Frequency locking a laser on a spectral hole pattern with a multi-channel heterodyne method using SDR and GnuRadio

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Abstract

High precision spectroscopic probing of a narrow spectral hole pattern imprinted in the inhomogeneously broadened absorption spectrum of $Eu^{3+} : Y_2SiO_5$ crystal can be used to stabilize a laser frequency. A multi-hole pattern can be burn and all the holes can be probed simultaneously using a multiple frequency signal. The dispersion induced dephasing acquired by the light through the crystal is measured to derive an error signal suitable to lock the laser frequency to the spectral hole pattern. An Ettus USRP X310 driven by a python program based on GNU Radio is used for both generating the multiple frequency signal and to compute the correction applied to the laser frequency.

1 Introduction

Frequency stabilization of ultra-stable lasers is typically realized using high finesse optical Fabry-Perot cavities (FPC) that can provide a stability of a few 10^{-16} at about 1 s integration time. However, recent development concerning optical lattice clocks appear to require lower frequency noise at this time scale to obtain the best performances of the clock.

A new direction of development for laser stabilization relies on spectral hole burning. The spectral pattern imprinted in a rare earth doped crystal at cryogenic temperature is expected to show higher stability than the brownian motion limited FPC [1], [2].

The spectral hole burning technique relies on two physical processes occuring in $Eu^{3+} : Y_2SiO_5$ crystals. First, the initially narrow $^7F_0 \rightarrow {}^5D_0$ transition of Eu^{3+} is, due to inhomogeneities in the host crystalline matrix, broadened from 120 Hz for an isolated ion to approximately 2 GHz. Secondly, at cryogenic temperatures, a narrow linewidth laser can excite some ions to metastable levels with a lifetime that can reach tens of days at 4 K. By doing so, the absorption is saturated around the laser frequency and a hole is created in the absorption spectrum that can be use as a frequency discriminator for laser stabilization.

2 Experimental setup

To ensure the possibility of spectral hole burning, the europium doped yttrium orthosilicate ($Eu^{3+} : Y_2SiO_5$) crystal is maintained at a cryogenic temperature, typically between 3.2K and 4K, in a commercial close-cycle cryostat with vibration isolation.

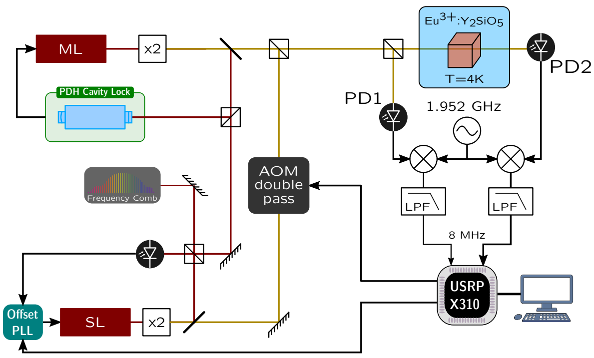

Figure 1: Schematics of the experimental setup. The GNU Radio flowgraph is driving the USRP to generate multi frequency signal for AOM and computing the correction applied to the offset of the PLL from the two RX signals

A two-laser optical system is used to burn and then probe the spectral hole. The master laser at 1160 nm is pre-stabilized to a high finesse FPC. An offset phase-lock loop is used to servo the slave laser at 1160 nm to the master laser with a controlled offset frequency (typically 980 MHz). Both lasers are independently frequency doubled to reach 580 nm, the center of the broadened transition $^7\mathrm{F}_0 \rightarrow {}^5\mathrm{D}_0$. The slave laser is then sent to a double-pass AOM to generate an arbitrary spectral pattern in the light (in the 1 MHz range around the center frequency). Both yellow lasers are then spatially overlapped and the resulting beam is splitted in two channels, one going through the crystal and to a 2 GHz bandwith photodiode, the other directly to an identical photodiode for reference.

The beatnote obtained on each photodiode is demodulated to 8 MHz and amplified before acquisition by the two RX channels of an Ettus USRP X310. One TX channel is used to drive the frequency offset between the two lasers. The other TX channel is used to drive the double-pass AOM.

The GNU Radio flowgraph is on the one hand deriving the error signal from the dephasing between RX channels induced by the spectral hole dispersion. A spectral mask is applied to band pass filter the RX signal arround different frequencies and remove any unwanted spectral component. The a proportionnal and integrator filter applied on the error signal provides a correction modulating the TX channel driving the offset frequency. On the other hand, another flowgraph is used to generate an arbitrary spectral pattern applied to the AOM.

3 Results

An optical frequency comb stabilized on a state-of-the-art ultrastable laser allows us to evaluate the stability of our laser over a timescale from 1 s to 1000 s. We can therefore measure the stability of the laser pre-stabilized to our FPC to approximately 10^{-14} fractional frequency instability at 1 s.

By using a double hole pattern with one reference mode (in a wide hole and so experiencing a small dispersion) and one signal mode (in a narrow hole, experiencing a big dispersion as a function ot the detuning), we obtain a good frequency lock of the laser on the narrow hole. The laser then exhibits a stability in the low 10^{-15} for 1 s to 10 s time scale. This result is almost one order of magnitude better than the previous results obtained on this experiment while using a single hole to derive the correction signal [3].

4 Conclusion

The double-hole based detection has improved a lot the detection noise of the detuning induces dispersion. Indeed, the previous detection scheme using only one hole was exhibiting a noise level compatible with a stability in the low 10^{-15} at 1 s. The new scheme shows a detection noise compatible with a stability in the mid 10^{-16} at 1 s.

We then infer that the residual instability of the laser when locked to the spectral hole is not due to the detection noise of the setup, but to other technical issues. Next imporvement will be to reduce the thermal fluctuation of the sample holder in the cryostat and the residual vibration due to the working cycle of the pulsed tube. An investigation to find the optimal spectral pattern will also be conducted to reach the low 10^{-16} at 1 s or below.

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