Quantum noise imaging using atom-based squeezed light sources

Status update on 2022 progress AFOSR FA9550-19-1-0066

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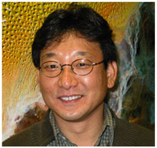
People


Savannah Cuozzo


Irina Novikova


Hwang Lee


Jon Dowling (1955-2020)

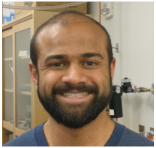

Charris Gabaldon


Ziqi Niu


Lior Cohen


Pratik Barge


Caitlyn Marat


Nikunjkumar Prajapati

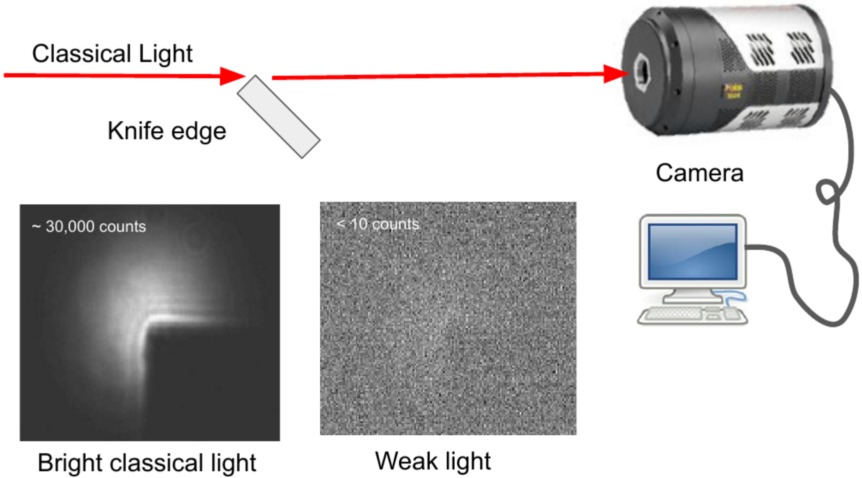

Narayan Bhusal


Elisha Metekole

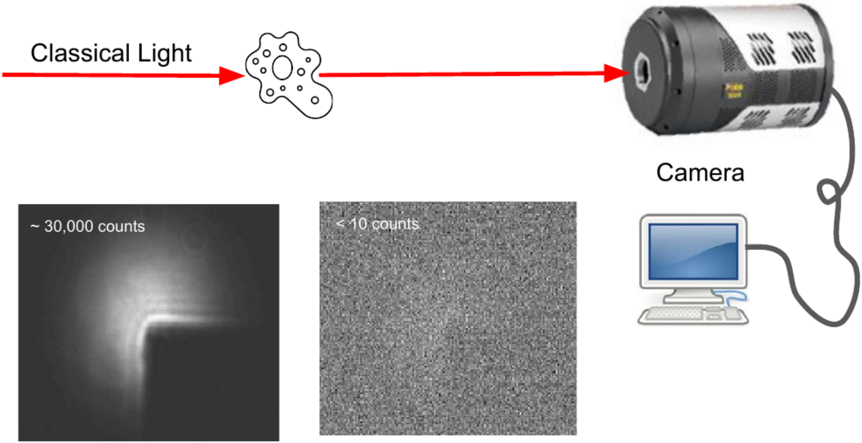
Outline

1. Shadow imaging with squeezed light
2. Squeezing mode search via optimization
3. Shadow imaging with thermal light
4. Imaging without camera: single pixel imaging
   - Classical detour: single pixel homodyning
   - Quantum quadrature single pixel homodyning

From bright to low light imaging



From bright to low light imaging

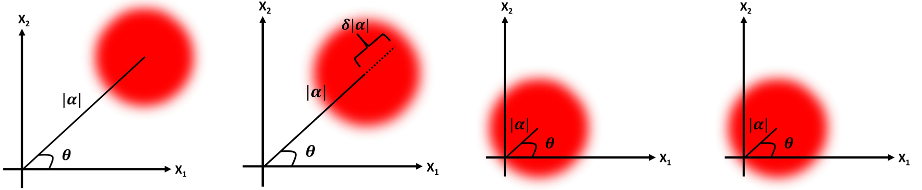


Bright classical light

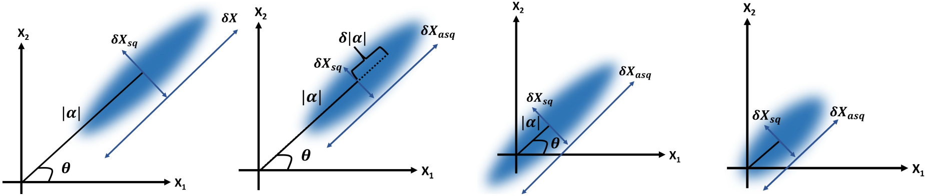
Weak light

Let's look at quantum picture

Bright state in | Bright state out | Low-light state in | Low-light out



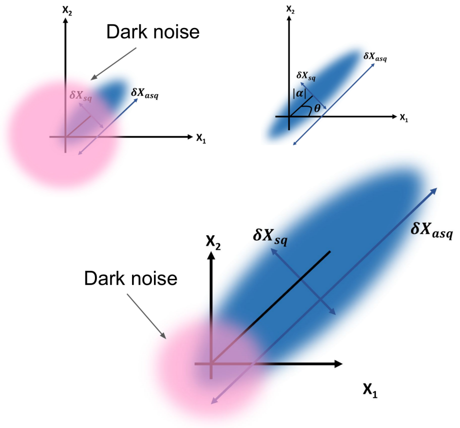
$$\alpha_{out}^2 = \alpha_{in}^2 T$$

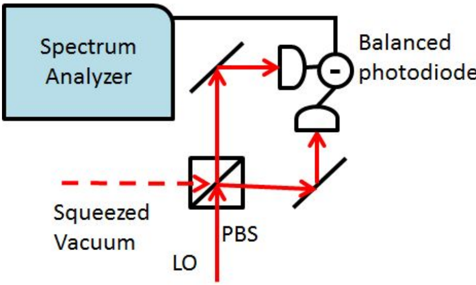


$$V = 1 + (\delta X_{sq/asq}^2 - 1)|\mathcal{O}|^2 T$$

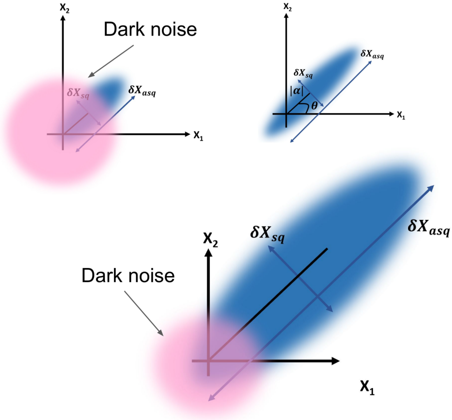
$$\mathcal{O} = \int_A u_{LO}^*(x,y) u_{in}(x,y) dA$$

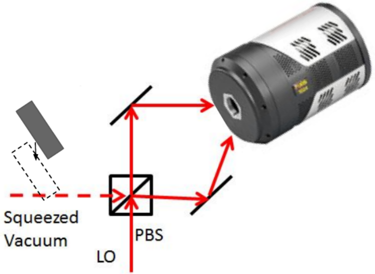
Detector dark noise





Detector dark noise



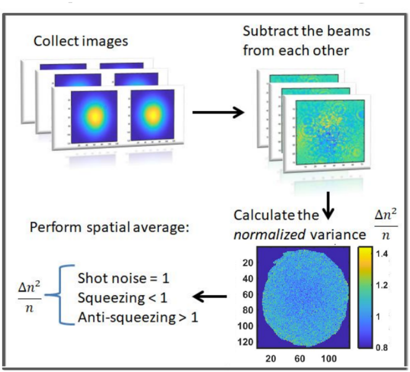


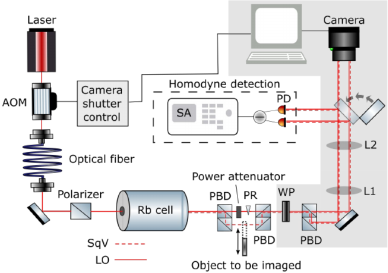

Elisha Metekole

“Quantum-Limited Squeezed Light Detection with a Camera”, Phys. Rev. Lett. **125**, 113602

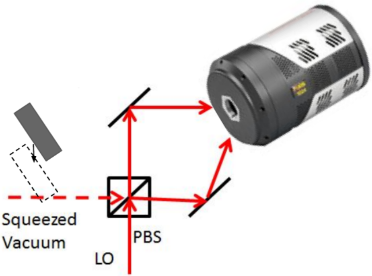
Imaging quantum noise

Savannah Couzzo

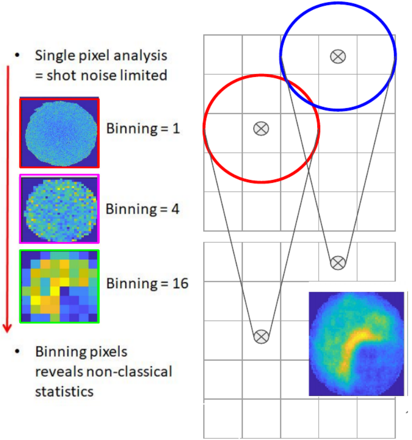




Imaging quantum noise with binning



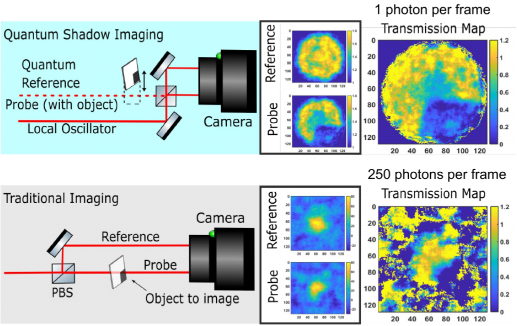
$$V = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}|^2 T$$

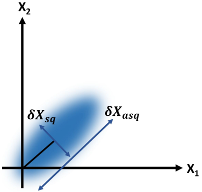


Shadow imaging

$$V_{pr} = 1 + (\delta X_{ref}^2 - 1)|\mathcal{O}|^2 T$$

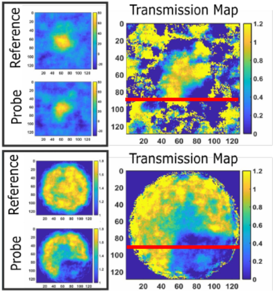
$$T = \frac{V_{pr} - 1}{V_{ref} - 1}$$



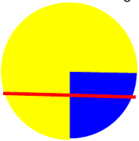


$$T = \frac{|\alpha_{pr}|^2}{|\alpha_{ref}|^2} = \frac{N_{pr}}{N_{ref}}$$

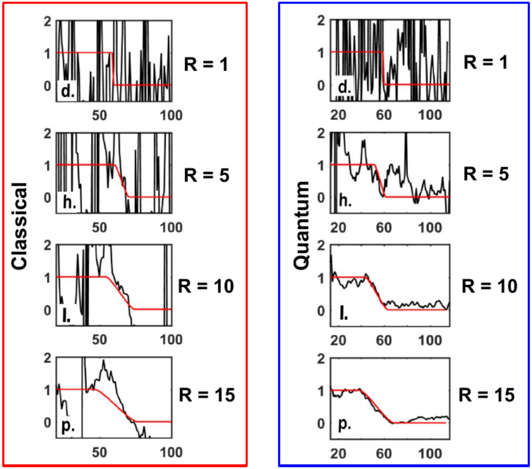
Similarity Parameter



Ideal case: T_o



Transmission Map Cross-section

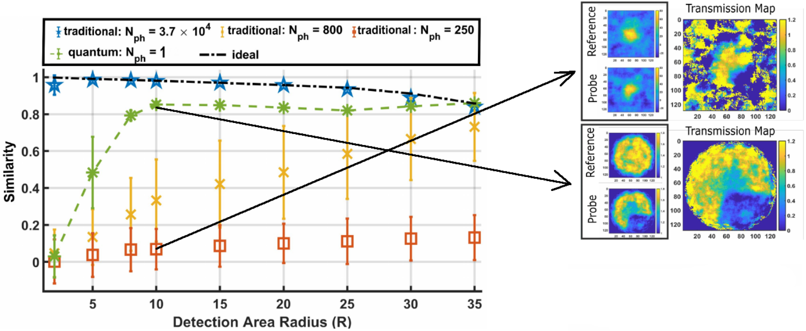


$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

Similarity Parameter

$$S = \frac{\sum T_{exp} T_o}{\sqrt{\sum T_{exp}^2 \sum T_o^2}}$$

Savannah Couzzo



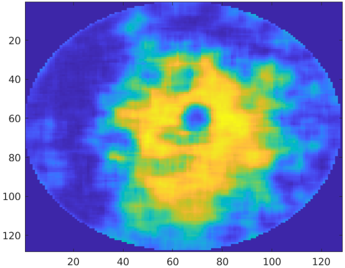
“Low-Light Shadow Imaging Using Quadrature-Noise Detection with a Camera”, **Advanced Quantum Technologies**, 2100147, (2022)

What is the spatial output of the squeezer?

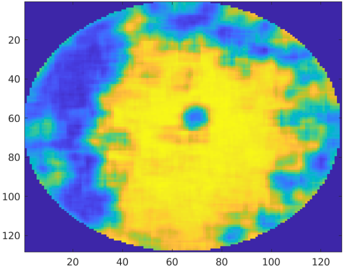
Caitlyn Marat

Find/optimize
$u_{sq}(x, y) \rightarrow$ max Variance.
Wait about 20 CPU hours.

Allow to toggle on 20%

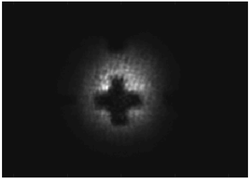


Allow to toggle on 50%

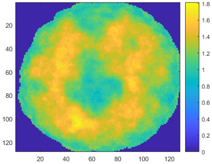


Comparing different imaging

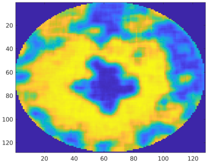
Classical



Quantum Binning



Quant. Optimization

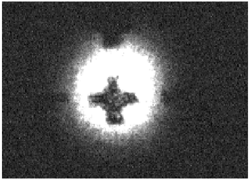


$u_{sq}(x, y) \to \max V$

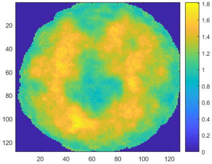
800 photons in total was used for quantum noise quadrature reconstruction

Comparing different imaging

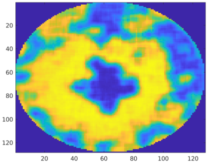
Classical



Quantum Binning



Quant. Optimization

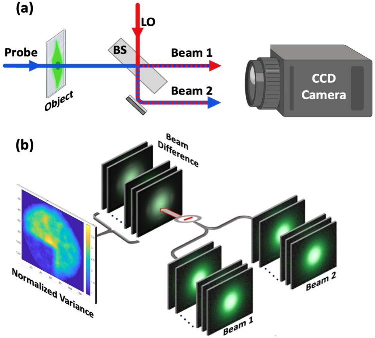


$u_{sq}(x, y) \rightarrow \max V$

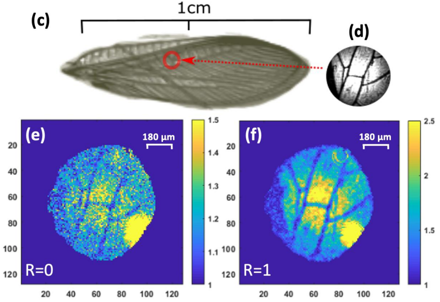
800 photons in total was used for quantum noise quadrature reconstruction

Imaging with thermal light

Ziqi Niu



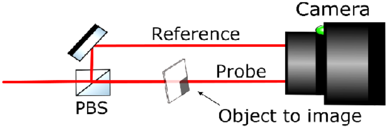
0.1 photon per pixel per exposure



Quadrature Shadow Imaging: theoretical framework

Pratik Barge

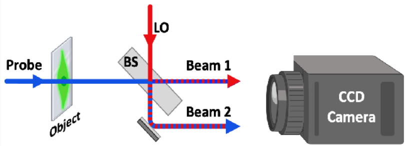
Classical differential imaging (CDI)



Measures intensity (photon number) directly

$$SNR_{CDI} = \frac{(1-t)\bar{n}}{\sqrt{(1+t)\bar{n} + (\Delta N_d)^2}}$$

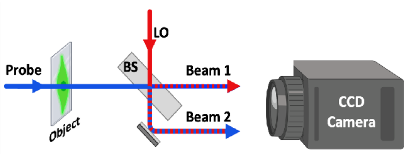
Quadrature Shadow Imaging (QSI)

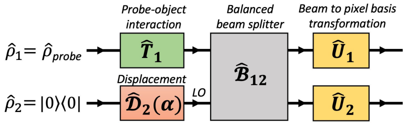


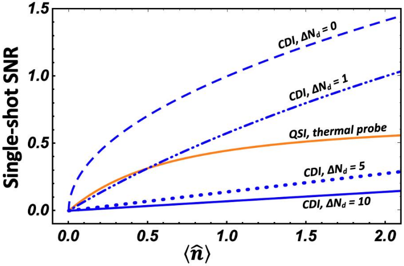
Measures variances in photon number

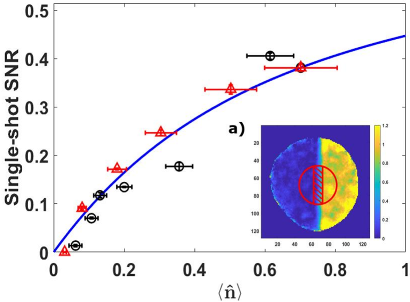
$$SNR_{QSI} = \frac{2(1-t)\bar{n}}{\sqrt{4 + 8(1+t)\bar{n} + 8(1+t^2)\bar{n}^2}}$$

Classical (CDI) vs quantum (QSI)









“Weak thermal state quadrature-noise shadow imaging”, Pratik J. Barge, Ziqi Niu, Savannah L. Cuozzo, Eugeniy E. Mikhailov, Irina Novikova, Hwang Lee, and Lior Cohen, **Optics Express** Vol. 30, Issue 16, pp. 29401-29408 (2022)

https://doi.org/10.1364/OE.455646

Classical single pixel imaging

Single-pixel imaging 12 years on: a review

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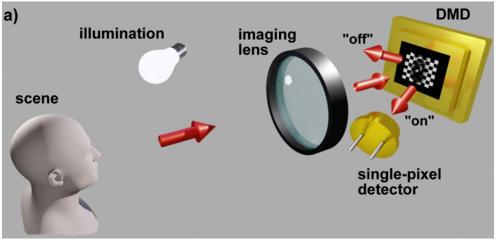
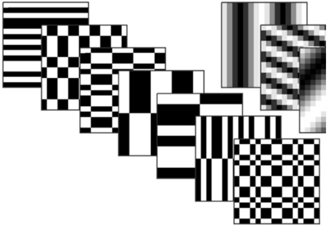
https://www.gla.ac.uk/schools/physics/ourresearch/groups/optics/

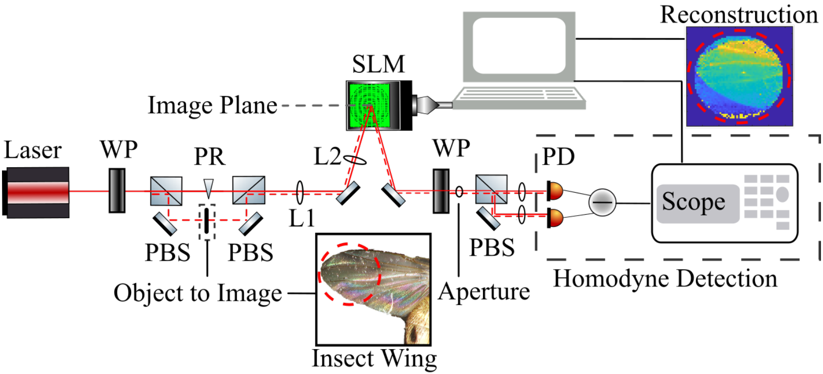


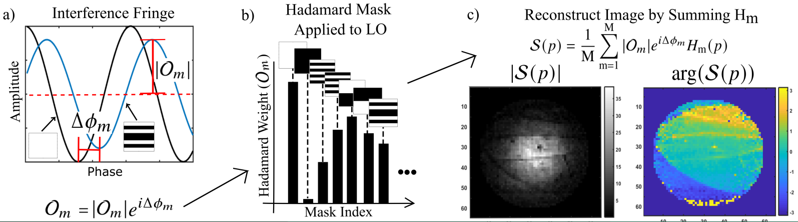


Reconstructed object

$$Ob(x, y) = \frac{1}{M} S_m P_m(x, y)$$

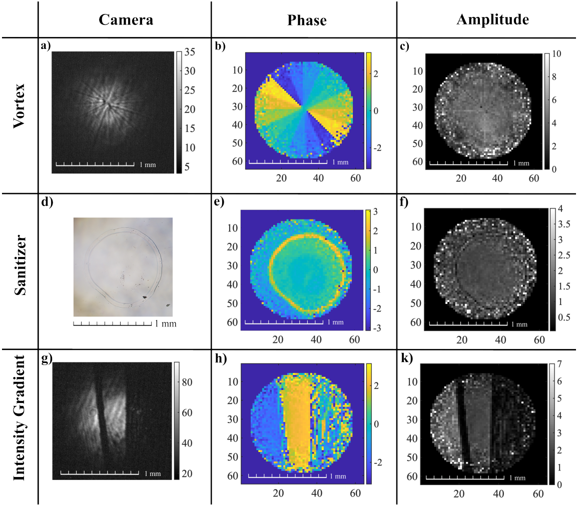
Classical single pixel homodyning





Homodyning = full wavefront reconstruction

Charris Gabaldon



Wavefront product

$$u^*_{LO}(p)u_{in}(p)$$

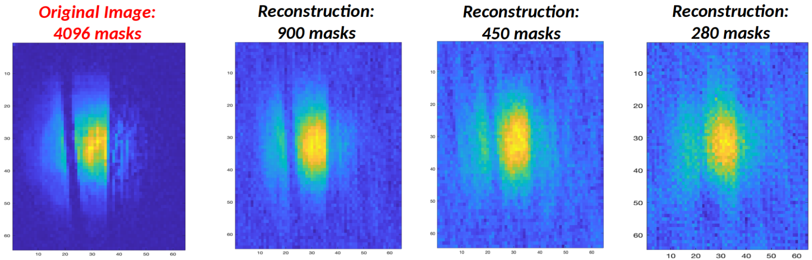
Transmission:

- amplitude
- phase

"Wave-Front Reconstruction via Single-Pixel Homodyne Imaging"

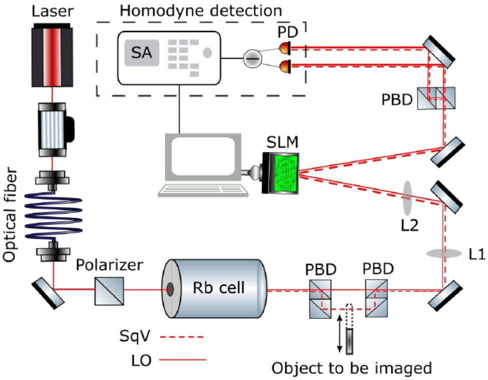
https://arxiv.org/abs/2208.02718

Compressive sampling modeling

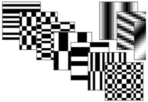


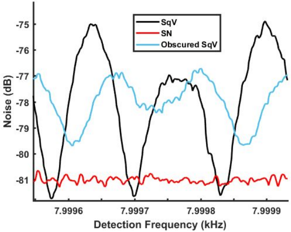
- Drastic reduction in acquisition time
- Increase in post processing complexity

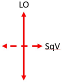
Single pixel homodyning imaging with quantum noise



Savannah Couzzo





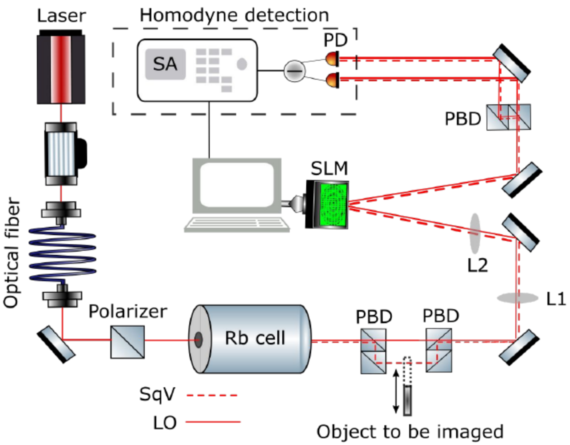


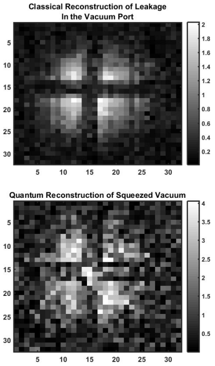
$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$

$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x, y)$$

Single pixel homodyning imaging with quantum noise: wire cross



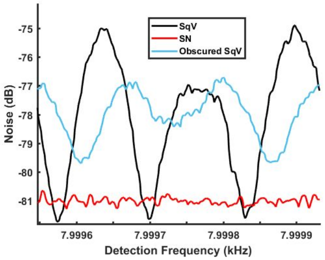


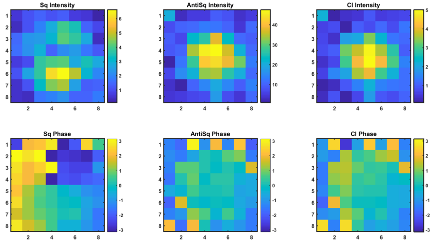
Single pixel homodyning using different quantum quadratures: squeezer output

$$V_m = 1 + (\delta X^2_{sq/asq} - 1)|\mathcal{O}_m|^2$$

$$\mathcal{O}_m = \int_A P_m u_{lo} u_q^* T dA$$

$$u_{lo} u_q^* T = \frac{1}{M} \sum \mathcal{O}_m P_m(x, y)$$





Summary

Developed methods

- Camera Quantum shadow imaging with squeezed or thermal states
- Single pixel homodyning for classical and quantum illumination

Advantages

- Overcome detectors dark noise
- Suitable for low light illumination: covert or avoiding sample damage
- Outperforming classical detection at low light illumination contaminated by detector dark noise

Next step

- Refining single pixel homodyning with quantum noise