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

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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.





Spectral Hole Burning (SHB)

The ${}^{7}F_{0}$ -> ${}^{5}D_{0}$ transition in Eu³⁺ has a narrow homogeneous absorption line of order ~100 Hz

Within the crystal, inhomogeneous constraints g^{0.6} lead to a broadening of the absorption spectrum.



$L_0 = N (\lambda/2) \implies f_0 = N (c/2L_0)$

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.

Absorption 580 nm yperfine tructure

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 (Y₂SiO₅) crystal.

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 cavityreferenced pre-stabilized master laser at 1160 The slave is frequency doubled and nm. to the absorption band of the tuned Eu³⁺:Y₂SiO₅ 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, PLI experiencing a phase retardation proportional to the frequency difference between the laser and 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]



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, $\epsilon = \phi_{PD2}^{P} - \phi_{PD1}^{P}$. The FPGA generates the correction signal tuning the PLL offset, actuating the slave laser towards the center of the spectral hole.

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 MYCRYOFIRM (~100mK) predicts an ~ 50000× reduction in temperature induced noise. A custom dilution refrigerator has been installed and cooled the crystal to ~90mK.



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.

probe multiple narrow We spectral holes simultaneously using corresponding laser probe modes, p_i. Right: We average over the modes, reducing uncorrelated noise.

To reduce correlated noise we utilize one mode as a 'monitor mode', m. Propagating on the

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 $f \propto T^4$ 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.

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

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 pathlength noise in real-time has 10 yielded high common mode noise rejection into the thousands of seconds.



 $\epsilon = \frac{1}{N} \sum (\phi_{\text{PD2}}^{\text{p}_i} - \phi_{\text{PD1}}^{\text{p}_i})$

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

[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).

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