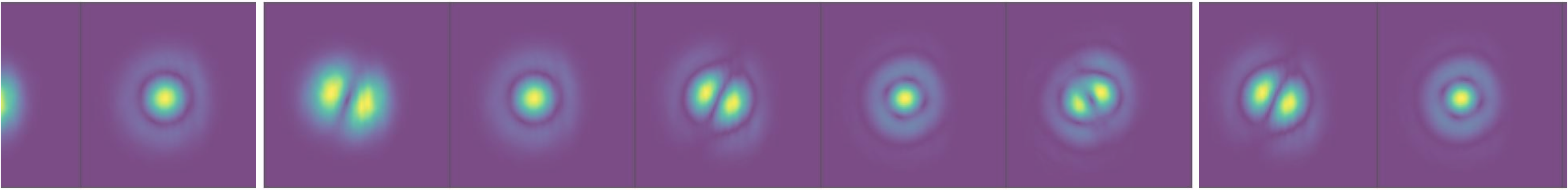
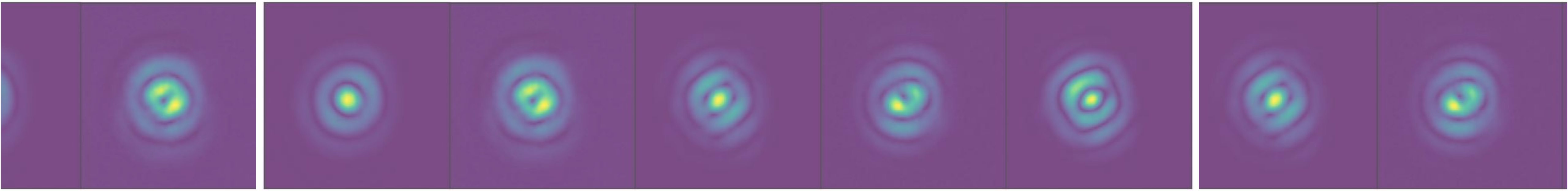


Locked cavity scan

using heterodyne detection with a phase camera



Ricardo Cabrita

Aaron Goodwin-Jones, Joris van Heijningen, Pavel Demin, Martin van Beuzekom, Matteo Tacca, Giacomo Bruno, Clement Lauzin

ricardo.cabrita@uclouvain.be

Increasing circulating power in GW detectors

Next generation detectors

Arm circ. power	**CE**	**ET (HF)**
	1.5 MW	3 MW

Current detectors

Arm circ. power	**LIGO A+**	**AdV +**
design	750 kW	150 kW
actual	**350 kW**	**96 kW**

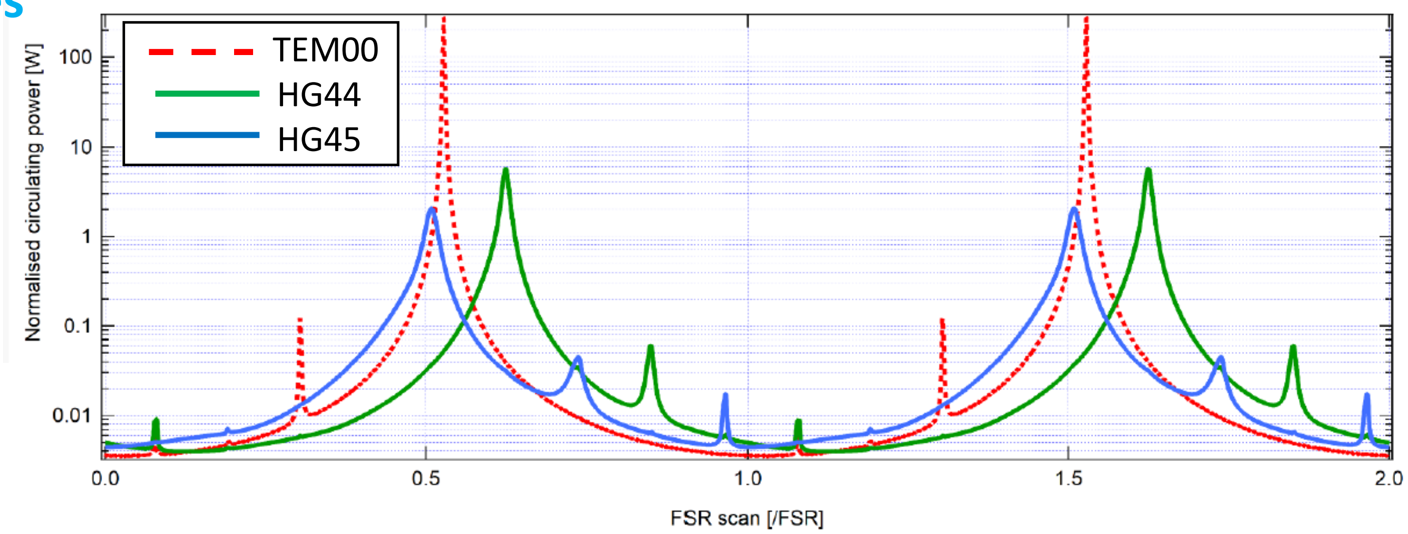
Sensitivity doesn't scale as expected with increased power.

Power losses to
- scattering,
- point defects,
- ITF working point degradation.

(some) issues with high optical power

Thermal effects can shift the cavity eigenmodes

Simulation by J. Degallaix – Virgo report VIR-0831A-24



Parametric instabilities

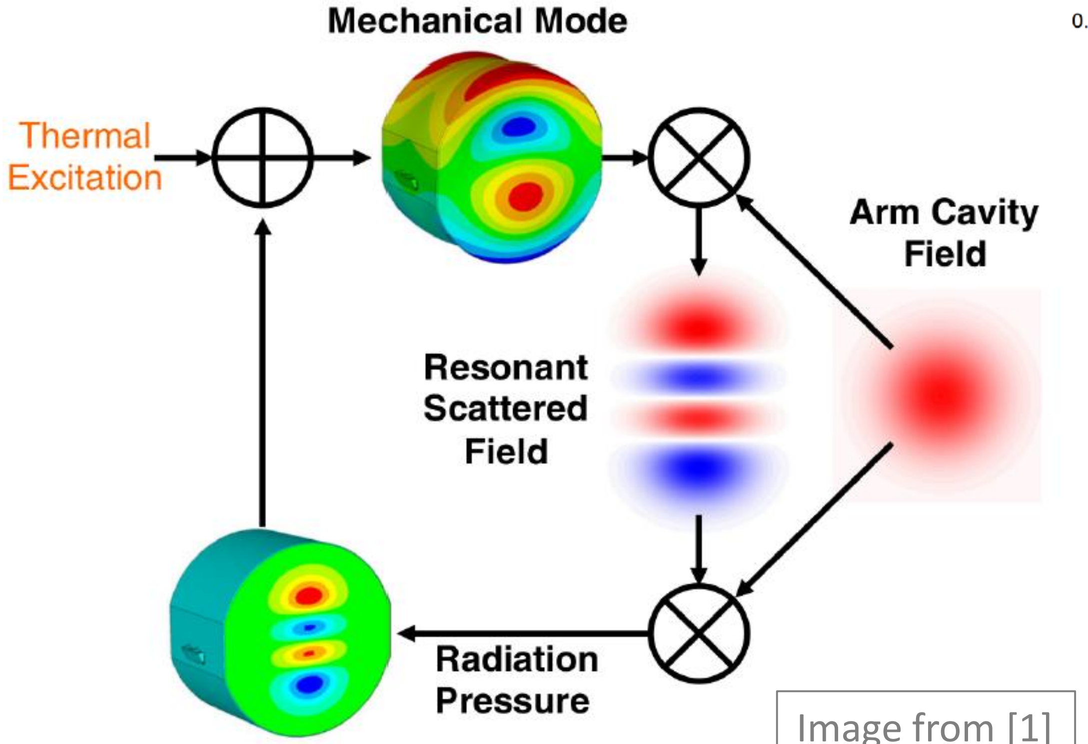


Image from [1]

high power + optical HOM overlapping with acoustic mode + radiation pressure

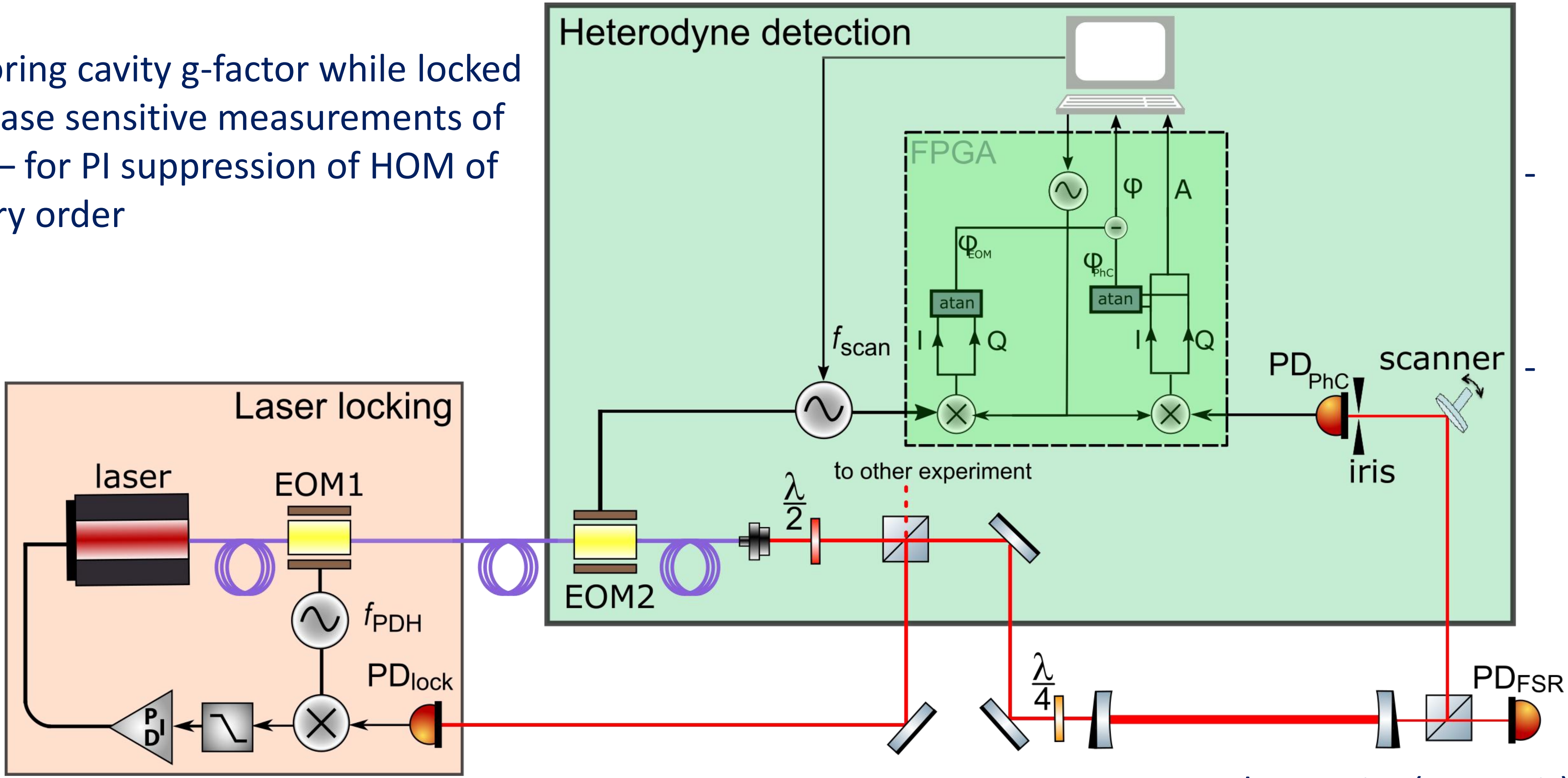
Suppression by injecting HOM with opposing phase (V. Bossilkov) [2]

Locked cavity monitoring with the phase camera

Table-top set-up at UCLouvain

Optical injection scheme + phase camera

- Monitoring cavity g-factor while locked
- Test phase sensitive measurements of HOMs – for PI suppression of HOM of arbitrary order



- Custom phase camera similar to Virgo's
- Pinhole photodiode breaks mode orthogonality

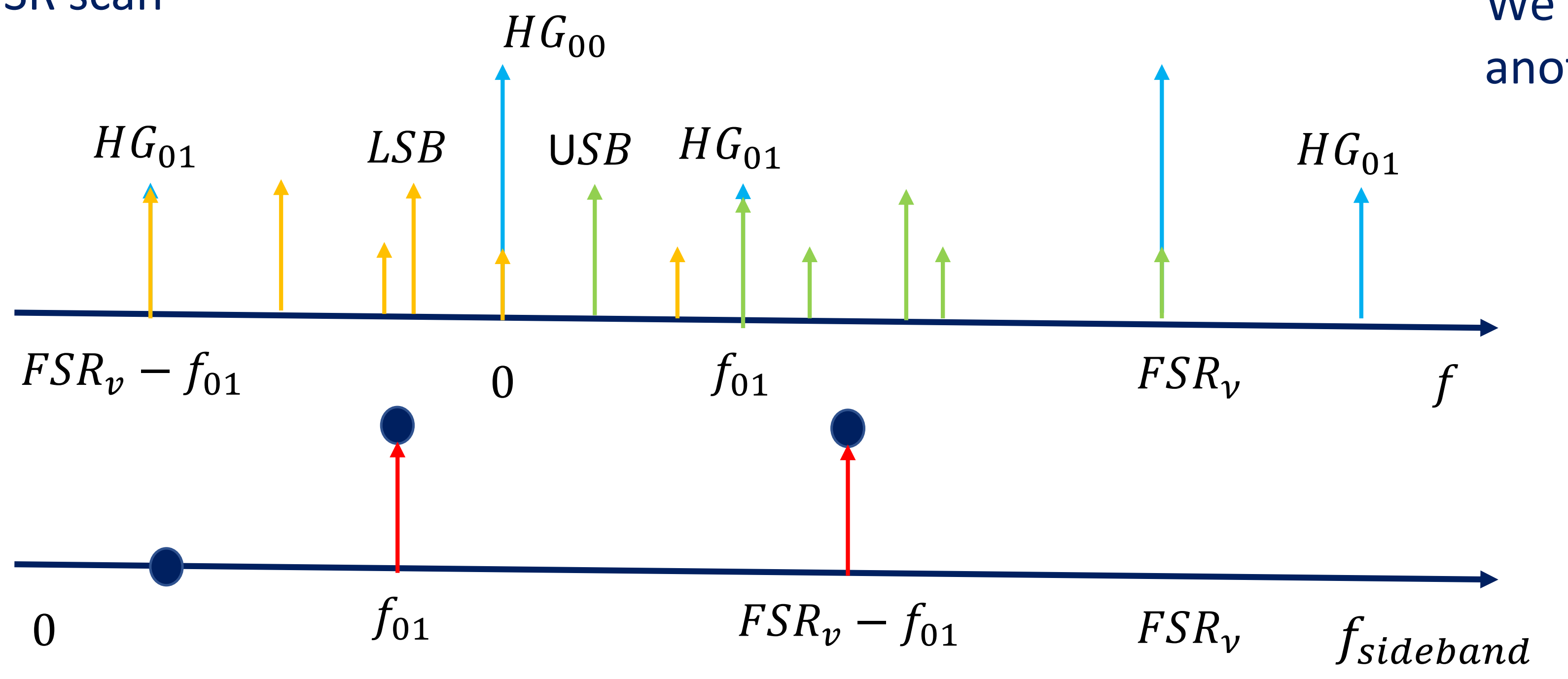
- Scanning EOM2 modulation frequency injects sideband HOM at key frequencies

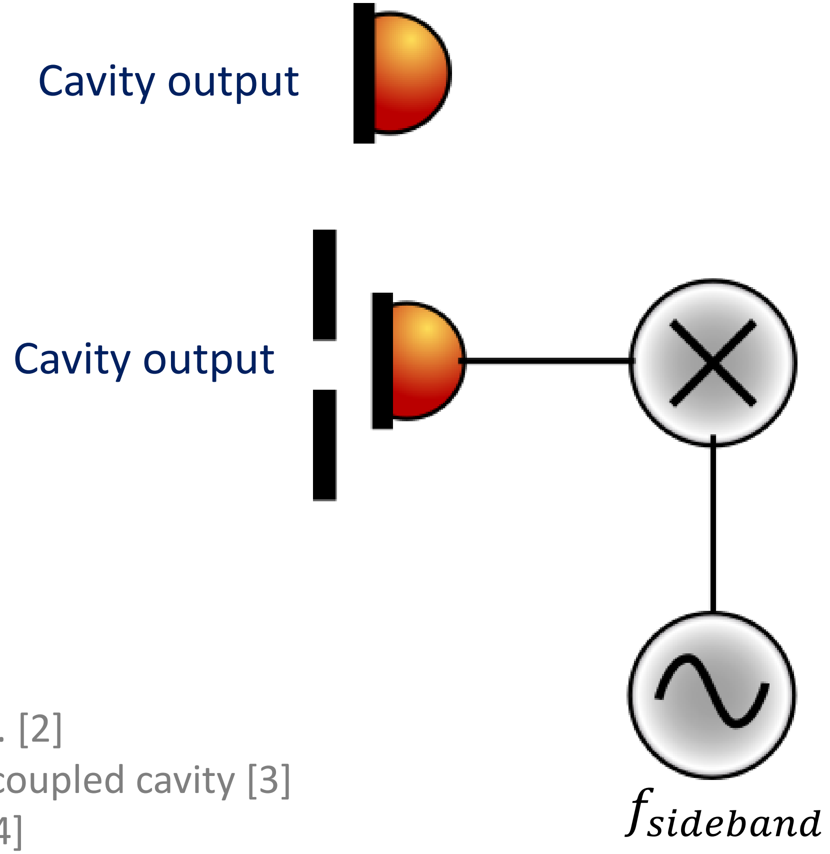
- Invar bar cavity (open air)
- 32 cm, (nominal) Finesse 360

Sideband HOM injection with EOM

FSR scan

We obtain a spectrum from the LSB and another from the USB at $\mathrm{FSR}_\nu - \mathrm{f}_{\mathrm{m+N}}$!





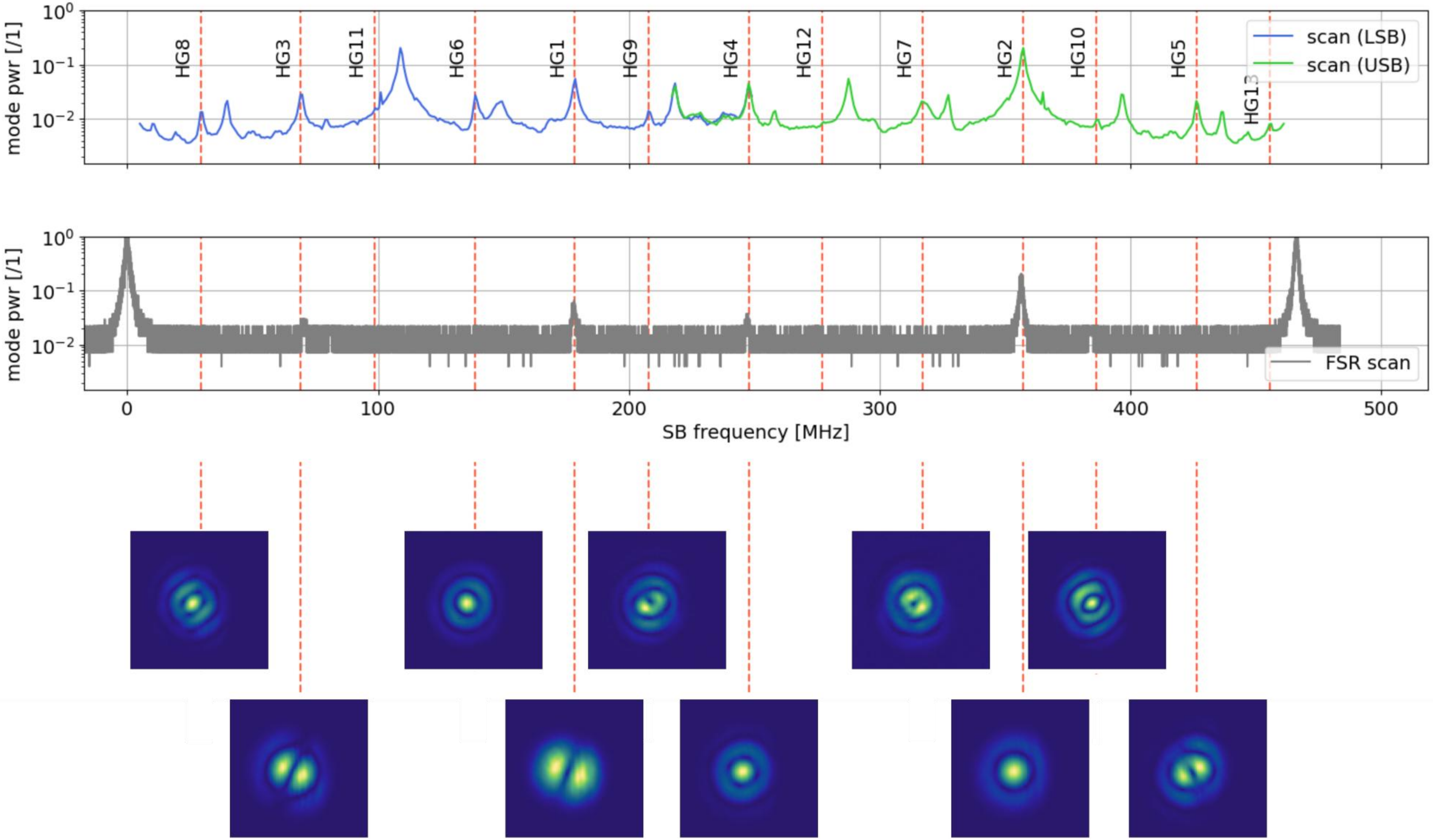
Sideband modulation frequency

Similar sideband injection scheme

- V. Bossilkov – 1st order mode injection + QPD readout – demonstration of PI suppression. [2]
- A. Goodwin Jones – 2nd order mode injection – mode mismatch simulation of linear and coupled cavity [3]
- M. Beaumont and D. Romanini - EOM scan, and blade + photodiode for v-shaped cavity [4]
- O. Schwartz – 1st order mode injection to characterize cavity concentricity (phase-contrast electron microscopy) [5]

Heterodyne scan results

Acquisition limited to 250 MHz but cavity FSR is 467 MHz – LSB probes first half of FSR and USB probes second half of FSR



Images are of the beating between carrier TEM00 and sideband HOM.

Record sideband TEM00 (500 kHz) to calibrate mode intensities.

Images can be used w/ mode decomposition to break m+n degeneracy.

Cavity g-factor measurement while locked

Fit mode positions for LSB (modes 8, 3, 6, 1, 9):

$$f_{LSB}(m+n) = \mathrm{FSR}_\nu \frac{m+n}{\pi} \arccos(1 - \mathrm{L/RoC})$$

Fit mode positions for USB (modes 4,7,2,10, 5):

$$f_{USB}(m+n) = \mathrm{FSR}_\nu - \mathrm{FSR}_\nu \frac{m+n}{\pi} \arccos(1 - \mathrm{L/RoC})$$

SB	FSR (MHz)	RoC (m)
LSB	466.186±0.021	0.5022±0.0005
USB	466.067±0.018	0.5022±0.0005

Overall fit

FSR (MHz)	Length (m)	RoC (m)	g
466.130±0.118	0.322±0.00044	0.5022±0.0005	0.360±0.0018

Different modes experience different round-trip losses (RTL):

– can be exploited to make RTL map.

Modes	FWHM (MHz)	RTL (%)
1	1.75±0.07	0.66
3	1.83±0.08	0.77
6	1.57±0.09	0.42
8	1.68±0.16	0.57

Factoring in cavity linewidth/finesse, precision comparable to [4]

300 s scan (100 pixels x and y cross section) – need to check impact of scanning speed.

Noise and detection limits

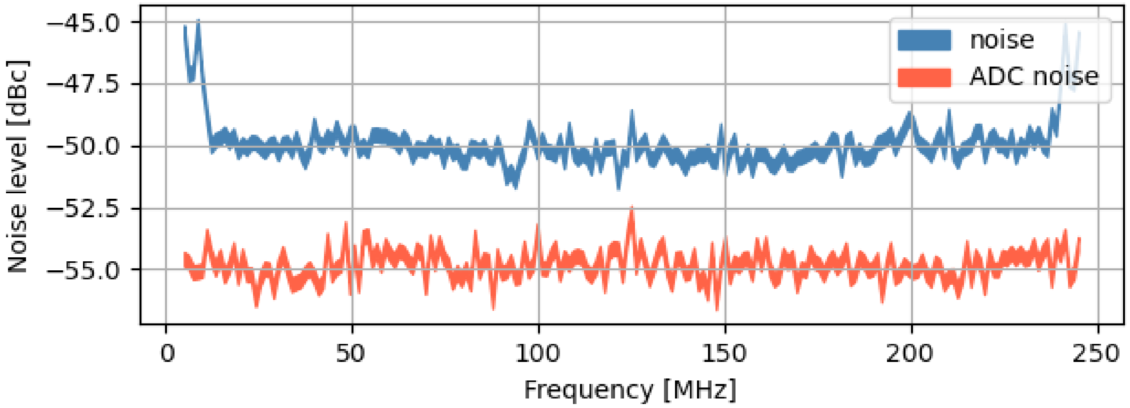
Power in sideband HOM in decibels relative to carrier [dBc]:

$$10\log_{10}\left(|k_{mn}|^2\frac{P_{SB}}{P_{carr}}\right)\quad[\text{dBc}]$$

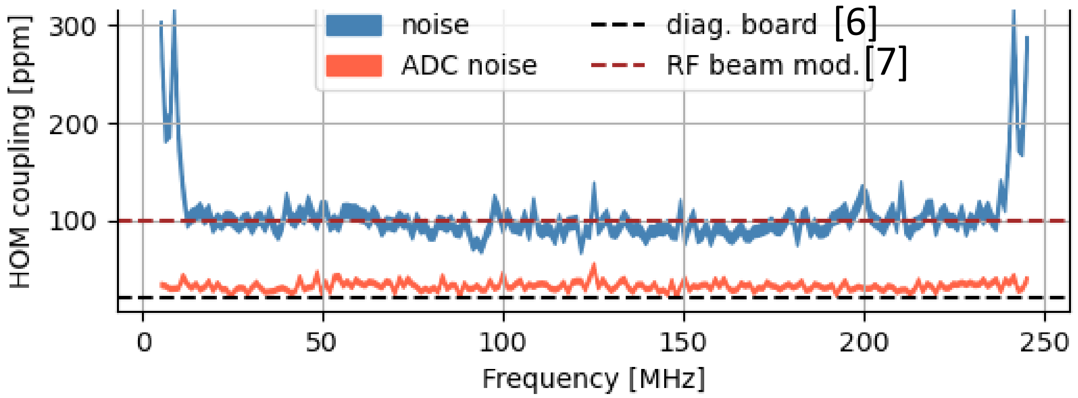
Coupling to HOM
(comparison with FSR scan)

Given by EOM calibration

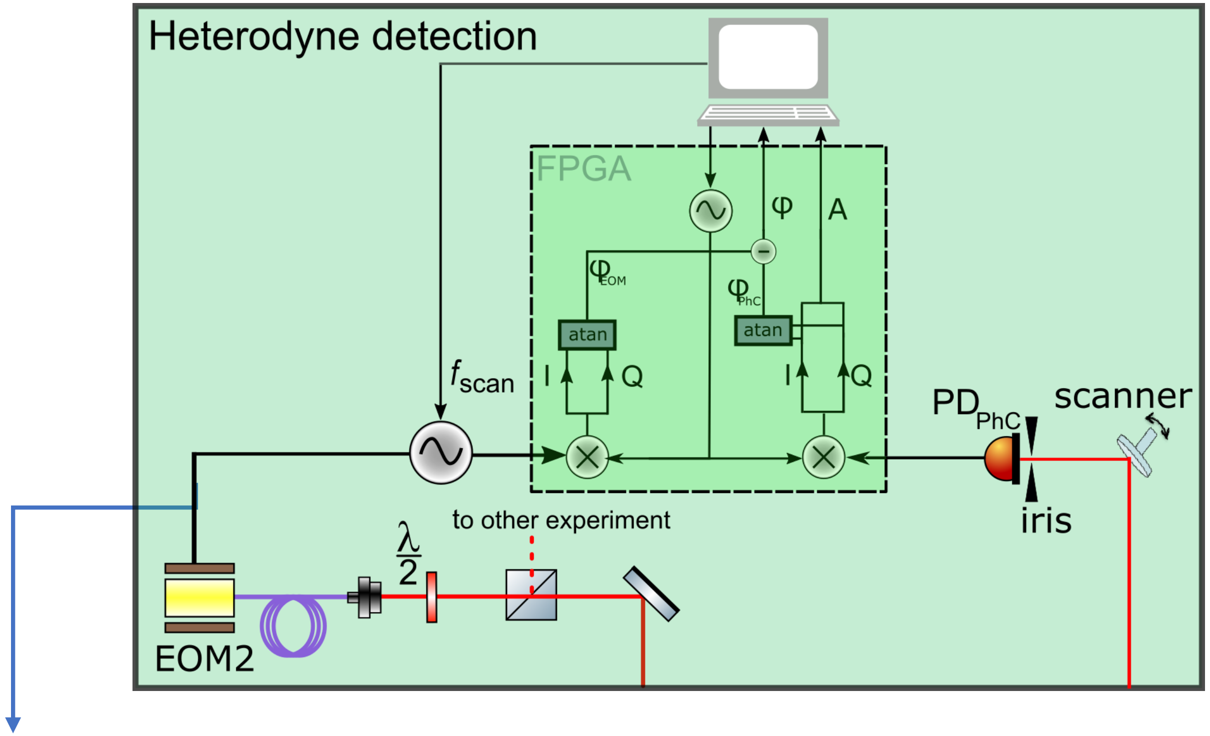
Calibrated noise measurements in dBc units

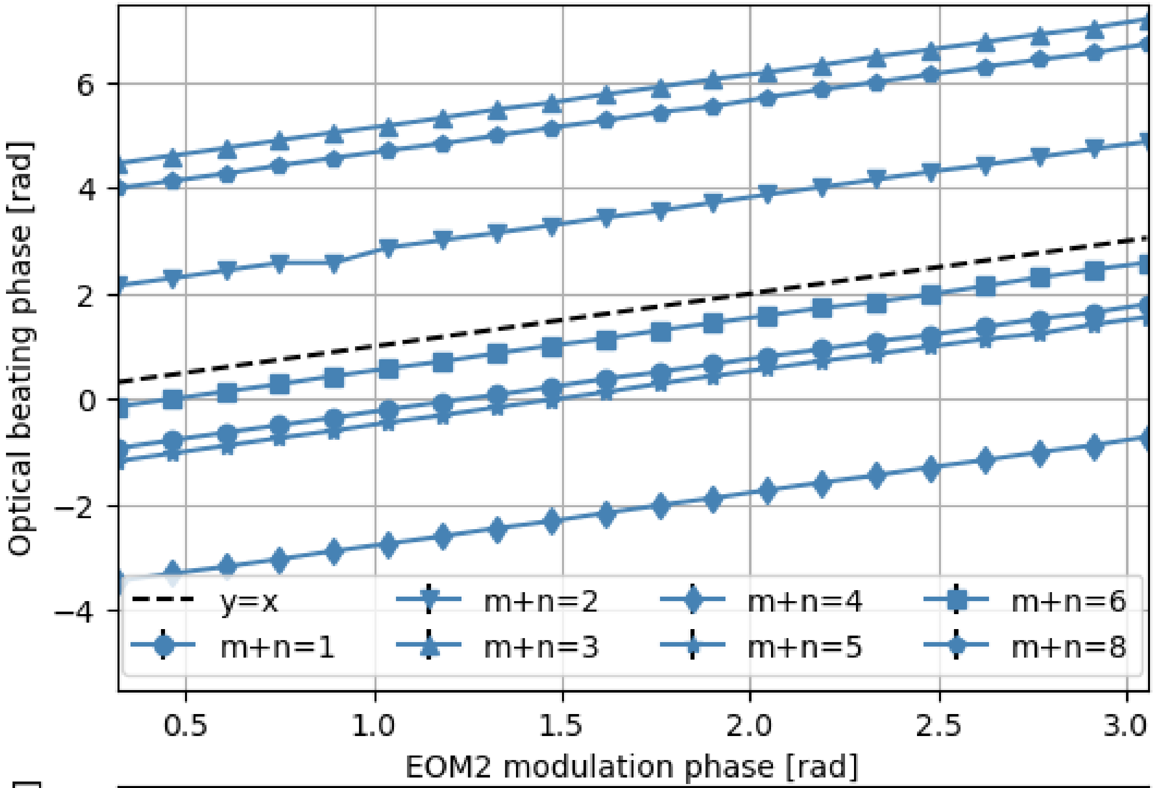


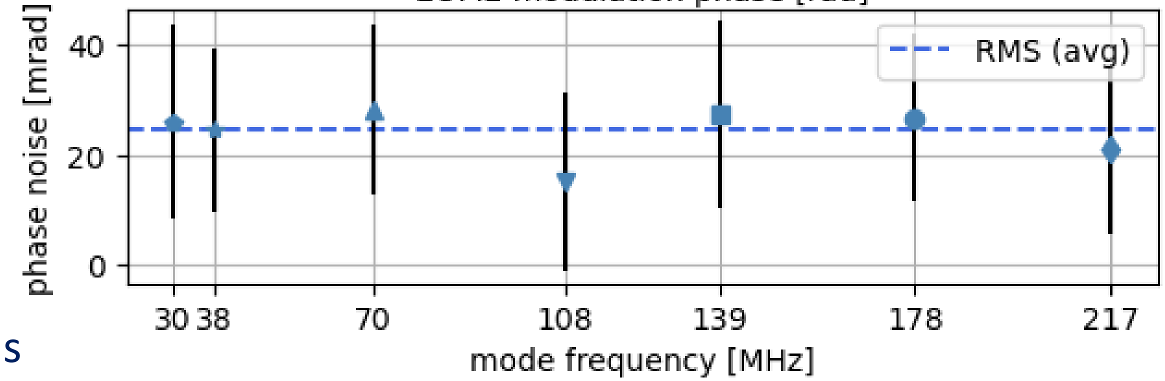
Converted to HOM coupling
assuming 10% sidebands.



Phase sensitive measurements



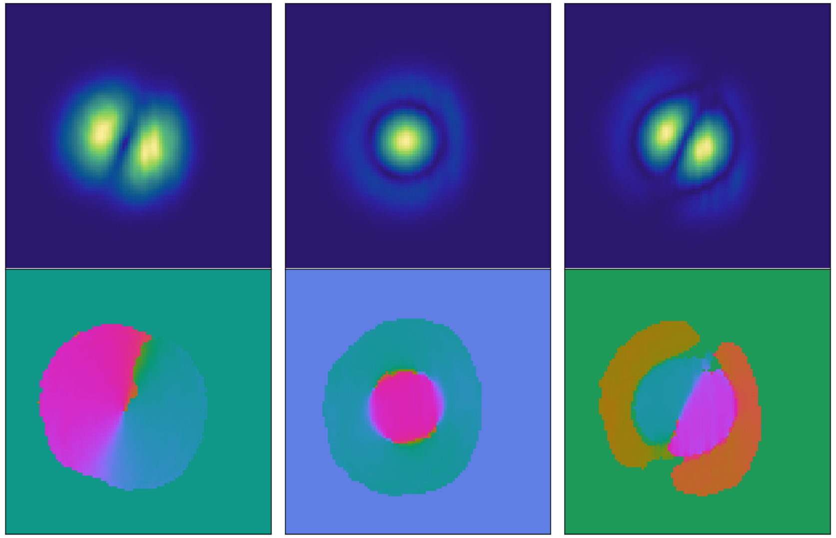




- Phase of EOM2 modulating sine is swept.
- Phase camera retrieves optical beating phase between carrier and sideband HOM – arctan(Q/I)

- Phase camera can be used for PI suppression of arbitrary HOMs
- Can also be used for mode mismatch and misalignment signals in transmission

Perspectives



Towards the MW goal in next generation detectors

Online monitoring of the interferometer eigenmodes to feedback into thermal actuators

- Test the technique at GW detectors.
- Use the mode images (including phase) and FHWM to map RTL as cavities heat up.
- Combine with simulations to match with real detector.

Publication in preparation (early draft): https://dcc.ligo.org/P2500129

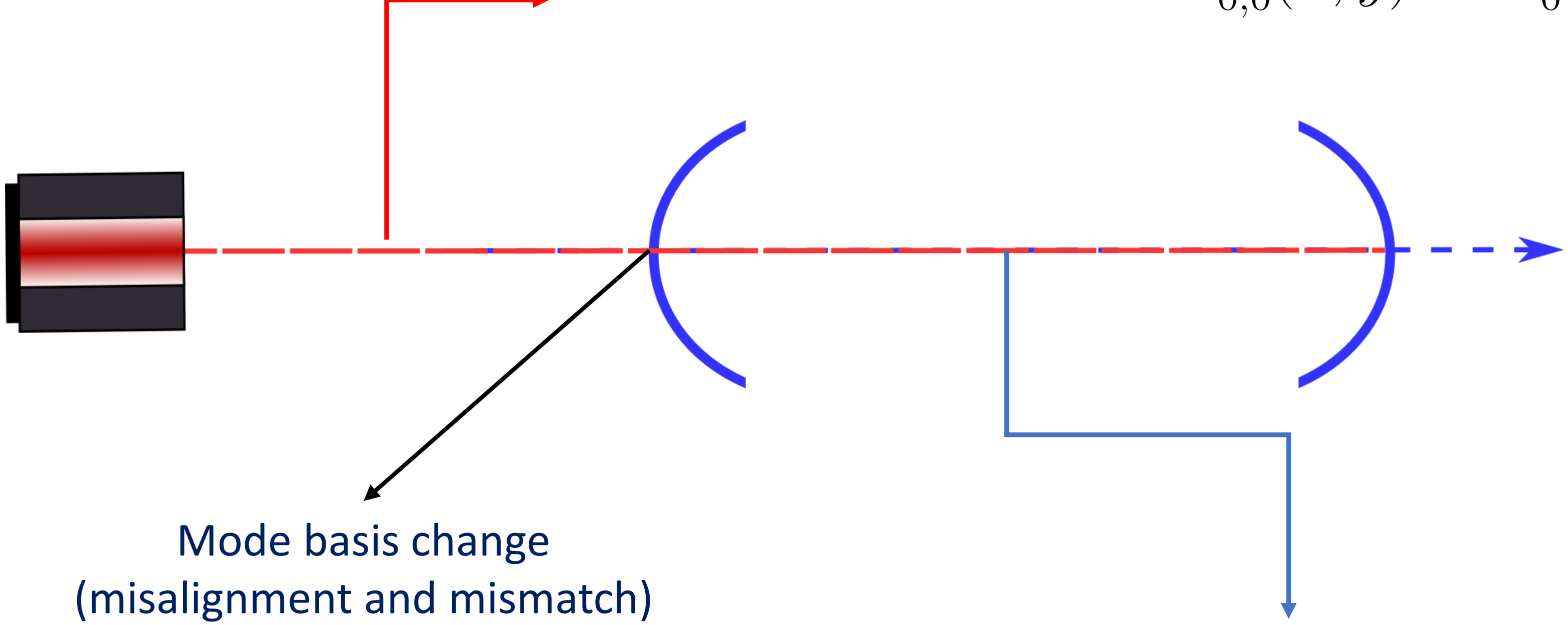
References

[1] M.Evans et al., ‘’ Observation of parametric instability at LIGO’’ Phys. Rev. Lett. 114, 161102 (2015)
[2] V. Bossilkov, Jian Liu et al., ‘’Demonstration of the parametric instability suppression through optical feebdack‘’ Rev. D 109, 102006 (2024)
[3] A. W. Goodwin-Jones, H. Zhu, et al., "Single and coupled cavity mode sensing schemes using a diagnostic field," Opt. Express 31, 35068-35085 (2023)
[4] M. Beaumont, I. Ventrillardet al., "Optical cavity spectroscopy using heterodyne detection with optical feedback laser frequency locking," Appl. Opt. 63, 2227-2233 (2024)
[5] O. Schwartz, J. J. Axelrod, S. L. Campbell, et al., “Laser phase plate for transmission electron microscopy,” Nat.methods 16, 1016–1020 (2019)
[6] P. Kwee, F. Seifert, B. Willke, and K. Danzmann, “Laser beam quality and pointing measurement with an opticalresonator,” Rev. scientific instruments 78 (2007).
[7] A. A. Ciobanu, D. D. Brown, P. J. Veitch, and D. J. Ottaway, “Mode matching error signals using radio-frequencybeam shape modulation,” Appl. Opt. 59, 9884 (2020).

Extra Slides

Mode basis changes and higher order modes

Beam in the laser mode basis $\Psi'_{0,0}(x,y) = H'_0(q_x)H'_0(q_y)$



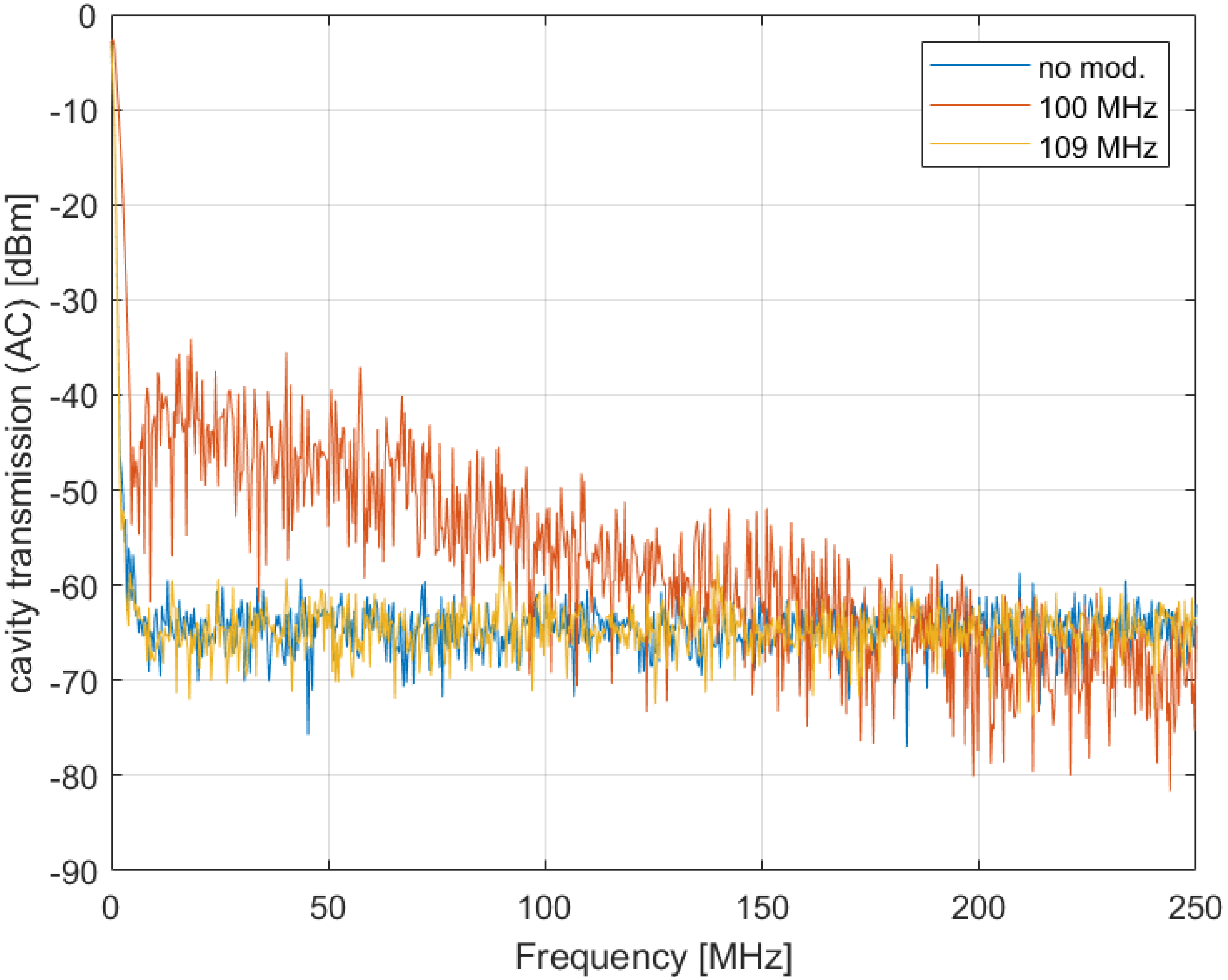
Mode basis change
(misalignment and mismatch)

$$K = \begin{pmatrix} k_{0',0} & \dots & k_{0',j} & \dots & k_{0',N} \\ \dots & \dots & \dots & \dots & \dots \\ k_{i',0'} & \dots & k_{i',j'} & \dots & k_{i',N} \\ \dots & \dots & \dots & \dots & \dots \\ k_{N',0} & \dots & k_{N',j} & \dots & k_{N',N} \end{pmatrix}$$

Beam in the cavity
mode basis

$$\Psi_{mn}(x,y) = H_m(q_x)H_n(q_y)$$

PDH + second sideband modulation



- PDH frequency = 50 MHz.
- The PDH lock is unaffected except for scanning frequencies at the PDH frequency times n (natural number).