Optical Lock-in Phase Camera for Gravitational Wave Detectors

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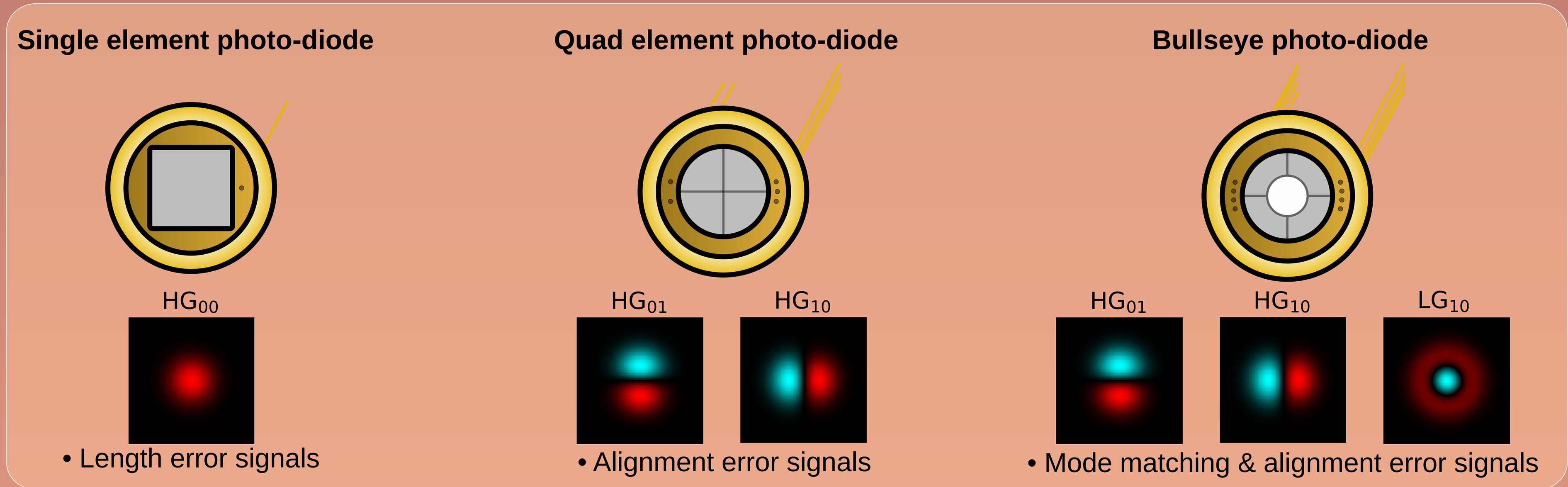
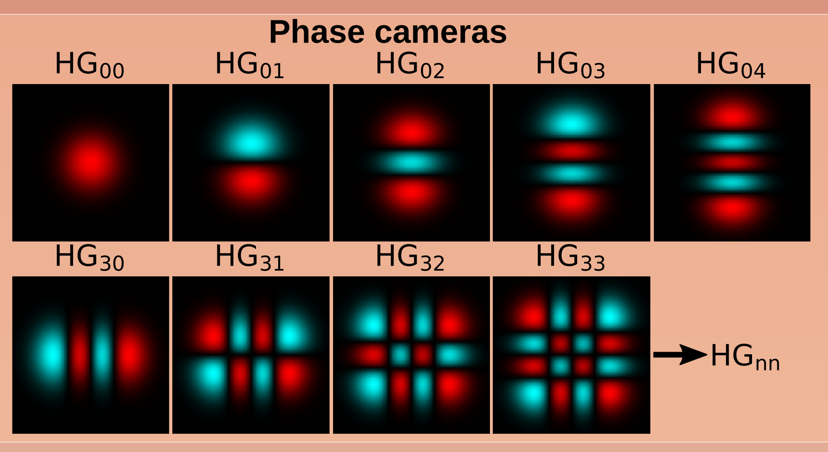
Motivation — Sensing high order modes in radio frequency sidebands

• Differential wavefront sensing with single & multi-element photo-diodes is used for length & alignment sensing in current detectors.
• These provide sensing of the low order Hermite-Gaussian (HG) modes in the RF sidebands:





Phase camera goals:
- Offsets in RF error signals
- Spatial overlap of sidebands
- Mode matching
- Thermal actuator error signals
- Point absorber HOM effects

• Phase cameras perform differential wavefront sensing at increased spatial resolutions, allowing the sensing of high order optical modes.

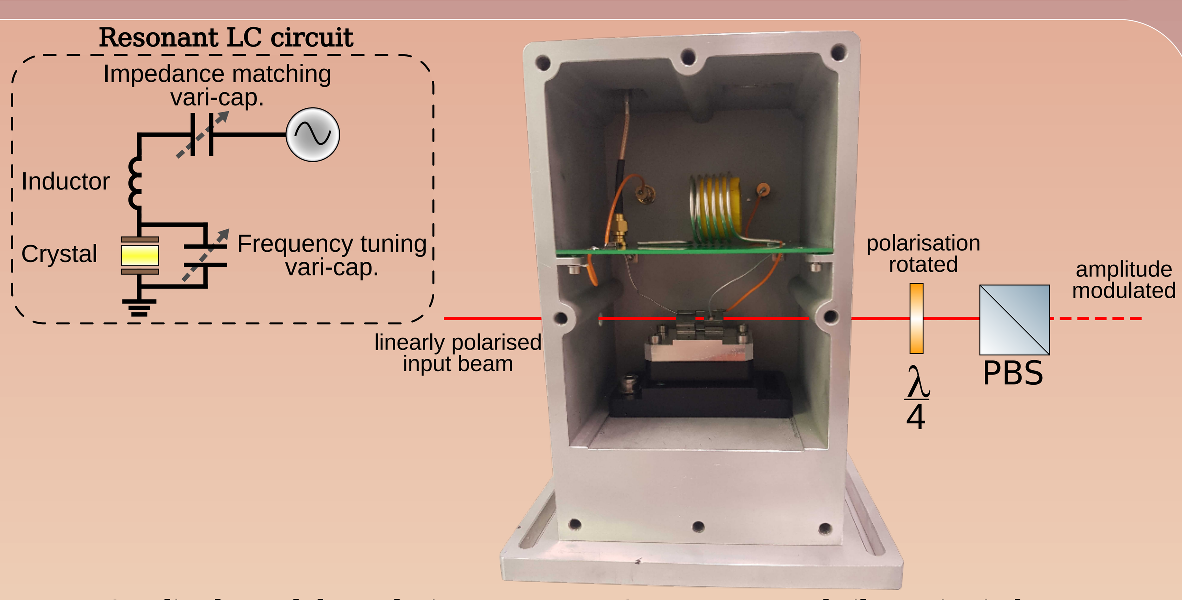
• The optical lock-in design of phase camera operates at high spatial/temporal resolutions and contains no moving parts.

Radio frequency optical amplitude modulator design

• Technique requires high depth optical amplitude modulation at radio frequencies.

• Modulator design uses a Pockels Cell as a voltage controlled half-wave plate to modulate the polarisation of the incident field.

• Polarisation modulation is then turned into amplitude modulation with a polarising optic.

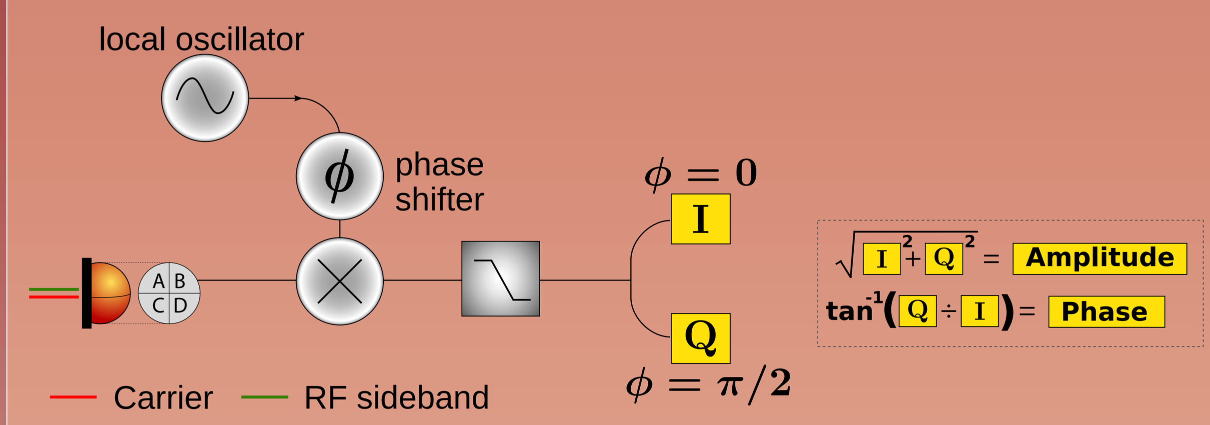


Amplitude modulator design prototype. A custom wound silver wire inductor is placed in series with the Pockels cell creating a resonant LC circuit to provide passive voltage amplification at the resonant frequency. The sealed enclosure provides RF isolation, with holes for laser beam to pass through.

Working principle
Radio frequency demodulation performed optically

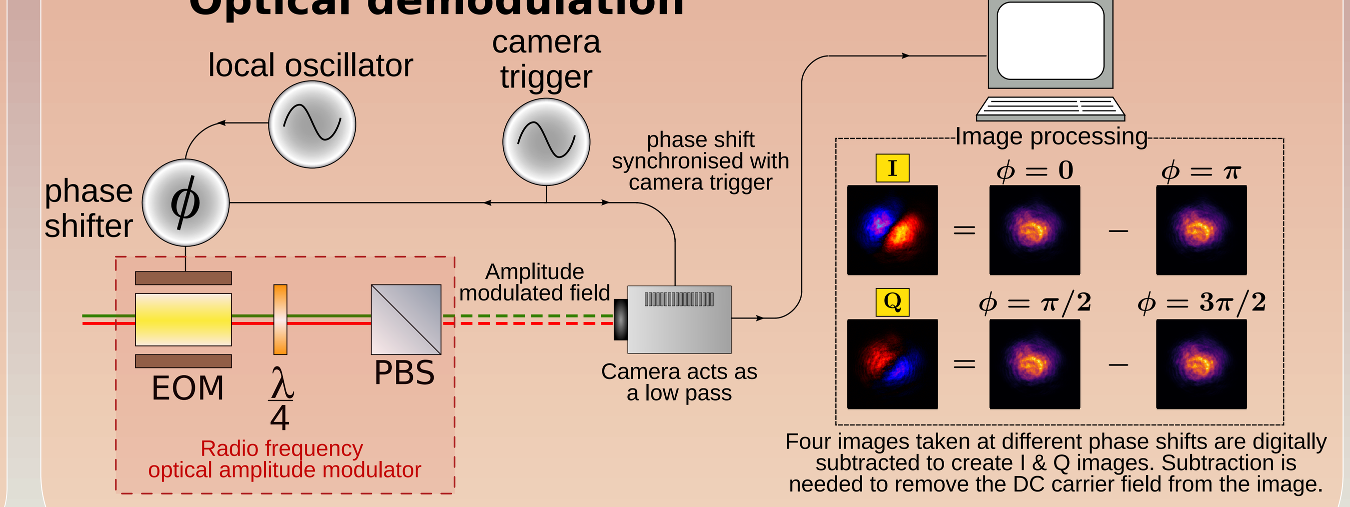
Phase cameras can be understood as a higher resolution quadrant photo-diode wavefront sensor (QPD). Electrically demodulating each quadrant of a QPD at the frequency of interest provides a 4 pixel reconstruction of the complex amplitude of the optical beat field.

Electrical demodulation



The optical lock-in technique operates similarly, however instead the amplitude of the optical field is modulated at the frequency of interest rather than the electrical signal from the photo-diode. The amplitude modulation down converts the RF beat note down to the bandwidth of the camera. In this way each pixel of the camera can act like the segments of a demodulated QPD, offering a ~1e6 times increase spatial resolution over a QPD for a typical SCMOS sensor.

Optical demodulation

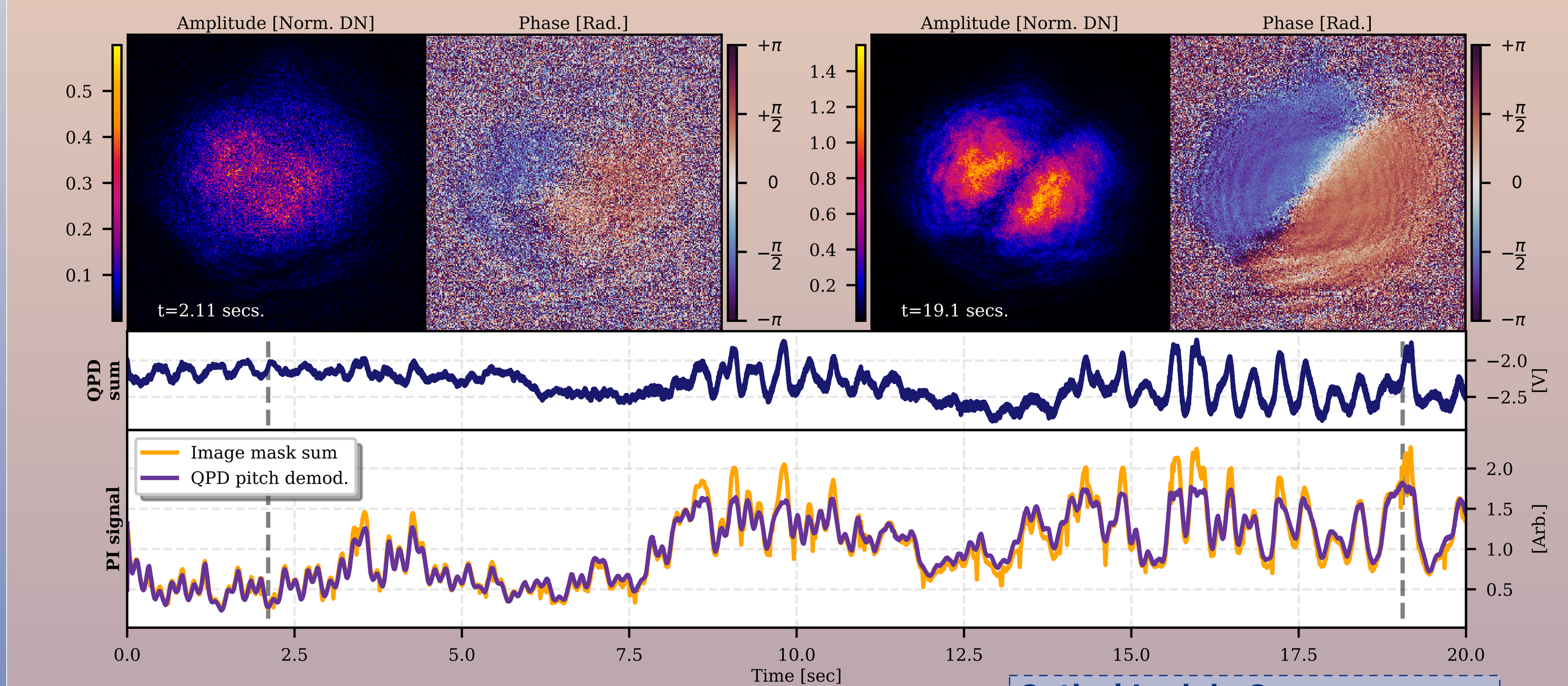


Four images taken at different phase shifts are digitally subtracted to create I & Q images. Subtraction is needed to remove the DC carrier field from the image.

Recent Publications Overview

Observing the optical modes of parametric instability

M. Schiworski, V. Bossilkov, C. Blair, D. Brown, A. Jones, D. Ottaway, and C. Zhao, Opt. Lett. 47, 1685-1688 (2022)

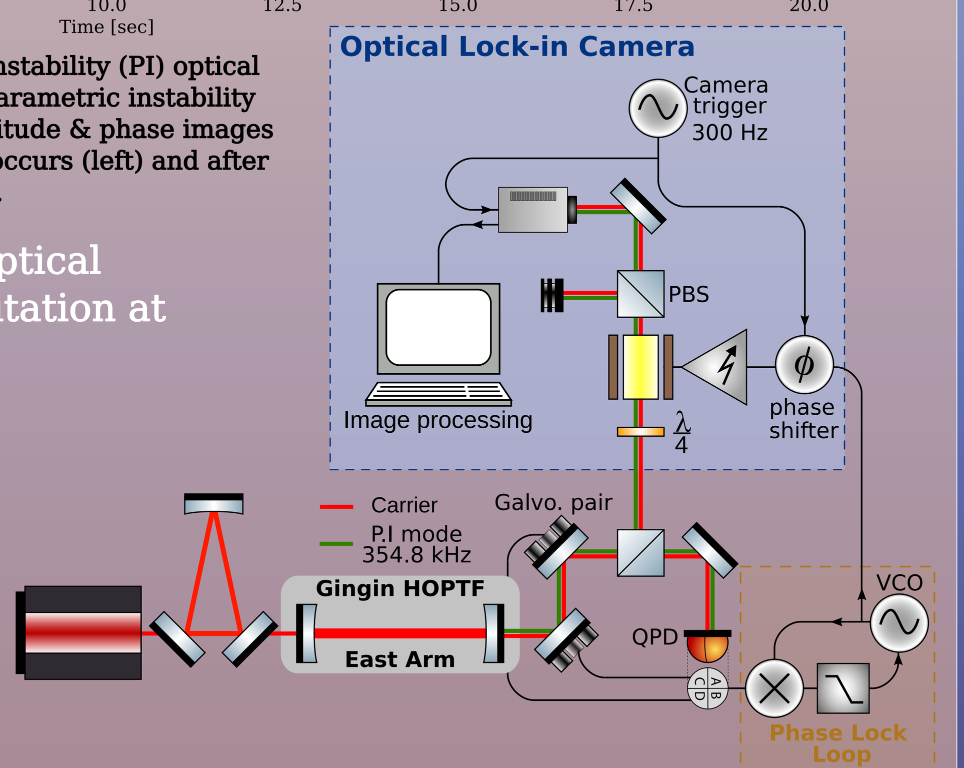


Comparison of the measurements of the parametric instability (PI) optical mode with a QPD and the optical lock-in camera as parametric instability occurs at the Gingin HOPTF east arm cavity. The amplitude & phase images of this higher order mode are shown above just as PI occurs (left) and after the PI mode has saturated (right).

• Phase camera used to image the optical parametric instability (PI) mode excitation at Gingin HOPTF.

• High frame-rate of optical lock-in design allowed for amplitude & phase maps at 75 Hz @ 256x256

• Phase cameras may have a role to play in studying/mitigating PI for future detector designs with higher optical power.



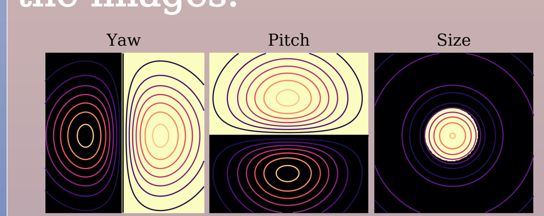
Simplified experiment schematic. The optical parametric instability mode generated in an 80m suspended high power cavity was imaged on transmission with the optical lock-in camera.

Differential wavefront sensing and control using radio-frequency optical demodulation

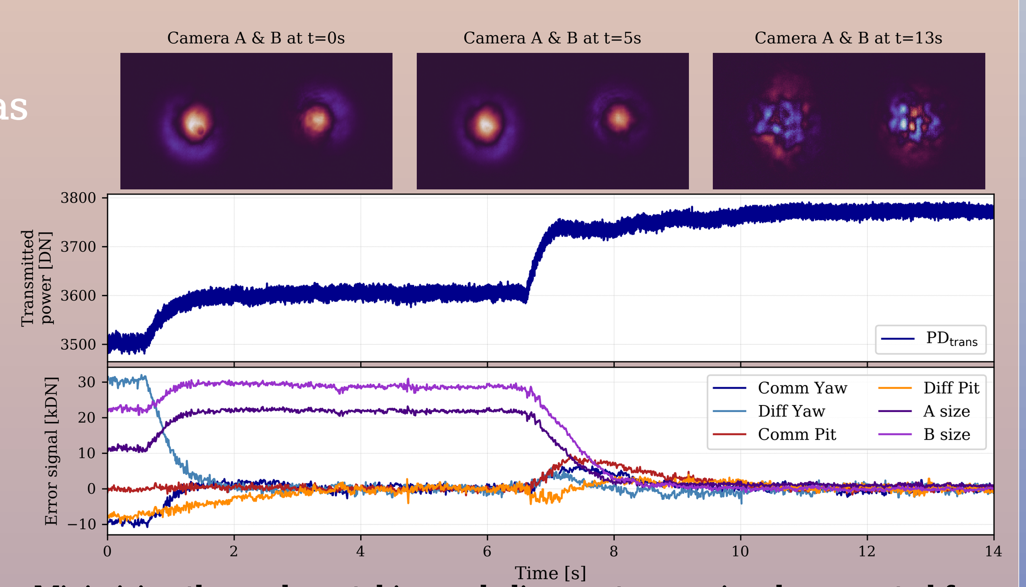
Daniel Brown, Huy Tuong Cao, Alexei Ciobanu, Peter Veitch, and David Ottaway, Opt. Express 29, 15995-16006 (2021)

• Mode matching & alignment error signals using phase cameras demonstrated in lab experiment.

• High order error signals are created simply by applying different summation masks to the images.



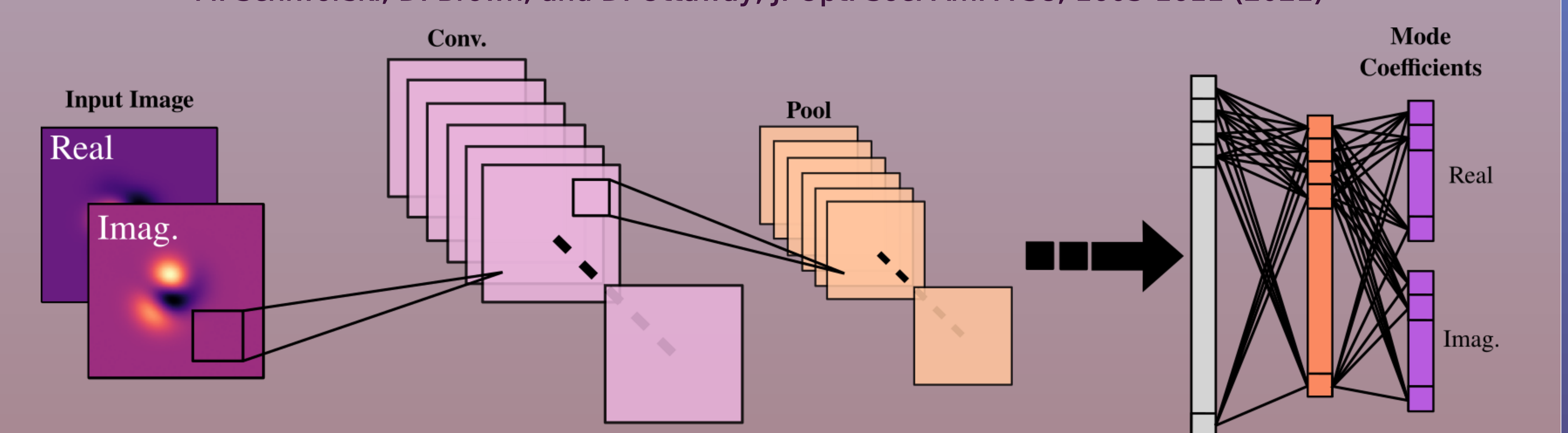
Summation masks applied to the phase camera images to generate alignment & mode matching signals.



Minimising the mode matching and alignment error signals generated from the phase camera images (bottom), corresponded to maximising the cavity transmitted power (middle). Afterwards phase camera images (top right) showed residual higher order aberrations from the liquid lens actuators.

Modal decomposition of complex optical fields using convolutional neural networks

M. Schiworski, D. Brown, and D. Ottaway, J. Opt. Soc. Am. A 38, 1603-1611 (2021)



Overview of the neural network processing scheme. The complex phase camera images are input into a convolutional neural network which processes them and outputs the Hermite-Gaussian modal coefficients.

• Neural network processing of phase camera images has been explored on **simulated** phase camera images.

• Published results showed machine learning based modal decomposition can outperform overlap integral methods in both accuracy and speed for non-centred sideband fields with randomised HOM content.

Links to publications

Optical lock-in phase camera

Observing the optical modes of parametric instability

Differential wavefront sensing and control using radio-frequency optical demodulation

Modal decomposition of complex optical fields using convolutional neural networks

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