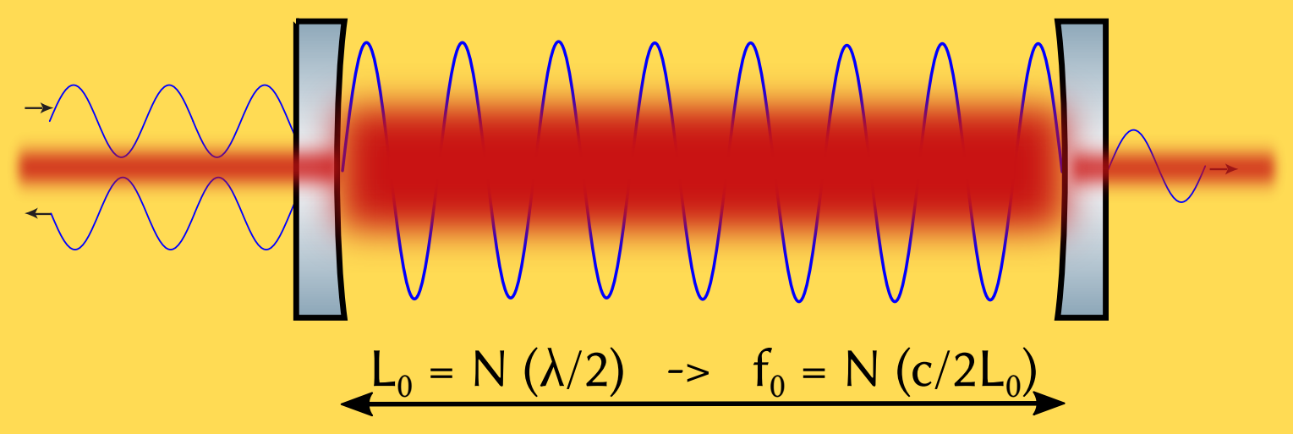
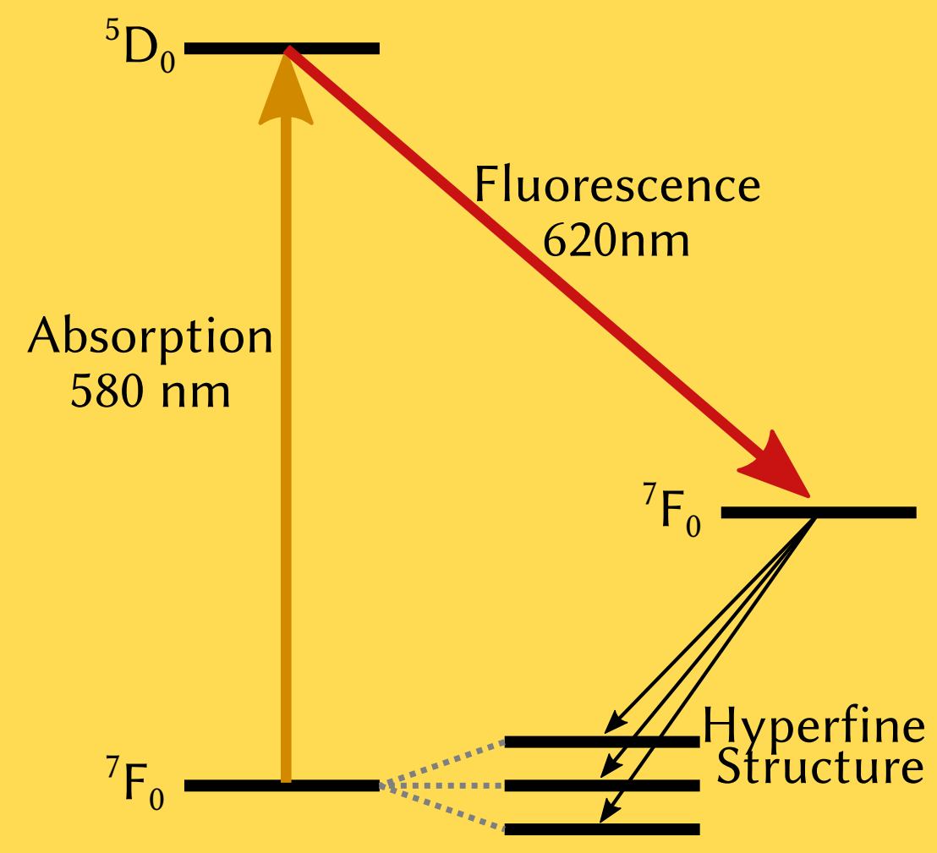
Collaboration

SYRTE SYstèmes de Référence Temps-Espace | l'Observatoire de Paris | PSL | cnrs | LNE | SORBONNE UNIVERSITÉ | NÉEL institut | UNIVERSITÉ Grenoble Alpes | Chimie ParisTech | IUF institut universitaire de France

Ultra-Stable Lasers The State of the Art

In order for optical clocks to reach their ultimate performance (quantum projection limit, ~10^{-17} fraction frequency stability at 1s), they require an ultra-stabilized probe laser, giving a **goal of 10^{-18} at 1 s.**





Traditionally, these lasers use length-stable optical cavities as a frequency reference.

Cavities have a fundamental limit, due to thermal noise, at ~10^{-16} at 1 s.

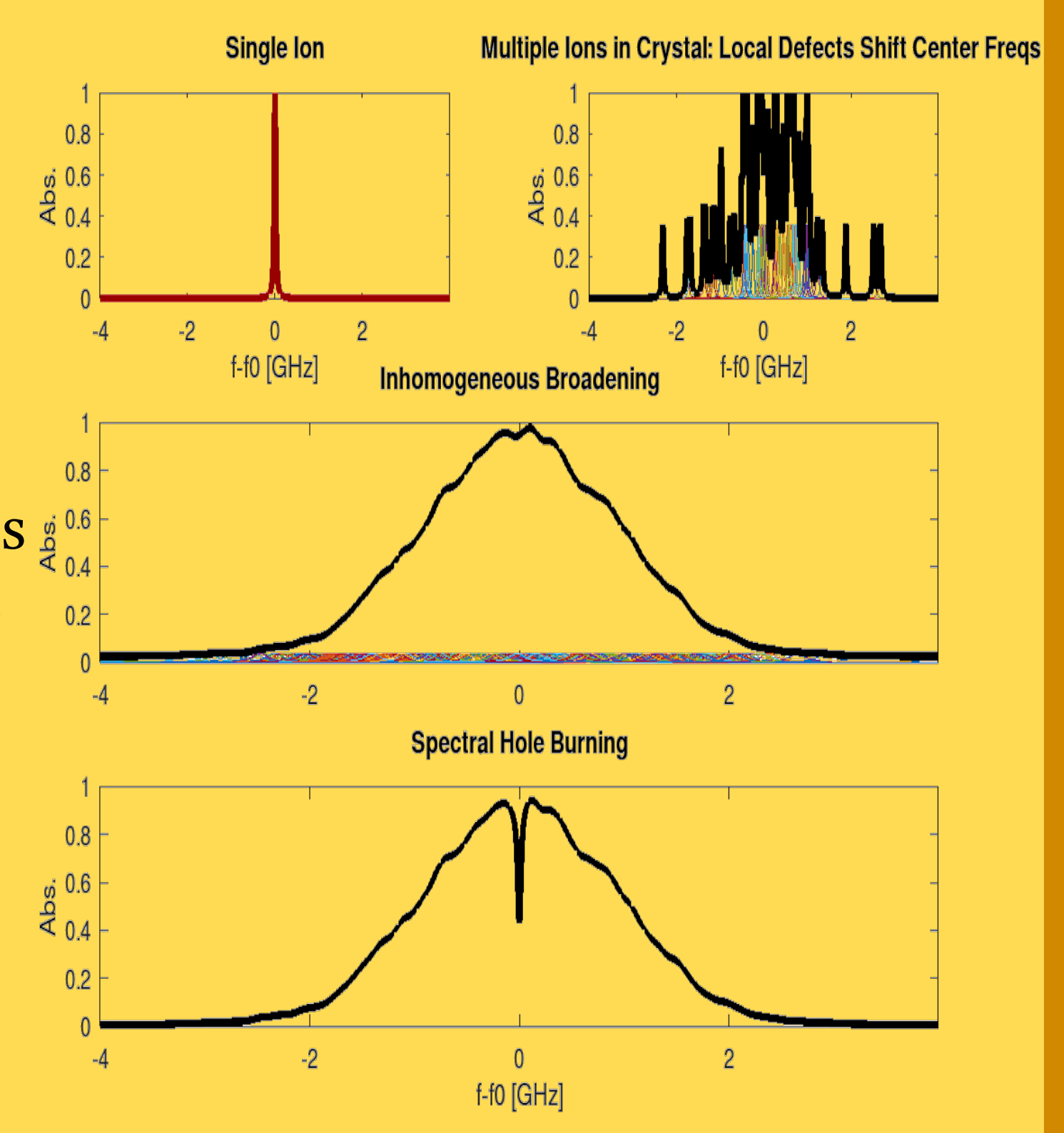
Efforts to mitigate thermal noise include alternate cavity geometries, use of high-Q materials, and cryogenic cavities.

- PTB, JILA: Cryogenic Cavities: 4×10^{-17} at 1 s
- PTB: Long Cavities: 8×10^{-17} at 1 s

While successful, this route faces considerable technological challenges.

We are researching a potential **paradigm shift in ultra-stable lasers: stabilization to an optical transition of a rare earth ion,** Europium (Eu^{3+}), doped into an Yttrium Orthosilicate (Y_2SiO_5) crystal.

Spectral Hole Burning (SHB)



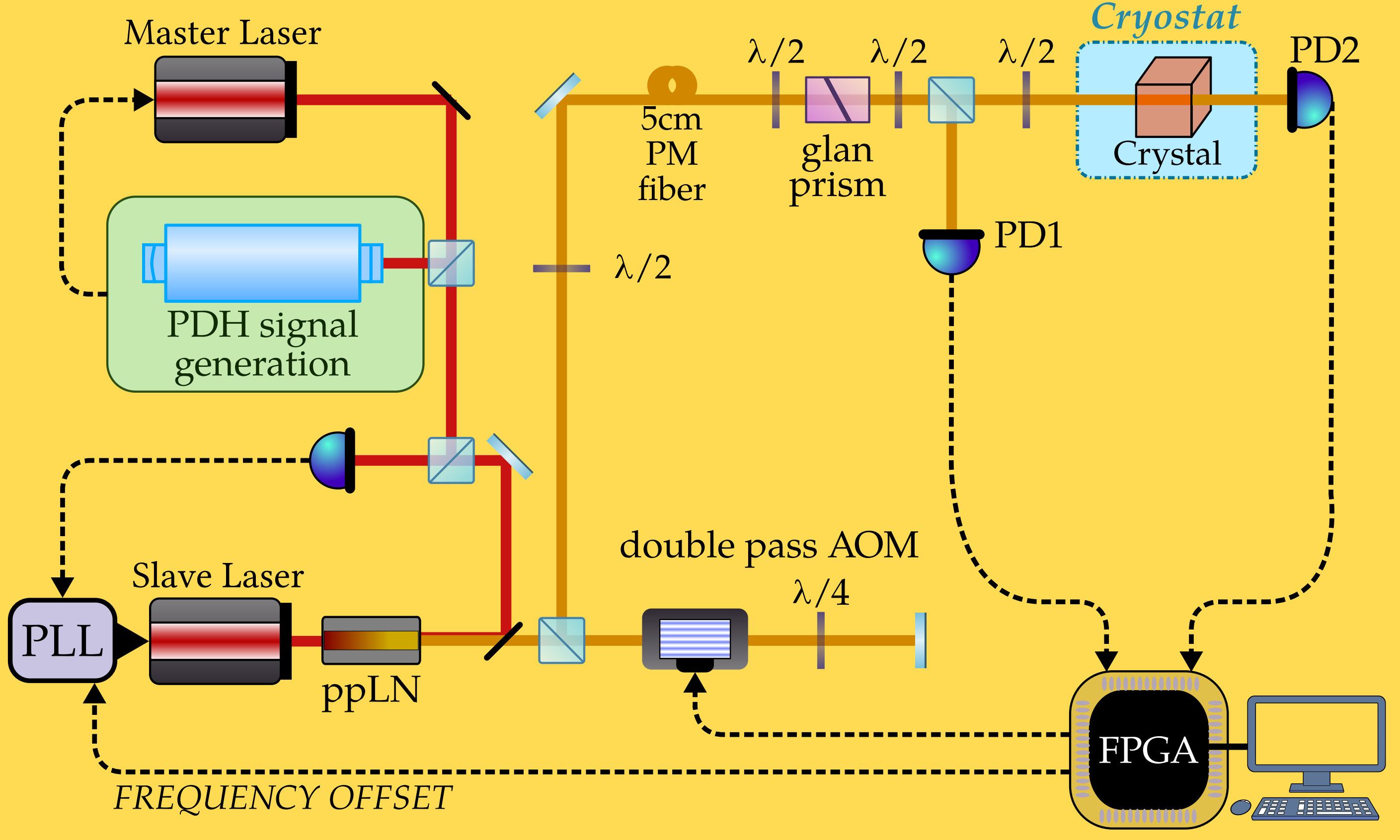
The $^7F_0$->$^5D_0$ transition in Eu^{3+} has a narrow homogeneous absorption line of order ~100 Hz

Within the crystal, inhomogeneous constraints lead to a broadening of the absorption spectrum.

A narrow linewidth pump beam at 580nm excites the ions, which drop into a hyperfine state.

Pumping all the ions out at one frequency produces a narrow transmissive 'spectral hole' in the absorption spectrum

Experimental Setup



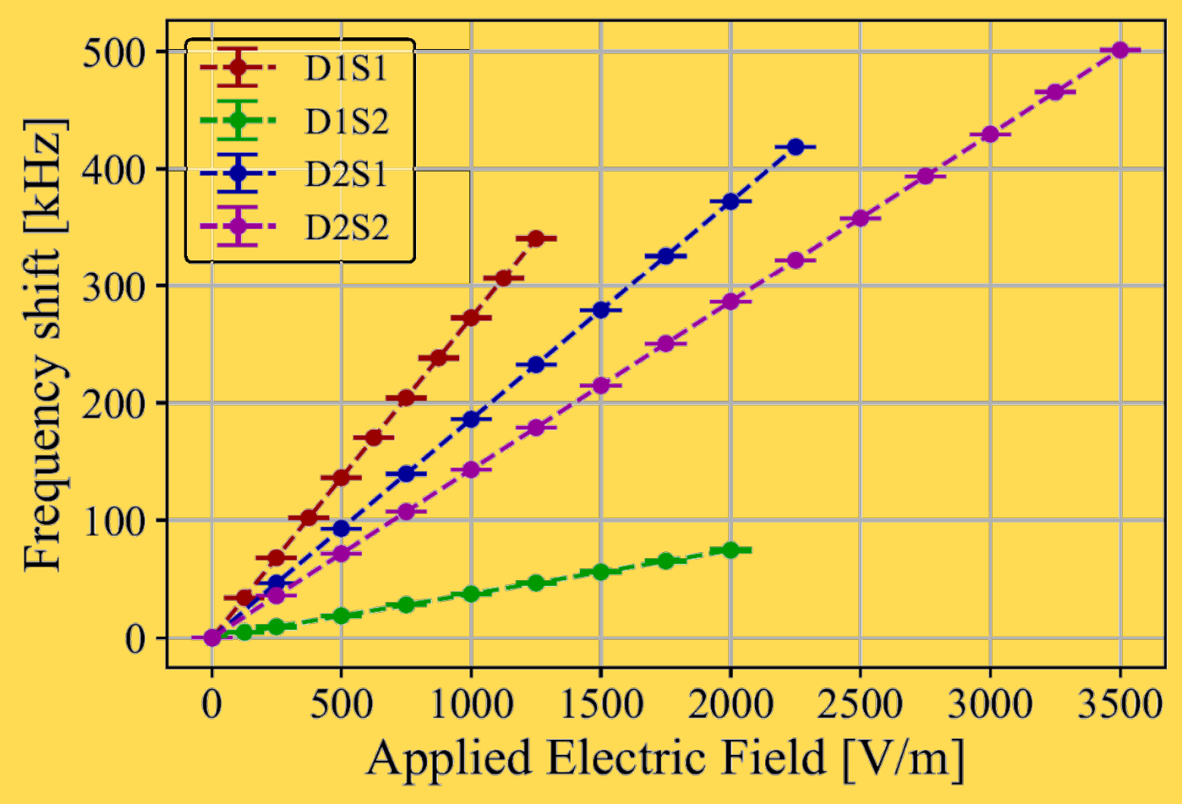
A slave laser is phase-locked to a cavity-referenced pre-stabilized master laser at 1160 nm. The slave is frequency doubled and tuned to the absorption band of the Eu^{3+}:Y_2SiO_5 crystal. The desired spectrum of beat notes is generated on the slave by an AOM driven by a GNU Radio controlled Ettus X310 FPGA-based USRP system.

At high power (1 uW) the slave laser acts as the pump, burning a spectral hole. Switching to low power (10 nW), it probes the hole, experiencing a phase retardation proportional to the frequency difference between the laser and spectral hole.

This phase difference is measured in the FPGA by comparing the transmitted beat note on PD2 with a reference beat on PD1, creating the error signal, $\epsilon = \phi^{\mathrm{p}}_{\mathrm{PD2}} - \phi^{\mathrm{p}}_{\mathrm{PD1}}$. The FPGA generates the correction signal tuning the PLL offset, actuating the slave laser towards the center of the spectral hole.

Previous Experiments and Characterizations

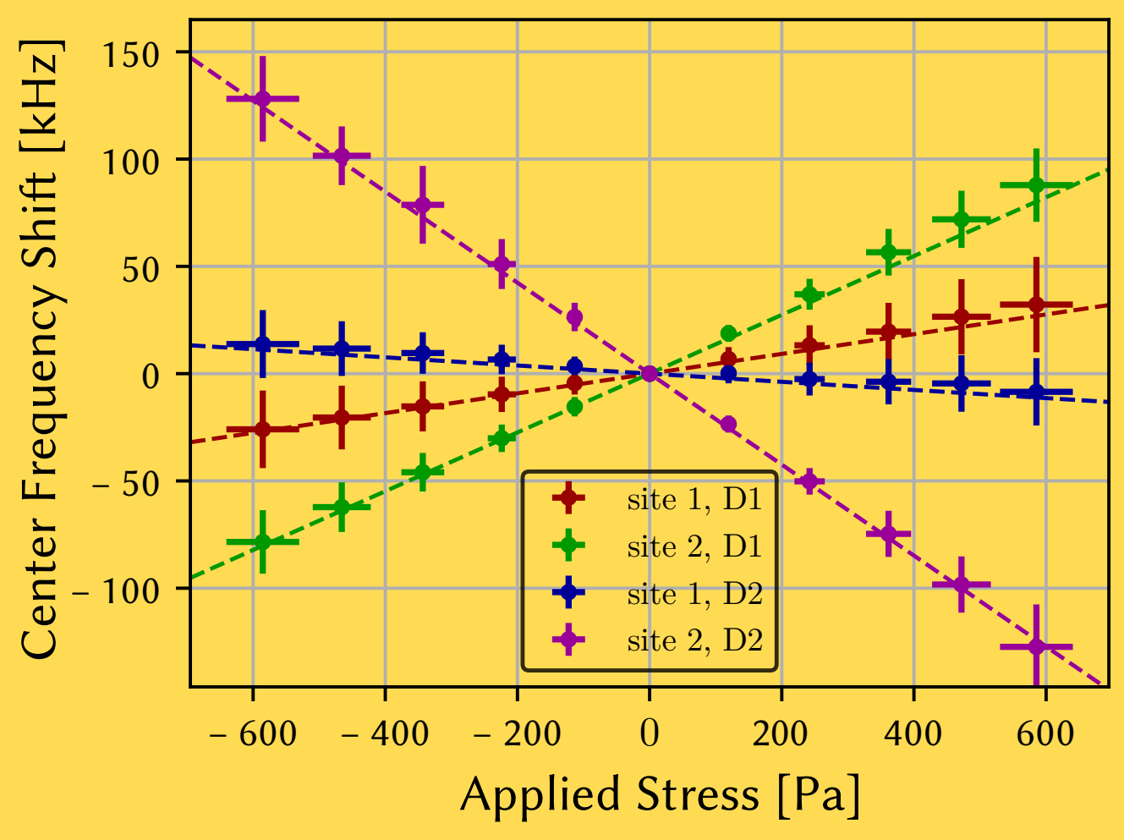
The first setup locked the laser to a spectral hole burnt at 3.7 K. The system saw a factor of 3 noise suppression over the cavity stabilized master laser, achieving a **stability of 1.7×10^{-15} at 1 s.** [1]



The experimental setup provided a testbed for novel physical measurements of spectral holes in Eu^{3+}:Y_2SiO_5.

Above: We measured the Stark effect, observing the effect on the spectral hole center frequency due to an electric field at spectroscopic sites S1=580.04 nm and S2=580.21 nm. [2]

Below: We characterized the opto-mechanical coupling, measuring the effect on the spectral hole resulting from an applied stress. [3][4]



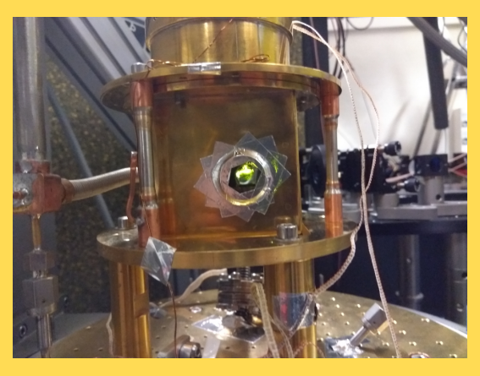
Additionally, the spectral line is well known to have a temperature dependence, with an expected f ∝ T^4 relation. In our system we measured a **9 kHz K^{-1} dependence at 3.2 K,** compatible with a previous measurement at NIST (10±2 kHz K^{-1}), when extrapolated to our working temperature.

At 3.7 K, our cryostat shows **fluctuations of 100 uK at 1s equating to a 1.7×10^{-15} fluctuation in fractional frequency**; compatible with our measured frequency stability, this implies a **temperature-limited performance.**

[1] N. Galland, et al., Opt. Lett. 45, 1930-1933 (2020).
[2] S. Zhang, et al., Appl. Phys. Lett. 117, 221102 (2020).
[3] N. Galland, et al., Phys. Rev. Applied 13, 044022 (2020).
[4] S. Zhang, et al., Phys. Rev. Research 2, 013306 (2020).

Move to Dilution Temperatures

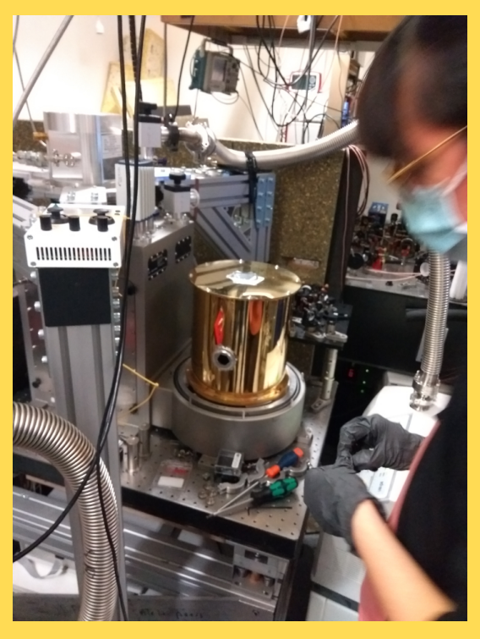
We are currently working toward operating at ultra-low temperatures, motivated by the first iteration of the experiment being limited by temperature-fluctuation induced frequency-noise.



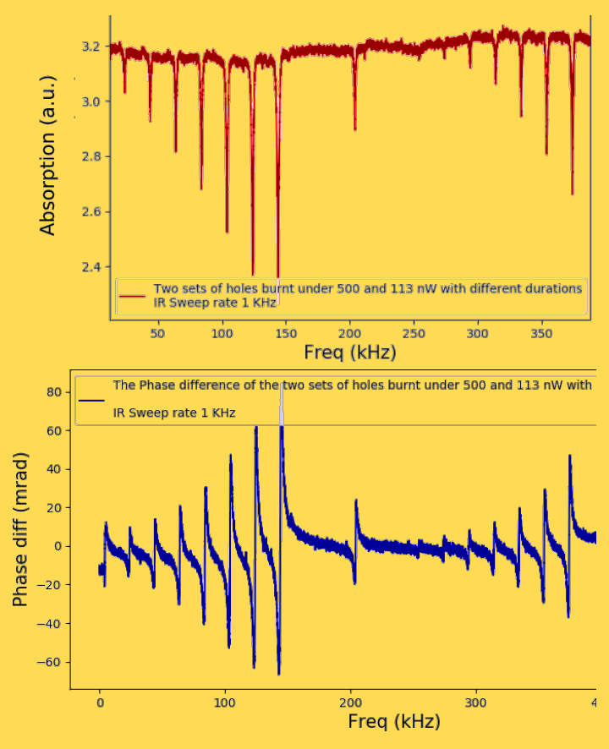
Moving to dilution temperatures (~100mK) predicts an ~ 50000× reduction in temperature - induced noise.

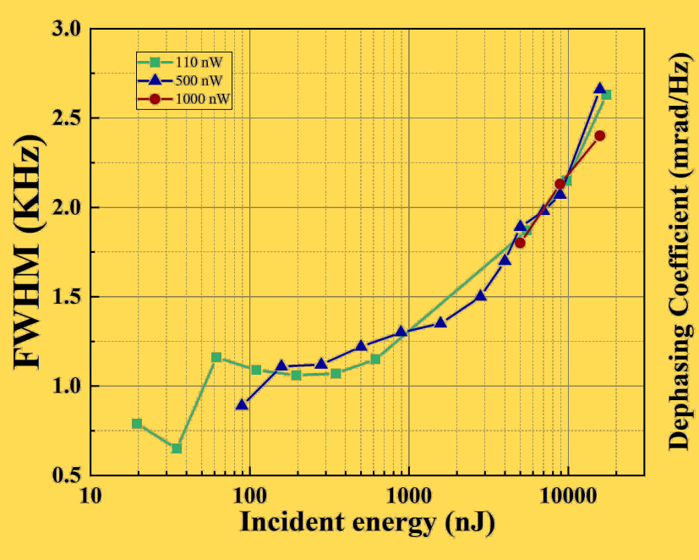
A custom dilution refrigerator has been installed and cooled the crystal to ~90mK.

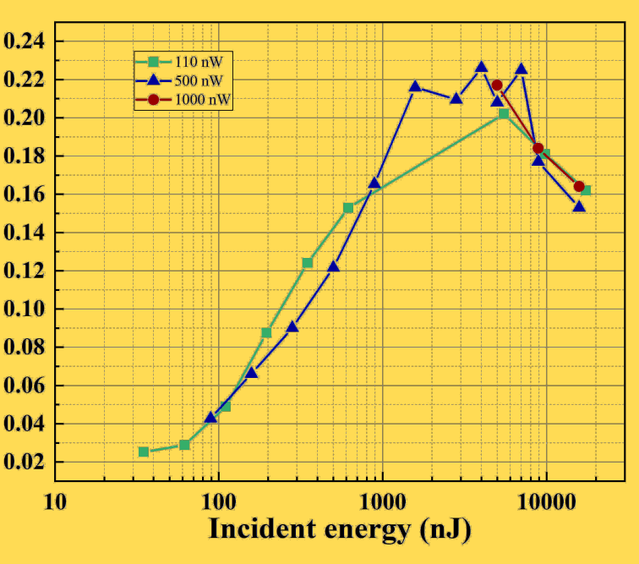
MYCRYOFIRM CRYOGENIC SOLUTIONS



Below: At this temperature, the first spectral holes have been burned and the burning process characterized.



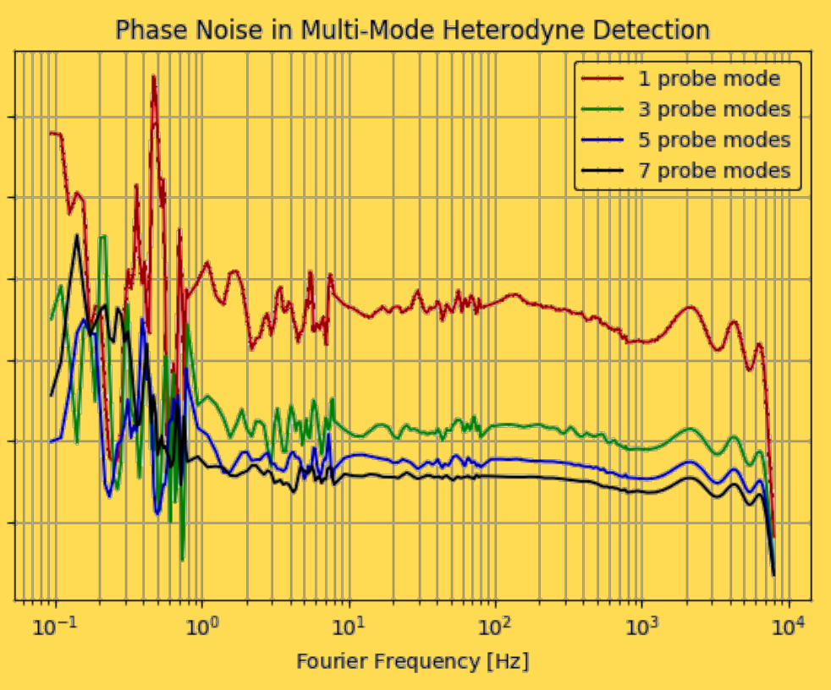




Current work is toward the measurement, at dilution temperatures, of the temperature scaling of spectral line center frequency.

Multi-mode Heterodyne Detection

We are simultaneously implementing a novel multi-mode heterodyne detection scheme to reduce sensing noise in our inherently low detection-power setup.



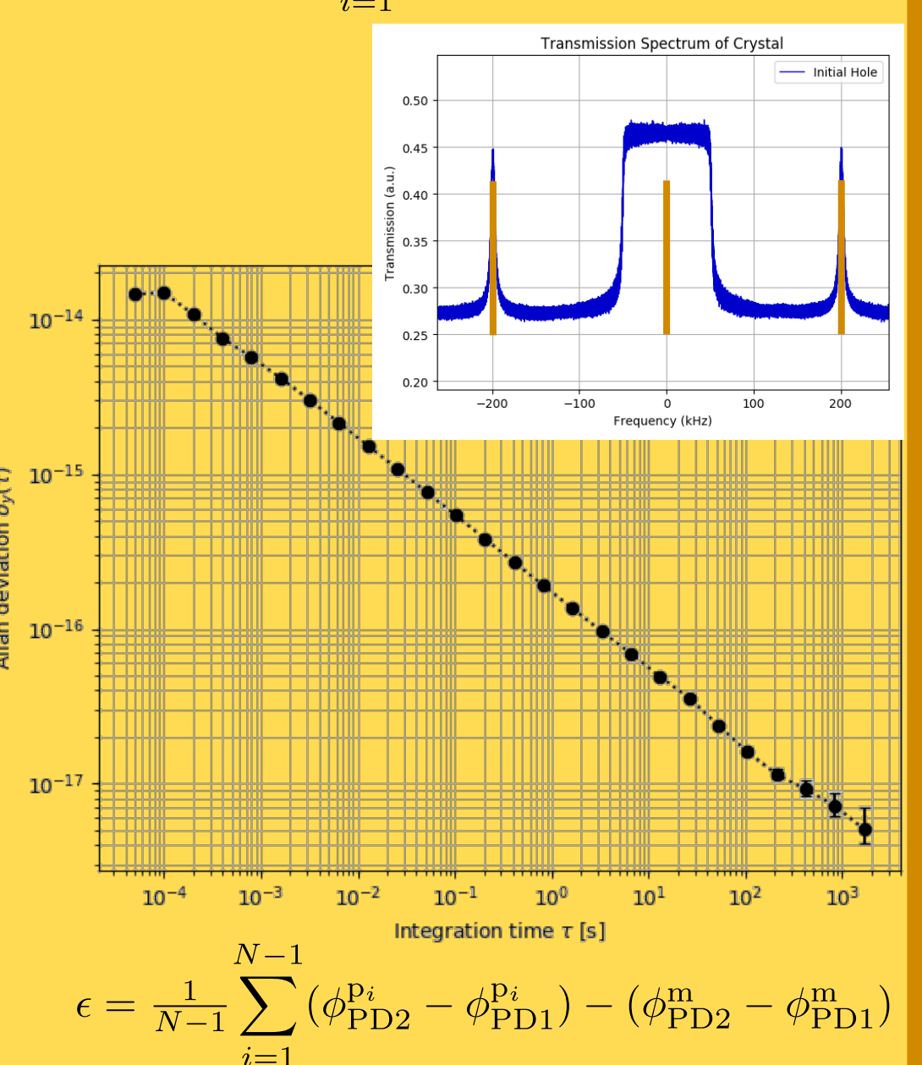
We probe multiple narrow spectral holes simultaneously using corresponding laser probe modes, p_i.

Right: We average over the modes, reducing uncorrelated noise.

$$\epsilon = \frac{1}{N}\sum_{i=1}^{N}(\phi^{\mathrm{p}_i}_{\mathrm{PD2}} - \phi^{\mathrm{p}_i}_{\mathrm{PD1}})$$

To reduce correlated noise we utilize one mode as a 'monitor mode', m. Propagating on the same beam, the monitor mode passes through a broad 'square' spectral hole, accumulating common path length noise.

Right: Measurement of sensing noise projected to frequency stability: subtracting path-length noise in real-time has yielded high common mode noise rejection into the thousands of seconds.



$$\epsilon = \frac{1}{N-1}\sum_{i=1}^{N-1}(\phi^{\mathrm{p}_i}_{\mathrm{PD2}} - \phi^{\mathrm{p}_i}_{\mathrm{PD1}}) - (\phi^{\mathrm{m}}_{\mathrm{PD2}} - \phi^{\mathrm{m}}_{\mathrm{PD1}})$$

Current efforts are toward the reduction of lag in the digital feedback loop for increased bandwidth.

Thanks To

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