Cavity mode matching with a phase camera

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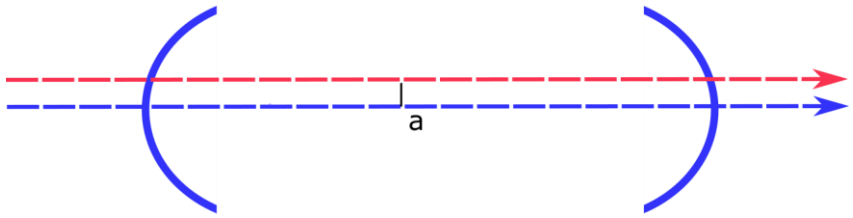
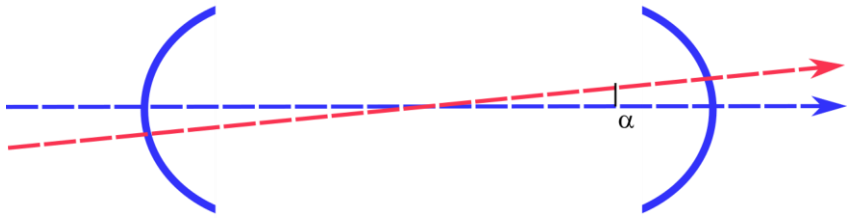
Degrees of freedom of a cavity

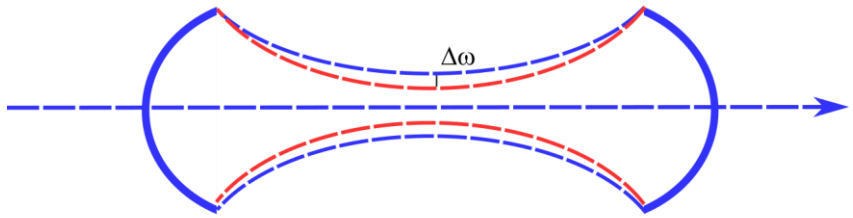
Transverse displacement



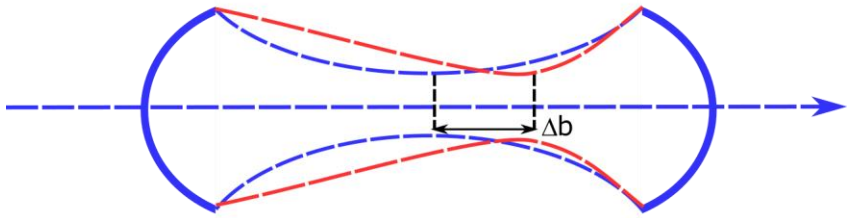
Tilt



Waist size mismatch

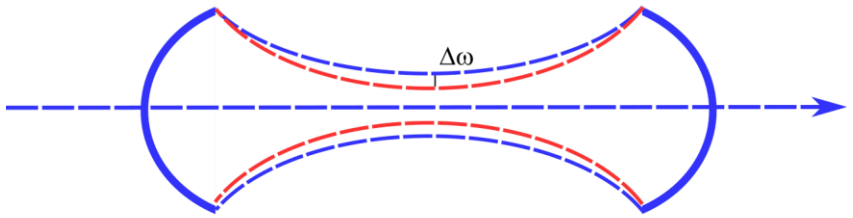


Waist position mismatch

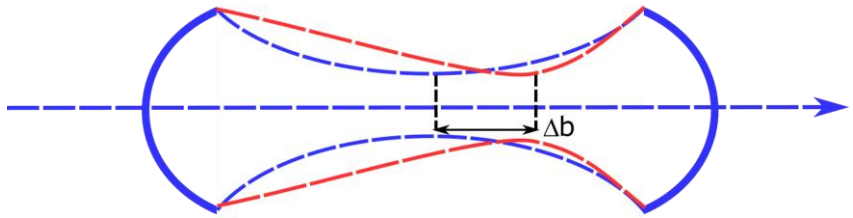


Mode mismatch

Waist size mismatch

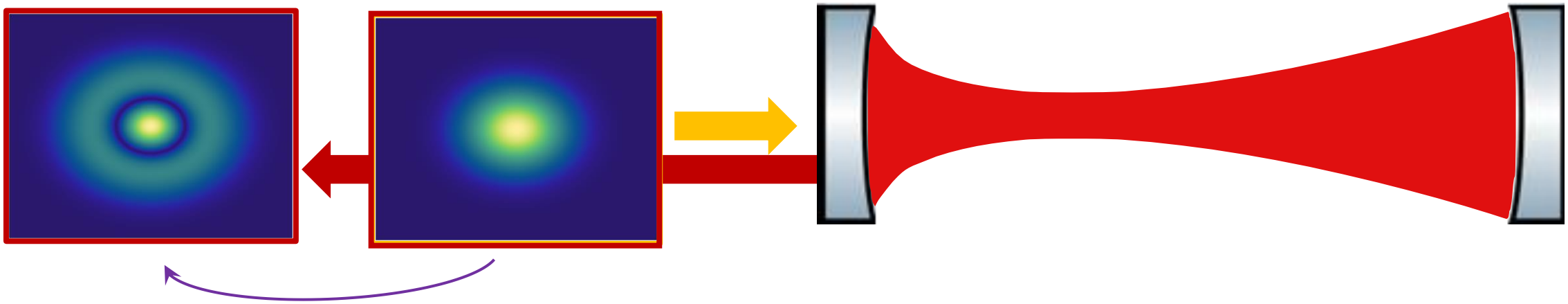


Waist position mismatch



Mode order 2

Mode order 0



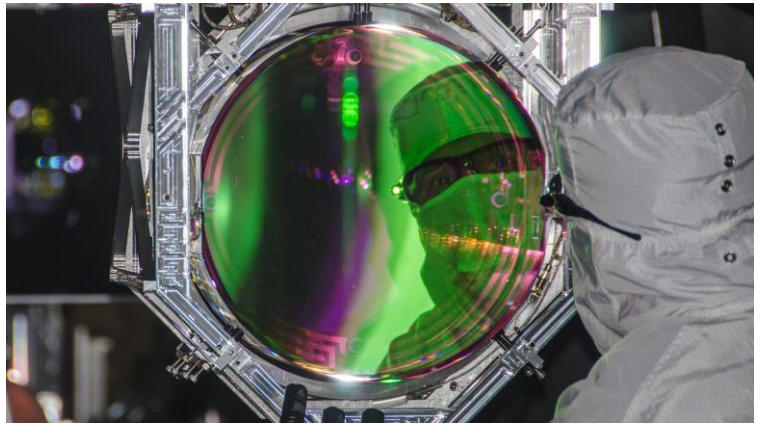
$$k_{0,2} = \frac{1}{2}(\Delta b - i\Delta\omega)\sqrt{2}$$

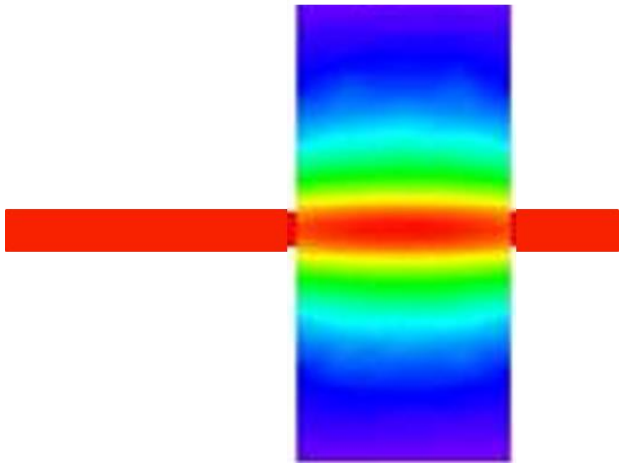
Most existing mode match sensing schemes need two sensors to measure both degrees of freedom.

A. W. Goodwin-Jones, R. Cabrita et al., Optica 11, 273-290 (2024)

Mode mismatch in GW detectors

Manufacturing defects and deviations of the radius of curvature of the optics introduce mode mismatch.





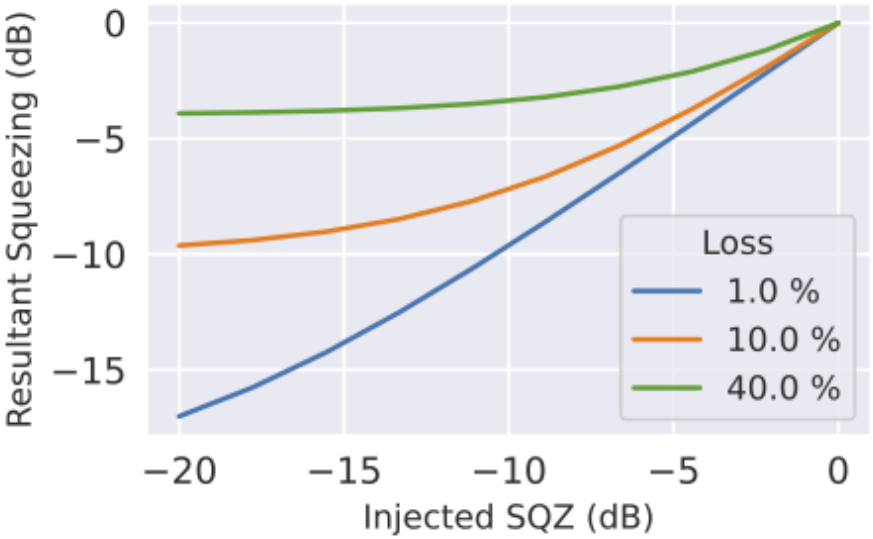
Thermal absorption in the mirrors leads to thermal lensing – hot and cold interferometer.

Next generation detectors are predicting 3 to 10 fold increase in circulating power. More thermal compensation will be needed with more actuators (e.g. at the beamsplitter).

Sensors and error signals will be needed to control all these degrees of freedom.

Impact of mode mismatch

A. W. Goodwin-Jones, R. Cabrita et al., Optica 11, 273-290 (2024)



Mode mismatch (and any optical loss) degrades squeezed light injection.

D. Töyrä, D. D. Brown, et al, Phys. Rev. D 96, 022006 (2017)

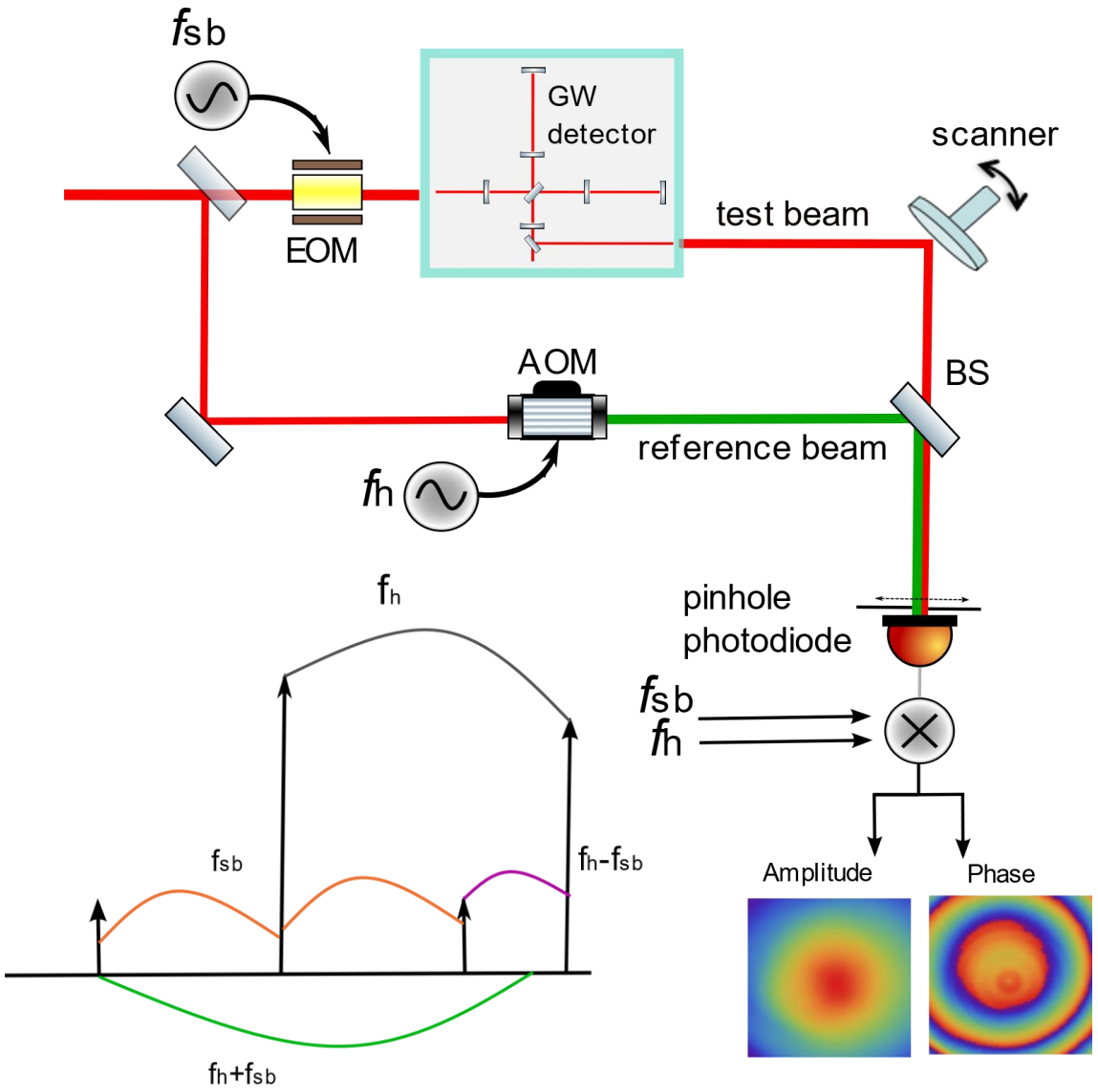
Mode mismatch can also cause unwanted rotation of the squeezing ellipse.

Complicates commissioning and operation of the detector as was observed at Virgo:

- Bi-stability working point of interferometer due to PRC/SRC matching.
- PRC/arm cavity mismatch causing offset in control loops of SRC.

P. Spinicelli, VIR-0402A-23 (GWADW) (2023)

The phase camera



Multi purpose sensor:

- Less optics and reduced complexity.
- Also monitors sideband powers, recycling gains, etc.
- Sensitive to higher-order aberrations.

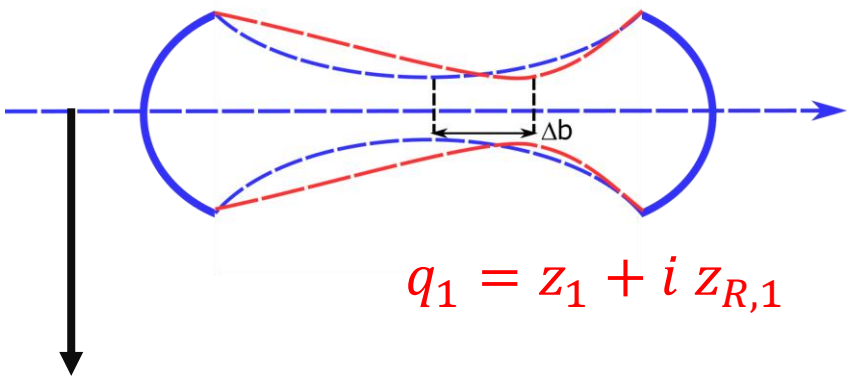
Direct access to phase information – only 1 sensor needed for mode matching.

Two phase cameras by Nikhef already installed at Virgo – can test technique in km-scale detector.

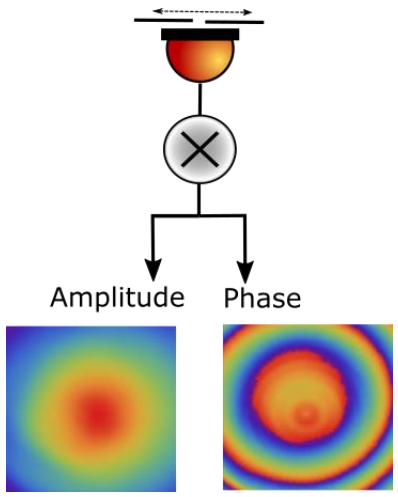
K. Agatsuma, L. van der Schaaf et al., Opt. Express 27, 18533-18548 (2019)

Error signal(s) for mode mismatch

$q_2 = z_2 + i\, z_{R,2}$



$q_1 = z_1 + i\, z_{R,1}$



Phase camera has direct access to the size and radius of curvature (phase) of beam

$$\frac{1}{q} = \frac{1}{R} + i\,\frac{\lambda}{\pi\omega^2}$$

Ideal mode mismatch error signal:

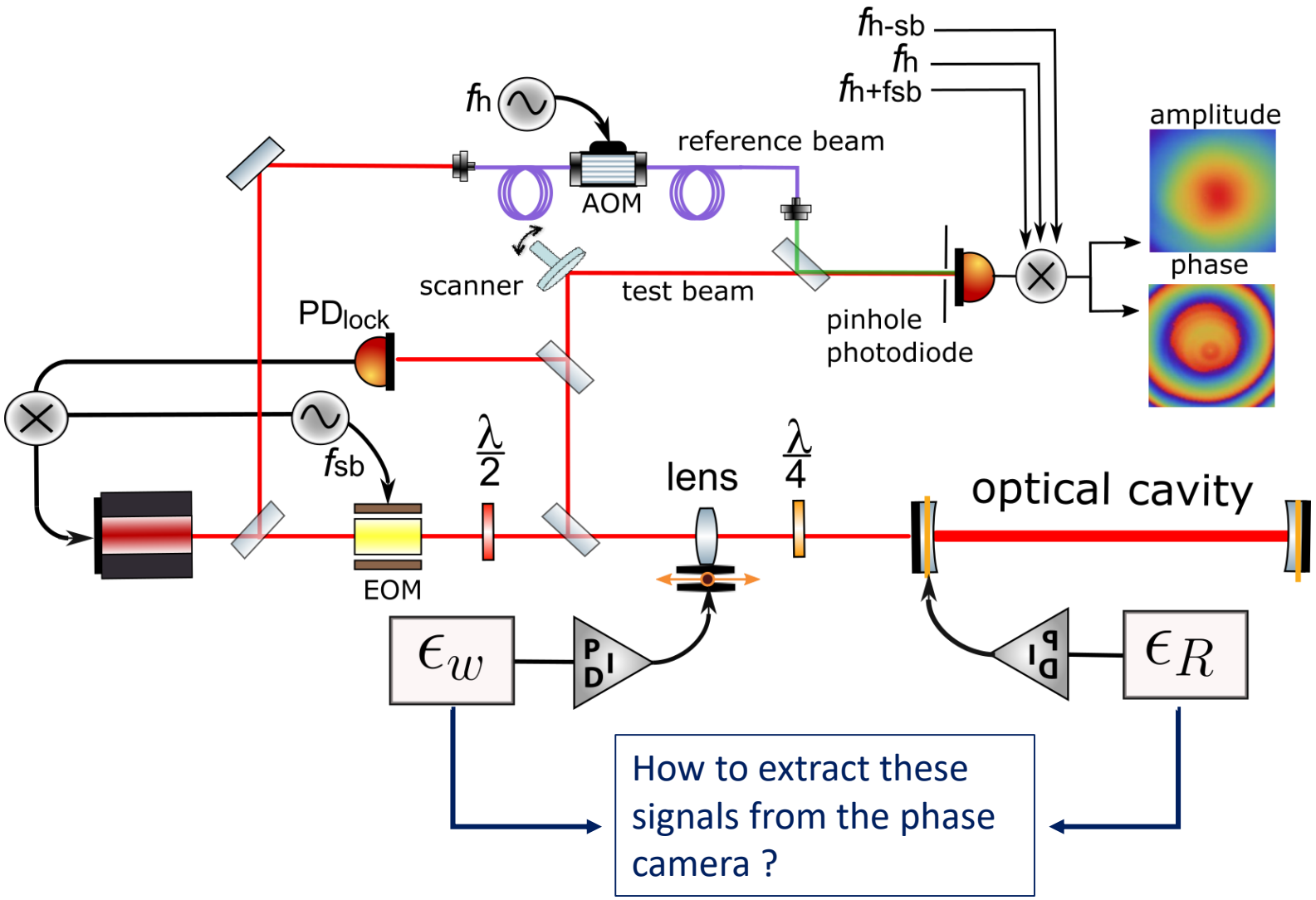
$$M = i\left(\frac{q_2 - q_1}{q_2 - q_1^*}\right) \approx \frac{i}{2}\frac{q_2 - q_1}{z_{R,1}} = \frac{i}{2}\epsilon_q$$

A. A. Ciobanu, D. D. Brown, et al., App. Opt. 59 31, 9884-9895 (2020)

The mode mismatch in the q reciprocal space will be related to:

$$\epsilon_q' = \frac{1}{q_2} - \frac{1}{q_1} = -\epsilon_R + i\epsilon_w$$

Simulating the error signals



Simulation done in OSCAR (matlab)

J. Degallaix, J. Phys. 228 1 (2010)

Phase camera monitoring the reflected beam of the cavity:

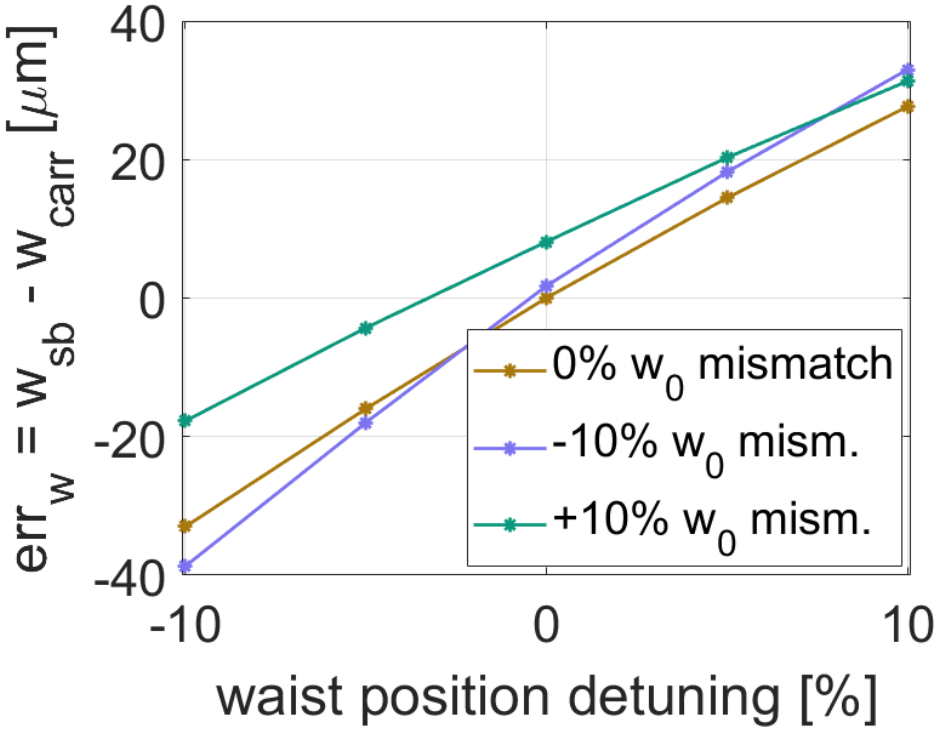
- resonant carrier leakage – cavity mode
- carrier higher-order modes
- non-resonant sidebands – input beam

Mode mismatch induced by detuning waist position and/or size of the input beam.

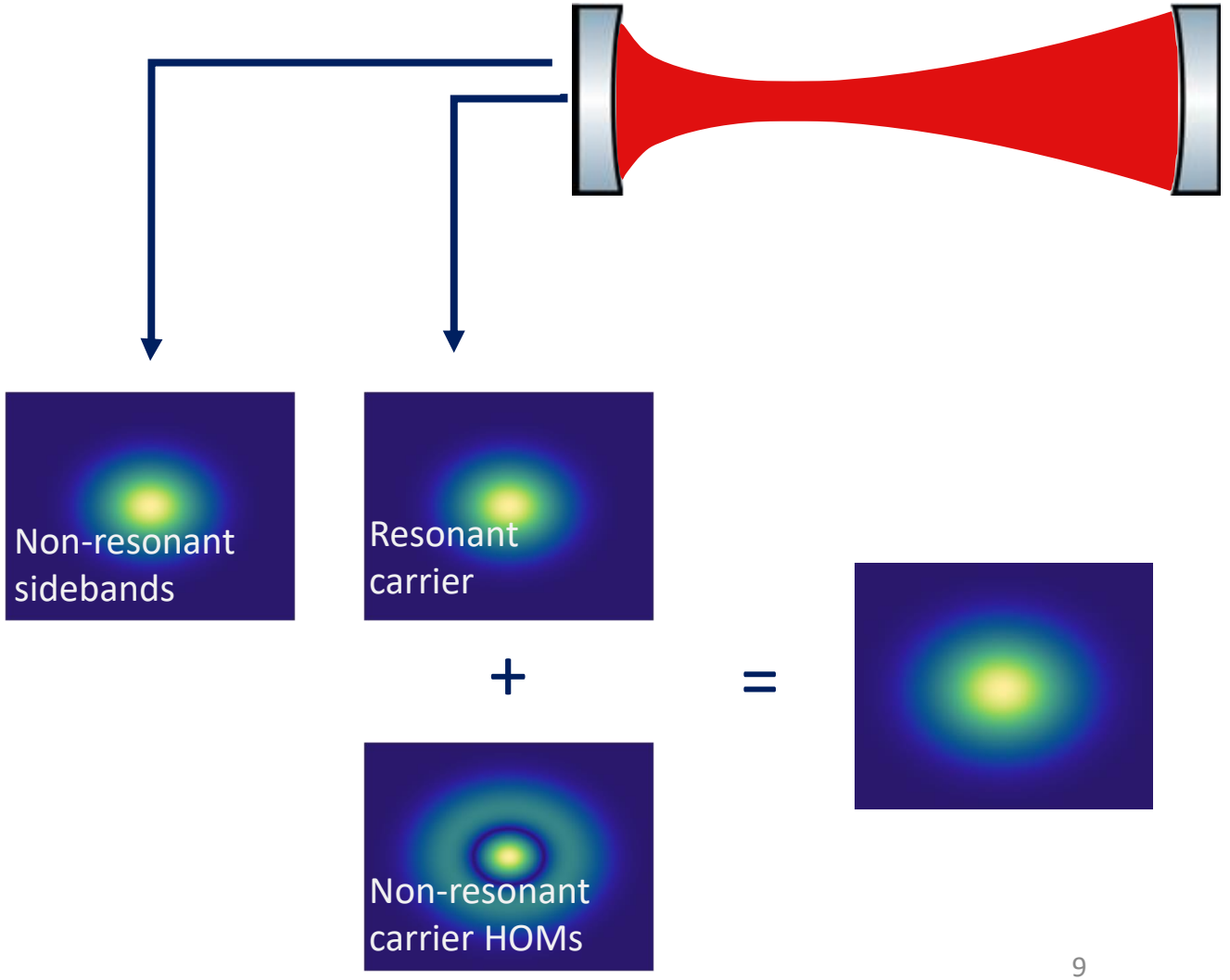
R. Cabrita, C. Lauzin, et al., NIM A 1068, 169806 (2024)

Amplitude error signal, err_w

Compare the radius of the sidebands (input beam) with the carrier (cavity mode)



More sensitive to waist position mismatch



R. Cabrita, C. Lauzin, et al., NIM A 1068, 169806 (2024)

Amplitude error signal, err_w

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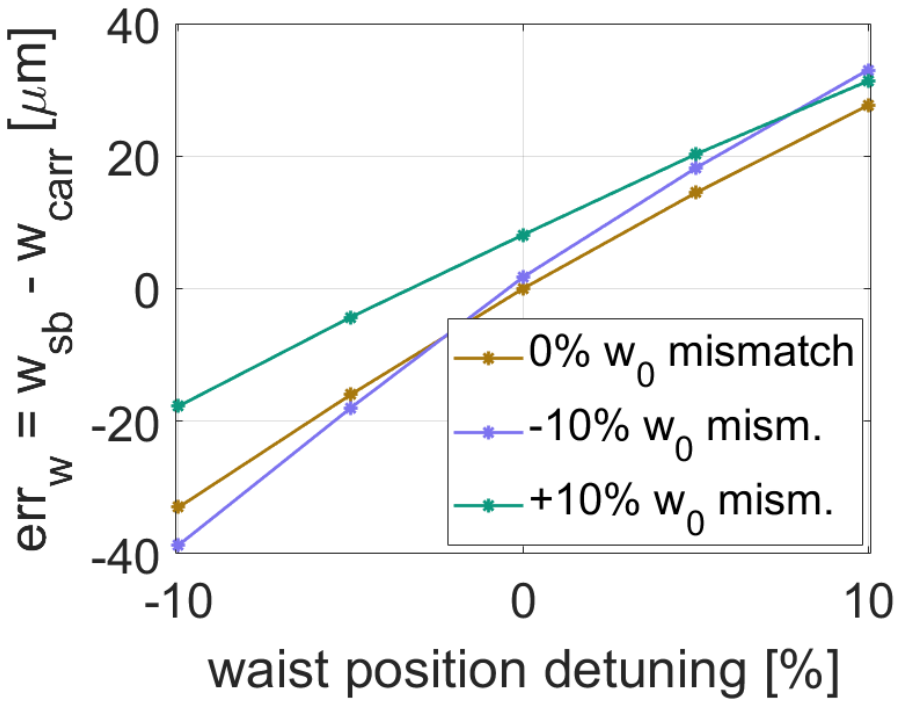
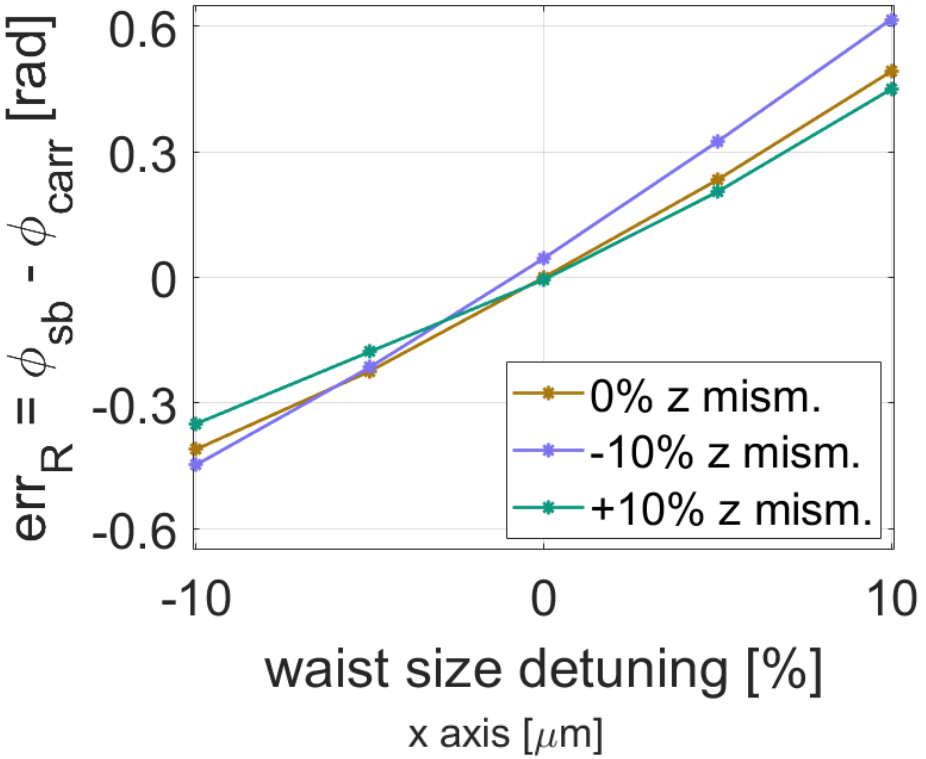


More sensitive to waist position mismatch

Phase error signal, err_ϕ

Compare the phase (cross section) of the sidebands and carrier

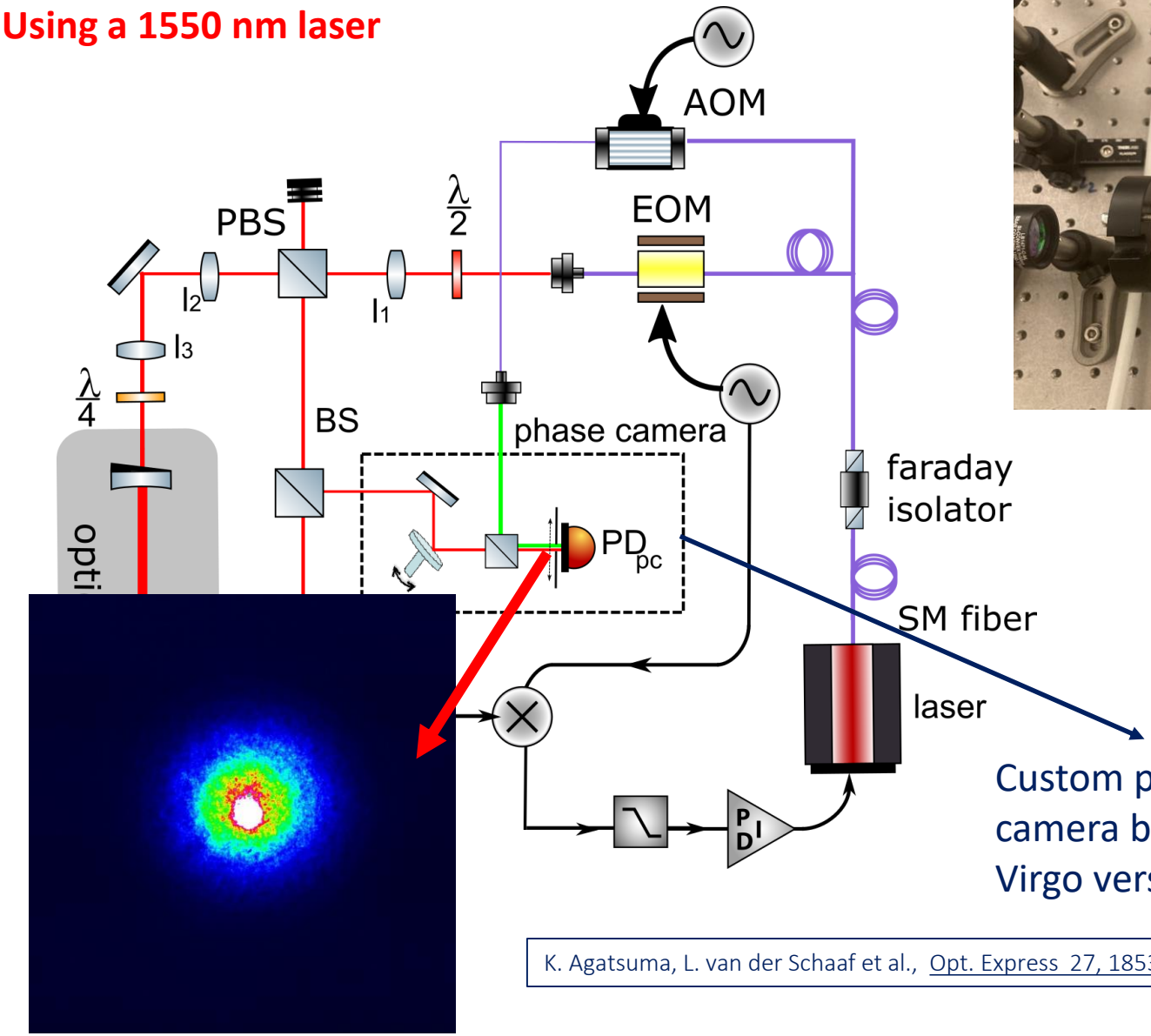


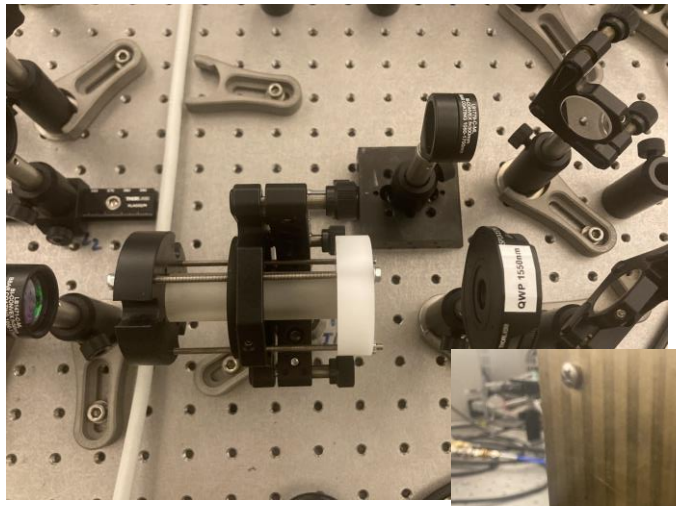
More sensitive to waist size mismatch

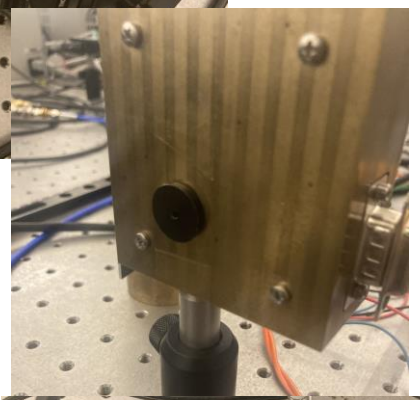
R. Cabrita, C. Lauzin, et al., NIM A 1068, 169806 (2024)

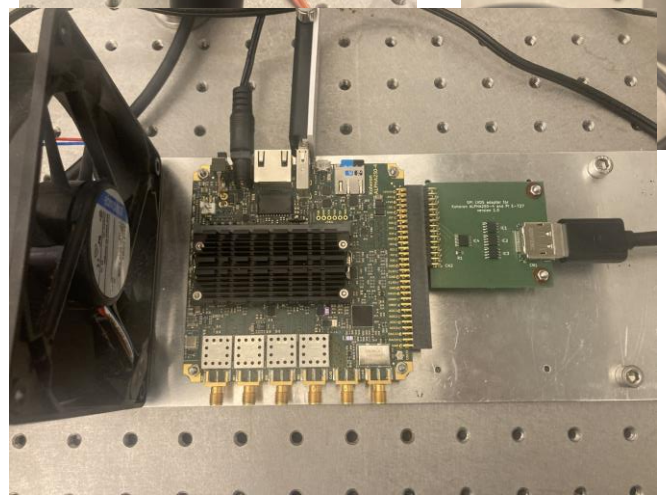
Tabletop experiment at UCLouvain

Using a 1550 nm laser





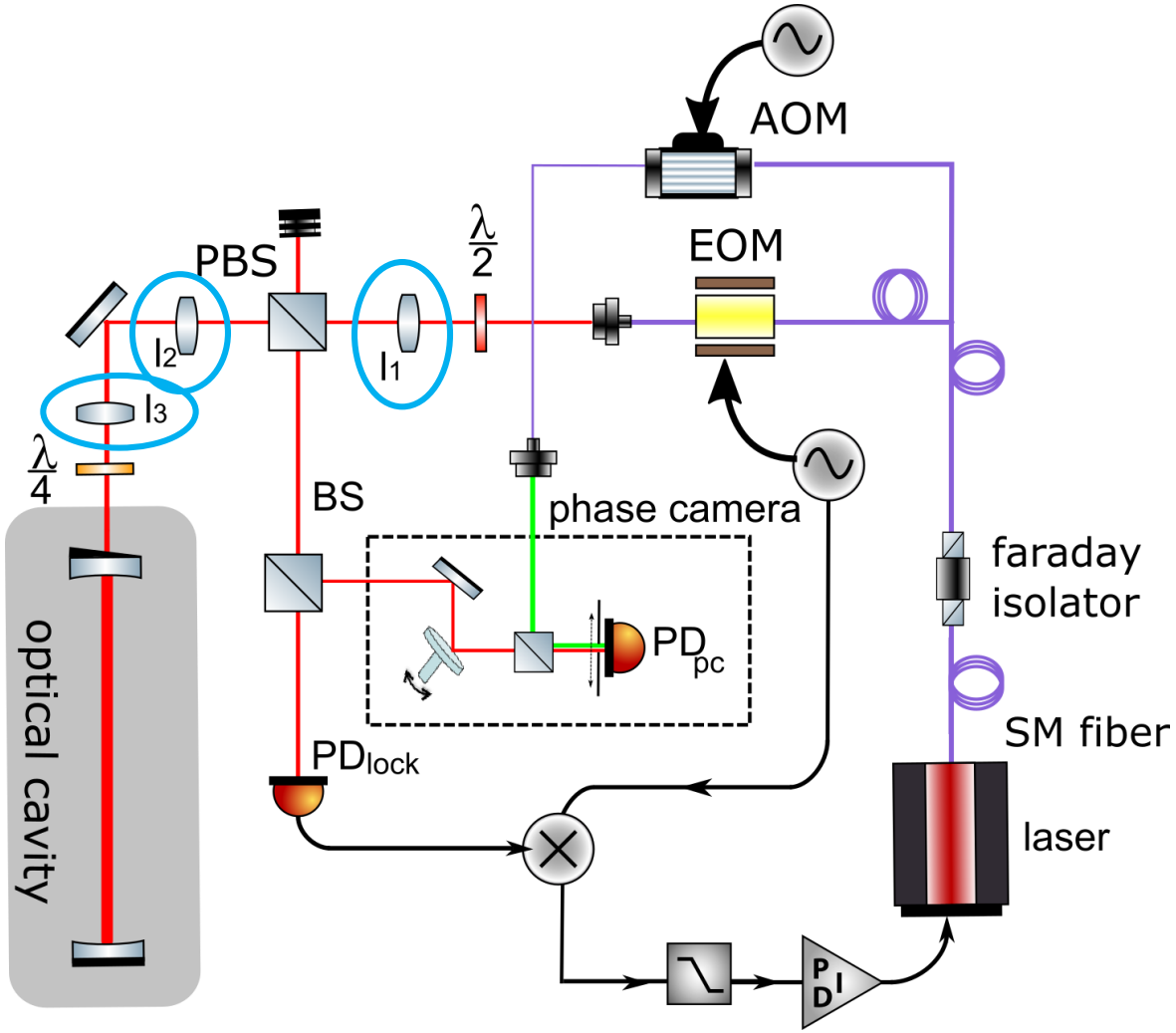


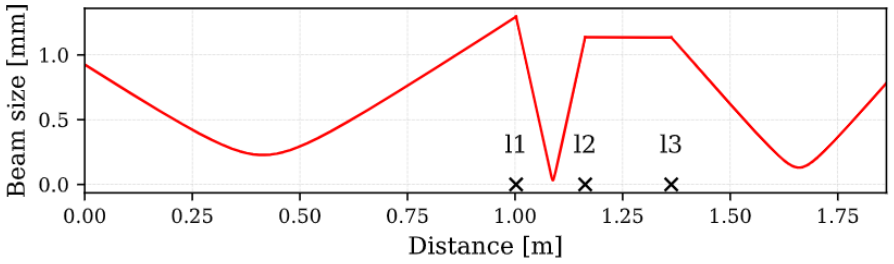


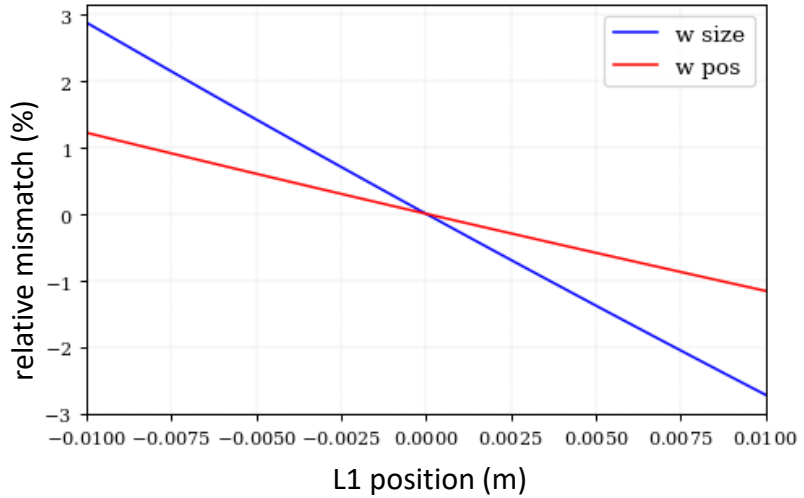
Custom phase camera based on the Virgo version.

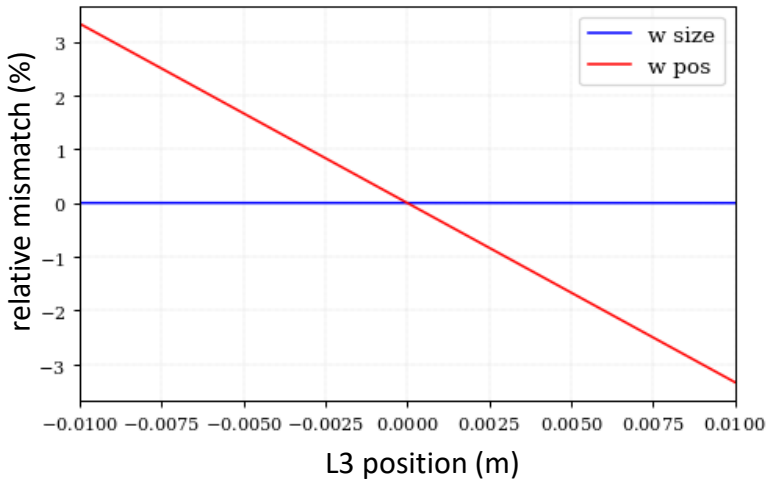
K. Agatsuma, L. van der Schaaf et al., Opt. Express 27, 18533-18548 (2019)

Mode matching telescope



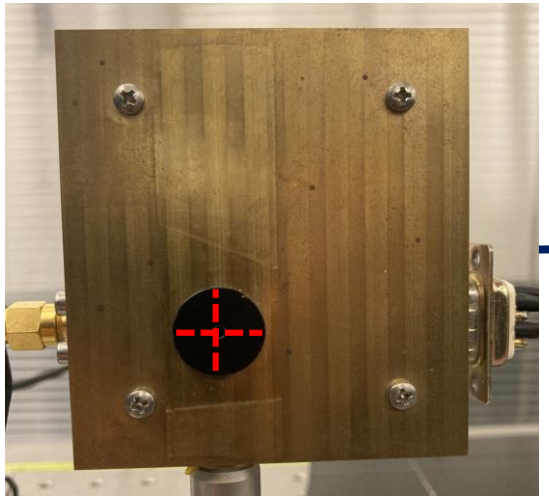


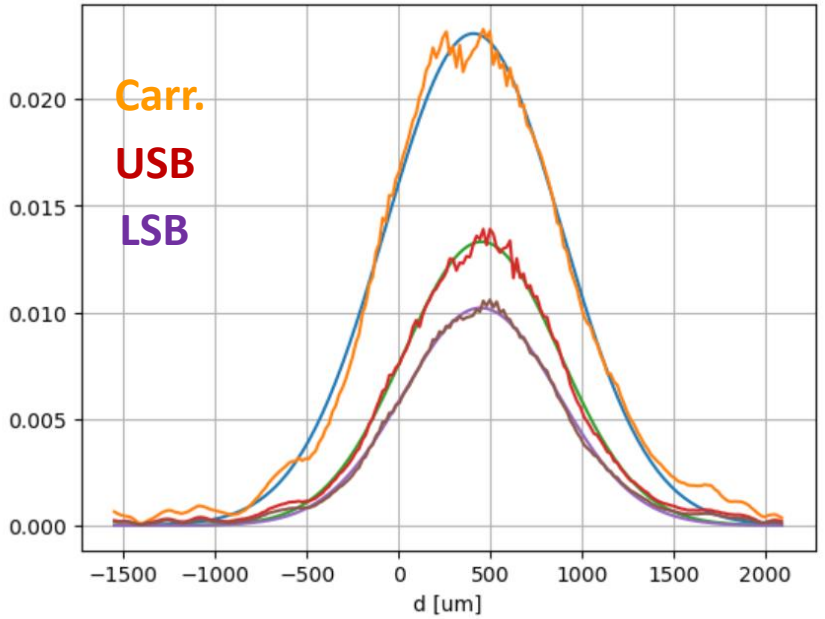




Measurements with the phase camera

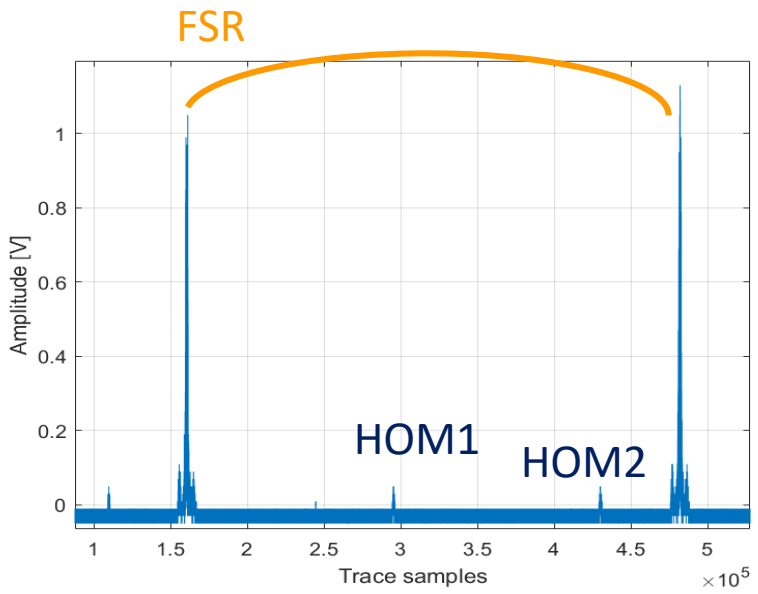
For each position of the lens:





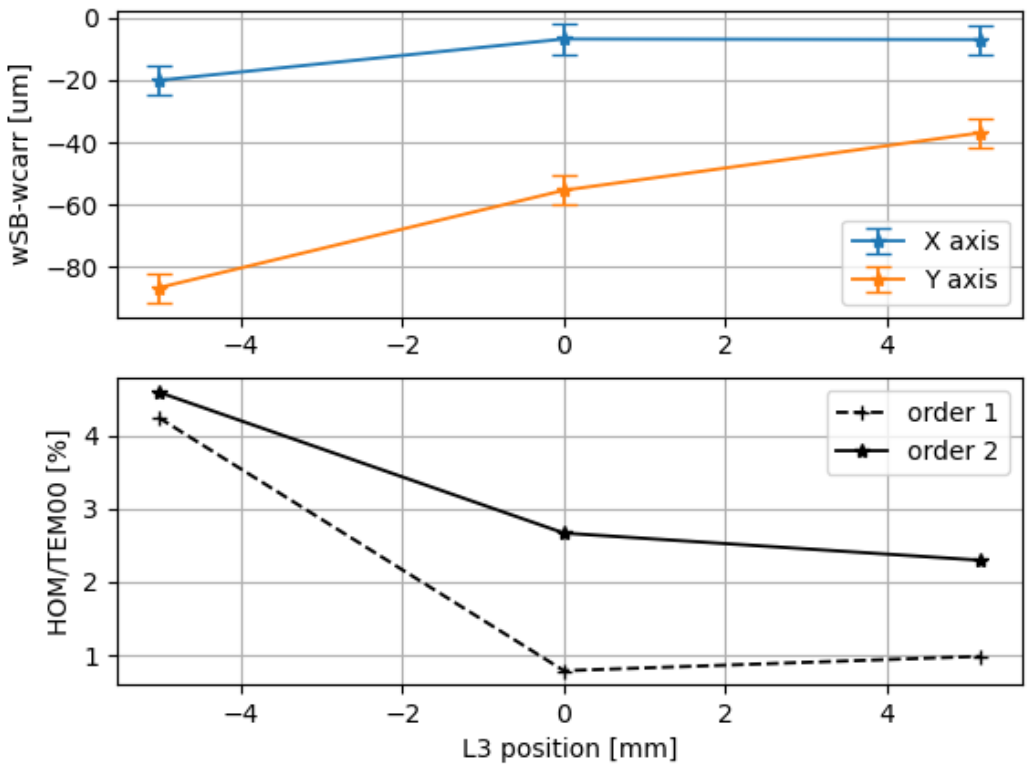
Scan and acquire data in x and y direction

Take FSR scans of the cavity to see the amount of mode mismatch.

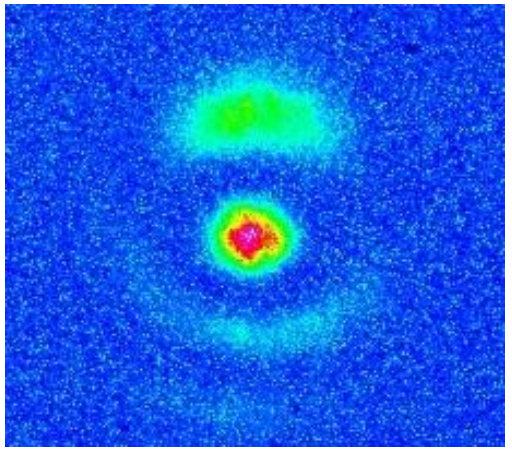


Preliminary results

Amplitude error signal measured with the phase camera



Mode order 2 in cavity transmission with 14% mode mismatch

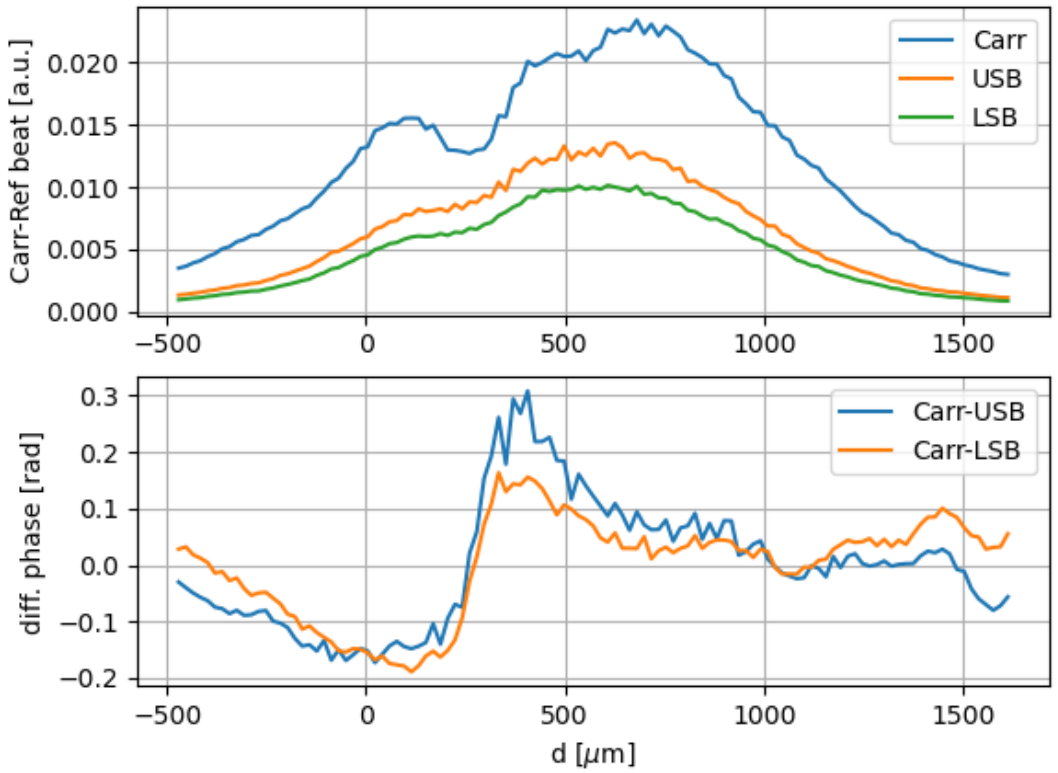


More mode mismatch in Y axis

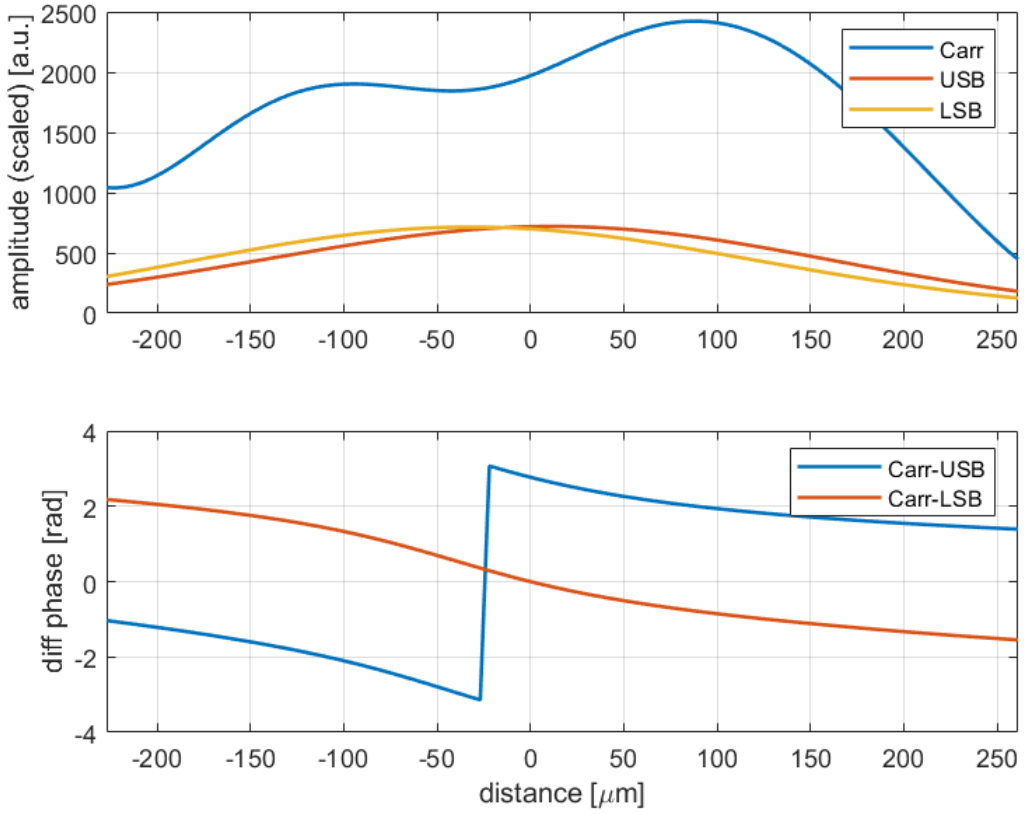
Need to calibrate this into waist position mismatch

Impact of misalignment

With 4.5% mismatch and 4.2% misalignment



Simulation in OSCAR



Next steps and perspectives

- Phase error signal analysis and full mode mismatch characterization

- Investigate zero crossing of the error signals.

- The results from the lab can be applied directly at Virgo where two phase cameras are already installed.
- It will be important to test these techniques in a real detector, ahead of O5 and next generation detectors which will operate at higher powers.

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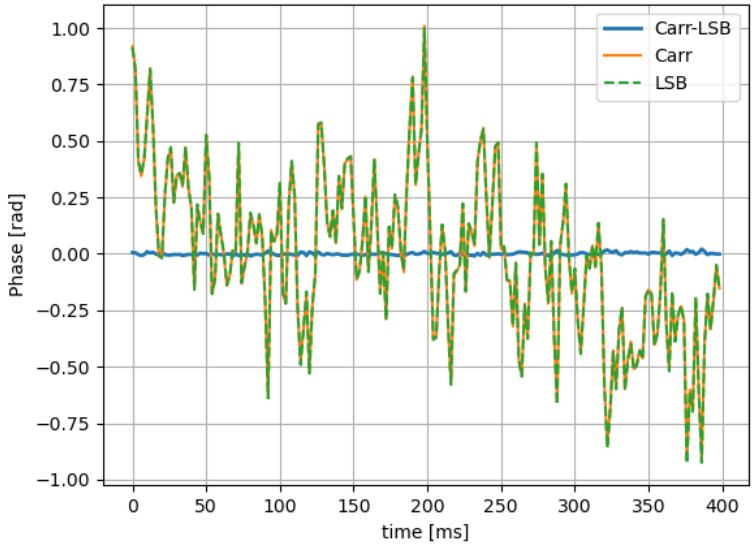
UCLouvain IRMP IMCN C3 Spectroscopy and Optics Atomic & Molecular Physics 2D Materials NAPS Rydberg States Functional Quantum Devices Imaging Quantum Transport BelGrav Nikhef

Extra slides

Uncertainties in the measurements

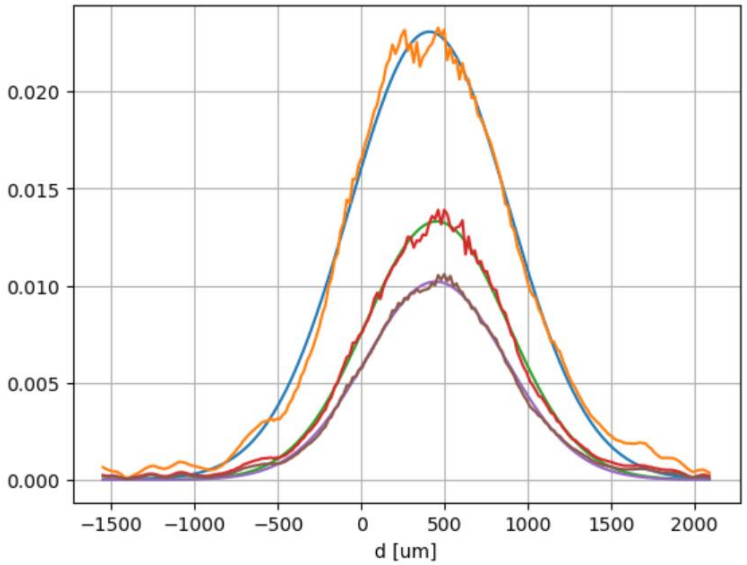
One pixel data



Differential phase: Std of phase goes down - measured between 6 and 9 mrad over 400 ms

The virgo phase camera has an optimal phase resolution of 3mrad

Cross section



About 5 um uncertainty in the radius fitting of cross section