Noise associated with the EOM in Advanced LIGO

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Laser noise coupling

- The coupling of laser noise to the readout signals arises through two mechanisms :

1. Loss difference of arm cavities (at high frequencies)
2. Technical radiation pressure noise (at low frequencies)

▼

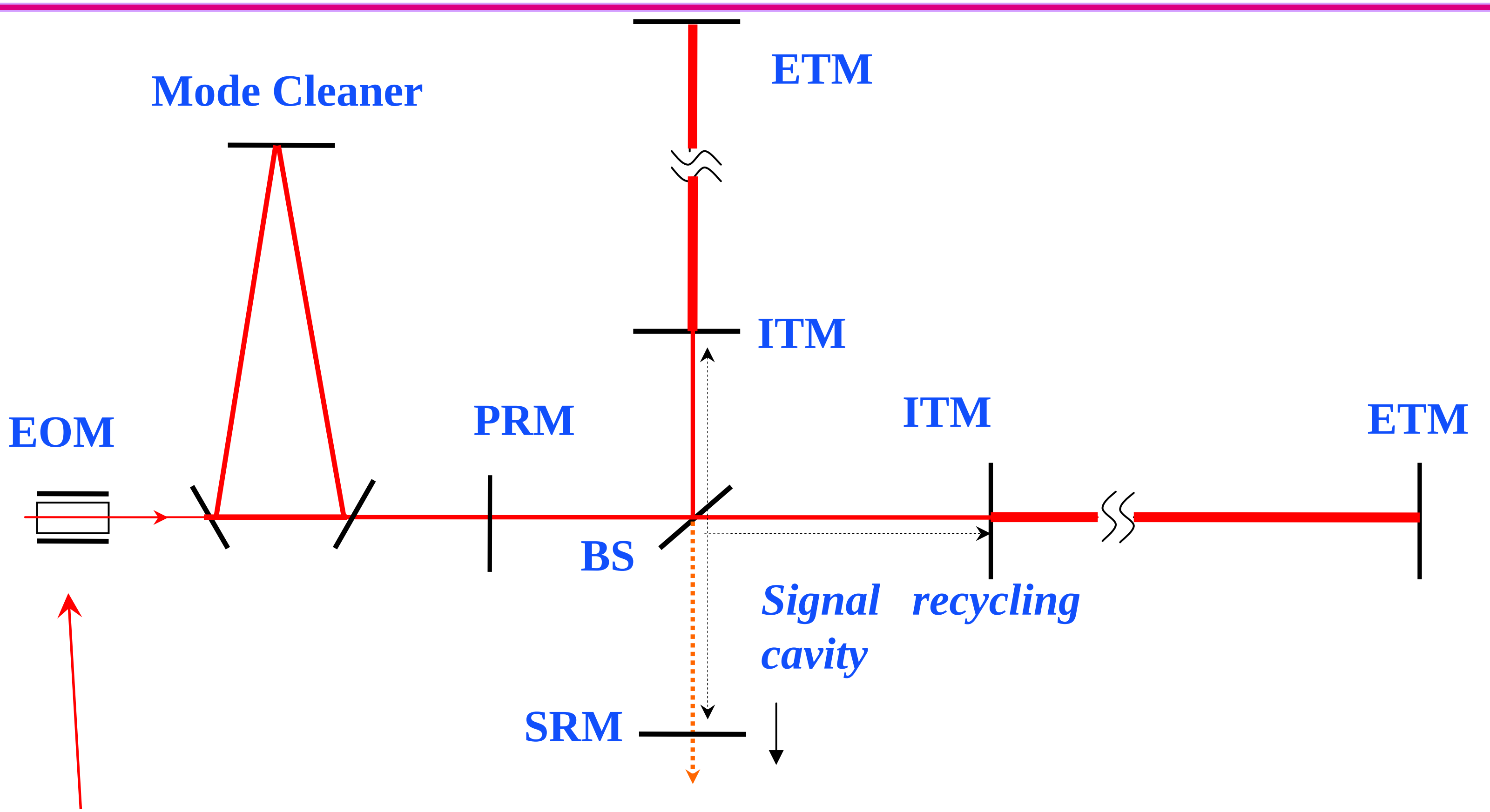
Requirement on the laser amplitude and phase noise.

The coupling effect in the DC sensing scheme is highly dependent on the readout phase (K. Somiya, Y. Chen, S. Kawamura, and N. Mio, Phys. Rev. D, 2006)

By choosing a proper readout quadrature, laser intensity noise ($\sim 2\times10^{-9}/\sqrt{Hz}$) and laser phase noise ($\sim 10^{-10}/\sqrt{Hz}$ at 100 Hz) will not be a problem

- EOM produces additional amplitude and phase noises on the transmitted light

EOM to be placed in Advanced LIGO



Noise due to the Mach-Zehnder configuration not discussed here

Noise generation mechanism I

- RF modulation on the laser:

$$\vec{E} = E_0 e^{i[\varpi t + m\sin(\Omega t+\phi)]} \approx \underbrace{J_0(m)E_0 e^{i\varpi t}}_{\text{Carrier}} + \underbrace{J_1(m)E_0 e^{i[(\varpi+\Omega)t+\phi]} - J_1(m)E_0 e^{i[(\varpi-\Omega)t-\phi]}}_{\text{Sidebands}} + \cdots$$

modulation index $m = \frac{\pi L}{\lambda} r_{33} n_z^3 \frac{V_z}{d}$

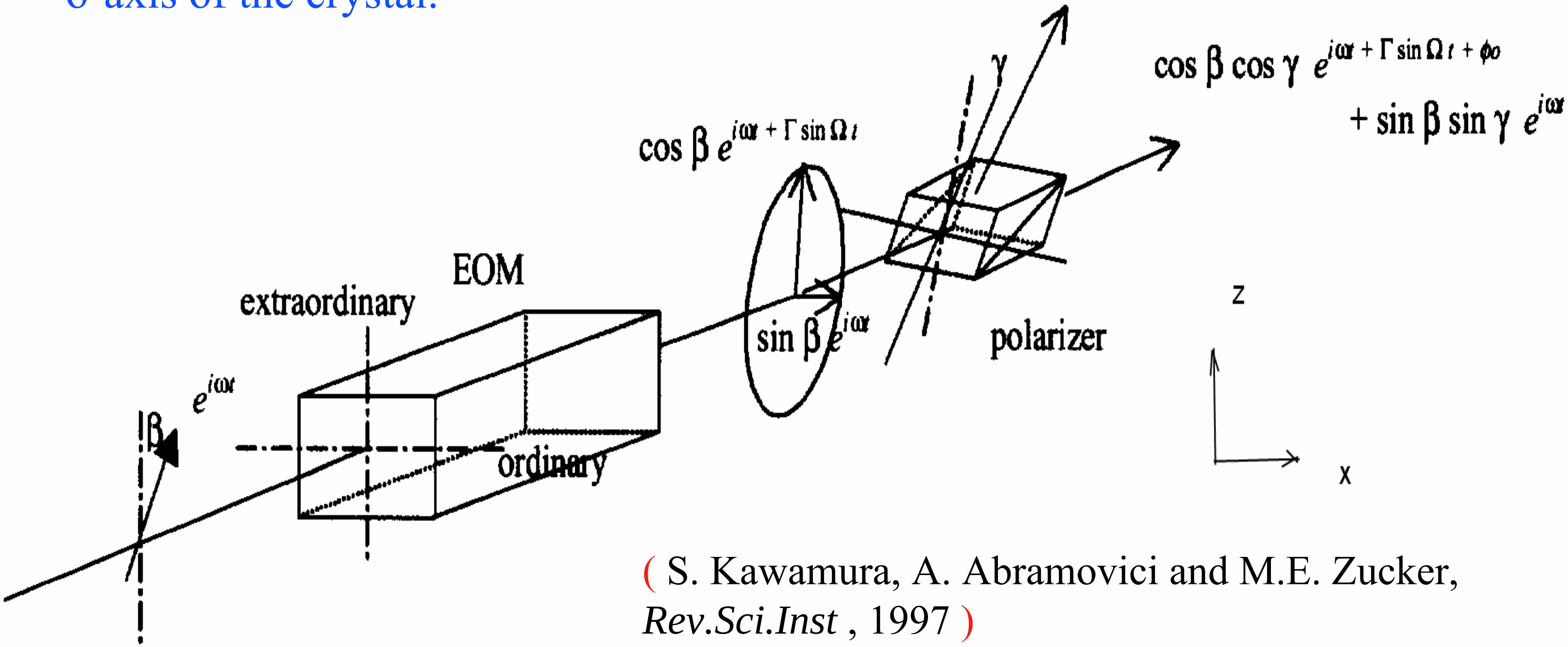
- Variation of modulation index changes the amplitude of both the carrier and the sidebands

$$\frac{\delta A_C}{A_C} = -\frac{J_1(m)}{J_0(m)} \delta m$$ (Guido Mueller, LIGO T020021-00)

Carrier light circulates inside the arm cavities and the power imbalance leads to the technical radiation pressure noise.

Noise generation mechanism II

- Misalignment of the EOM imposes a phase retardation ($\Delta\phi$) between the linear polarized light orthogonal components – along the e-axis and along the o-axis of the crystal.



(S. Kawamura, A. Abramovici and M.E. Zucker, *Rev.Sci.Inst* , 1997)

Noise generation mechanism II

Fluctuation of $\Delta\phi$ in the gw band → Phase noise on the light

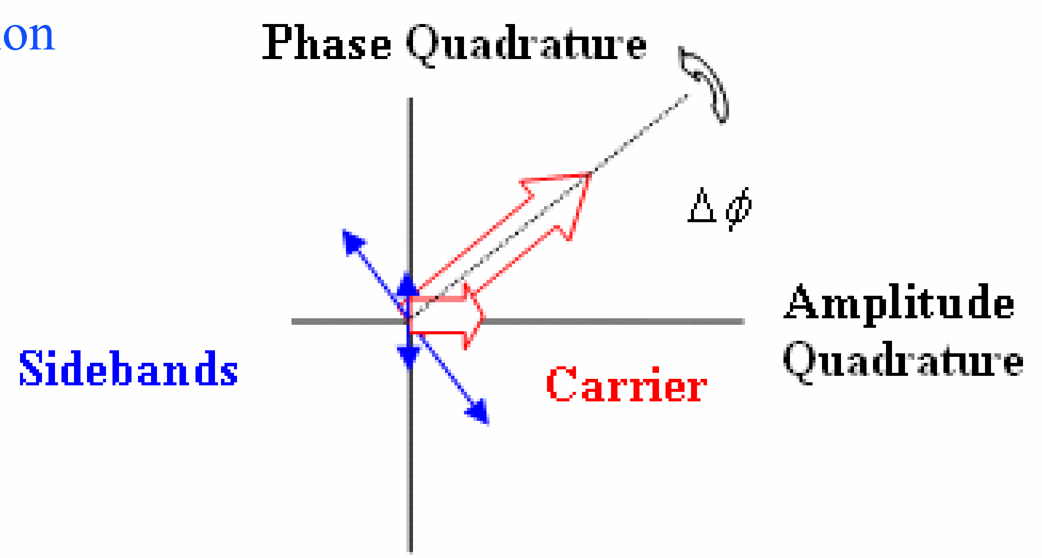
↓

Residual amplitude modulation

(laser amplitude noise)

phase retardation

$$\Delta\phi = \frac{2\pi}{\lambda}(n_z - n_x)L$$



Noise generation mechanism III

- Fabry-Perot cavity effect due to the reflectivity of the front and end surfaces of the crystal.

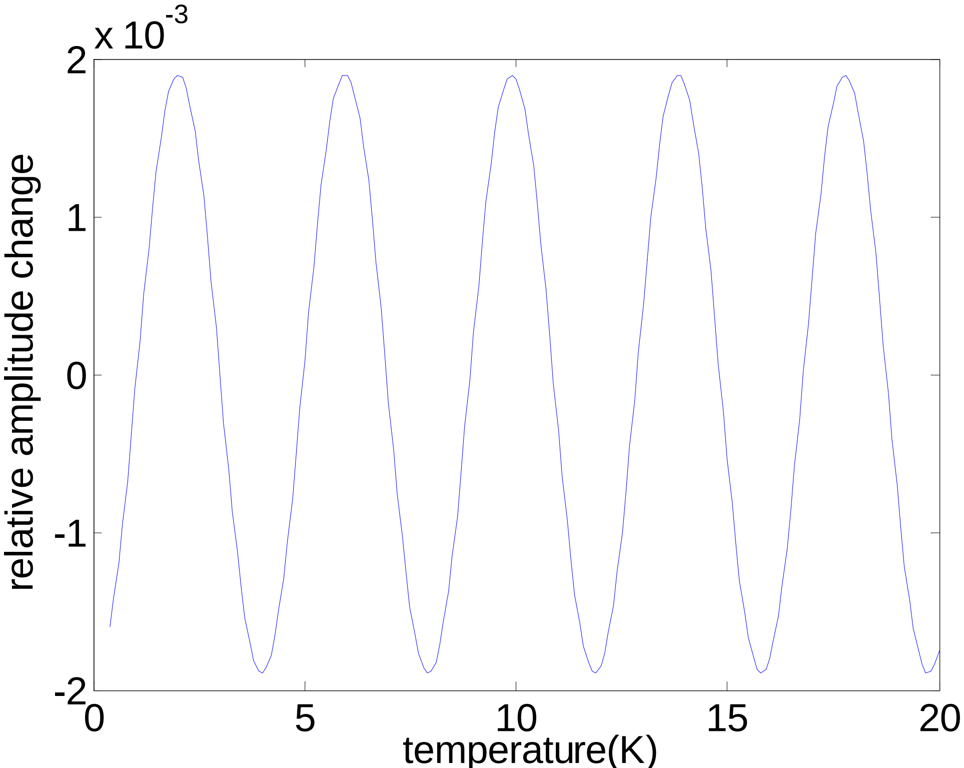
$$\vec{E} = E_0 e^{i\omega_0 t}\left(A_c T_c + A_s T_s e^{i\Omega t} - A_s T_s e^{-i\Omega t}\right) + c.c$$

$$T = \frac{\sqrt{\left(1 - r_1^{\,2}\right)\left(1 - r_2^{\,2}\right)}\, e^{-i\frac{n\omega L}{c}}}{1 - r_1 r_2 e^{-i\frac{2n\omega L}{c}}}$$

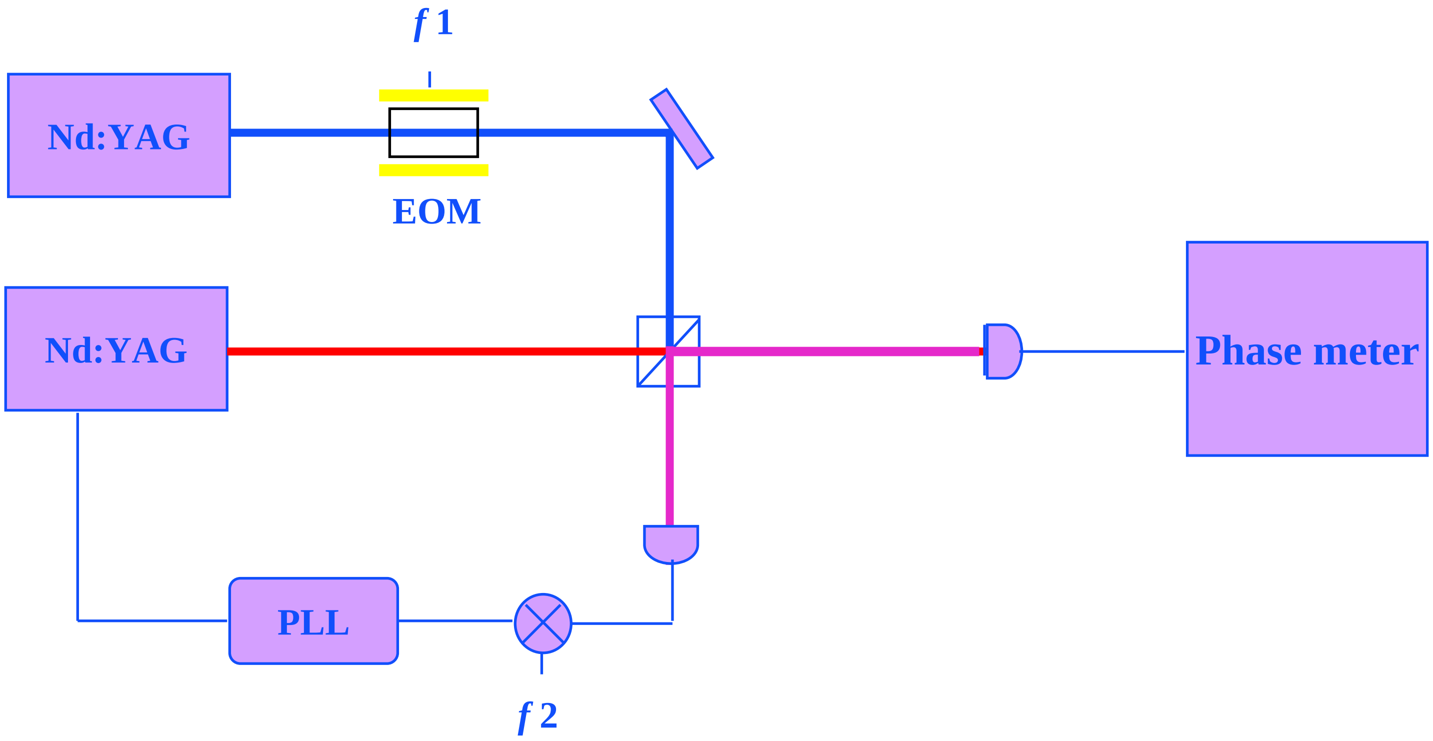
$$T_c = T\left(\omega_0\right)$$

$$T_s = T\left(\omega_0 + \Omega\right)$$

Possible amplitude change due to the 0.2% reflectivity



Measurement of the intrinsic EOM noise



- **Phase lock two lasers with a frequency offset**
- **Measure the beat signals –** Carrier-Carrier (C-C), Carrier-Sideband (C-S)

Phase meter

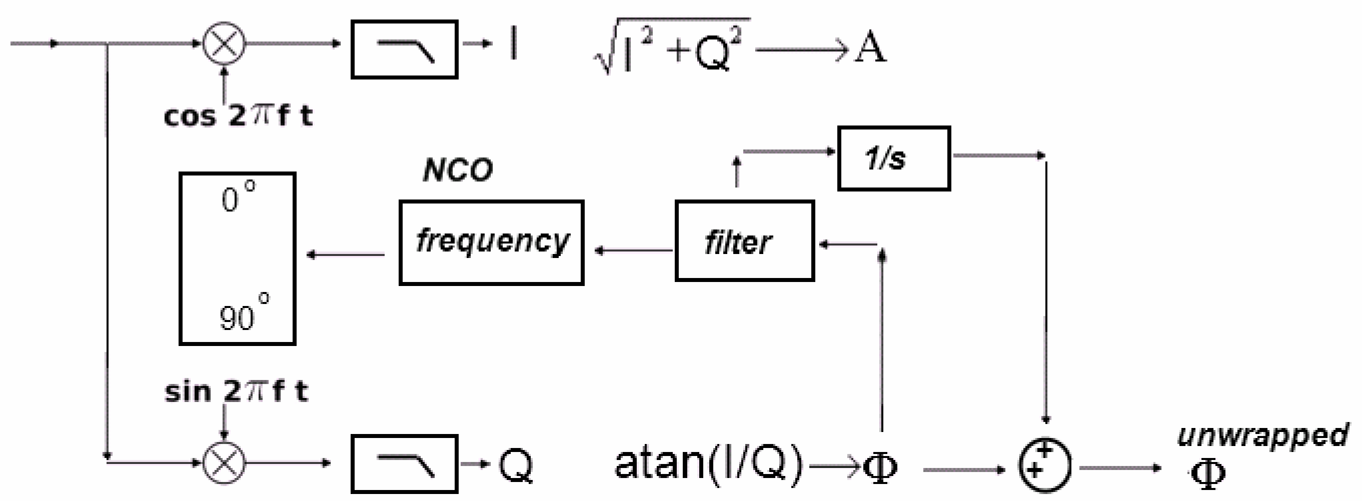
- Phase meter is the DSP instrument to have the I/Q measurement on the RF signals

- developed by UF LISA group

- 100 MHz sampling frequency

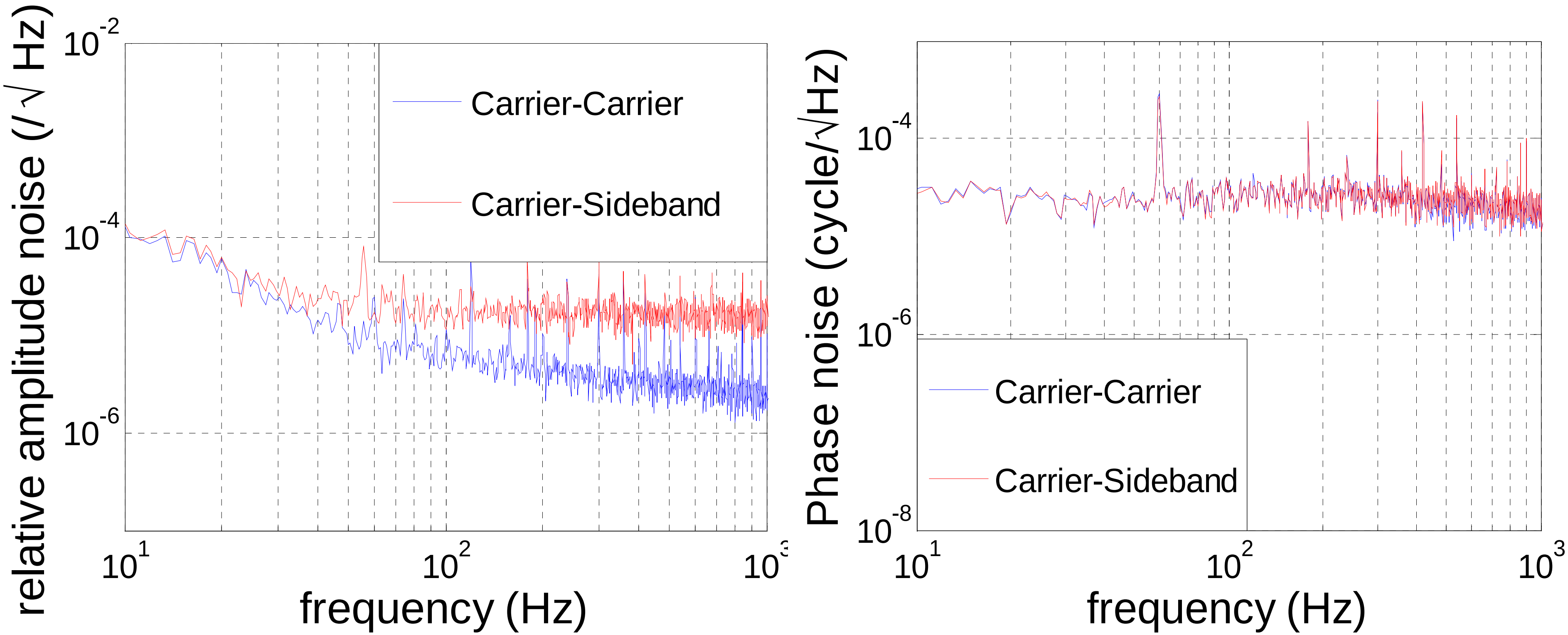
- time series measurement on the mixture of signals

- output amplitude and unwrapped phase



Advantage we gain: Avoid using diode mixers!

Amplitude noise & phase noise



Noise in the beat notes

Noise in two beat signals (C-C, C-S) in common mode

- Beam jitter between two laser beams
- Laser intensity noise

Noise in two beat signals in differential mode (amplitude & phase noise)

- produced by the EOM

Common mode noise rejection analysis

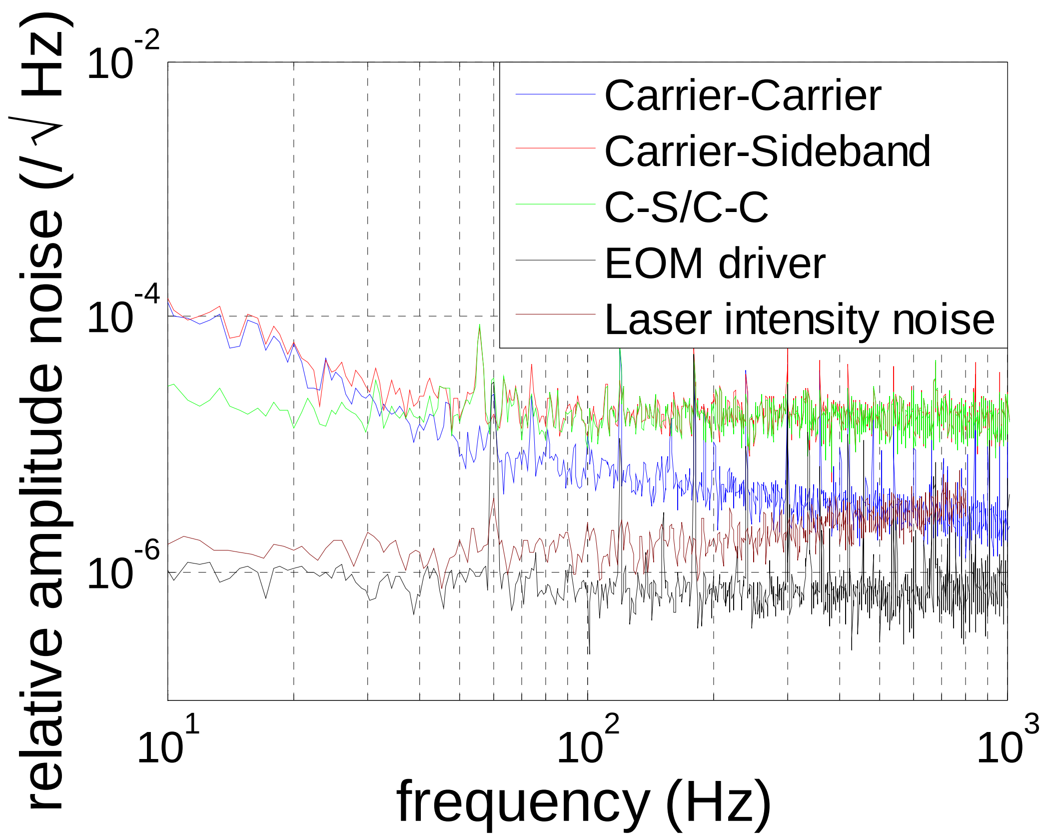
Amplitude

$$fft\left\{\frac{amplitude \quad of \quad C-S}{amplitude \quad of \quad C-C}\right\}$$

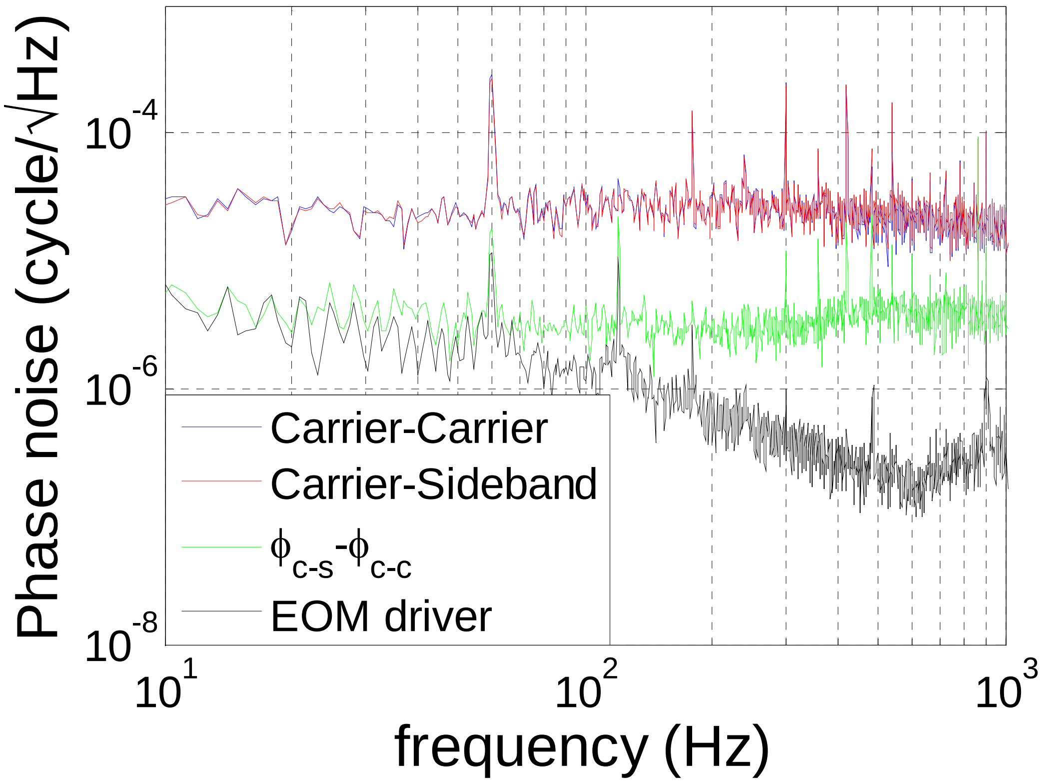
Phase

$$fft\left\{\phi_{C-S} - \phi_{C-C}\right\}$$

Data analysis



Data analysis



recommendation

- Two important factors: ***n*** and ***L***

Temperature effect: $$n_{(e,o)} = n_{0(e,o)} + \frac{dn_{(e,o)}}{dT}\Delta T \qquad L = L_0 + \alpha \Delta T$$

Acoustic vibration could also change the length of the crystal ***L***.

Need temperature stabilization and possibly acoustic isolation

Test a modulator made of wedged crystal.