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► **To cite this version:**

M. T. Hartman, X Lin, B Pointard, R Le Targat, B Fang, et al.. First Measurements of Spectral Hole Line Shifts at Dilution Temperatures for Laser Stabilization. 2023 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium (EFTF/IFCS), May 2023, Toyama, Japan. hal-04460611

**HAL Id: hal-04460611**

**<https://hal.science/hal-04460611>**

Submitted on 15 Feb 2024

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# First Measurements of Spectral Hole Line Shifts at Dilution Temperatures for Laser Stabilization

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**Abstract**—Here we report on the status of the Spectral-Hole Burning (SHB) laser-stabilization experiment at LNE-SYRTE, focusing on our first measurements of thermally induced frequency shifts of spectral holes at dilution temperatures ( $T_0 < 1$  K). The effect, which is predicated to scale as  $T^4$ , produces shifts of order 1 – 10 Hz over its  $\approx 517$  THz center at these temperatures. To meet this challenge, we introduced a novel temperature-modulation based approach to spectral-hole line shift measurements, allowing integration time of the small signals. We find a preliminary value for the line-shift constant of  $\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$ ,  $\alpha = 107 \text{ Hz K}^{-4}$ , a first at dilution temperatures.

**Index Terms**—Spectral Hole Burning, Laser Frequency Stabilization, Metrology, Spectroscopy

## I. INTRODUCTION

The spectral-hole burning (SHB) experiment at LNE-SYRTE aims to produce an ultra frequency-stable laser by spectroscopic methods. The current state of the art ultra-stable lasers involve locking to a length-stable optical cavity as a frequency reference [1] [2]; however, this approach is reaching a fundamental materials limit, Brownian noise in the cavity mirrors. The SHB experiment explores a different approach to laser stabilization by utilizing, as its frequency reference, a transmissive spectral line (spectral hole) which we imprint (burn) at one of two absorption sites (homogeneously broadened about 580.039 nm and 580.211 nm) in a rare-earth-ion doped crystal,  $\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$  [3].

The SHB group has previously demonstrated the technique, stabilizing a laser to a pulse tube cooled crystal ( $T_0 = 3.7$  K) achieving a fractional frequency stability of  $1.7 \times 10^{-15}$  over 1 s [4], as well as studying the effects of mechanical stress [5] [6] and external electric fields [7]. Further characterizations of our experimental detection noise floor [4] and of the spectral hole thermal line shifts in the 3 – 6 K range [Manuscript in Press, Phys Rev A] suggest that these are performance limiting effects. The  $T^4$  scaling of the thermal shifts motivates our move to a dilution refrigerator to cool our sample below 1 K. Here we present our initial measurements of spectral-hole line shifts at dilution temperatures.

This project is funded by Ville de Paris Emergence Programme, Agence Nationale de la Recherche, LABEX FIRST-TF (ANR-10-LABX-48-01); H2020 Excellent Science (EMPIR 20FUN08 NEXTLASERS - EMPIR programme cofinanced by the Participating States and from the EU Horizon 2020 Research and Innovation Programme).

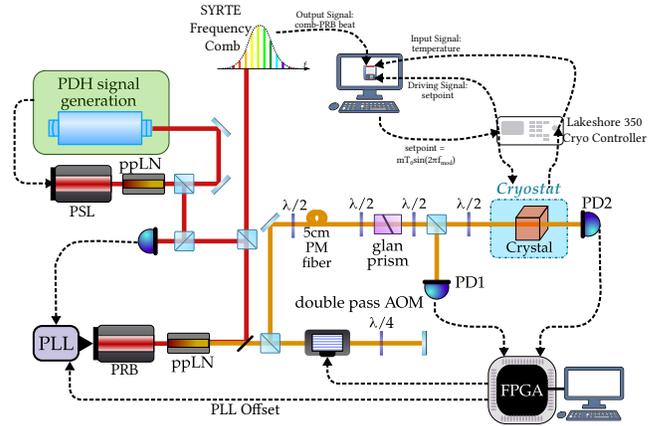


Fig. 1. Illustration of the SHB setup at LNE-SYRTE.

## II. EXPERIMENTAL SETUP

The setup, illustrated in Fig. 1, uses two tunable 1160 nm diode lasers. An infrared pre-stabilized laser (PSL) is locked to an optical cavity. The infrared probe laser (PRB) is locked to the PSL transferring its initial stability through an offset phase-lock-loop (PLL). The PLL offset is sourced by an FPGA based software defined radio (SDR) system (Ettus USRP X310) upmixed by a function generator. A portion of the infrared light is sent to the frequency comb at LNE-SYRTE, providing a stable and robust frequency count of the PRB.

The PRB is frequency doubled to interrogate the spectroscopic sites near 580 nm. The yellow 580 nm beam completes a double-pass through a high-speed AOM where the light is frequency shifted by a custom spectrum, also generated by the SDR at a second output. As we implement a multi-spectral-hole interrogation scheme, several probe modes are imprinted at this point. The resulting spectrum of beat signals is split: a reference beam is measured by photodetector PD1, and the other beam probes the crystal where each probe mode experiences a phase delay proportional to the difference frequency between the laser and the spectral hole. PD2 measures the dephased beat notes. The signals from PD1 and PD2 are digitized by the SDR which produces the error signal. The PRB is actuated toward the center of the spectral hole by controlling the PLL offset.

### III. METHODS

Similar to our own previous thermal line shift measurements [Manuscript in Press, Phys Rev A], two groups have made earlier measurements of thermal line shifts in  $\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$  by measuring the change in the absorption profile for increasing crystal temperatures from 2.5 K and above [8] [9] where temperature sensitivities at spectroscopic site 1 are on the order of  $10\,000\text{ Hz K}^{-1}$  and higher. For dilution temperatures, where the sensitivities are on order  $10 - 100\text{ Hz K}^{-1}$ , we implement a different approach.

We lock the PRB laser to a spectral hole burned in the crystal held at 700 mK. The crystal temperature is controlled by a resistive heater in an active loop driven by a commercial cryogenic temperature controller (Lakeshore 350). A custom control program modulates the temperature set-point, simultaneously recording 0) the registered set-point (the system's driving signal), 1) the measured actual temperature (the system's input signal) and 2) the PRB-frequency comb beat (the system's output signal). Care is taken in optimizing the feedback PID gain, selecting appropriate modulation depths ( $m = 0.01, 0.02$ ) and frequency ( $f_{\text{mod}} = 31.6\text{ mHz}$ ) to ensure that the temperature tracks the set-point. An example data point is shown in Fig. 2. A fit to the system driving signal provides the reference sinusoid. The amplitude and phase of the temperature ( $A_1, \phi_1$ ) and beat note signal ( $A_2, \phi_2$ ) modulation are determined through I-Q demodulation with the fitted reference sinusoid. The temperature sensitivity of the frequency is then calculated directly,  $\frac{df}{dT} = \frac{A_2}{A_1}$ .

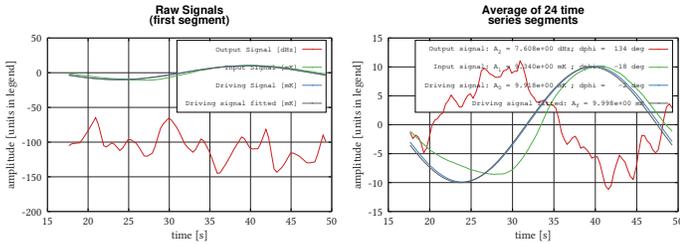


Fig. 2. An example data point of recorded temperature set-point, measured temperature, and frequency data. Left: Raw time series segment covering 1 modulation period. Right: Signals after averaging and removing offset

### IV. RESULTS

Staying locked to the spectral hole over a period of several hours, we actuate the mean crystal temperature to each measurement point, stopping to modulate for 24 periods. The resulting plot of temperature dependent temperature sensitivities is shown in Fig. 3. At temperatures below the Debye Temperature, the absolute shift in the spectral line center frequency is given in terms of the line shift constant,  $\alpha$ :  $\Delta f = \alpha T^4$ . Over the temperature range  $0.5 - 0.9\text{ K}$ , we fit this constant to be  $\alpha = 107\text{ Hz K}^{-4}$  at site 1 from our preliminary data. By comparison, at site 1 others have measured this constant to be  $\alpha_1 = 168 \pm 25\text{ Hz K}^{-4}$  fitting over  $70 - 100\text{ K}$  [8] and  $\alpha_1 = 76 \pm 15\text{ Hz K}^{-4}$  measuring over the range  $2.5 - 5.5\text{ K}$  [9].

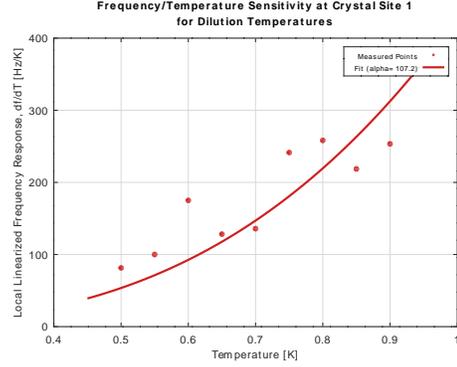


Fig. 3. Preliminary measurements of temperature spectral line sensitivity of spectral holes in  $\text{Eu}^{3+}:\text{Y}_2\text{SiO}_5$  for temperatures from  $0.5 - 0.9\text{ K}$ , and a fit of the spectroscopic site 1 line shift constant  $\alpha$ .

### V. DISCUSSION

These early results support our expected 3 order of magnitude reduction in temperature sensitivity by moving from pulse-tube to dilution temperatures. Considering measured cryostat temperature fluctuations of order  $100\text{ }\mu\text{K}$  over 1 s, this reduces the temperature-induced limit to fractional laser frequency stability from order  $10^{-15}$  down to  $10^{-18}$ . This measurement, a first in spectral-hole spectroscopy, marks a major step towards achieving our goal realizing an ultra-stable laser with a fractional frequency stability of  $10^{-18}$  at 1 s.

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