Laser Frequency Stabilization for Aerospace Applications

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Abstract

Long term frequency stability of lasers is a key parameter in many research areas ranging from dimensional metrology to fundamental physics. Many solutions have been proposed by the scientific community and lasers whose frequency is referenced to molecular transitions are commonly used when long term stability and wavelength accuracy are needed. Our goal is the development of a frequency stabilization system with a relative frequency stability (Allan variance) of 10^{-12} over 1 second integration time which will be suitable for aerospace applications. The frequency reference is a 10 cm long Fabry-Perot optical resonator which has been designed in order to withstand the huge launch loads (up to 30g at 1 kHz). As the stability of the resonant frequency is determined by the long term stability of the cavity length, a low CTE material (ULE) was adopted as the cavity spacer. During the laboratory tests the cavity has been housed inside a mechanical insulating vacuum chamber, thermally controlled by a digital system. The laser is referenced to one of the cavity resonances by means of a digital implementation of the Pound-Drever-Hall technique. An FPGA equipped with a small number of auxiliary components provides a flexible and reconfigurable digital system. A laser was locked to an iodine transition using the "digital PDH" and a classical analog system; the same frequency stability (parts in 10^{13} over a 1 second integration time) was measured. Currently we are working on the implementation of the thermostat in order to properly length-stabilize the Fabry-Perot resonator and to characterize the coefficient of thermal expansion of the ULE spacer we are using.

1. Classical Pound-Drever-Hall scheme

A typical PDH laser stabilization scheme, shown in Figure 1a, is used to measure the detuning of a laser from the frequency reference and to correct the frequency fluctuations of the laser itself. The incoming laser beam is phase modulated by means of an Electro Optical Modulator (EOM) at radiofrequency f_m and the reflected optical power is converted by a photodiode to the electrical signal v_{rf} at the same frequency. The synchronous demodulation by means of a mixer and a lowpass filter yields a signal which is a function of the laser - reference detuning. Finally, a suitable loop filter locks the laser frequency to the reference. Theory in [1] shows that an appropriate modulation depth of the optical beam maximizes the system sensitivity to detuning.

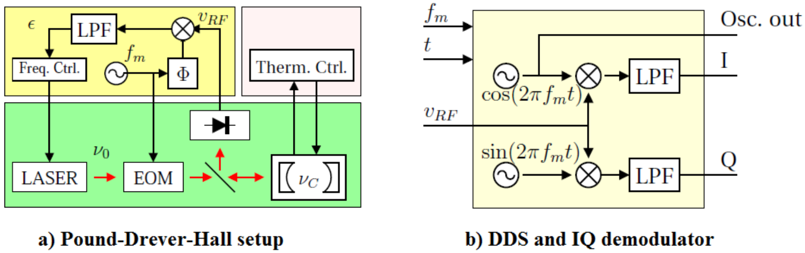


Figure 1: Pound-Drever-Hall stabilization scheme and DDS/IQ block

1.1. DDS and IQ demodulator on FPGA

A digital IQ demodulator is used in our experiment as a replacement of the mixer and the phase shifter Φ. The system is equipped with a DDS sine generator and a low-pass filter for each output. The resulting device constitutes the elementary block of our frequency stabilization system. One of the advantages of our proposed system with respect to the classical implementation is the extra information about the system behaviour obtained by observing the shape of the IQ diagram versus the laser-reference detuning.

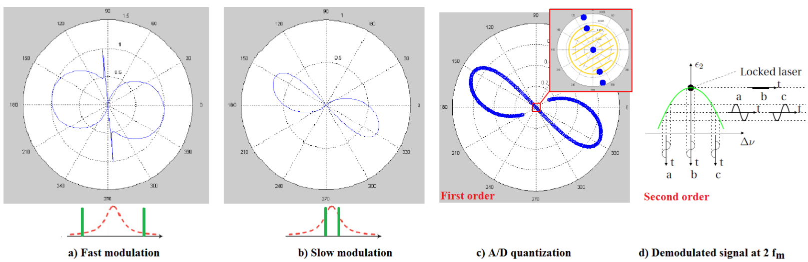


Figure 2: IQ plot versus detuning (fast and slow modulation)

Figures 2a and 2b show the effect of the phase modulation at a frequencies f_m below or above the cavity linewidth. An exact knowledge of f_m allows measuring the cavity linewidth by a simple inspection of the IQ diagram.

1.2. FPGA and Conversion Board

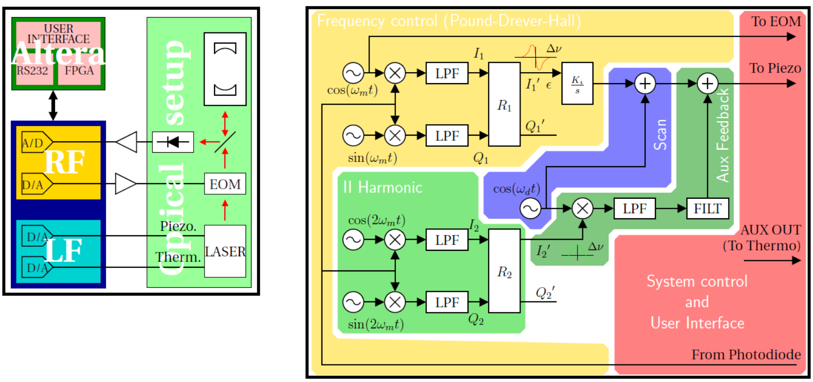
The whole stabilization scheme shown in Figure 3a is constituted by the electro-optical setup, an Altera Cyclone II board which is used to implement the signal processing and an A/D, D/A board used to supply the EOM with the RF signal at f_m=500 kHz, acquire the photodiode RF output and correct the laser frequency.

1.2.1 Effect of quantization

When the laser is locked to the cavity, the 500 kHz signal from the photodiode is below the A/D threshold; this implies that a dead zone exists in which the laser frequency can't be stabilized further; according to calculations, our system shows a 500 - 600 Hz wide dead zone and Figure 2c shows the simulated effect. The quantization effect problem can be prevented by observing the second harmonic signal at 1 MHz too. Indeed in the lock range the ε_2 error signal demodulated at the second harmonic has the parabolic expression $\varepsilon_2=\alpha(\Delta\nu)^2 + \gamma$, thus presenting a maximum at zero detuning. As shown in Figure 2d, an auxiliary low frequency modulation can be used to find the maximum of ε_2 when the 1st order error signal is no more observable.

1.3. Complete stabilization scheme on FPGA

The complete frequency stabilization system is shown in Figures 3a and 3b.



a) Experiment b) Digital PDH

Figure 3: Block diagrams of the experiment and the digital PDH on the FPGA

2. Measurements

Because of a delay in the delivery of the optical resonator we tested the digital PHD using a molecular reference (iodine). The laser stability was measured by beating it with a second iodine stabilized laser and the resulting relative frequency stability was 6 parts in 10^{13} at 10 s (Allan deviation) as shown in Figure 4.

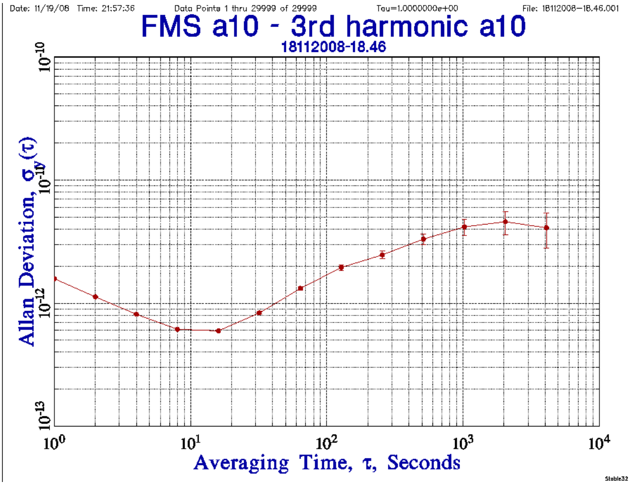


Figure 4: Performance of the control system

2.1. Current activity

The ULE reference resonator is currently under test. A measurement and thermal control system are being developed in order to investigate the temperature-frequency dependence and thus estimate the coefficient of thermal expansion of the resonator. Results will be presented at conference time.

With minor modifications our setup could be transformed in a facility for the characterization of low-CTE materials.

References:

[1] R.W.P. Drever et al.,"Laser phase and frequency stabilization using an optical resonator", Appl. Phys. B, 31, pp. 97-105 (1983)

[2] E.D.Black, "An introduction to Pound–Drever–Hall laser frequency stabilization", Am. J. Phys. 69 (1), Jan. 2001