How to stabilize the absolute length of the RLG diagonals

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OVERVIEW

1. Motivation

2. A triple frequency-modulation technique for absolute length measurements

3. Preliminary results

4. Conclusions & future perspectives

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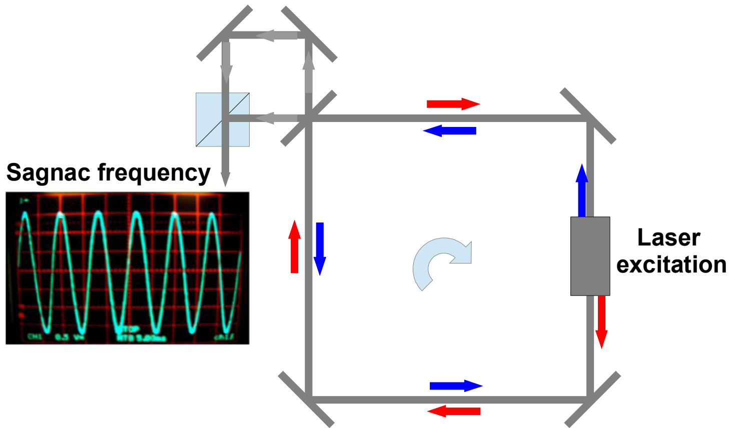
Sagnac frequency accuracy



$$\Delta f_{Sagnac} = \frac{4}{\lambda} \frac{A}{p} \boldsymbol{n} \cdot \boldsymbol{\Omega}$$

$$k_s = \frac{A}{p}$$

Geometrical scale factor

$$\Omega_{shot-noise} = \frac{c}{2Q} \frac{p}{A} \sqrt{\frac{h\nu}{P_{out} T}}$$

$$\boldsymbol{\Omega} = \boldsymbol{\Omega}_{Earth} + \boldsymbol{\Omega}_{REL}$$

$$\boldsymbol{\Omega}_{REL} \simeq 10^{-9} \boldsymbol{\Omega}_{Earth}$$

The measurement of relativistic precessions requires to control the local geometry (i.e. k_s) better than 10^{-10}

↓

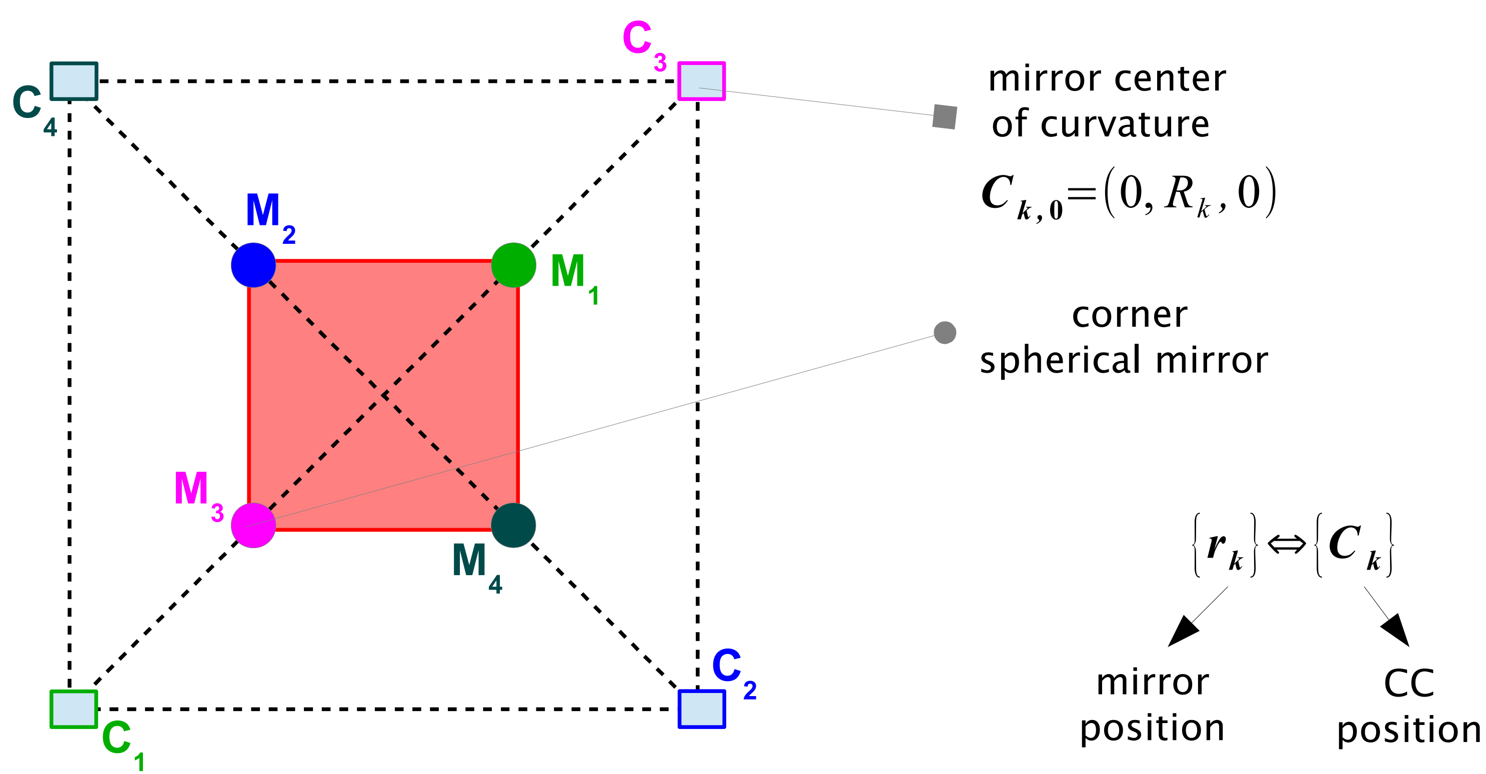
Corner mirror relative position and orientation should be accurate better than 1 nm and 1 nrad!

Our idea is to achieve a perfect square configuration by locking length and orientation of the Fabry–Pérot diagonal cavities

Degrees of freedom

Thanks to mirror spherical symmetry, the radiation path inside a 4-spherical mirror cavity is univocally defined by the positions of the four centers of curvature (CC).

Then, the whole optical cavity, which we suppose having a shape very near to a plane square, can be defined by 12 degrees of freedoms which are linear combinations of linear CC displacements (or, equivalentely, of mirror displacements).



Numerical simulations

Tracing out rigid body movements (6 d.o.f.) of the whole apparatus, a set of linear combinations of the CC movements can be chosen that produces:

- relative motions of the two diagonals, keeping fixed their lengths (no rotation)

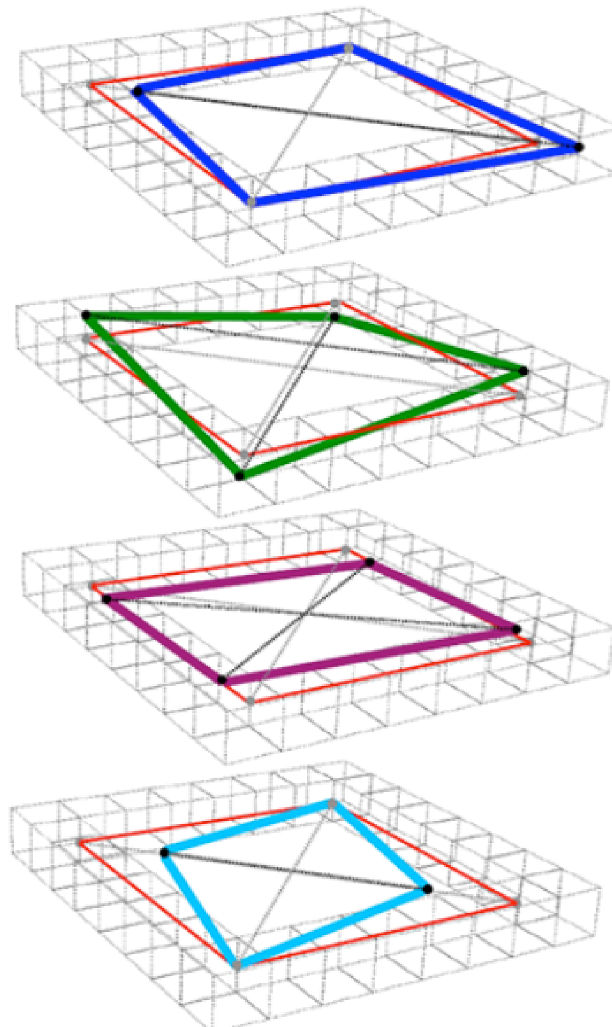
  2 d.o.f. horizontal + 1 d.o.f. vertical

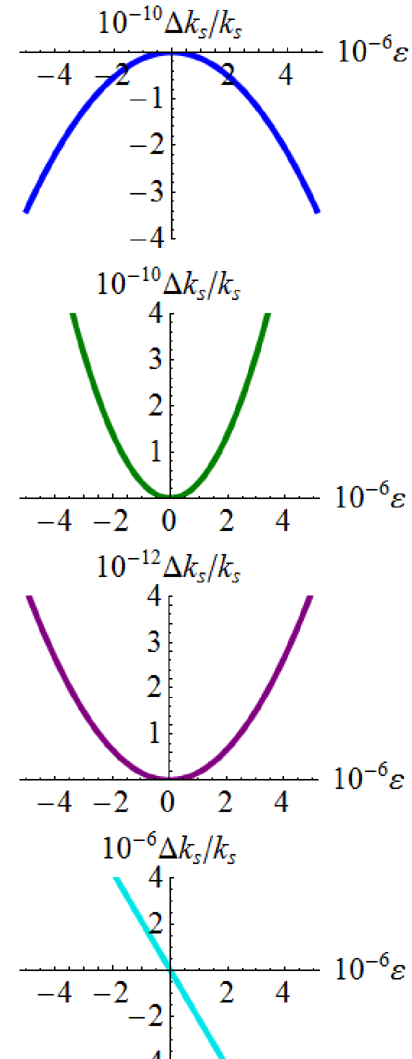
- relative rotations of the diagonals keeping fixed their lengths

  1 d.o.f.

- stretching of the square diagonals

  2 d.o.f.





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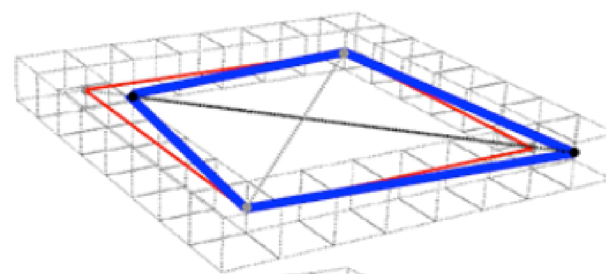
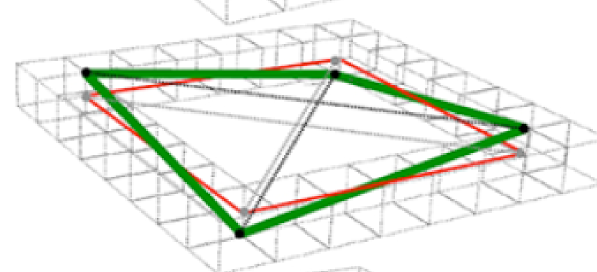
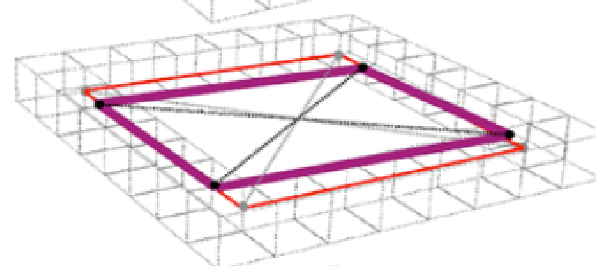


- ◆ relative motions of the two diagonals, keeping fixed their lengths (no rotation)

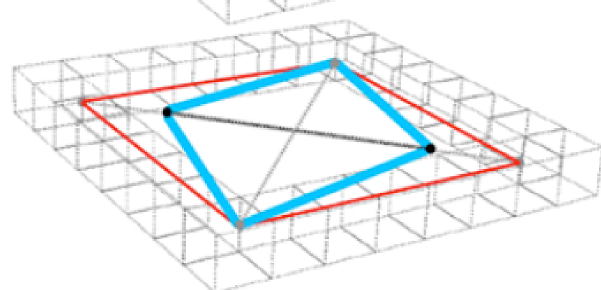
  2 d.o.f. horizontal + 1 d.o.f. vertical





- ◆ relative rotations of the diagonals keeping fixed their lengths

  1 d.o.f.



- ◆ stretching of the square diagonals

  2 d.o.f.

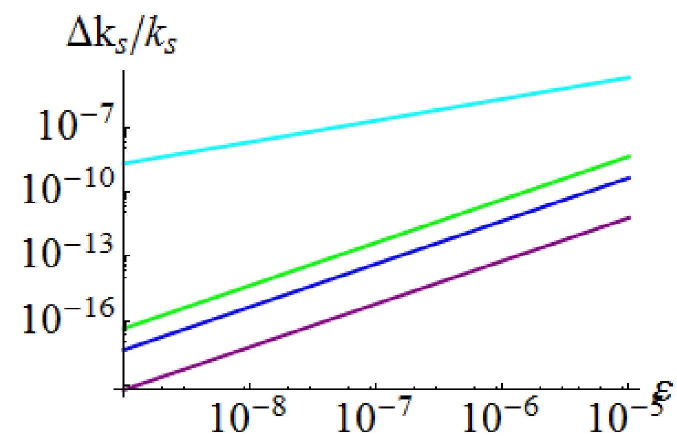


Fig.1 Comparison of the relative changes induced in the scale factor of 1 m side ring laser by the 6 d.o.f

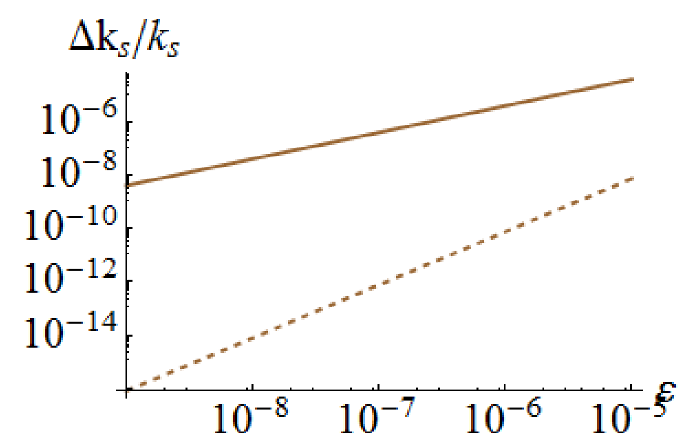


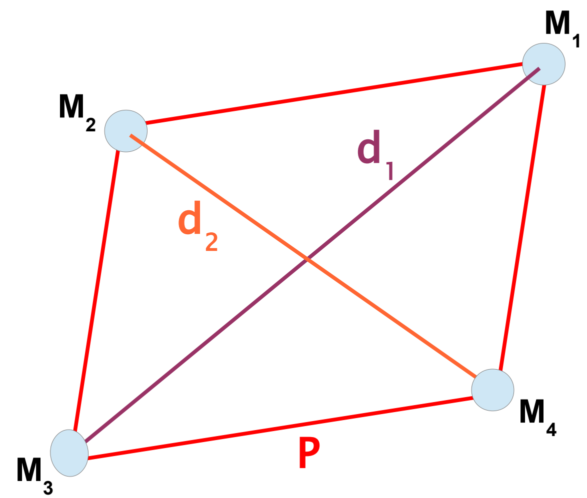
Fig.2 Total relative change in the scale factor i) with no constraint (continous line), and ii) by fixing the diagonal length (dashed line)

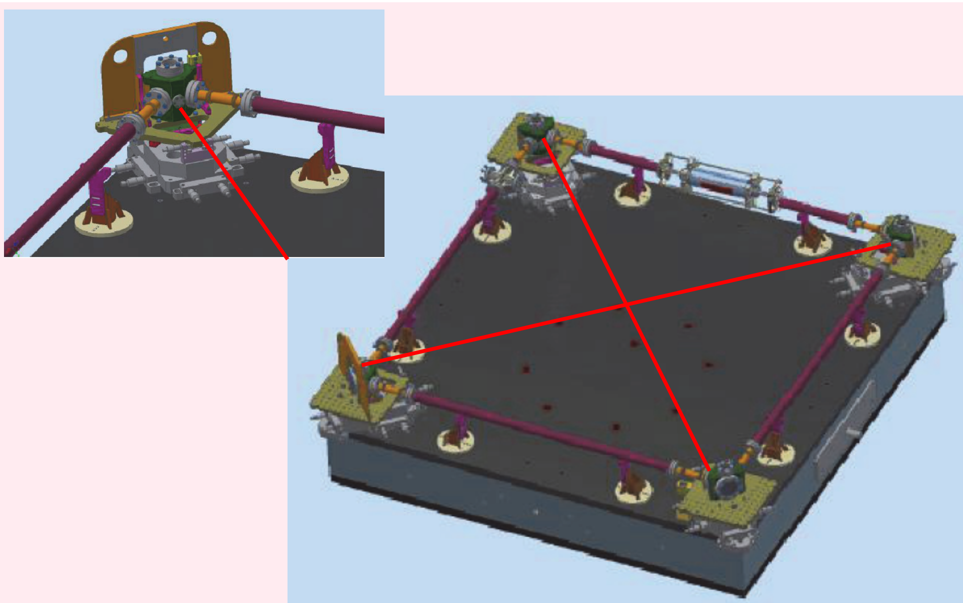
How to reach a perfect square configuration?

- the ring cavity perimeter can be known with very high accuracy ($>10^{11}$) by the beat note of the laser emission and a reference laser

- in a near-square 4-mirror cavity, the opposite mirrors define two Fabry-Pérot resonators whose length can be locked to the reference laser

→ Keeping the diagonal lengths locked, the other d.o.f. can be optimized one by one





GP2

- Square optical cavity 1.60 m x 1.60 m on granite slab
- Access to FP diagonal cavities
- 6 PZT actuators
  - 3 axial on 1 mirror tower
  - 1 axial, in diagonal direction, on the other 3

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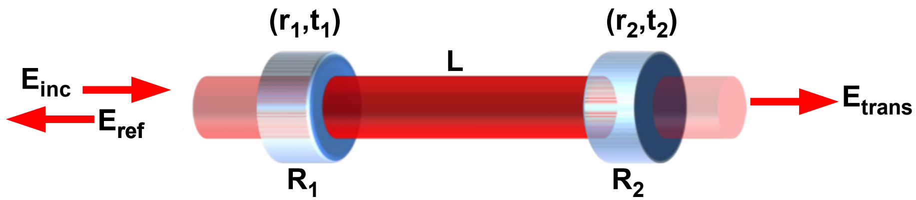
Aim of esperiment

The aim of this first experiment (University of Pisa, Department of Physics & INFN Section of Pisa) is to lock the absolute length of two linear cavities to a frequency standard by use of frequency-modulated light



Cavity length

$$L=\frac{c}{2f_n}(n+\varepsilon)$$

f_n Resonance frequencies for TEM00 mode

$$0<\varepsilon=\frac{1}{\pi}\cos^{-1}\sqrt{\left[\left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right)\right]}<1$$

To measure the cavity length **L** with 10^{-10} accuracy we have to:

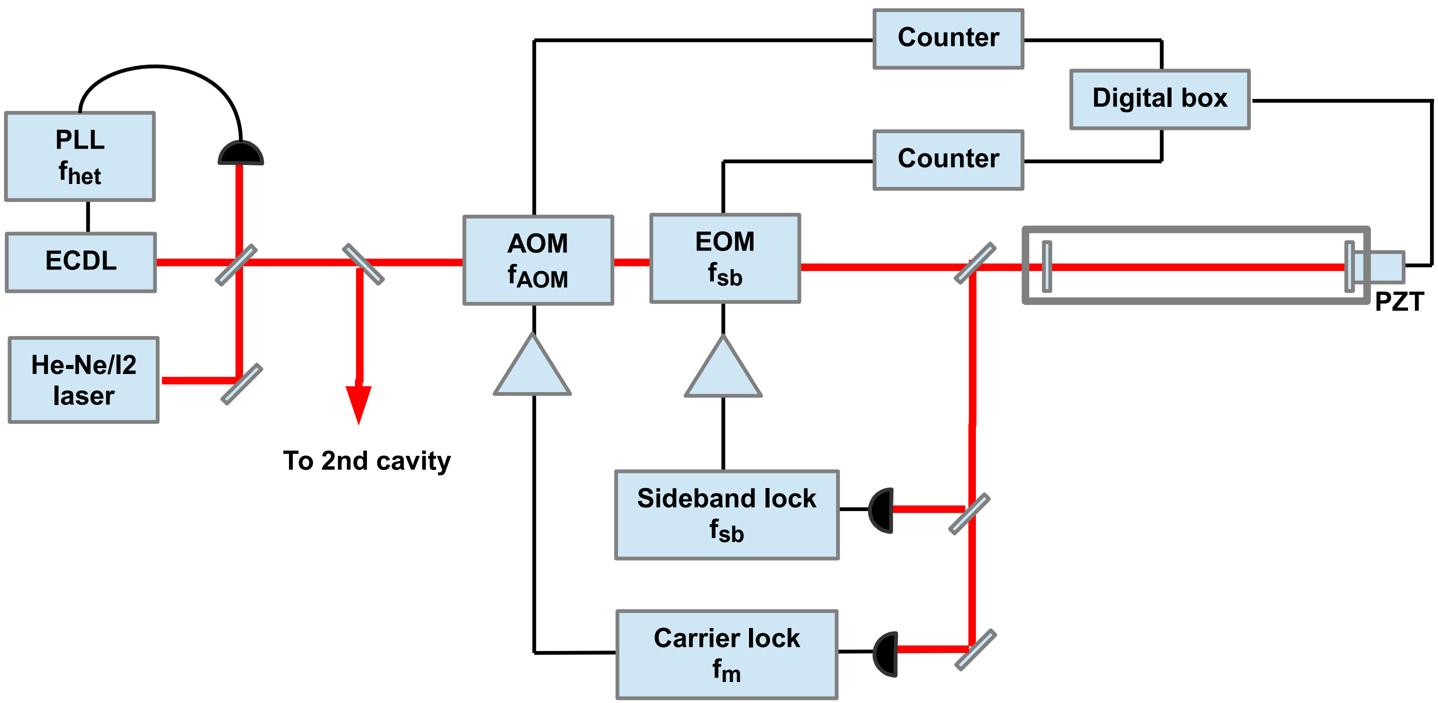
1. measure f_n with the same accuracy
2. define univocally the value of n

   → to measure FSR=c/2L better than 1/n

3. $f_{n+q}-f_n=q\,FSR$ → the accuracy on Free Spectral Range increases as q

Detection scheme

The diagonal lengths can be measured with respect to an interrogating high-stability laser by a two frequency Pound-Drever-Hall circuit

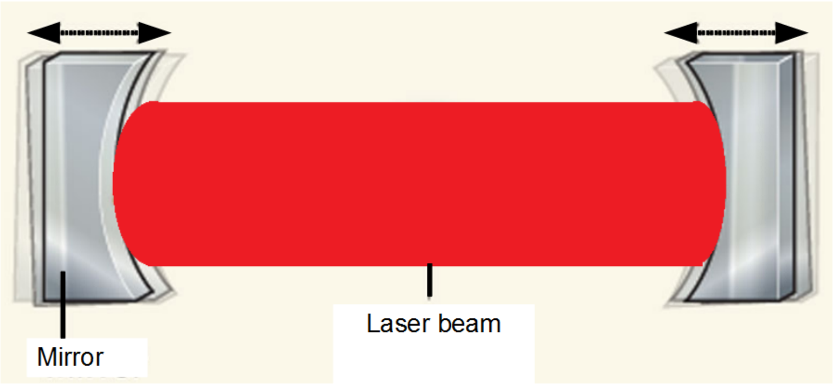


First frequency modulation circuit → relative phase lock

Second frequency modulation circuit → measure of interference order n

Locking laser to cavity: why?

Acoustics: unavoidable uncertainty on the measurement of the instantaneous length



In a RLG, mirror positions actuators have a limited bandwidth (< 100 Hz)
due to mirror holders inertia!!

→ Locking laser to cavity using AOM

- AOM compensates perfectly this noise by shifting the laser frequency
- This noise is reduced by a factor n on the measurement of FSR

$$\Delta n = \frac{n}{L}\sqrt{\frac{S_L}{\tau}}$$

In order to determine n, one needs to integrate for a time τ (GP2):

$$n = 5\times 10^{6}$$
$$S_L = 10^{-12}\, m/Hz$$
$$L = 2.26\, m$$

$$\xrightarrow{\Delta n < 1} \quad \tau > 4\, s$$

Frequency Modulation

FM signal $E(t) = A\exp\{[i[\omega + \gamma f(t)]t]\}$

carrier $p(t) = \exp(i\omega t)$

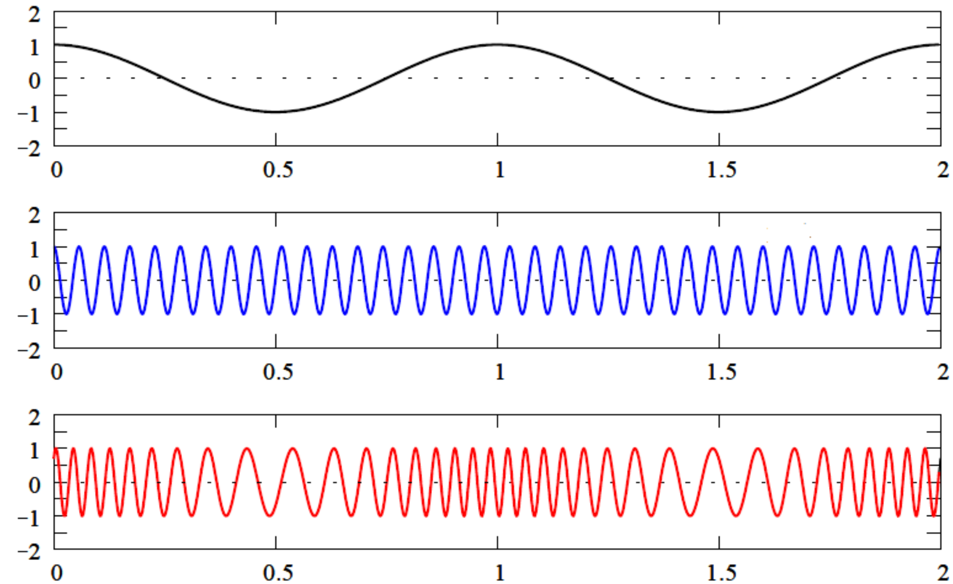
sinusoidal modulation $m(t) = \exp[i\gamma f(t)t] = \exp[i\gamma\sin(\omega_m t)t]$

ω optical frequency

ω_m modulation frequency

$\gamma = \frac{\Delta\omega_{max}}{\omega_m}$ modulation index

$\Delta\omega_{max} = \omega_{FM}(t) - \omega_0$ frequency deviation

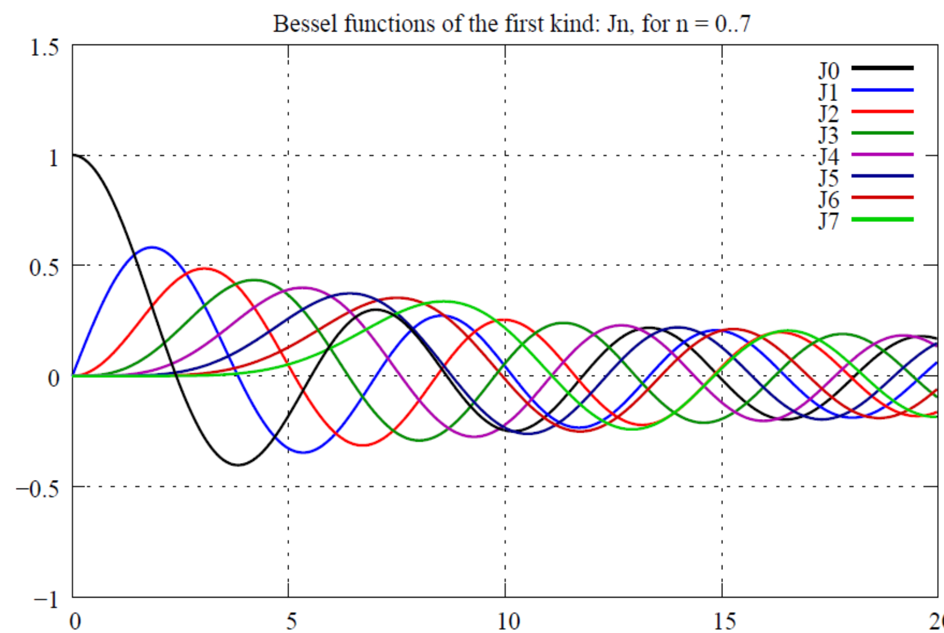


Using the Bessel functions of the 1st kind identity

$$\exp(i\gamma x) = \sum_n (-1)^n J_n(\gamma)\exp(inx)$$

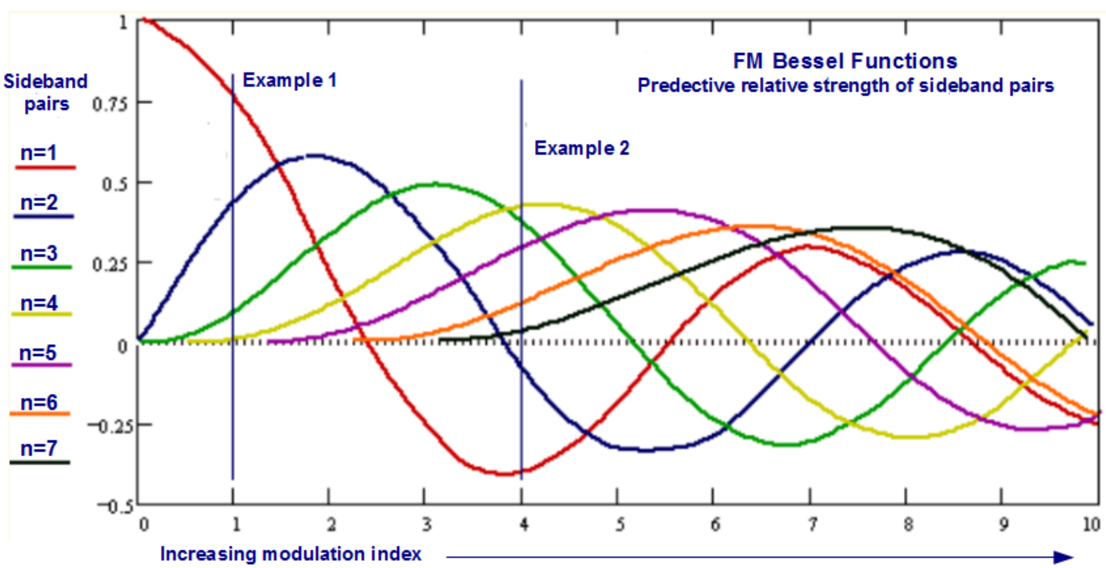
the FM signal can be rewritten as:

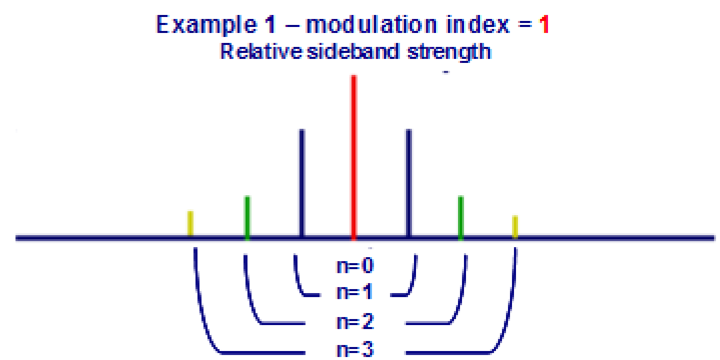
$$E(t) = A\exp(i\omega t)\sum_n (-1)^n J_n(\gamma)\exp(in\omega_m t)$$

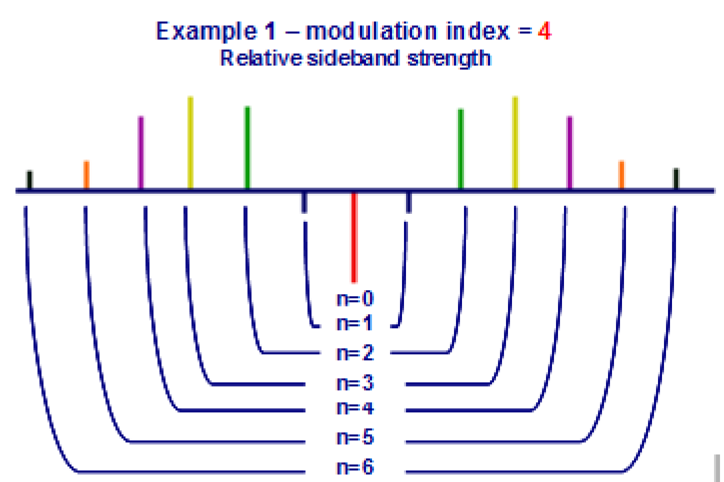


FM signal spectrum

The spectrum of a FM wave contains the carrier and in the sidebands an infinite set of spectral lines symmetrically arranged on both sides of the carrier, at a distance of f_m, $2f_m$, $3f_m$, …. from it.







FM bandwidth (98% of the transmitted power)

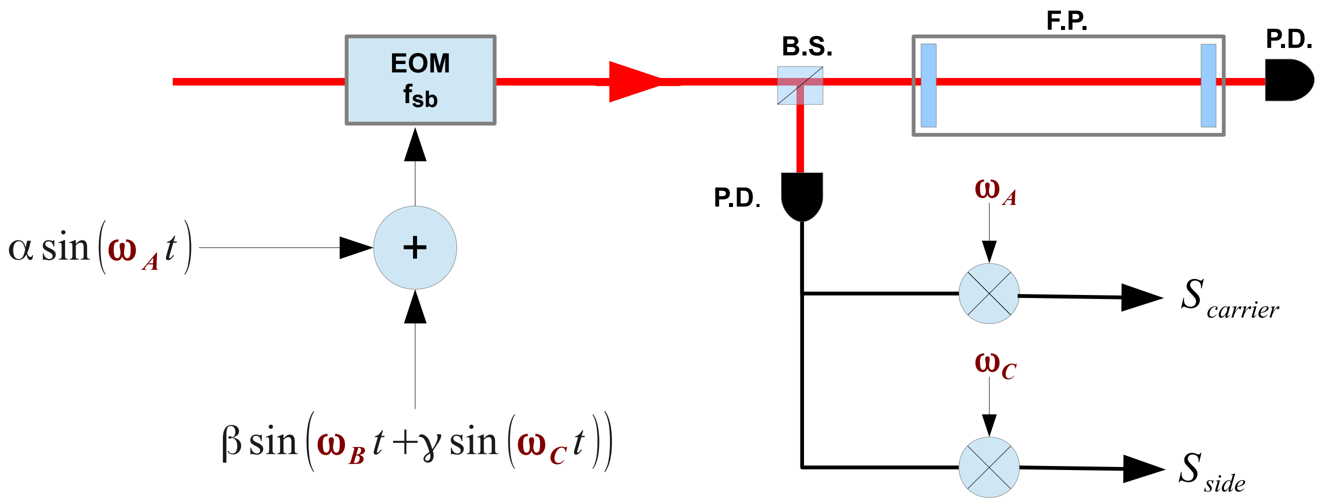
$$B = 2(\gamma + 1) f_m$$ *Carson's rule*

When the modulation index is small almost all the power is in the carrier and the first order sidebands

Triple modulation model with a single EOM

The incident electric field in the experimental set-up that we propose is triple frequency-modulated:

$$E_i(t)=E_0\exp\left\{i\left[\omega_0 t+\alpha\sin\left(\omega_A t\right)+\beta\sin\left(\omega_B t+\gamma\sin\left(\omega_C t\right)\right)\right]\right\}$$



Using the Bessel functions of the 1st kind identity:

$$E_i(t)=E_0\exp\left\{i\,\omega_0 t\left[\sum_n(-1)^n J_n(\alpha)\exp\left(i\,n\,\omega_A t\right)\right]\left[\sum_m(-1)^m J_m(\beta)\exp\left(i\,m\,\omega_B t\right)\exp\left[i\,m\,\gamma\sin\left(\omega_C t\right)\right]\right]\right\}$$

Incident and reflected electric field

For small modulation indices (α,β,γ<2) the laser electric field can be expanded using the first Bessel functions (n=m=0,-1, +1):

$$E_i(t)=E_0\exp\left\{i\omega_0 t\left[\sum_n(-1)^n J_n(\alpha)\exp(in\omega_A t)\right]\left[\sum_m(-1)^m J_m(\beta)\exp(im\omega_B t)\exp[im\gamma\sin(\omega_C t)]\right]\right\}$$

$$=E_0\exp\{i\omega_0 t[J_0(\alpha)-J_1(\alpha)\exp(i\omega_A t)-J_1(\alpha)\exp(-i\omega_A t)]$$

$$[J_0(\beta)-J_1(\beta)\exp(i\omega_B t)\exp(i\gamma\sin(\omega_C t))+J_{-1}(\beta)\exp(-i\omega_B t)\exp(-i\gamma\sin(\omega_C t))]\}$$

The reflected beam is obtained by multiplying the incident beam with the cavity transfer function given by the mirror reflection coefficient (symmetric cavity; no losses):

$$F(\omega)=\frac{r(\exp(i\omega/FSR)-1)}{1-r^2\exp(i\omega/FSR)}$$

r amplitude reflection coefficient

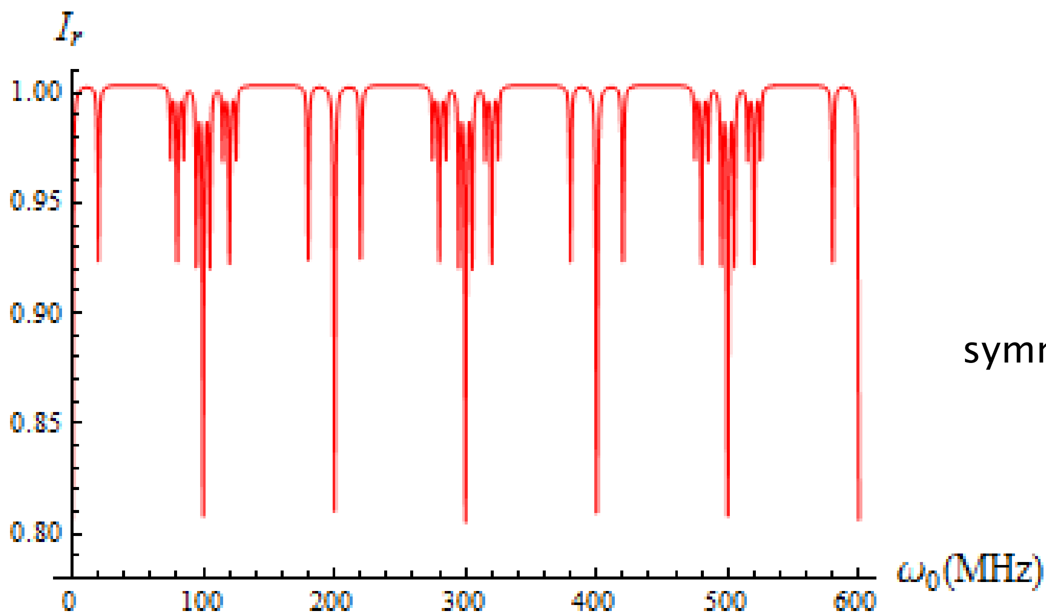
$\varphi=\frac{\omega}{FSR}=\frac{\omega}{c/2\mathrm{L}}$ phase the light picks up in one round trip inside the cavity

→ $$E_r(t)=\sum_n F(\tilde{\omega}_n)E_i(\tilde{\omega}_n,t)$$ *n* monochromatic components

Reflected intensity

The reflected intensity (components oscillating at the optical frequency are averaged out by the detector) is:

$$I_r = E_r(t)\,E^*_r(t)$$
$$= J_0^2(\alpha)J_0^2(\beta)\left[F(\omega_0)F^*(\omega_0)\right]$$
$$+J_1^2(\alpha)J_0^2(\beta)\left[F(\omega_0+\omega_A)F^*(\omega_0+\omega_A)\right]+\{\omega_0+\omega_A \Rightarrow \omega_0-\omega_A\}$$
$$+J_0^2(\alpha)J_1^2(\beta)J_0^2(\gamma)\left[F(\omega_0+\omega_B)F^*(\omega_0+\omega_B)\right]+\{\omega_0+\omega_B \Rightarrow \omega_0-\omega_B\}$$
$$+J_1^2(\alpha)J_1^2(\beta)J_0^2(\gamma)\left[F(\omega_0+\omega_A-\omega_B)F^*(\omega_0+\omega_A-\omega_B)+F(\omega_0+\omega_A+\omega_B)F^*(\omega_0+\omega_A+\omega_B)\right]+\{\omega_0+\omega_A \Rightarrow \omega_0-\omega_A\}$$
$$+J_0^2(\alpha)J_1^2(\beta)J_1^2(\gamma)\left[F(\omega_0+\omega_B-\omega_C)F^*(\omega_0+\omega_B-\omega_C)+F(\omega_0+\omega_B+\omega_C)F^*(\omega_0+\omega_B+\omega_C)\right]+\{\omega_0+\omega_B \Rightarrow \omega_0-\omega_B\}$$
$$+J_1^2(\alpha)J_1^2(\beta)J_1^2(\gamma)\left[F(\omega_0+\omega_A+\omega_B+\omega_C)F^*(\omega_0+\omega_A+\omega_B+\omega_C)+F(\omega_0+\omega_A-\omega_B-\omega_C)F^*(\omega_0+\omega_A-\omega_B-\omega_C)\right.$$
$$\left.+F(\omega_0+\omega_A+\omega_B-\omega_C)F^*(\omega_0+\omega_A+\omega_B-\omega_C)+F(\omega_0+\omega_A-\omega_B+\omega_C)F^*(\omega_0+\omega_A-\omega_B+\omega_C)\right]+\{\omega_0+\omega_A \Rightarrow \omega_0-\omega_A\}$$



21 frequency components

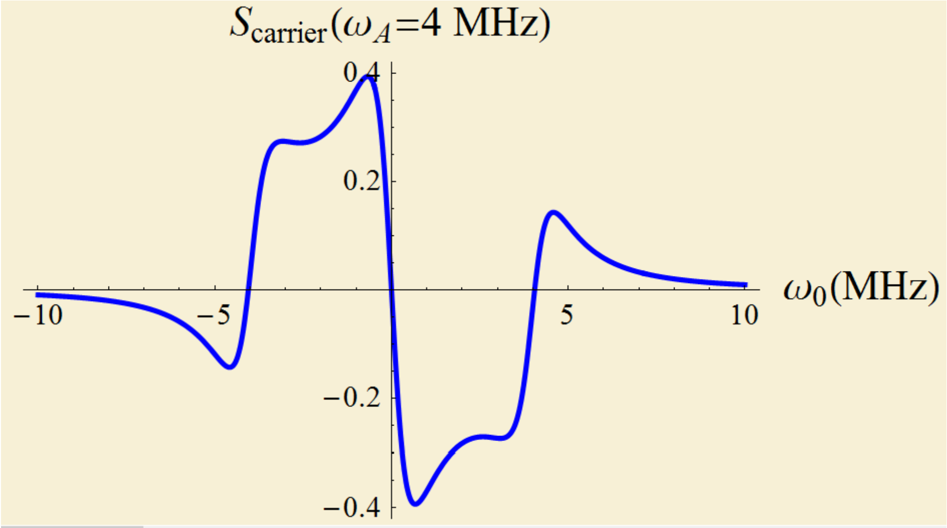
symmetrically distributed around the carrier

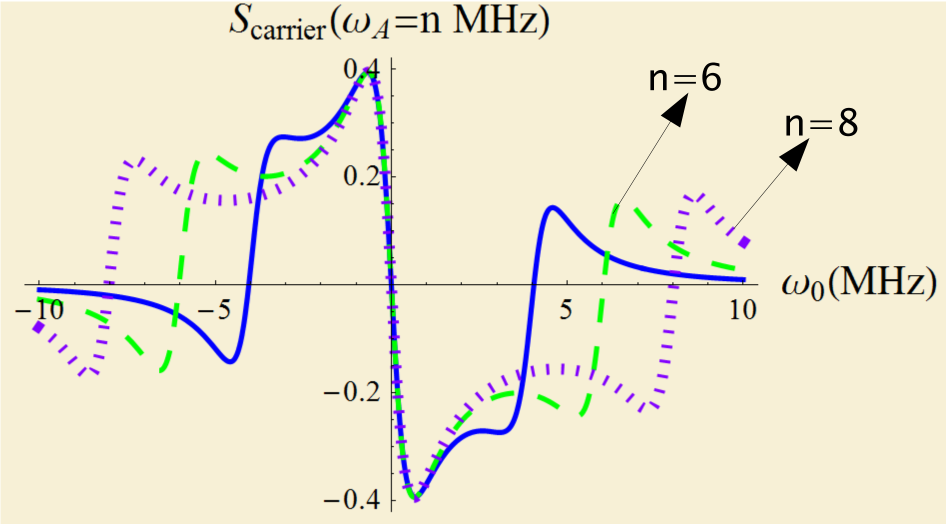
Reference signals for the carrier resonance

The mixer pulls out the term that is proportional to $\sin(\omega_A t)$, so the carrier error signal is:

$$S_{carrier}(\omega_0, \omega_A) = i\, a_0(\alpha,\beta)\, a_1(\alpha,\beta) \{ [-F(\omega_0) F^*(\omega_0+\omega_A) + F(\omega_0+\omega_A) F^*(\omega_0)] + [+ \Rightarrow -] \}$$

with
$$\begin{cases} a_0(\alpha,\beta) = J_0(\alpha) J_0(\beta) \\ a_1(\alpha,\beta) = J_1(\alpha) J_0(\beta) \end{cases}$$





Error signal slope
(near resonance)

$$D = \frac{16\sqrt{P_{carrier} P_{side}}\, Finesse}{\lambda}$$

Reference signals for the sidebands resonance

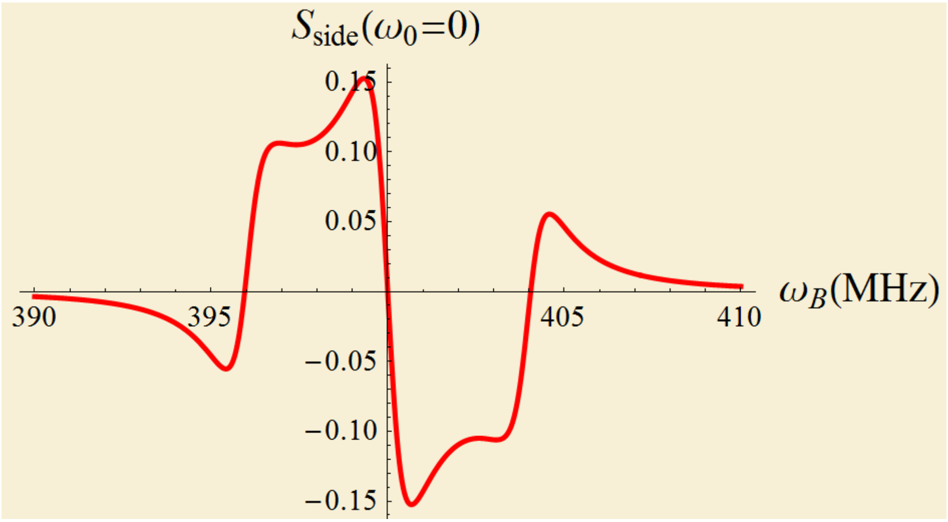
The mixer pulls out the term that is proportional to $\sin(\omega_C t)$, so the sidebands error signal is:

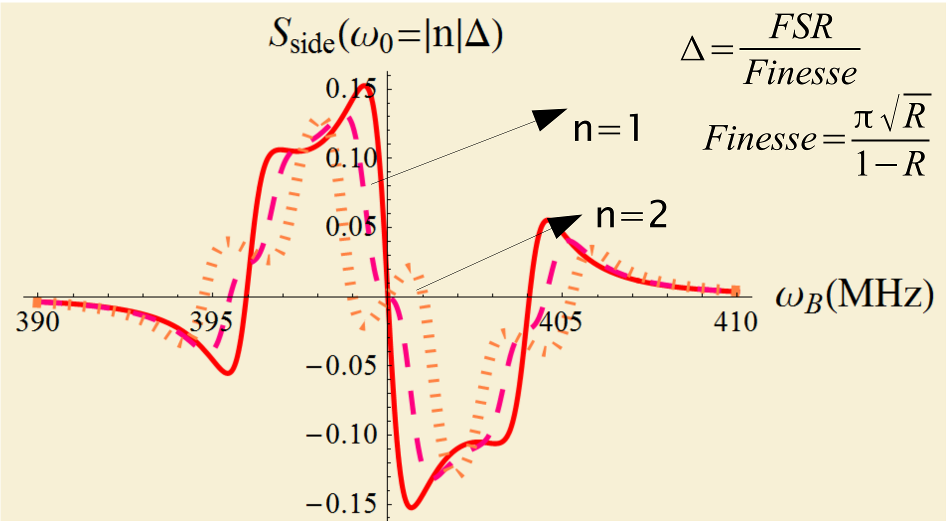
$$S_{side}(\omega_0, \omega_B, \omega_C) = i\, a_2(\alpha,\beta,\gamma)\, a_4(\alpha,\beta,\gamma) \{ [F(\omega_0-\omega_B) F(\omega_0-\omega_B+\omega_C) - F(\omega_0+\omega_B) F(\omega_0-\omega_B+\omega_C)$$

$$+ F(\omega_0+\omega_B-\omega_C) F(\omega_0+\omega_B) + F(\omega_0+\omega_B+\omega_C) F(\omega_0+\omega_B)] + [+ \Rightarrow -] \}$$

with

$$\begin{cases} a_2(\alpha,\beta,\gamma) = J_0(\alpha) J_1(\beta) J_0(\gamma) \\ a_4(\alpha,\beta,\gamma) = J_0(\alpha) J_1(\beta) J_1(\gamma) \end{cases}$$





Compatibility between FM theory and our experimental set-up! 🙂

Effect of carrier detuning on sidebands resonance:

- It causes signal deformation and change in the sign of the slope
- This criticity could be enhanced for an high Finesse!

Modulation index optimization

We have to determine the proper (α, β, γ) to obtain the *best* signal for the sidebands resonance reference signal as well as for the carrier reference signal.

A good criterion is to maxime the two product

$$A_{carrier}(\alpha, \beta) = a_0(\alpha, \beta) a_1(\alpha, \beta) = J_0(\alpha) J_1(\alpha) J_0^2(\beta)$$

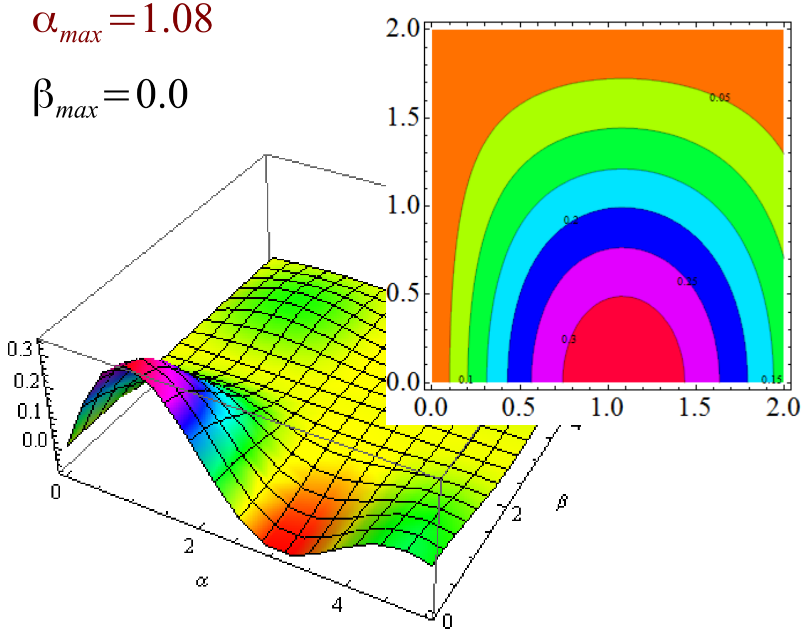
$$A_{side}(\alpha, \beta, \gamma) = a_2(\alpha, \beta, \gamma) a_4(\alpha, \beta, \gamma) = J_0^2(\alpha) J_1^2(\beta) J_0(\gamma) J_1(\gamma)$$

to obtain the maximum Signal to Noise Ratio on the two signals.

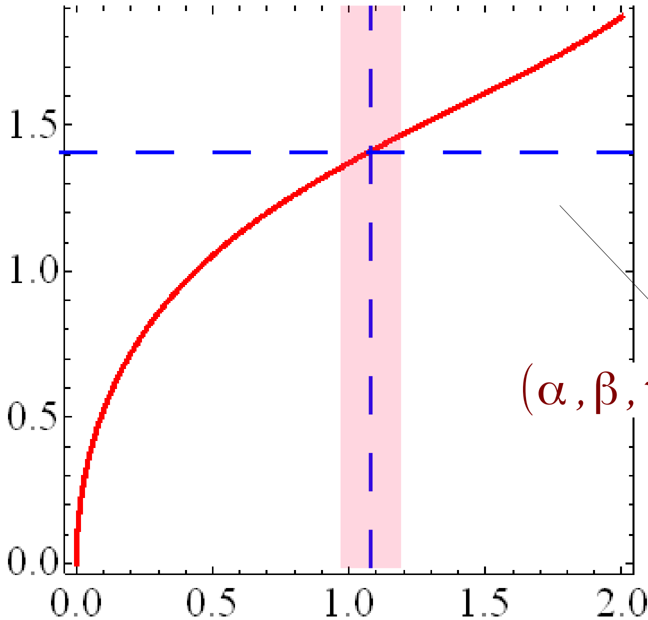
CARRIER MAXIMIZATION

$\alpha_{max} = 1.08$

$\beta_{max} = 0.0$



AMPLITUDE EQUALIZATION (γ_{max}=1.08)



$(\alpha, \beta, \gamma) = (1.08, 1.41, 1.08)$

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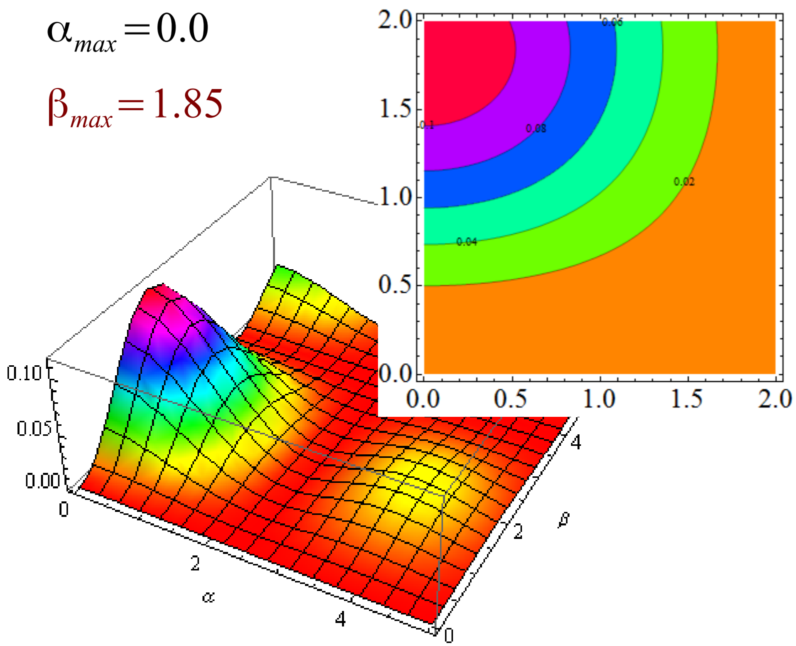
$$A_{carrier}(\alpha,\beta)=a_0(\alpha,\beta)a_1(\alpha,\beta)=J_0(\alpha)J_1(\alpha)J_0^2(\beta) \qquad A_{side}(\alpha,\beta,\gamma)=a_2(\alpha,\beta,\gamma)a_4(\alpha,\beta,\gamma)=J_0^2(\alpha)J_1^2(\beta)J_0(\gamma)J_1(\gamma)$$

to obtain the maximum Signal to Noise Ratio on the two signals.

SIDEBANDS MAXIMIZATION (γ_{max}=1.08)

$\alpha_{max}=0.0$

$\beta_{max}=1.85$



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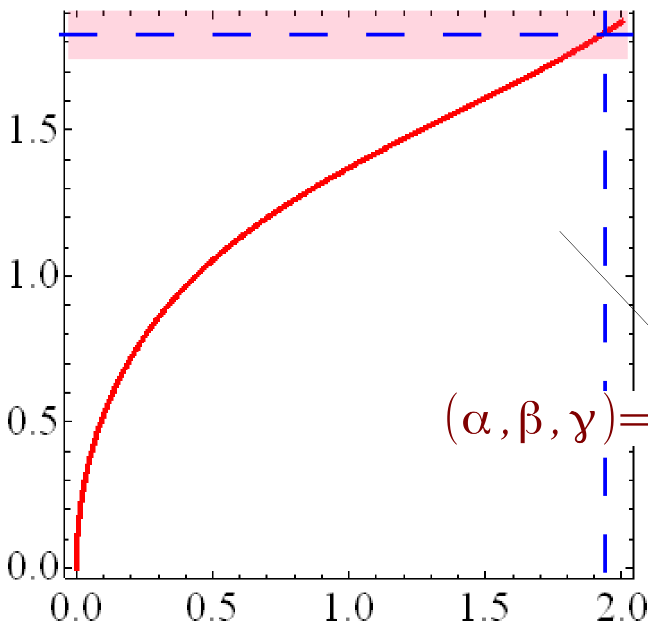


$(\alpha,\beta,\gamma)=(1.94, 1.85, 1.08)$

Modulation index optimization

We have to determine the proper (α,β,γ) to obtain the *best* signal for the sidebands resonance reference signal as well as for the carrier reference signal.

A good criterion is to maxime the two product

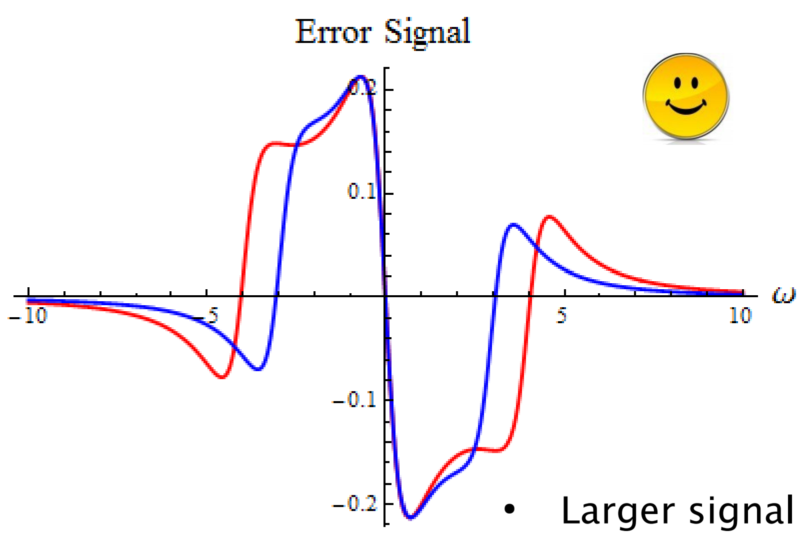
$$A_{carrier}(\alpha,\beta)=a_0(\alpha,\beta)a_1(\alpha,\beta) = J_0(\alpha)J_1(\alpha)J_0^2(\beta)$$

$$A_{side}(\alpha,\beta,\gamma)=a_2(\alpha,\beta,\gamma)a_4(\alpha,\beta,\gamma) = J_0^2(\alpha)J_1^2(\beta)J_0(\gamma)J_1(\gamma)$$

to obtain the maximum Signal to Noise Ratio on the two signals.

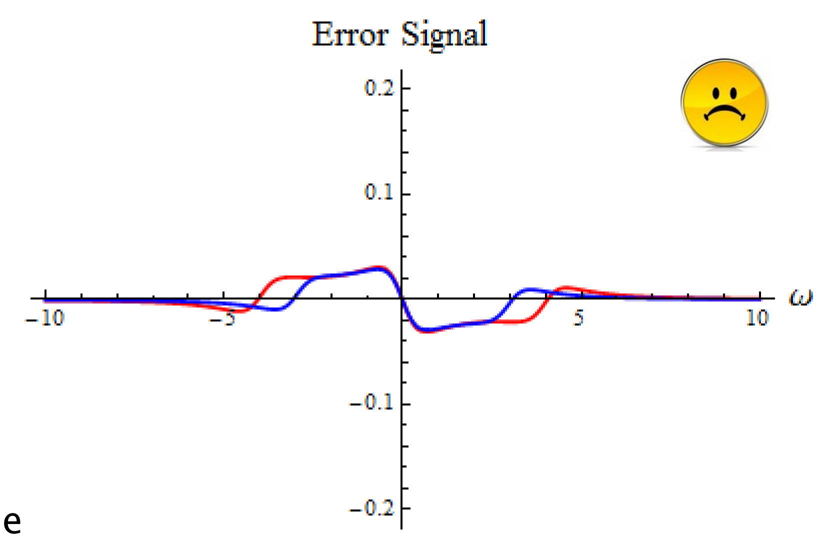
CARRIER MAXIMIZATION

$$(\alpha,\beta,\gamma)=(1.08,1.41,1.08)$$



SIDEBANDS MAXIMIZATION

$$(\alpha,\beta,\gamma)=(1.94,1.85,1.08)$$



- Larger signal amplitude
- Smaller modulation index

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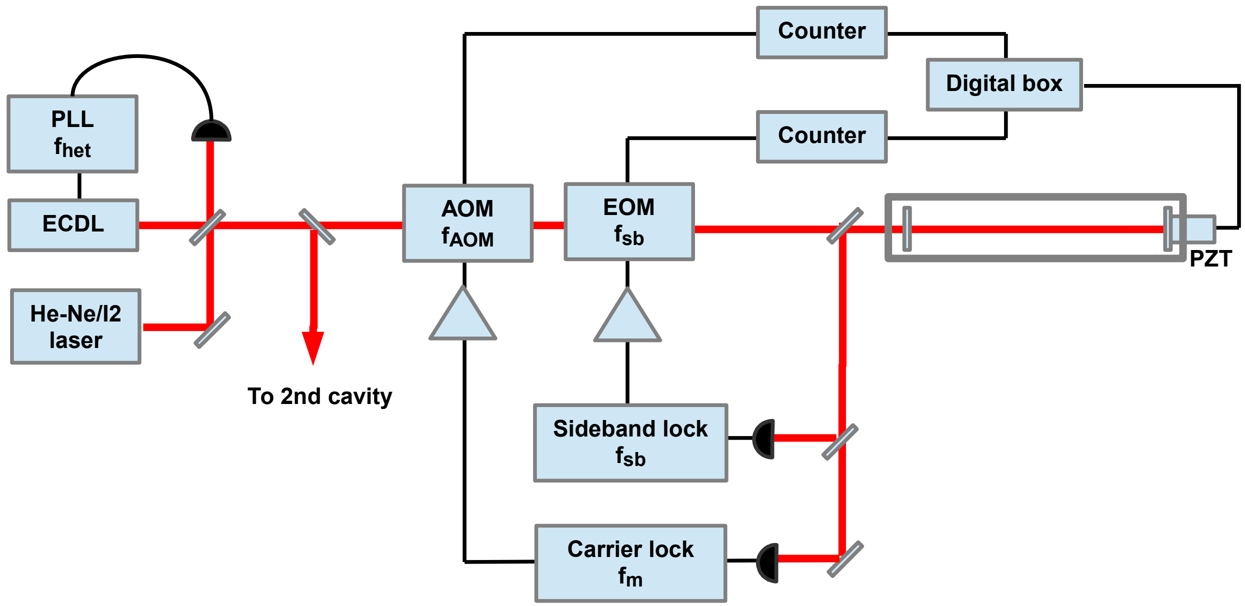
Experimental set-up

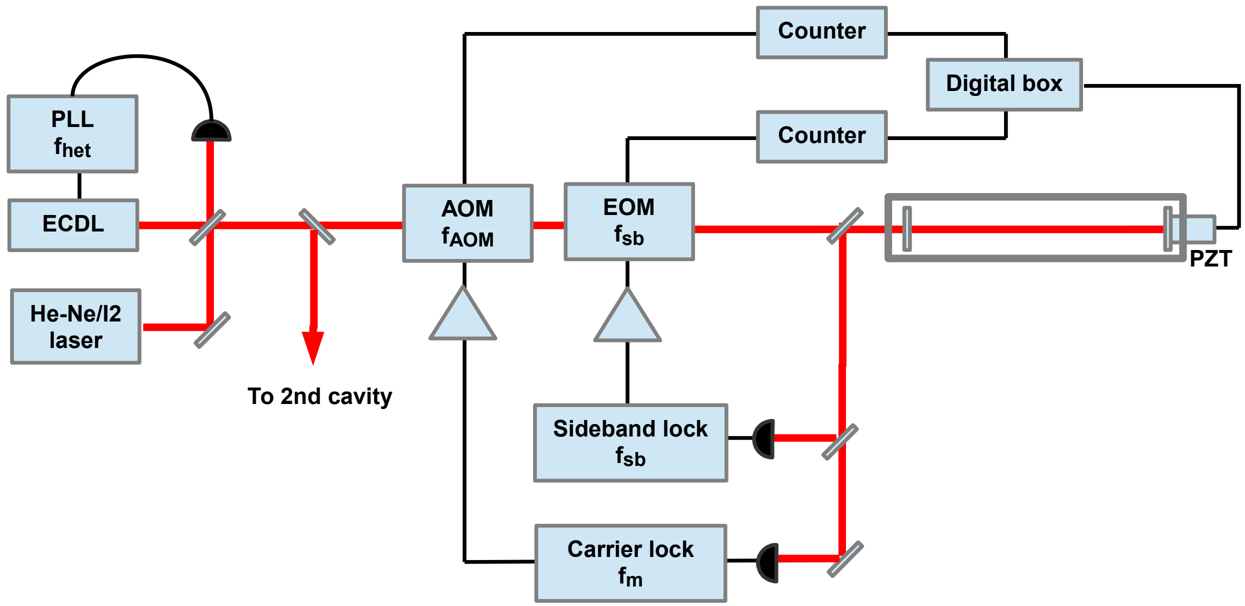


Resonance frequencies

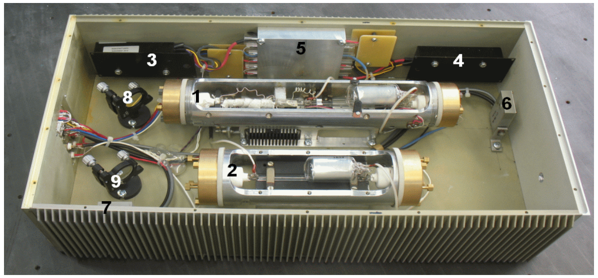
$$f_n = f_{iodine} + f_{het} + f_{AOM}$$

Description	Frequency	Purpose	Accuracy
f_{iodine}	473.61235412(3) THz	frequency standard	10^{-11}
f_{het}	5 GHz	PLL offset frequency	10^{-6}
f_{AOM}	200 MHz	Carrier locking frequency shift	10^{-5}
f_{sb}	m FSR	Sideband locking frequency modulation	5/m $*10^{-7}$

Experimental set-up

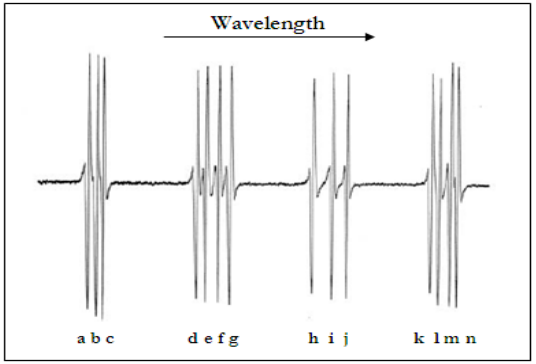


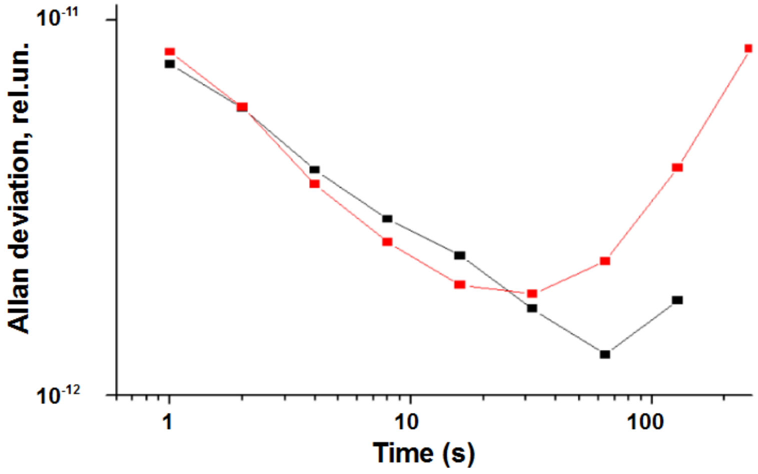
He-Ne/I2 frequency standard



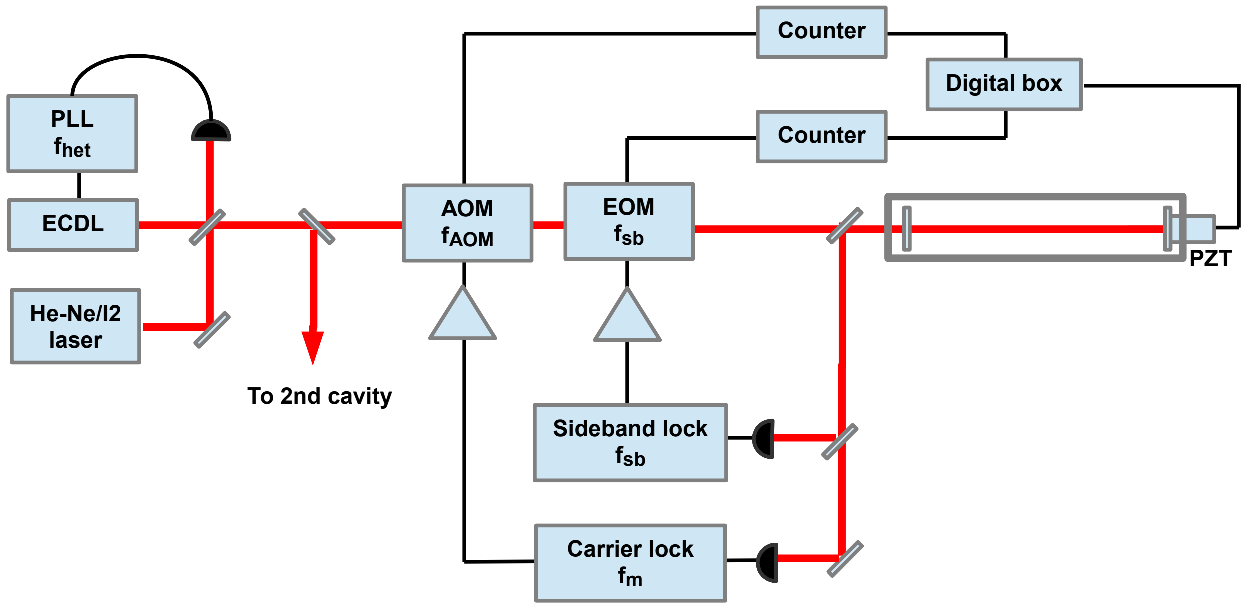
The master frequency is locked so that $f_M - f_S = 8$ MHz (SNR optimization); than the slave frequency is locked to the center of a transition as seen from master: in this way the master frequency is driven by slave

The hyperfine components are from 11-5 R(127) transition; the separation between components "d" and "g" is approximately 40 MHz





Experimental set-up



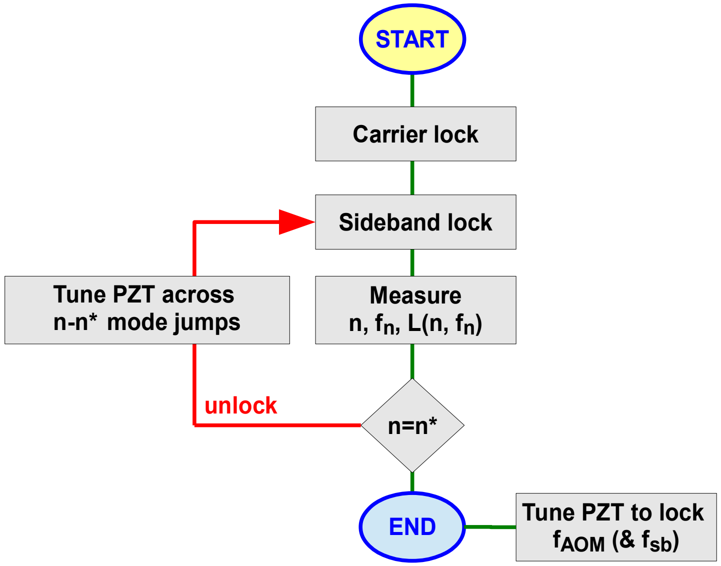
Procedure flow chart

Accuracy in mirrors positioning $\delta L \simeq 30 \mu m$

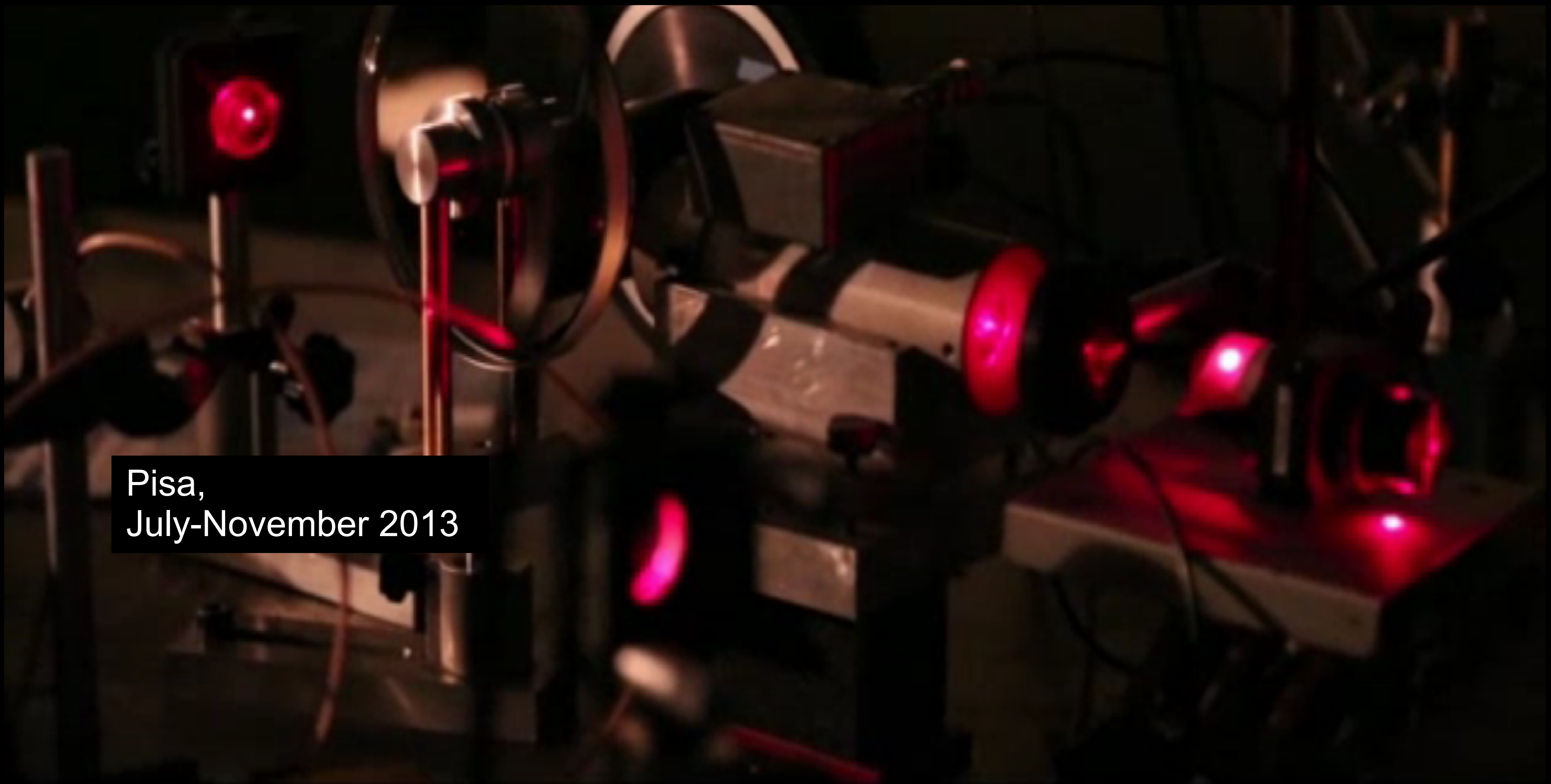
$$\rightarrow \begin{cases} \delta n = \dfrac{2\delta L}{\lambda} \simeq 100 \\ \delta f_n = \dfrac{\delta n}{n} \times f_n \simeq 1\, GHz \end{cases}$$

AOM tuning range $f_{AOM} \approx 10\, MHz$

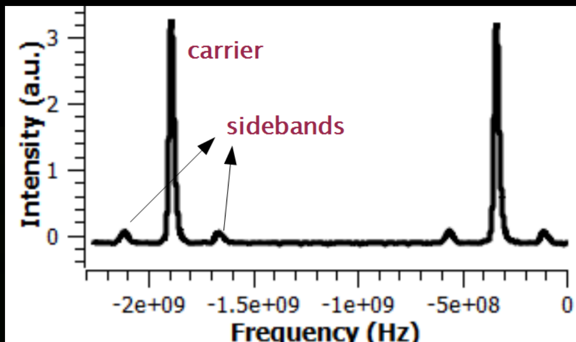
Length measurement (and stabilization) can be done without unlocking the carrier only approximately within a given value of n



"GP2ino"

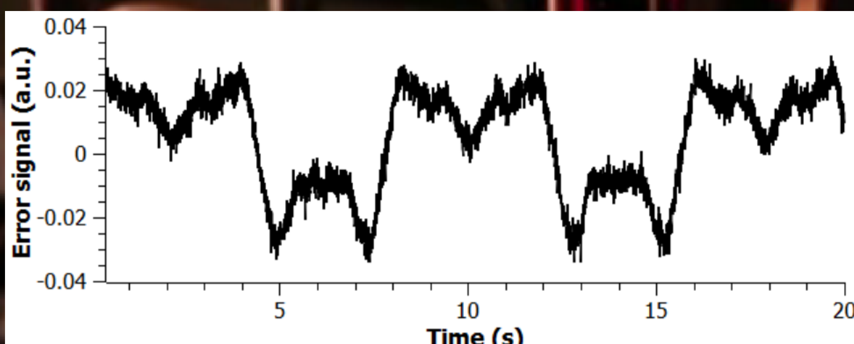


Locking the laser to cavity (feedback to ECDL)

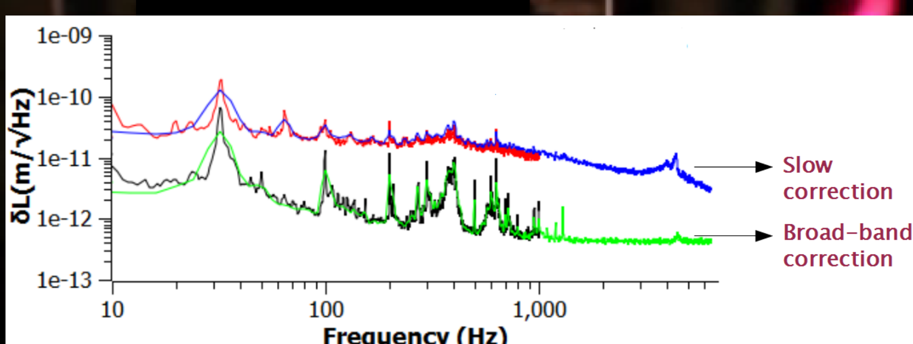


Modulated light spectrum (f_m=226 MHz)

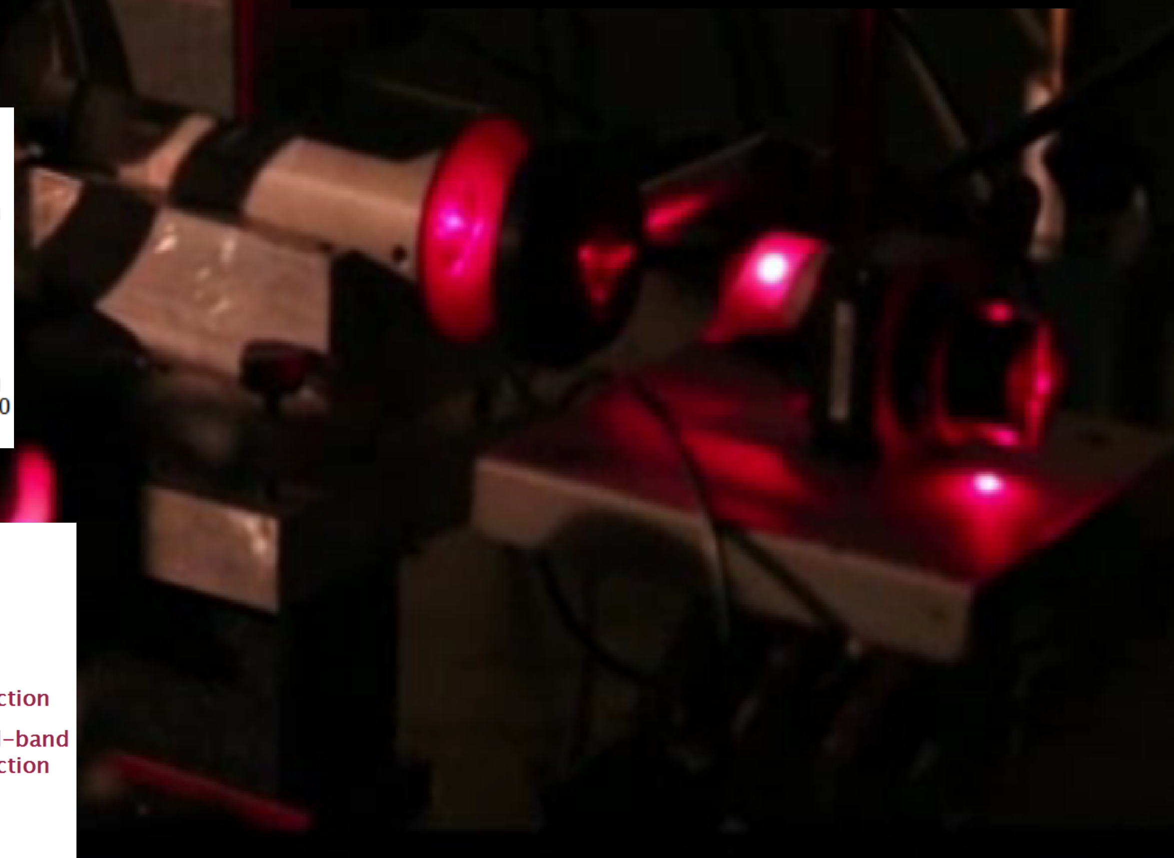
Cavity length	L=1.31992 m
Quality factor	$Q=1.86 \times 10^9$
Finesse	F=466
Mirror reflectivity	R=99.33%



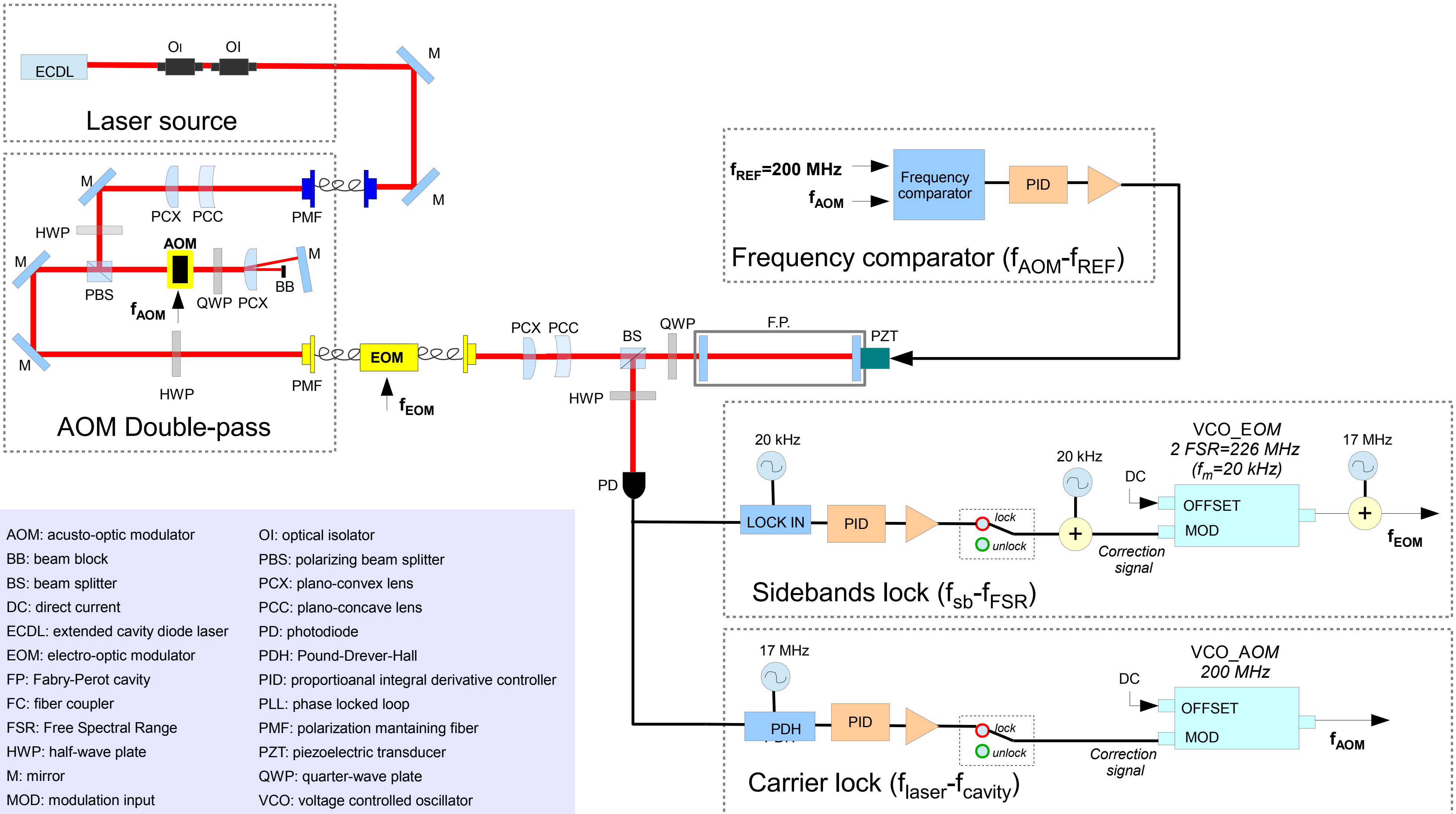
Sidebands lock error signal



Spectral density of the cavity length with the laser locked to the cavity by slow (to cavity PZT) and broad-band correction (to laser current)



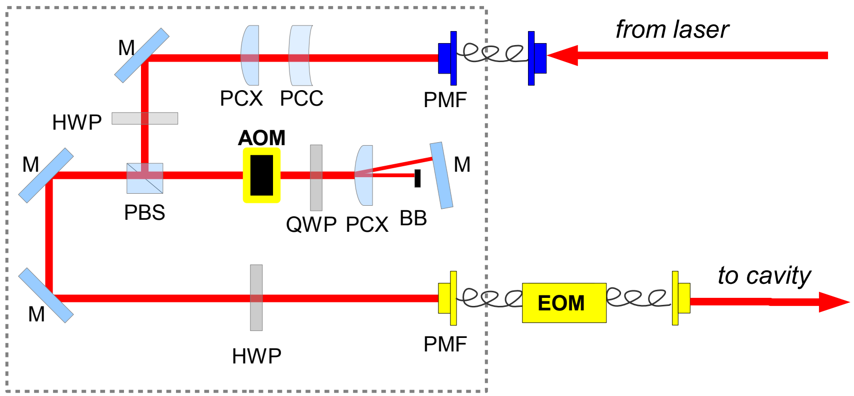
Locking the laser to cavity (feedback to AOM)



AOM: acusto-optic modulator
BB: beam block
BS: beam splitter
DC: direct current
ECDL: extended cavity diode laser
EOM: electro-optic modulator
FP: Fabry-Perot cavity
FC: fiber coupler
FSR: Free Spectral Range
HWP: half-wave plate
M: mirror
MOD: modulation input
OI: optical isolator
PBS: polarizing beam splitter
PCX: plano-convex lens
PCC: plano-concave lens
PD: photodiode
PDH: Pound-Drever-Hall
PID: proportioanal integral derivative controller
PLL: phase locked loop
PMF: polarization mantaining fiber
PZT: piezoelectric transducer
QWP: quarter-wave plate
VCO: voltage controlled oscillator

Double-pass acusto-optic modulator system

To eliminate beam deflections due to dependence of the laser beam diffraction angle on the modulation frequency we made a double-pass AOM system (October 2013)



- AOM: acusto-optic modulator
- BB: beam block
- EOM: electro-optic modulator
- HWP: half-wave plate
- M: mirror
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- PMF: polarization mantaining fiber
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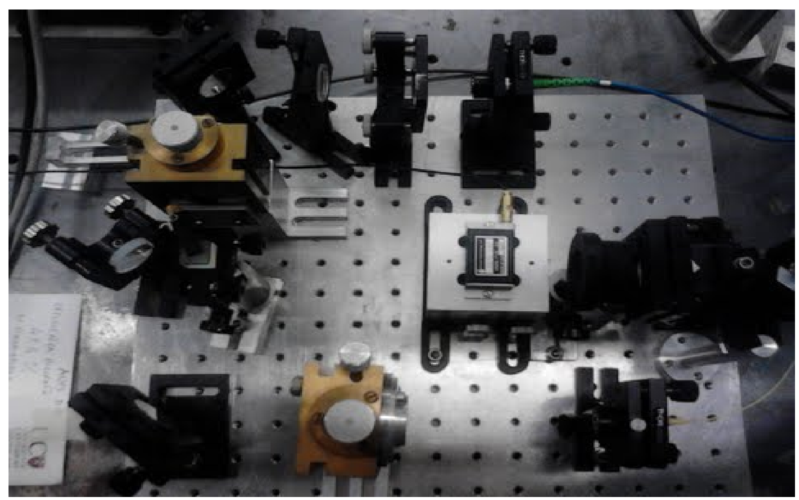

On a second pass through AOM the beam, with its polarization rotate by 90°, is deflected back such that it counterpropagates the incident laser beam and it can be separated from the input beam with a PBS

E. A. Donley et al., Review of Scientific Instruments 76, 063112 (2005)

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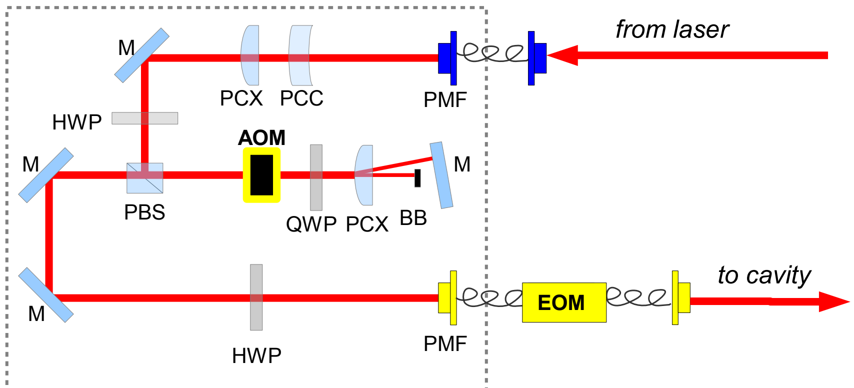

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QWP: quarter-wave plate

Specifications

AO Medium	TeO2
Active Aperture	2.5 x 1.5 mm
Center Frequency	200 MHz
RF Bandwith	50 MHz @ -10 dB return loss
Wavelength	470-690 nm
Bragg angle range (mr)	11.2 - 16.4

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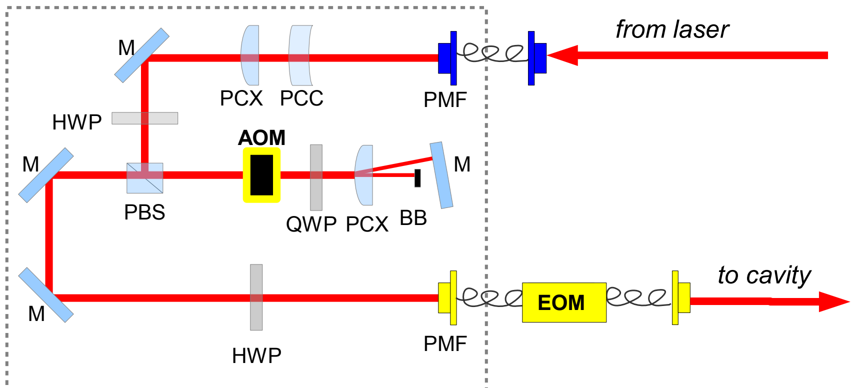

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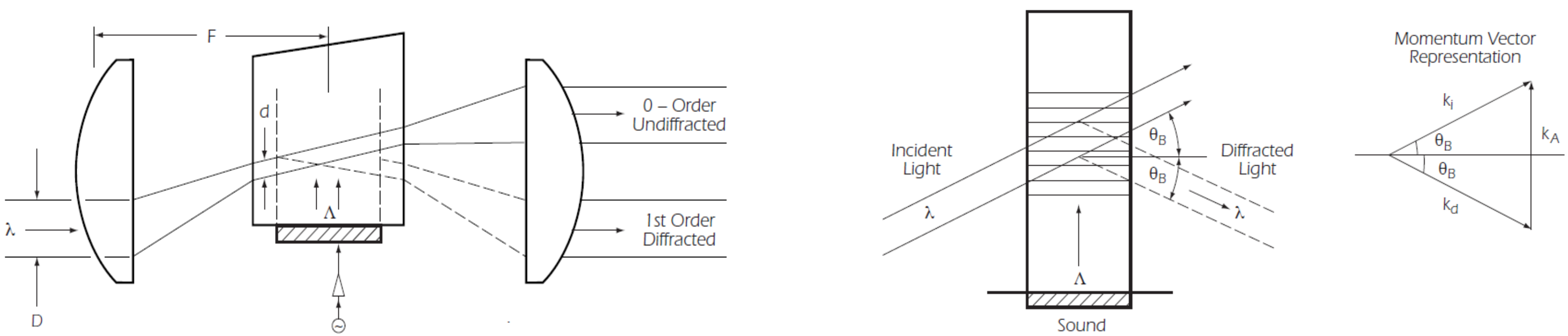
Modulator configuration



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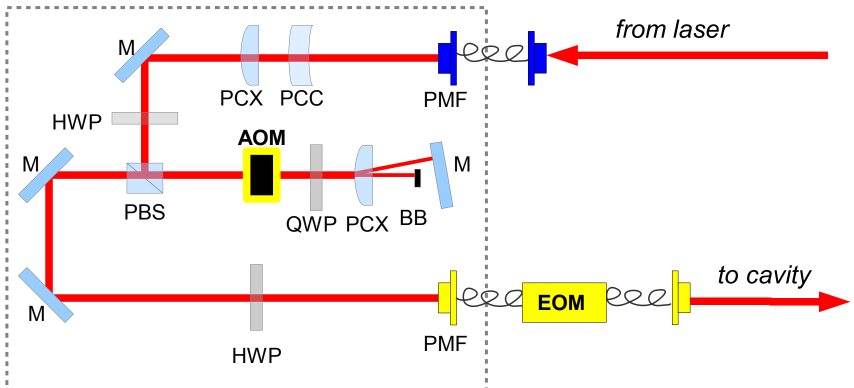

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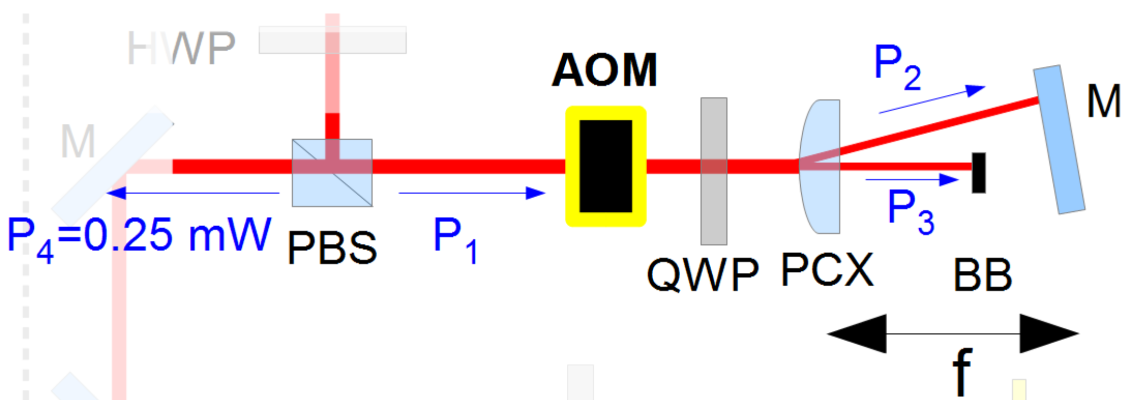
Cat's eye retroreflector



System efficiency

Diffraction efficiency=P2/P3=70%

Double pass efficiency=P4/P1=60%

Zero order beam   First order beam

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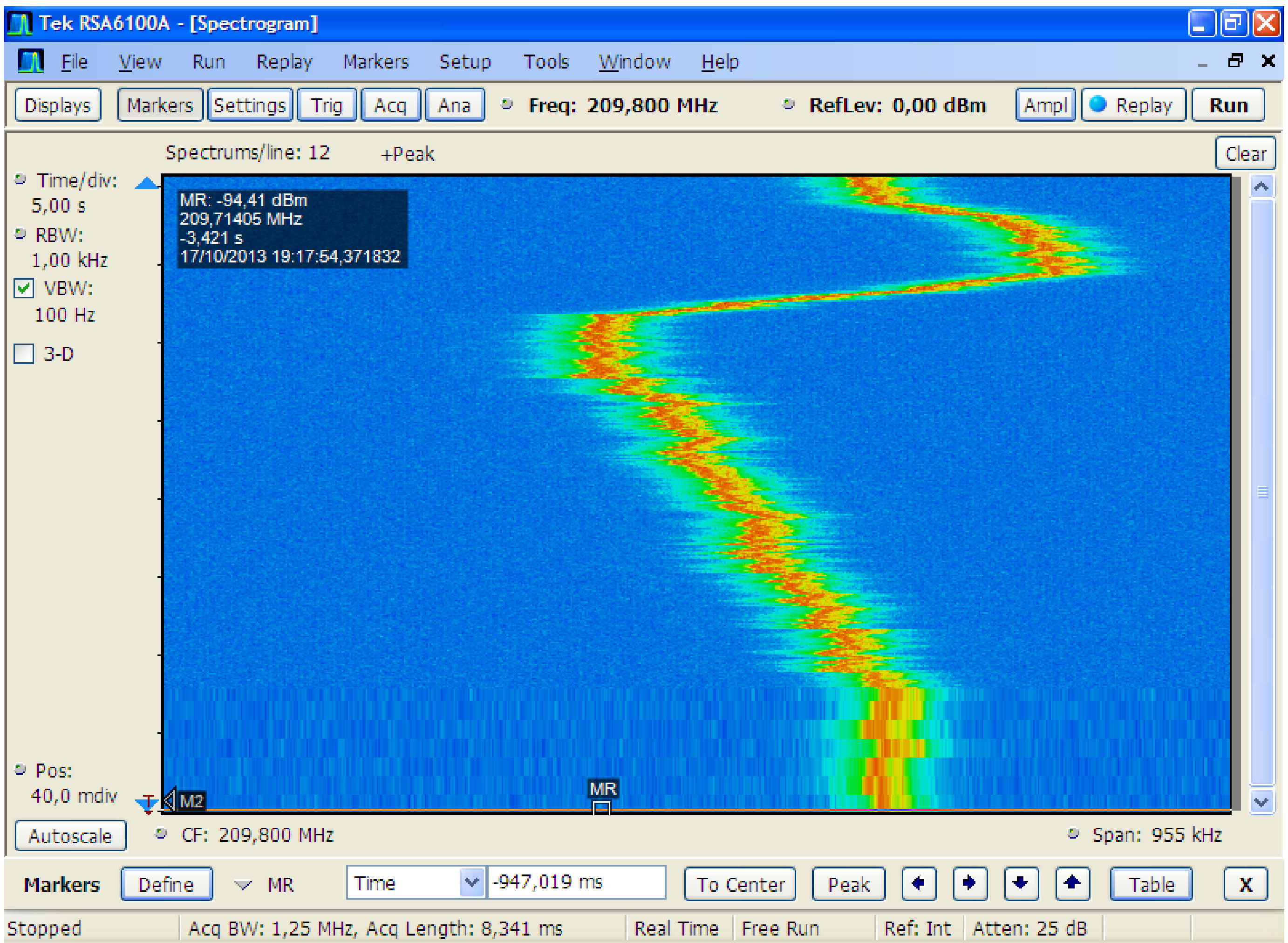
AOM locking to cavity

To test locking performance we record the spectrogram trace of the laser frequency shift (with respecto to frequency reference 200 MHz) due to an artificial change of the cavity length (i.e. change induced by us acting on cavity PZT)



$$\frac{\Delta \nu}{\nu} = \frac{\Delta L}{L}$$

$$L = 1.31992\, m$$

$$\nu = 4.53 \times 10^{8}\, MHz$$

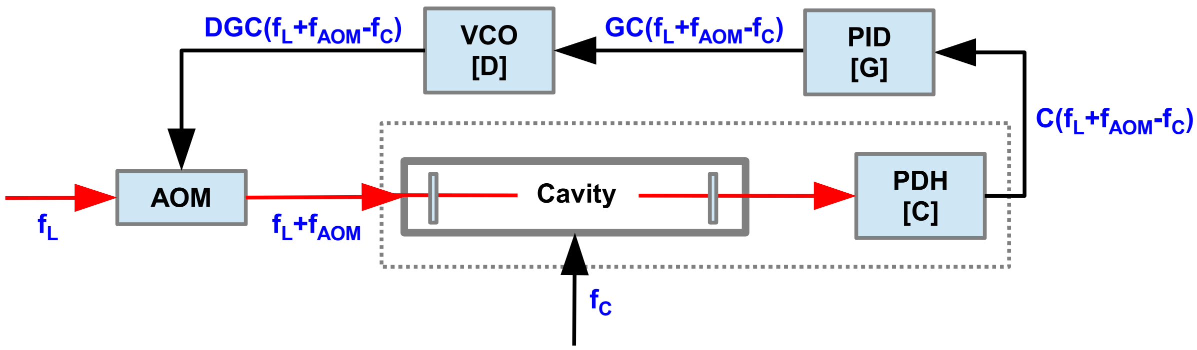
$$\Delta \nu = 500\, MHz$$

$$\downarrow$$

$$\Delta L = L \frac{\Delta \nu}{\nu} \simeq 6\, nm$$

Double lock (AOM & cavity)

We report a preliminary locking of the interrogating laser to our diagonal prototype using AOM double-pass and giving the correction to cavity PZT by @LabVIEW



$C = 1\, MHz/V$ Pound-Drever slope

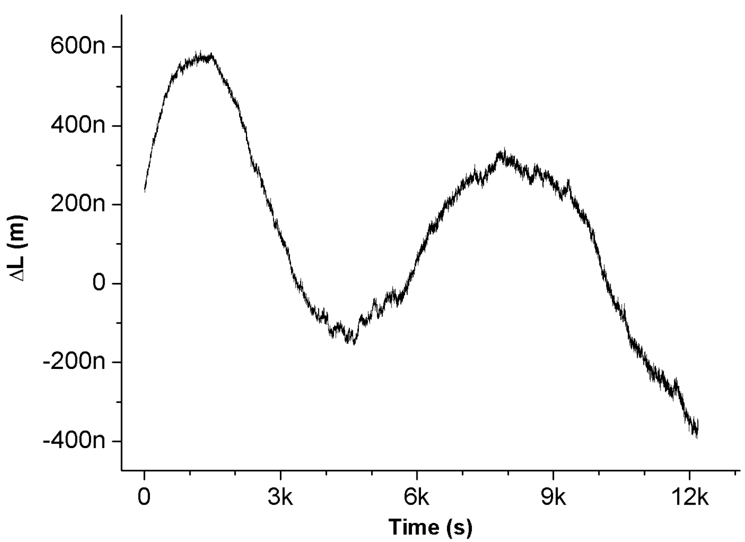
$G \simeq 1.5$ PID transfer function

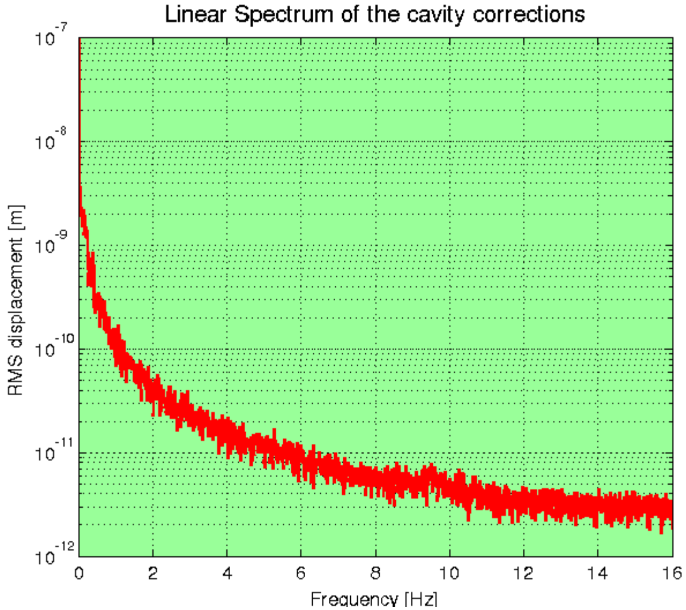
$D \approx 260\, V/MHz$ VCO gain

$$f_{AOM} = \frac{CDG(f_L - f_C)}{1 + CDG}$$

$$f_C = f_{Iodine} + f_{AOM}$$

3 hours measurement time, November 2013



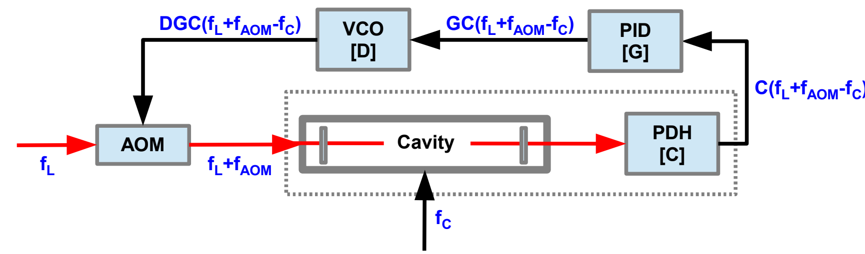


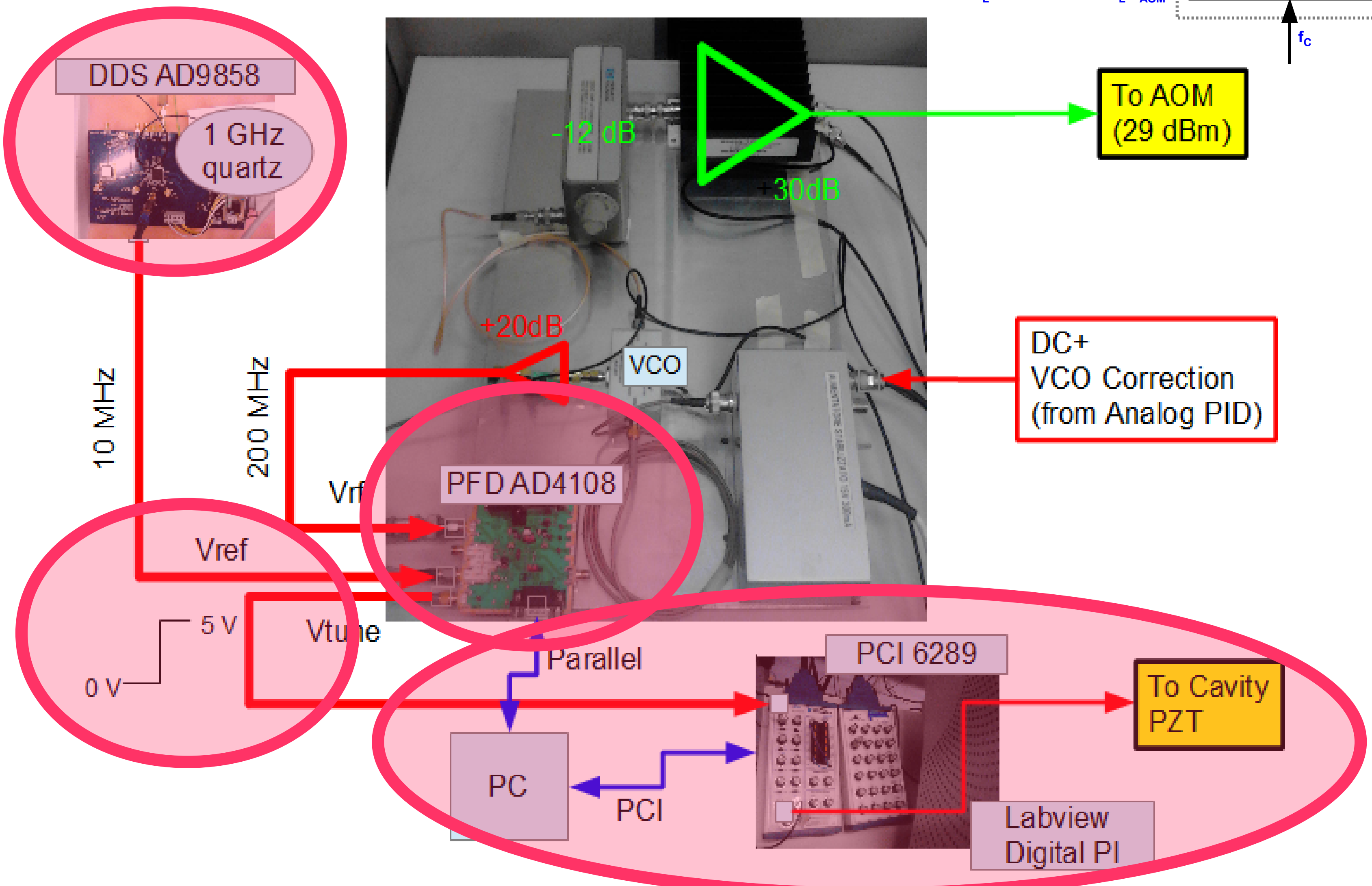
PZT PARAMETERS

Response 3.9 nm/V

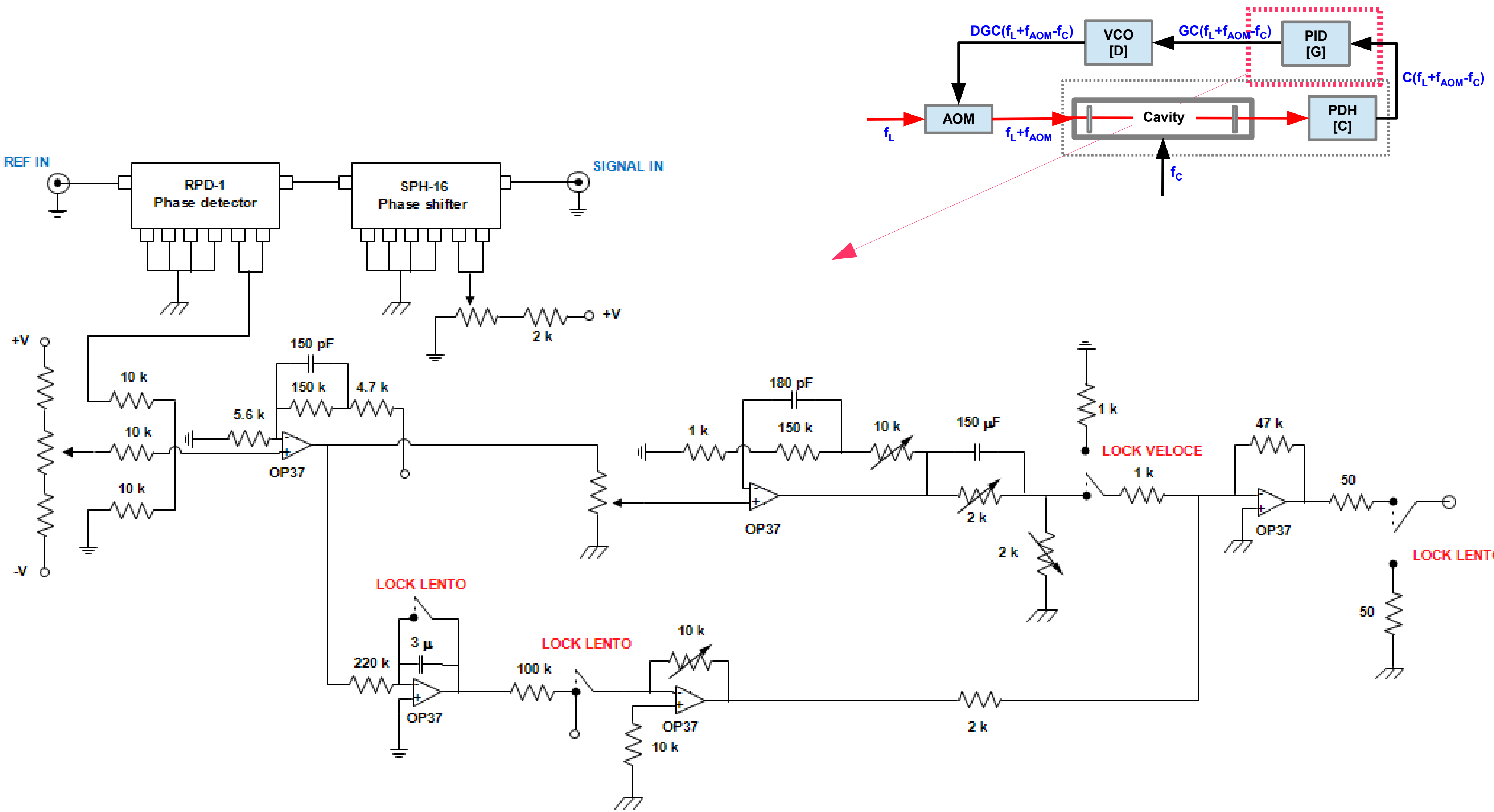
Tuning range 2.98 μm

Double lock (AOM & cavity) - Electronics

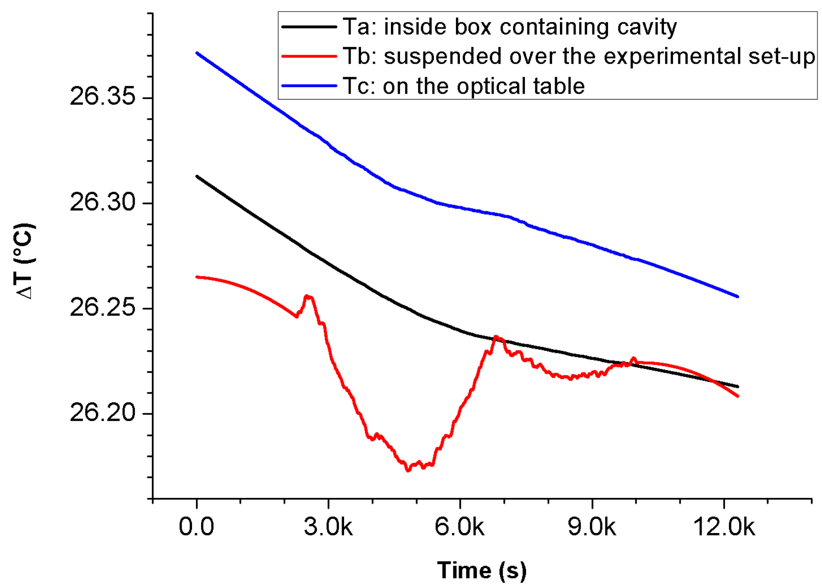


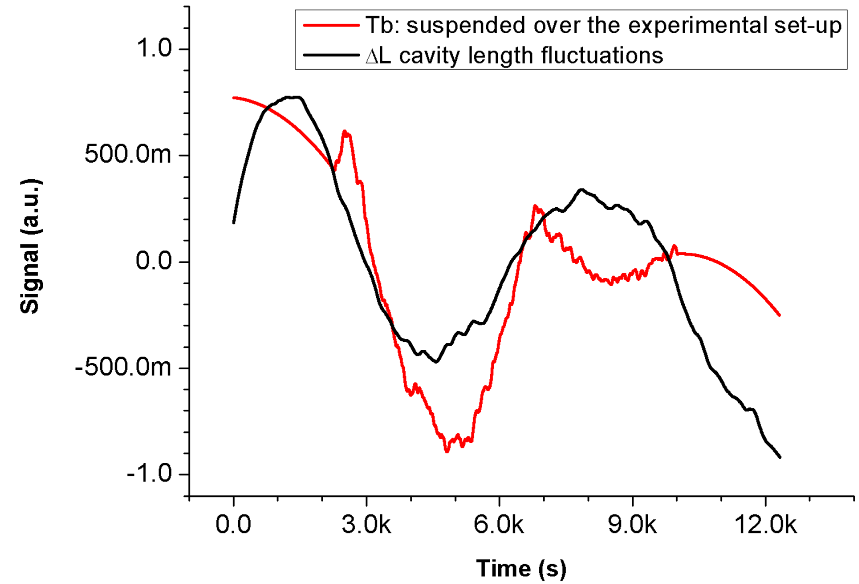


Double lock (AOM & cavity) – AOM Loop Filter

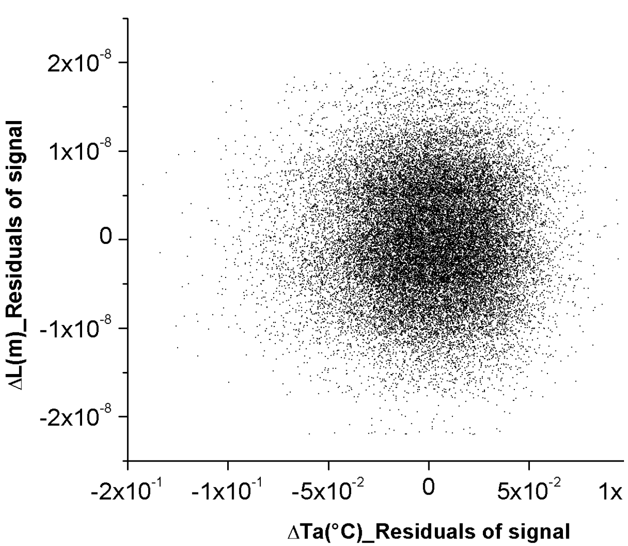


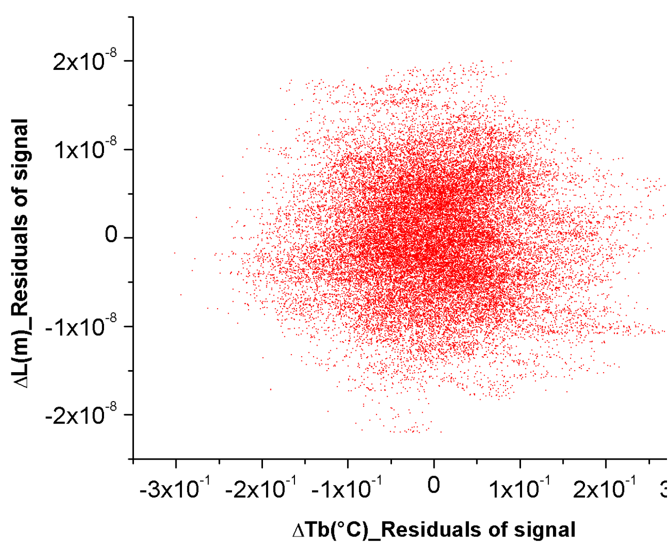
Room temperature fluctuations

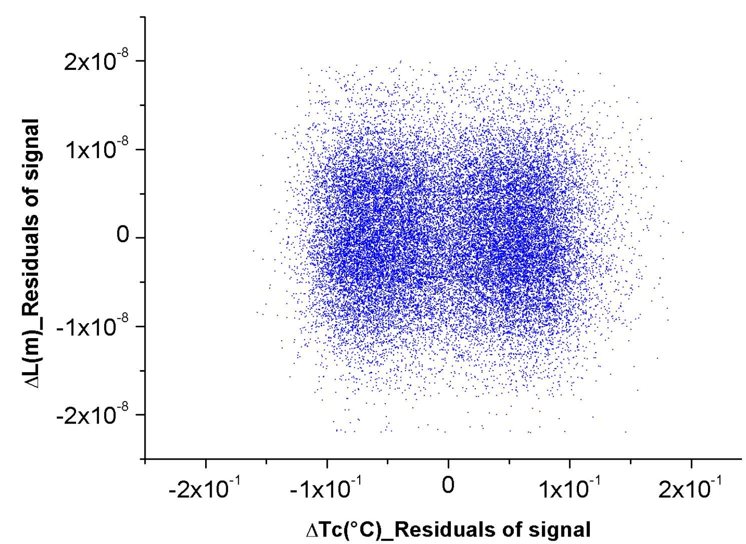




Short-time correlations







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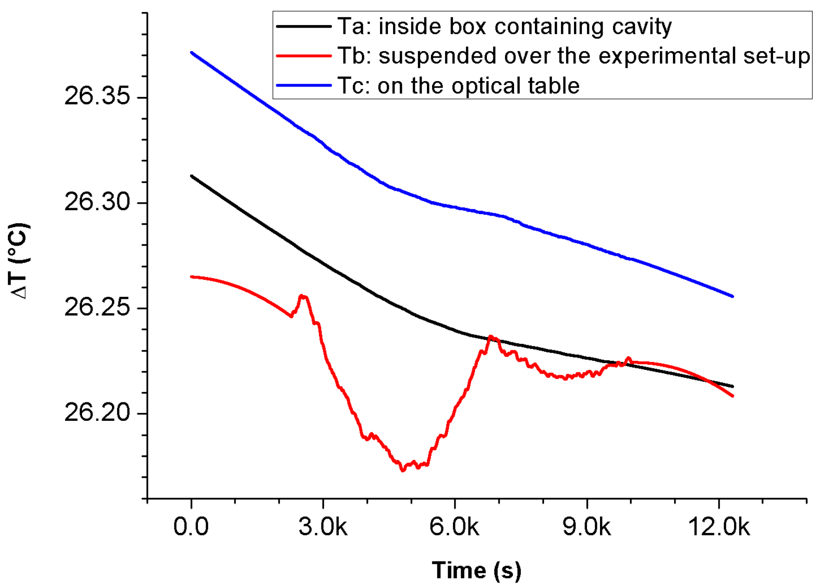
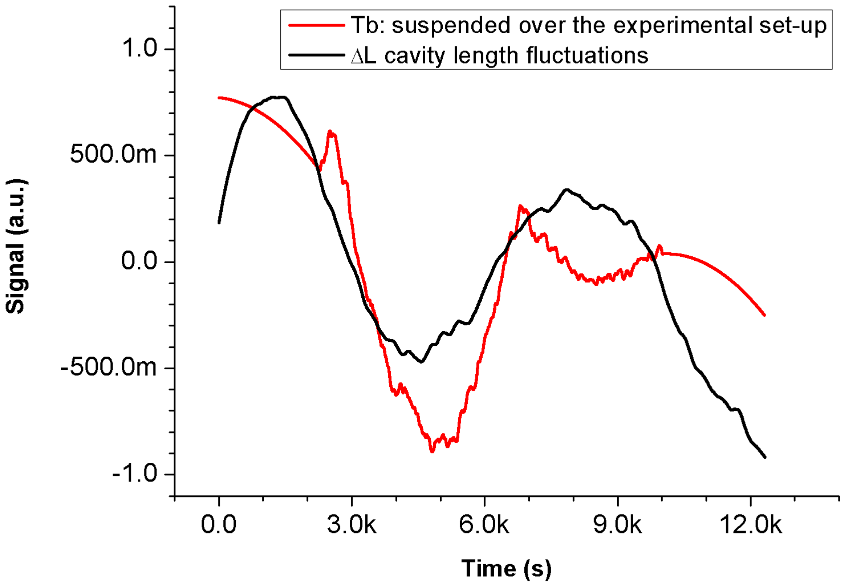
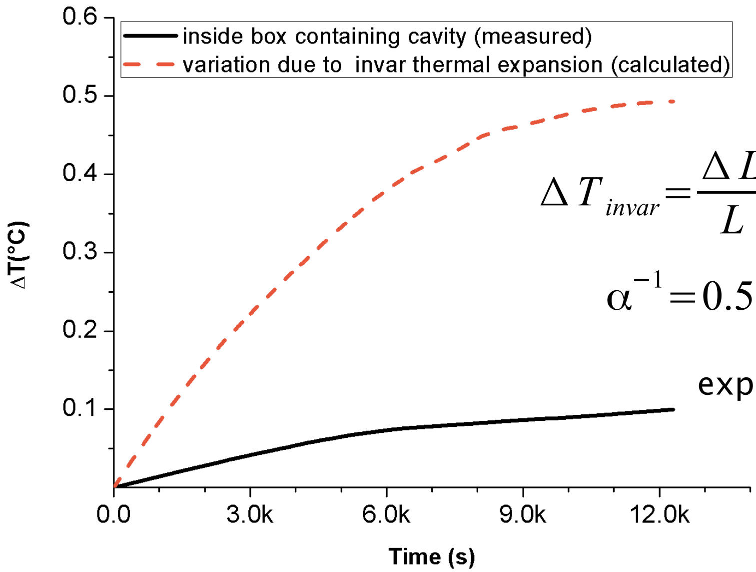




Invar thermal expansion



$$\Delta T_{invar} = \frac{\Delta L}{L} \alpha^{-1}$$

$$\alpha^{-1} = 0.5 \times 10^{-6} \, {}^{\circ}C$$

Invar thermal expansion coefficient

→ We have to stabilize the laser source using the He-Ne/I2 frequency standard!

OVERVIEW

1. Motivation

2. A triple frequency-modulation technique for absolute length measurements

3. Preliminary results

4. **Conclusions & future perspectives**

Conclusions & future perspectives

We have reported the first results concerning an experimental technique for the absolute RLG diagonal lengths control using a triple-frequency modulation scheme.

- The triple-frequency modulation model elaborated shows the compatibility between the modulation theory and the error signals that we want to use in our detection scheme

  → optimization of the model using experimental validation

- The preliminary locking of the interrogating laser to one diagonal cavity proves the feasibility of the experiment, but to achieve our goal we have to stabilize the laser source

  → He-Ne/I2 frequency standard

  → location with less environmental noise (INFN lab, Polo Fibonacci) and a more mechanical stability of experimental set-up

Thank you for your attention!