Lensless ultra-miniature CMOS computational imagers and sensors

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Computational Sensing and Imaging
Rambus Labs

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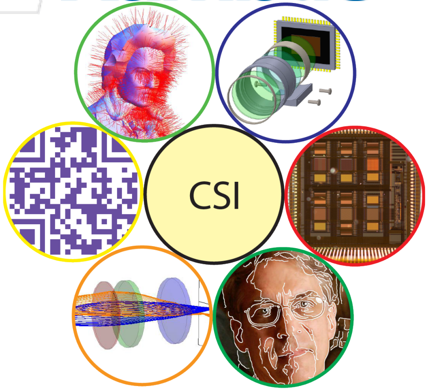
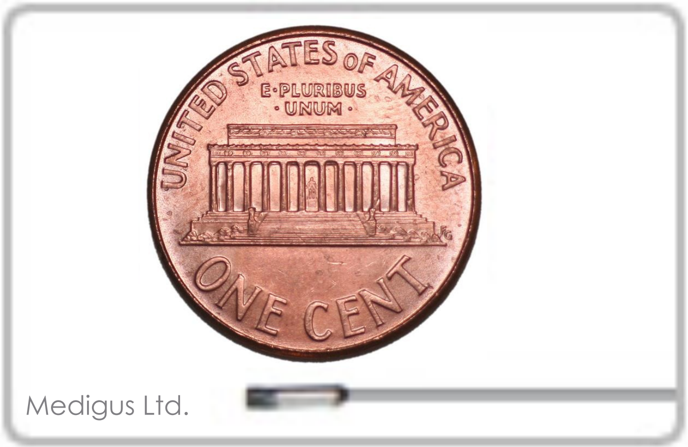
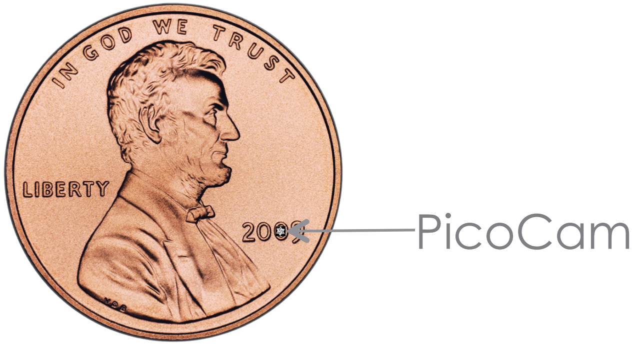
Rambus



SensorComm 2013
Barcelona, Spain

Ultra-miniature optical imagers and sensors

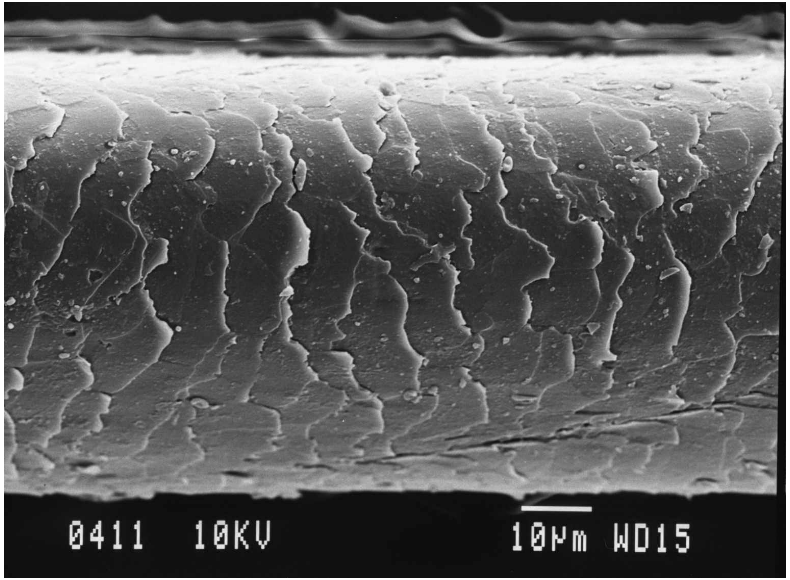




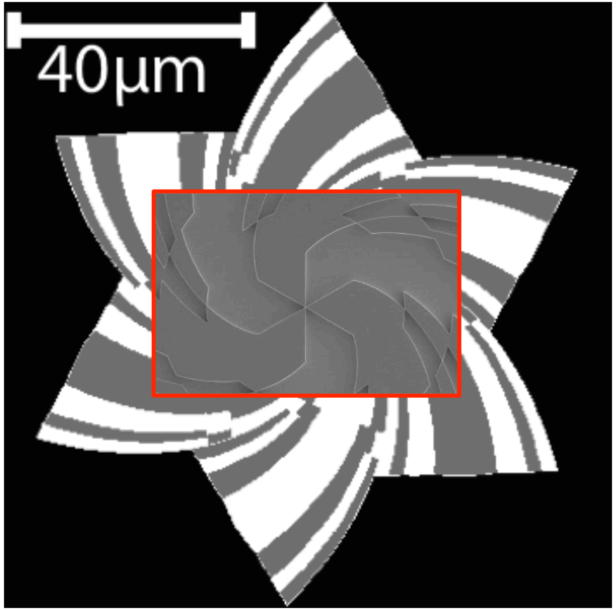
- Smallest traditional focusing cameras are roughly 1 *mm* in diameter
- Size limited by need for lenses

- **New approach**: shift some of the burden of focusing to computation
- Permits new classes of *lensless* imagers—*PicoCams*—much smaller than traditional focusing systems

Lensless ultra-miniature optical sensors



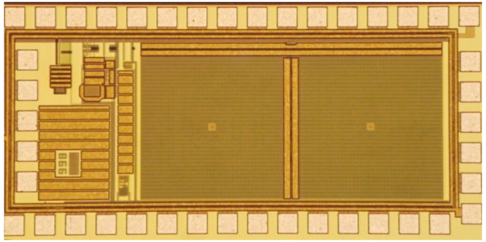
Human Hair
[courtesy Wales Bioimaging Lab]



PicoCam sensor

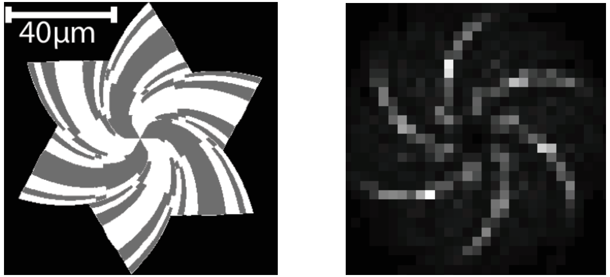
Imaging from angle-sensitive optical phenomena

Refraction



PFCA*: diffraction

Reflection



PicoCam: diffraction

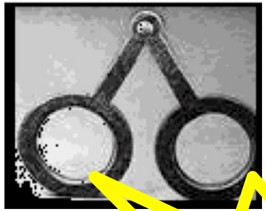
- Incident light redirected through reflection, refraction and diffraction
- Reflection and refraction are used to focus light
- New diffraction-based sensors yield non-image signals
- Digital images are *computed*, not captured

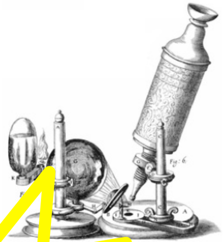
*Planar, Fourier Capture Array, Gill, Lee, Sivaramakrishnan, Molnar, 2012

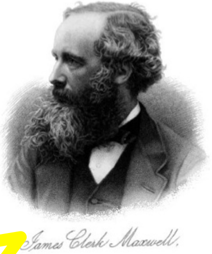
Electro-optical imaging timeline

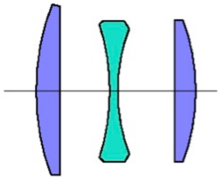
Optical

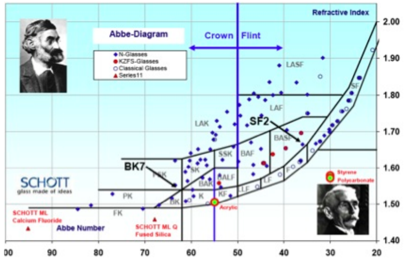
1268	1590	1837	1865	1890	1900s
spectacles	microscope	Photograph	Maxwell's Eqs	Cooke Triplet	New Glass Types











1: Focus

2: Fix image

Electro-optical imaging timeline

3: Digital image capture

4: Compute image

Optical

1910
New Triplet
Forms

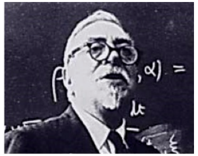
1960
Optical CAD
Tools

Optical

Digital

Digital

1920
Signal
Theory



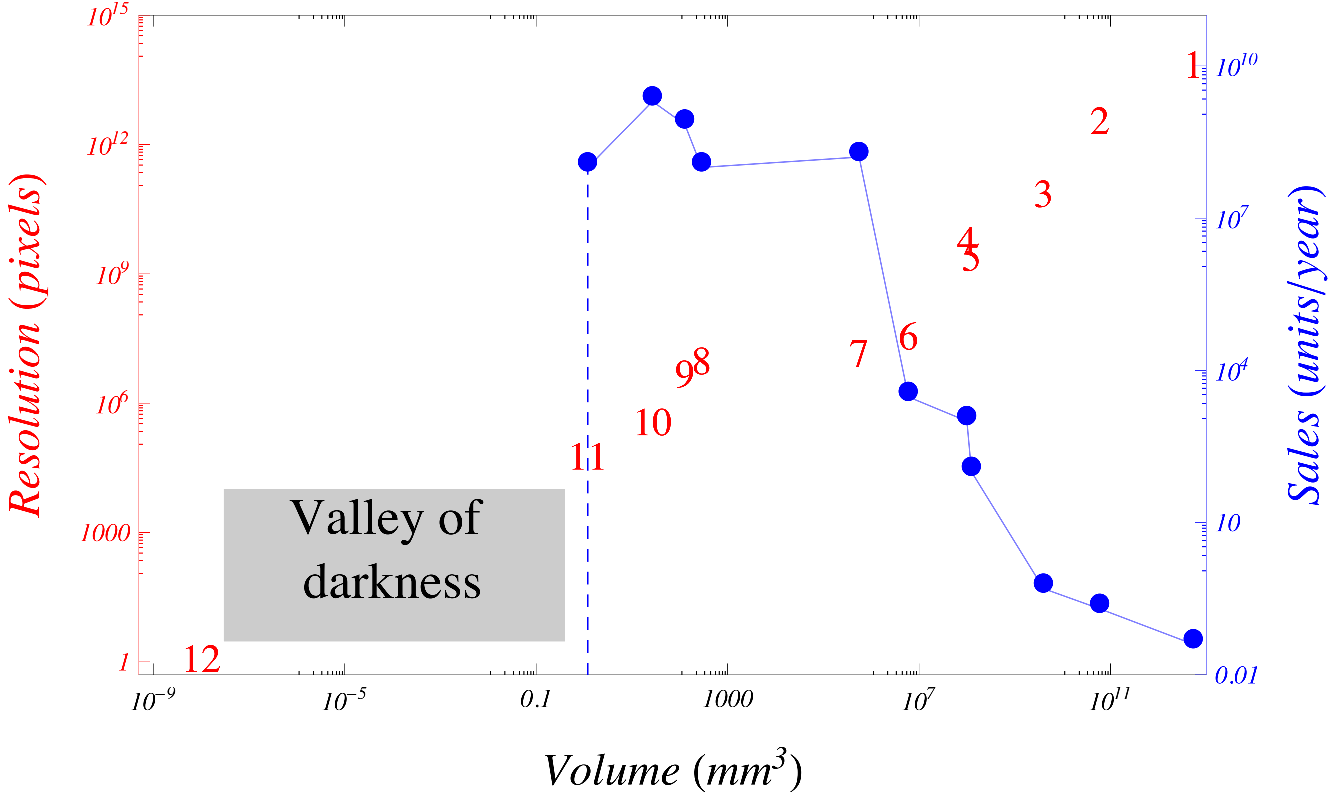
1948
Information
Theory

1969
CCD

1980s
Digital
Copier

1990s
Digital
Cameras

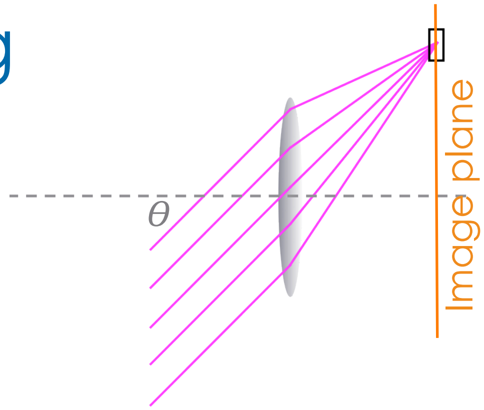
Imager resolution vs. physical volume
Worldwide sales vs. physical volume

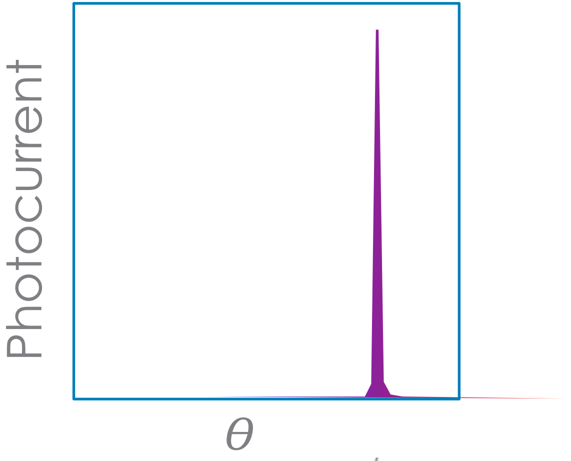


1. Gran Canaria Telescope
2. Hubble telescope
3. 1*m* telescope
4. 30*cm* telescope
5. AWARE 2 camera
6. Professional camera
7. Consumer digital camera
8. iPhone camera
9. Pelican camera
10. Miniature VGA
11. Medigus medical camera
12. Single photodiode

Refractive and reflective focusing yield δ-function sensitivity

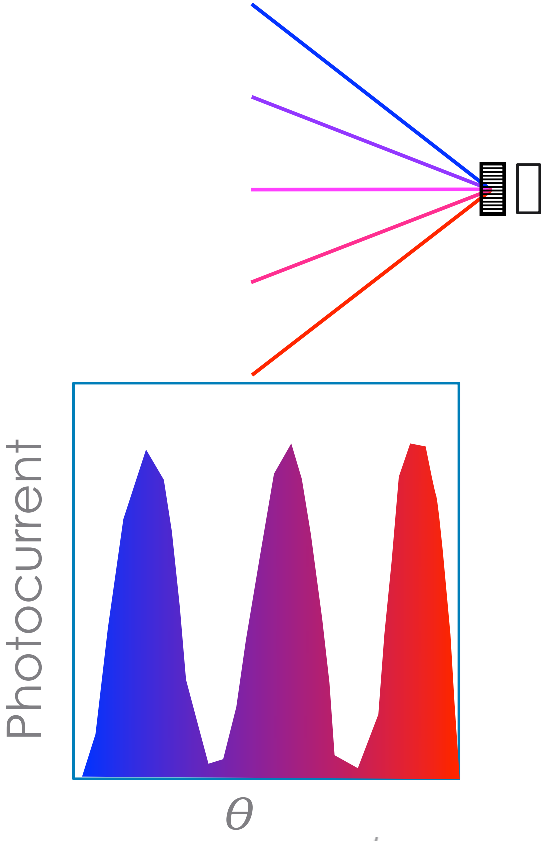
- Focusing: concentrating light from one incident angle at one location
- Requires light transport on the inside of the camera; at least one focal length deep
- Produces a 1:1 transfer function between incident angle and sensor readings
- Little computation necessary to produce final digital image



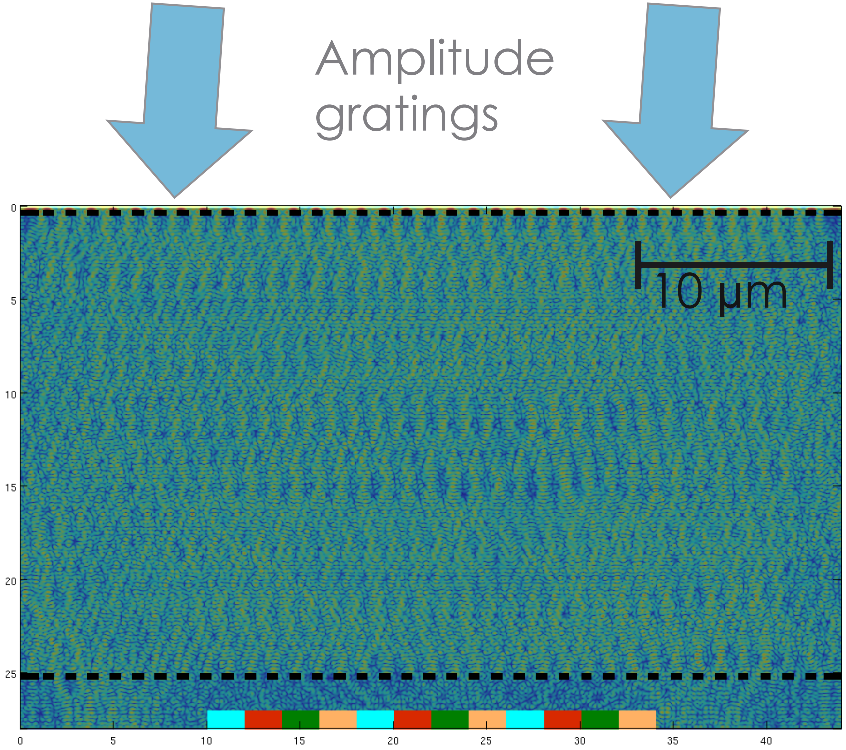


Diffraction-based sensors

- One sensor location sensitive to multiple incident angles
- Relaxes requirement of transporting light from each point in the scene to a single location on the sensor
- Transfer function between complete scenes and full sensor readings can still be 1:1, if the imager is designed properly
- Computation becomes an essential part of digital image formation



Diffraction from regular amplitude gratings (PFCA)



- Wires in CMOS serve as amplitude gratings
- Each pixel has a sinusoidal sensitivity versus incident angle
- Computation produces digital image
- Acceptable for low low-resolution applications, but for high resolution problems arise:
  - Depth- and wavelength-sensitivity
  - Low area efficiency
  - Low quantum efficiency

Gill, Lee, Sivaramakrishnan, Molnar 2012

PFCA optics: Sinusoidal sensitivity of pixels under two amplitude gratings at different heights

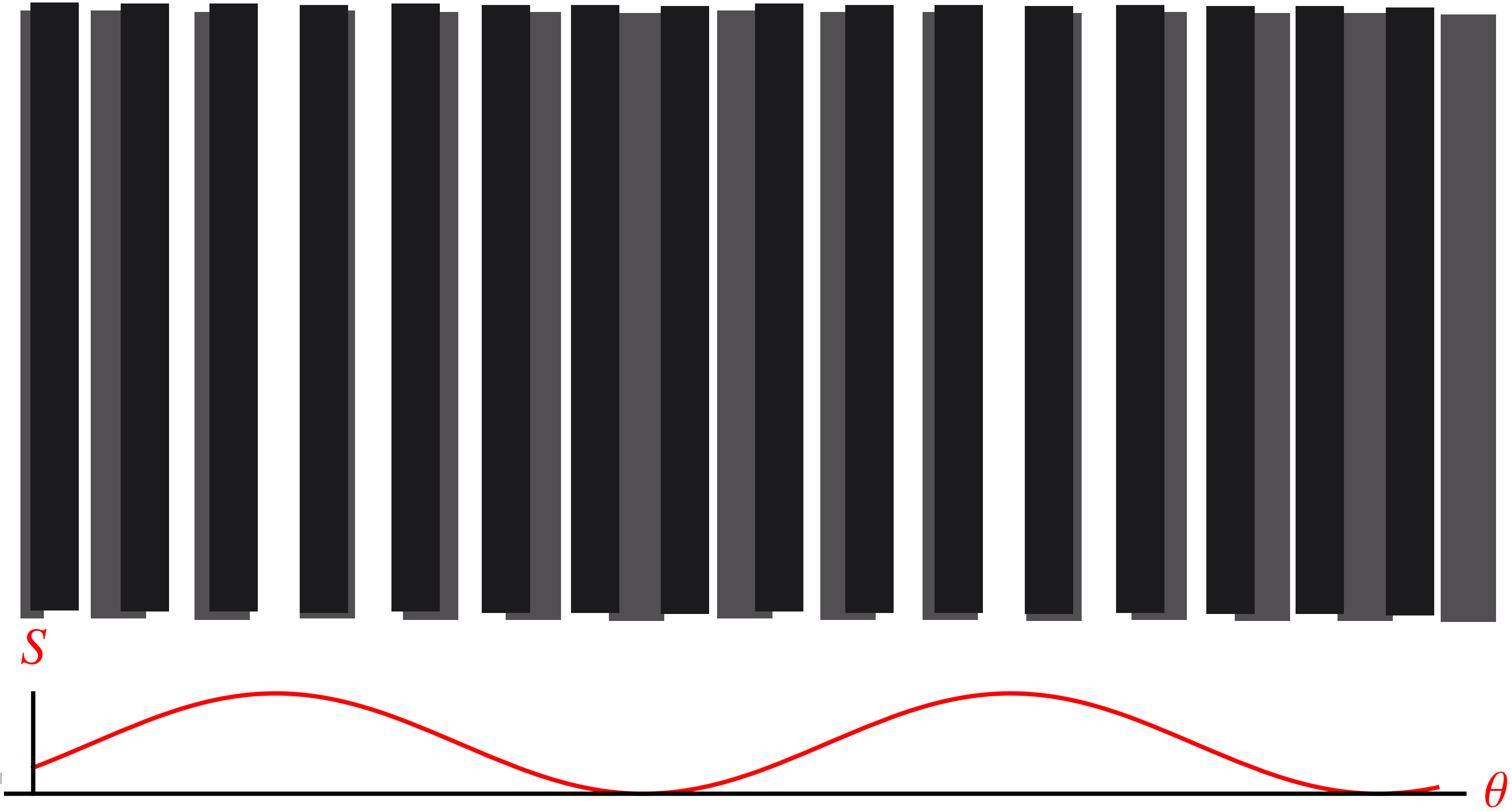
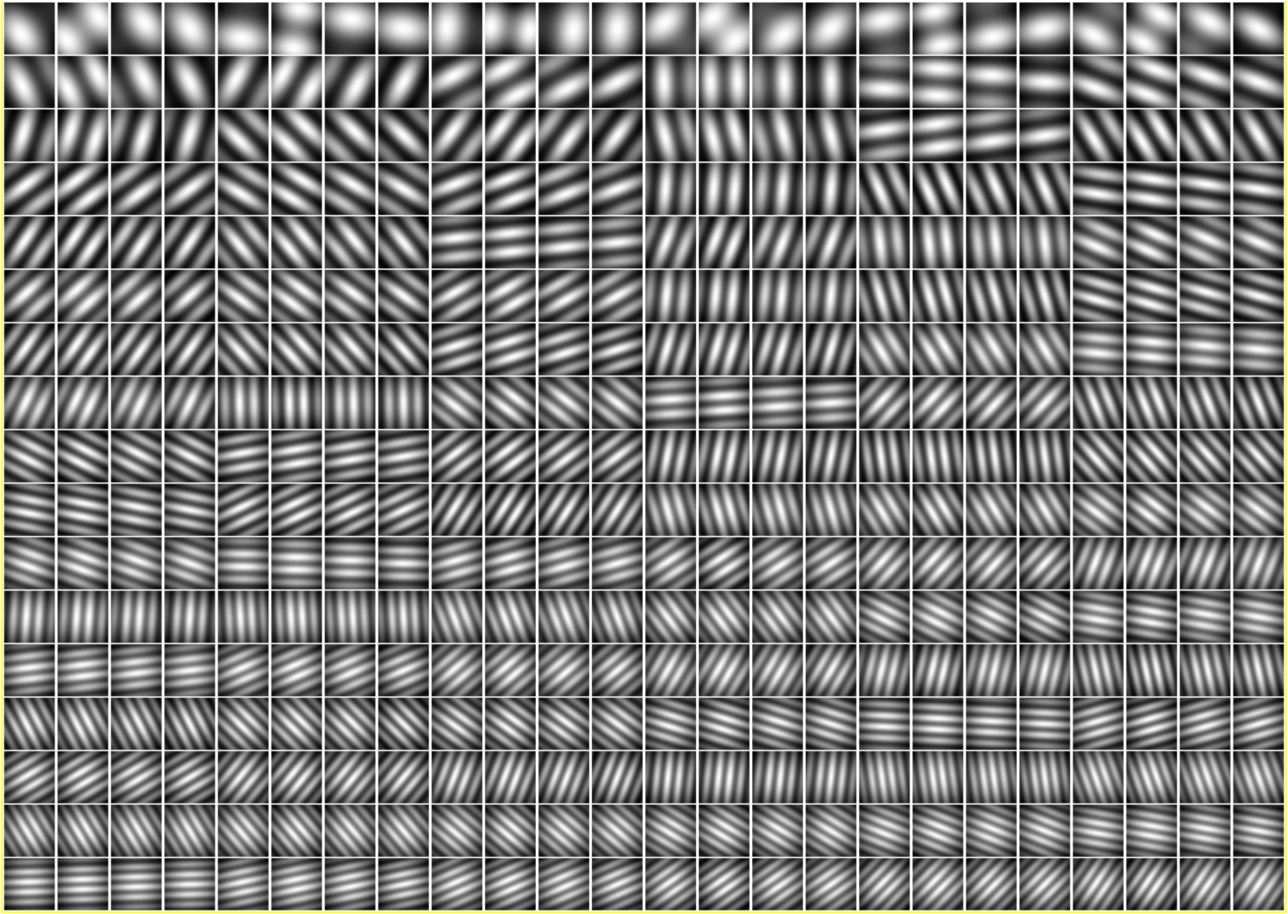
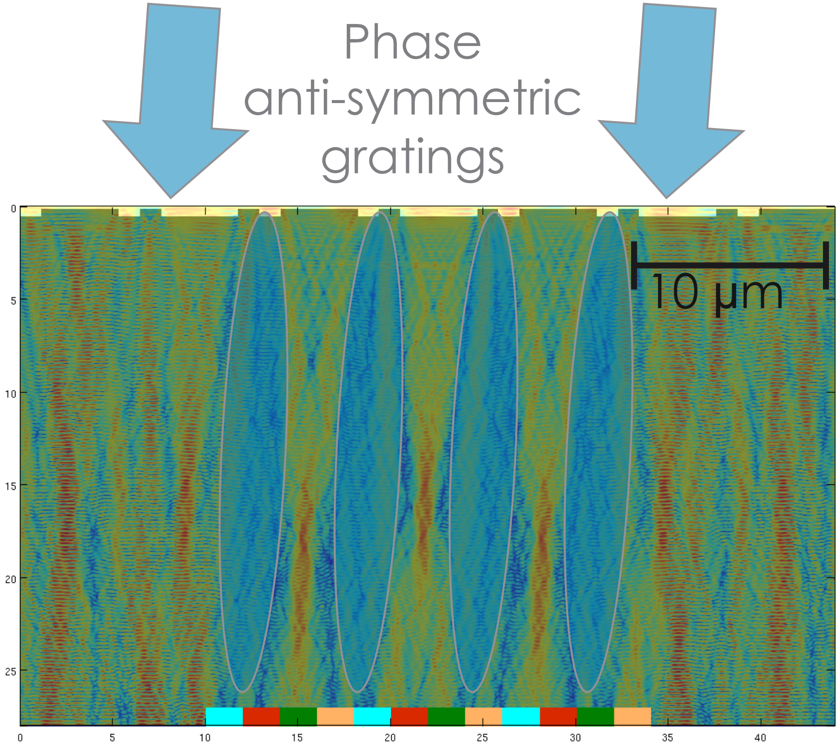


Image basis set from PFCA

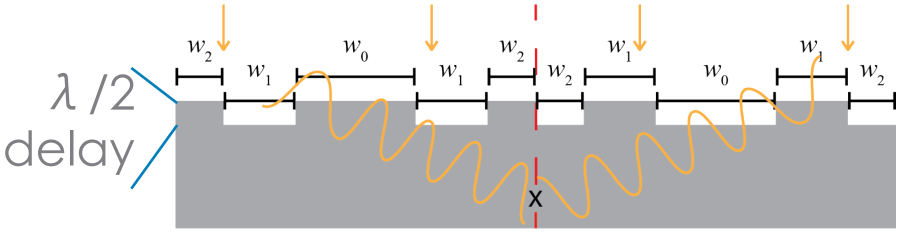


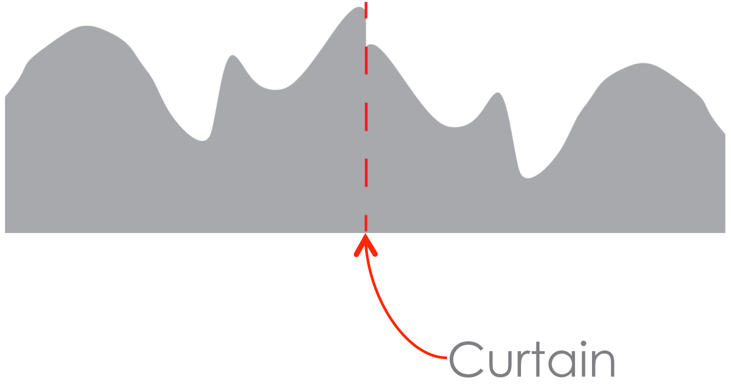
PicoCam: Phase anti-symmetric gratings



- New class of diffractive optic, which produces robust nulls called "curtains"
  - Insensitive to manufacturing depth variations
  - Robust to 2x change in wavelength
- Higher area efficiency
- Good quantum efficiency

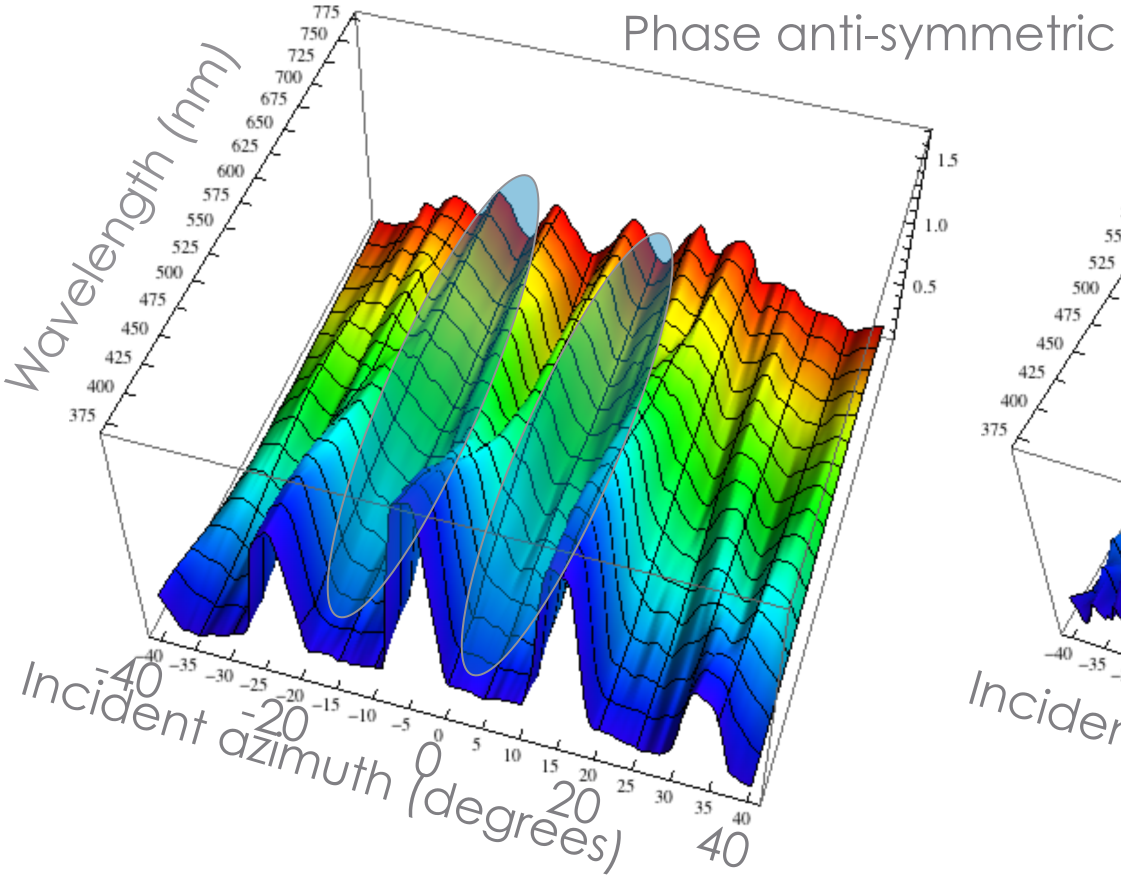
Properties of phase anti-symmetric gratings

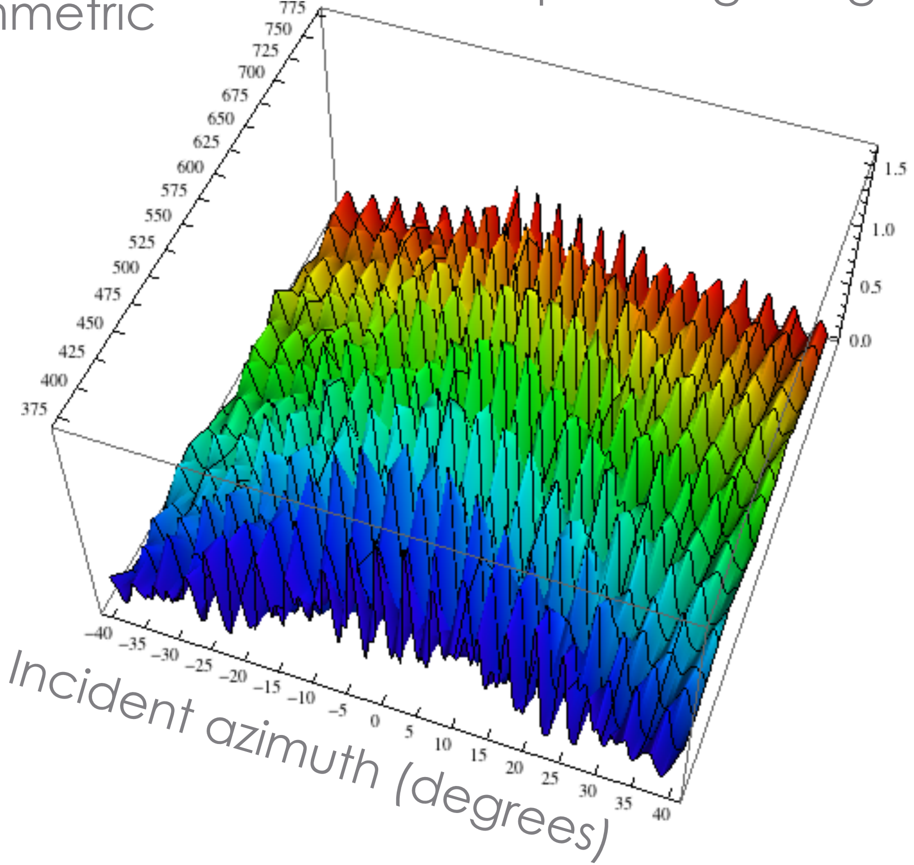




- Contribution from left cancels contribution from right due to $\lambda/2$ shift (phase difference = π)
- Curtains are planes of perfect cancellation
  - Discrete and piecewise-continuous designs both possible
- Curtains robust against depth and wavelength changes
- Only phase anti-symmetric gratings structures have this property

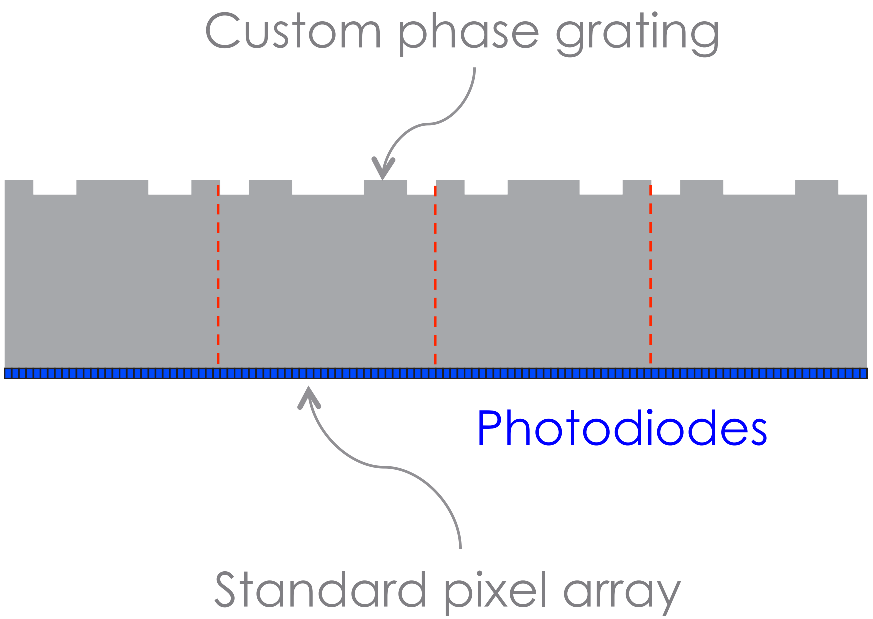
Wavelength robustness of phase anti-symmetric gratings: Curtains remain regardless of wavelength



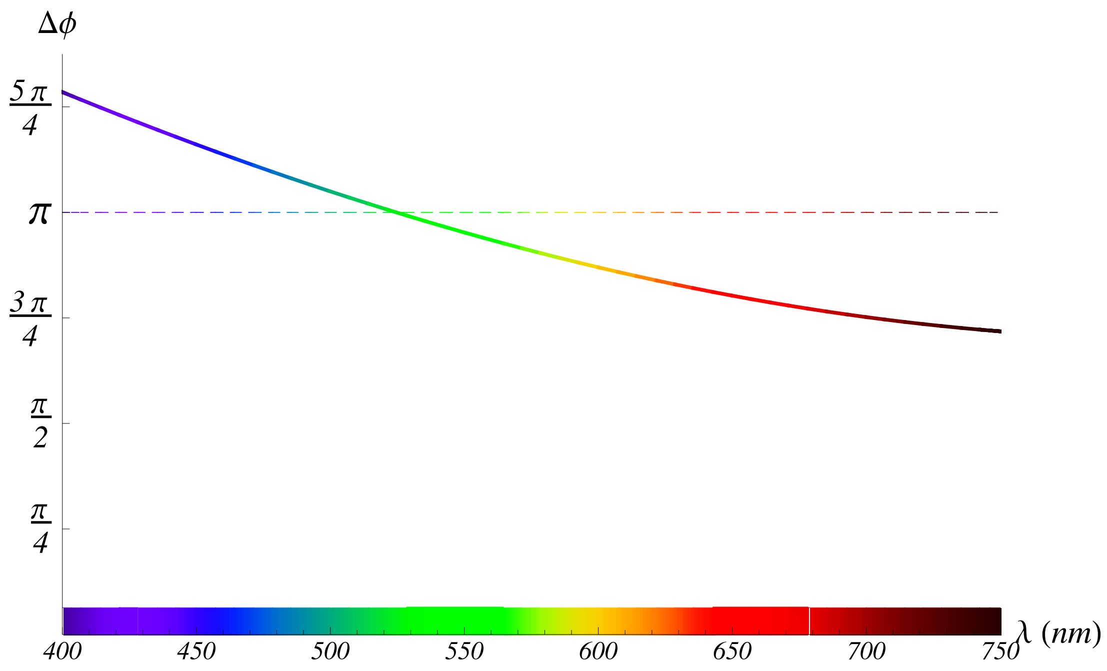


PicoCam phase anti-symmetric linear imager

- Grating parameters w_i can be optimized for concentrating light onto a small spot on a photodiode
- Focus is only very slightly depth- and wavelength-dependent
  - Optimal w_i for blue light slightly smaller than for red light
- Relates all information about Fourier components of far-away scene transverse to grating orientation

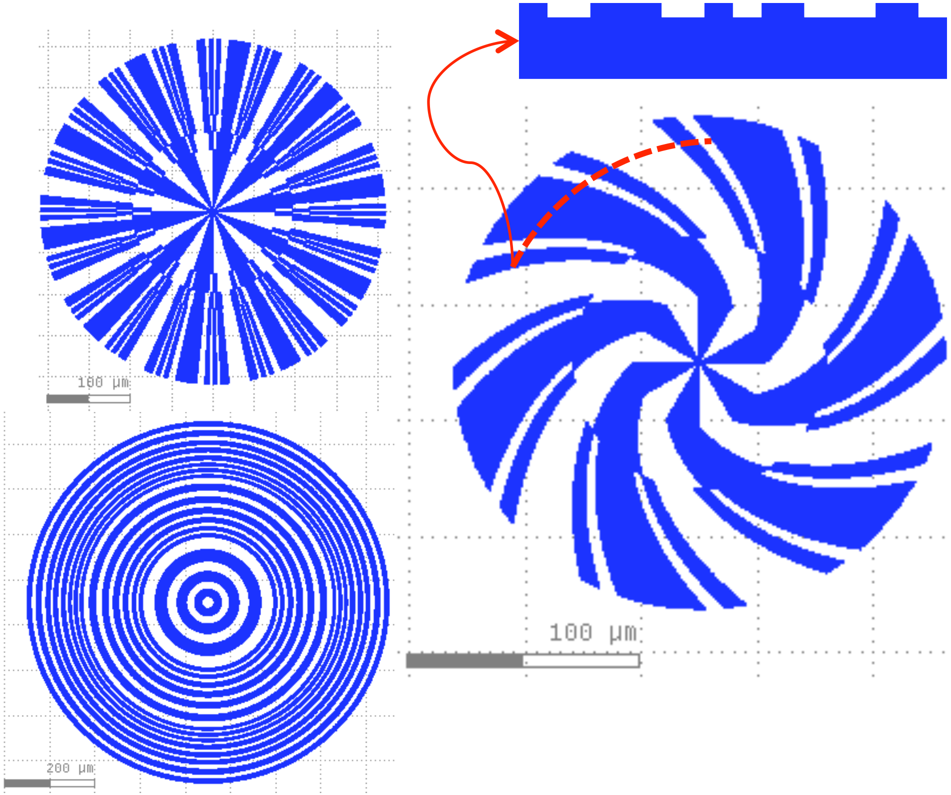


Half-wavelength (π) phase difference nearly independent of wavelength



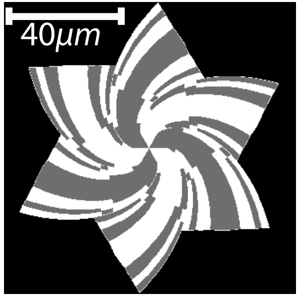
- High-*n*, low-dispersion substrate; low-*n*, high-dispersion coating

Grating designs that capture full 2D Fourier information

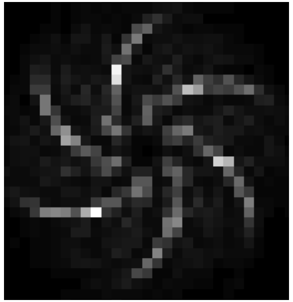


- Good performance for all visible light
  - Range of w_i
  - Differing number of fringes
- Information about all orientations
  - Curtains at all orientations
- Star, concentric or spiral patterns have smooth sweep of w_i, orientation, or both

Lensless imaging with a PicoCam

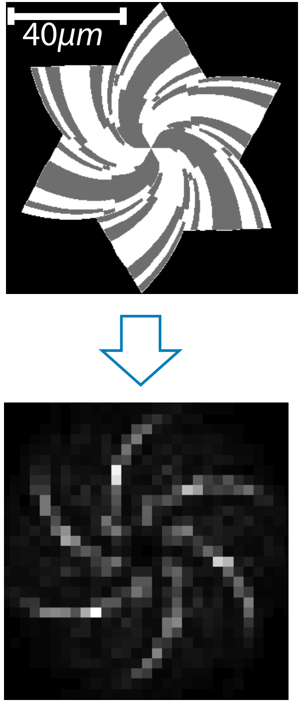


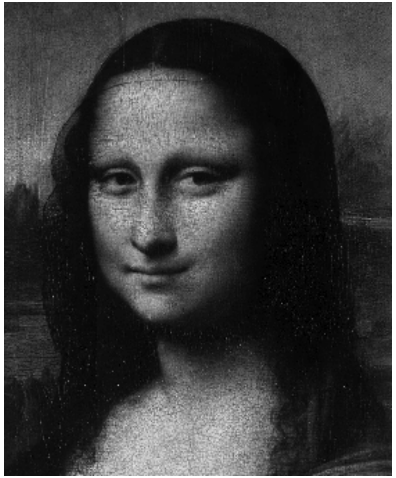
Phase grating



Optical simulation of photocurrent from 1.67 μm pixels

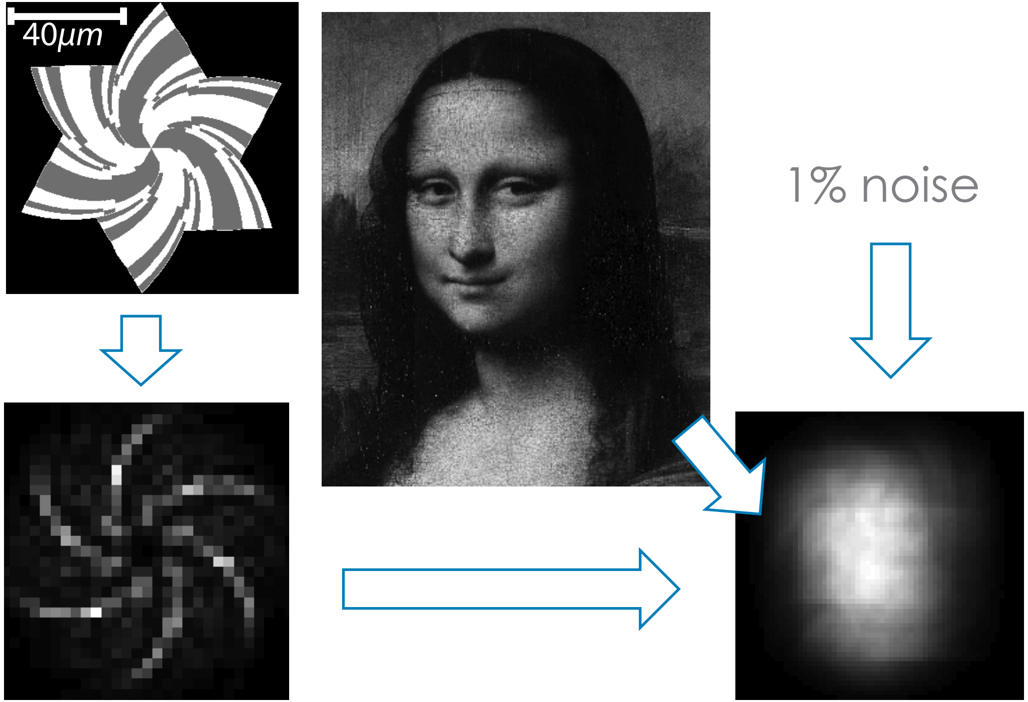
Lensless imaging with a PicoCam



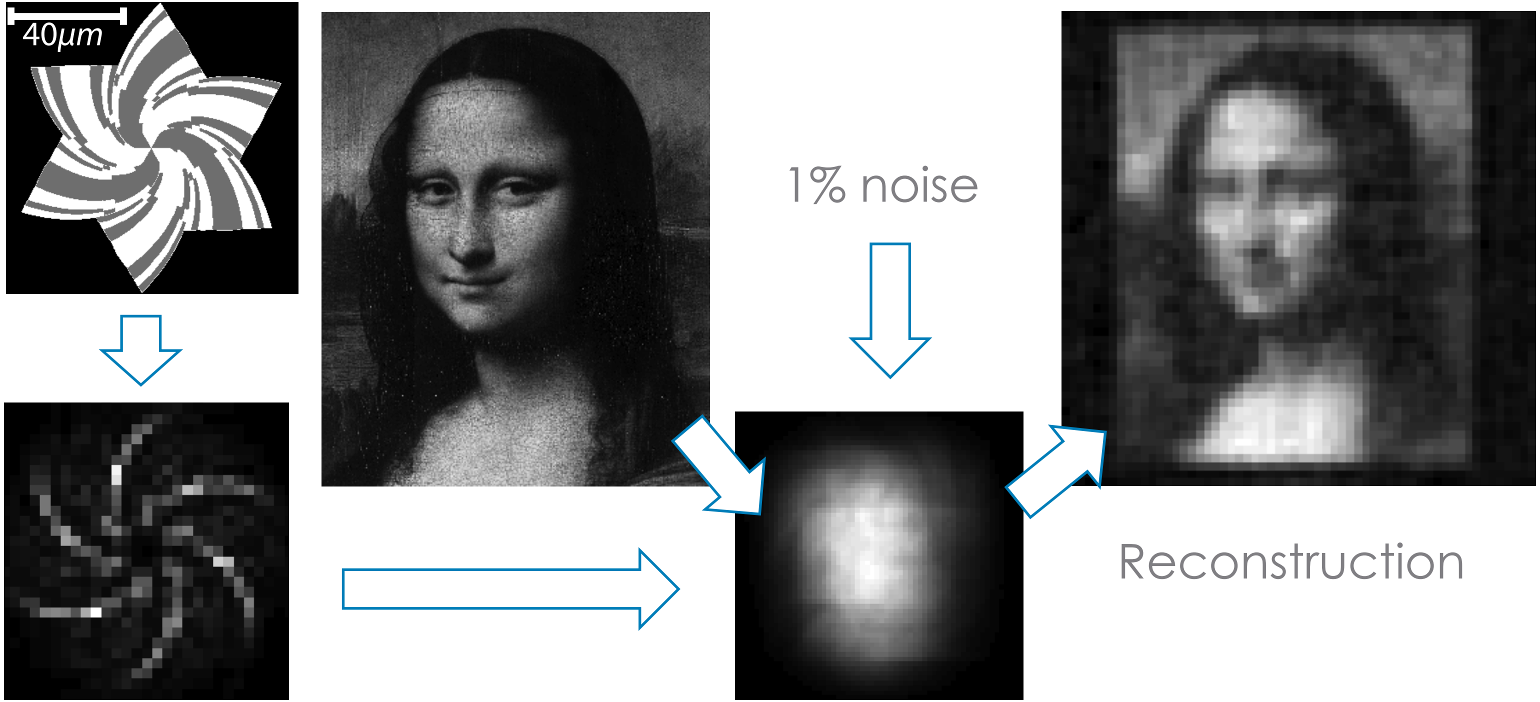


Input image

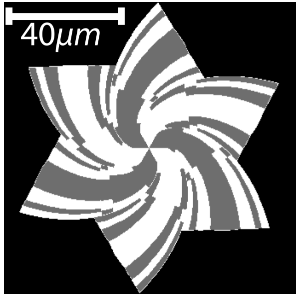
Lensless imaging with a PicoCam

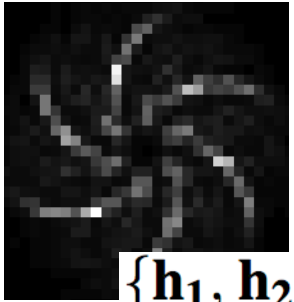


Lensless imaging with a PicoCam

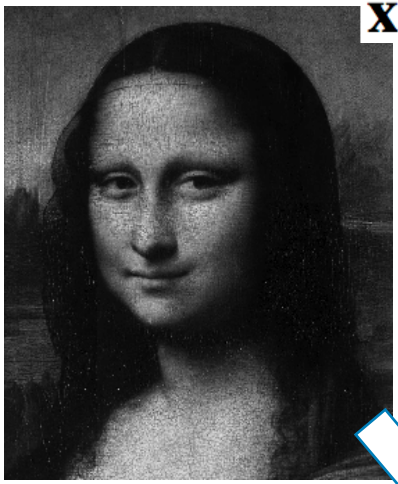


Lensless imaging with a PicoCam





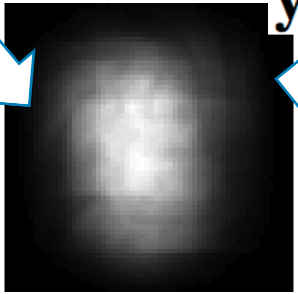
$$\{\mathbf{h}_1, \mathbf{h}_2, \ldots\} = \mathbf{H}$$



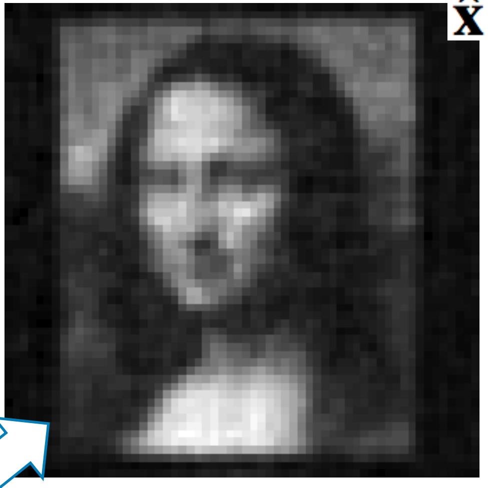
$\mathbf{x}$

$$\mathbf{B} \equiv \left(\mathbf{H}^{\mathrm{T}}\mathbf{H} + \lambda\mathbb{I}\right)^{-1}\mathbf{H}^{\mathrm{T}}$$

1% noise



$\mathbf{y}$

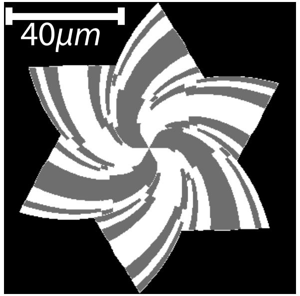


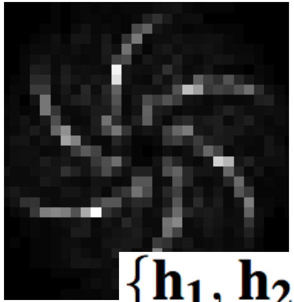
$\hat{\mathbf{x}}$

Reconstruction

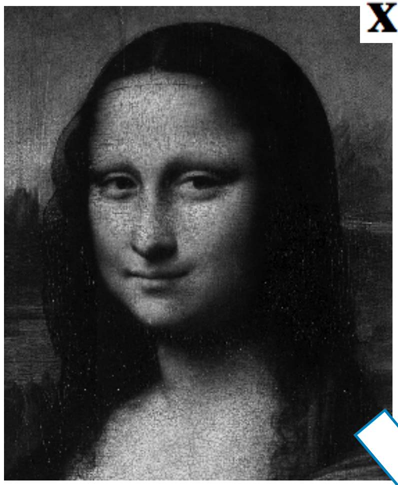
$$\hat{\mathbf{x}} = \begin{cases} \mathbf{By} & O(n^2) \end{cases}$$

Lensless imaging with a PicoCam





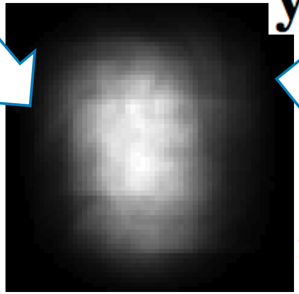
$$\{\mathbf{h}_1, \mathbf{h}_2, \ldots\} = \mathbf{H}$$



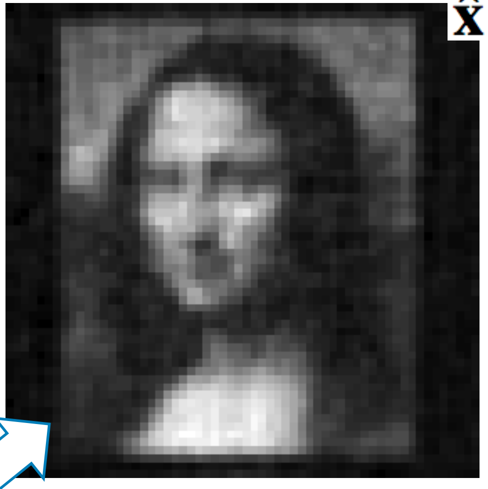
$$\mathbf{B} \equiv (\mathbf{H}^T\mathbf{H} + \lambda \mathbb{I})^{-1}\mathbf{H}^T$$

$$\mathbf{c} \equiv \frac{\mathscr{F}(\mathbf{h})^*}{|\mathscr{F}(\mathbf{h})|^2 + \lambda}$$

1% noise



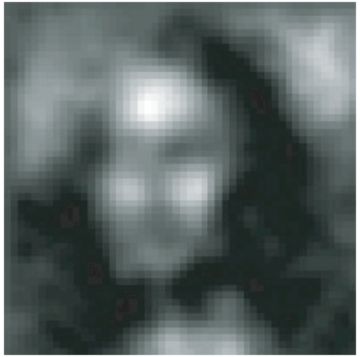
PicoCam



Reconstruction

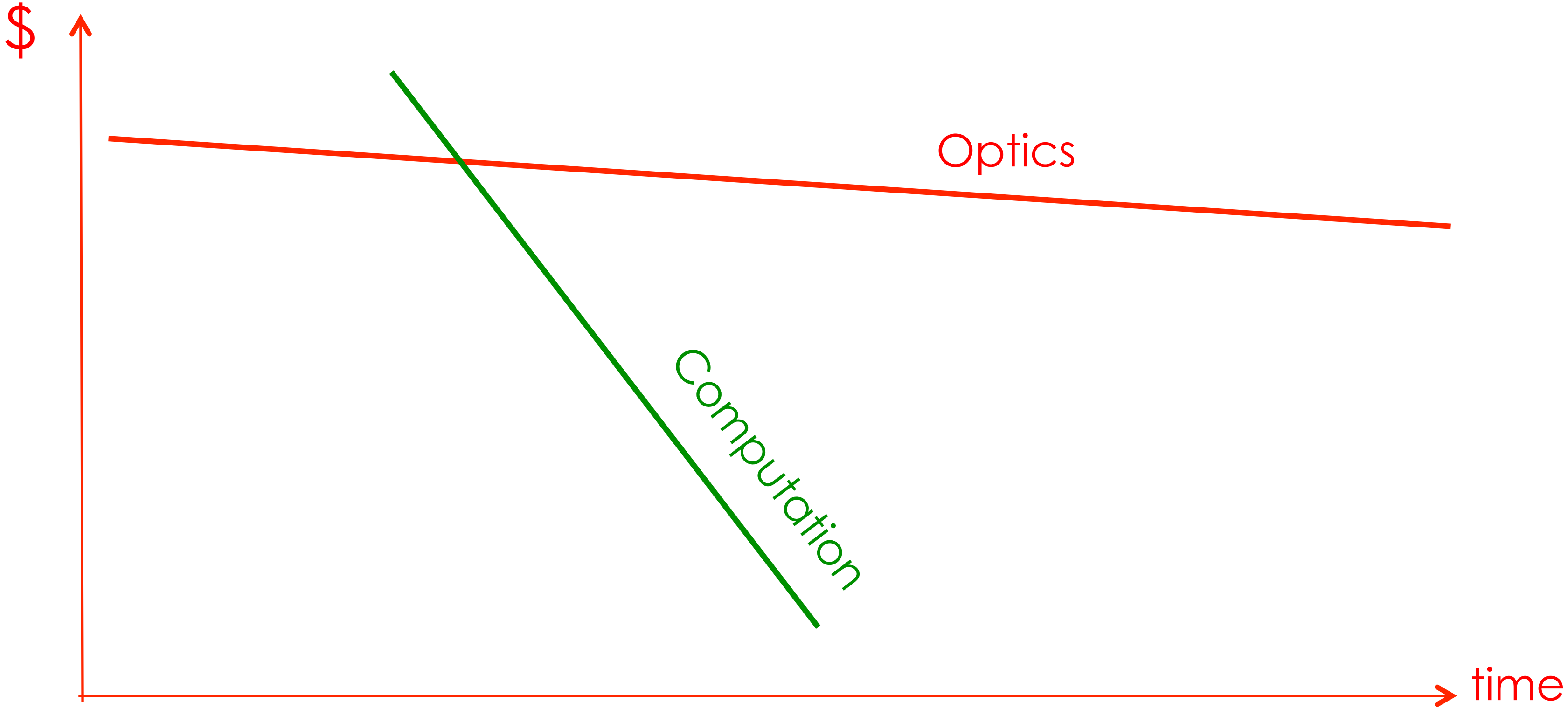
$$\hat{\mathbf{x}} = \begin{cases} \mathbf{B}\mathbf{y} & O(n^2) \\ \mathscr{F}^{-1}(\mathbf{c}\mathscr{F}(\mathbf{y})) & O(n \log n) \\ \ell_1, TV \text{ or other prior} & \geq O(n \log n) \end{cases}$$

PFCA: Amplitude gratings

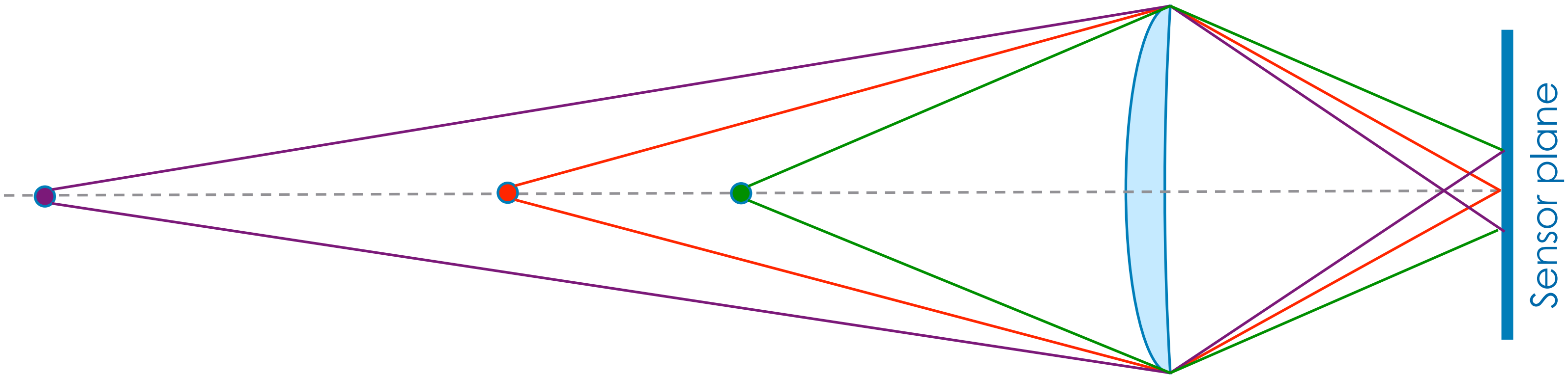


Previous work, factor 37x area

Cost of optics and computation

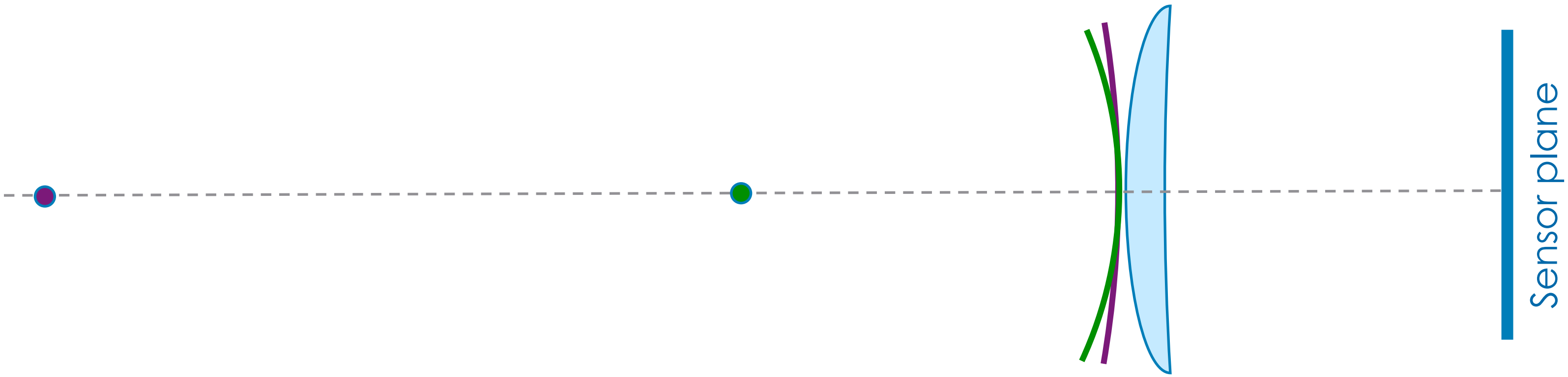


Depth of field in lens-based imagers



www.pcpro.co.uk

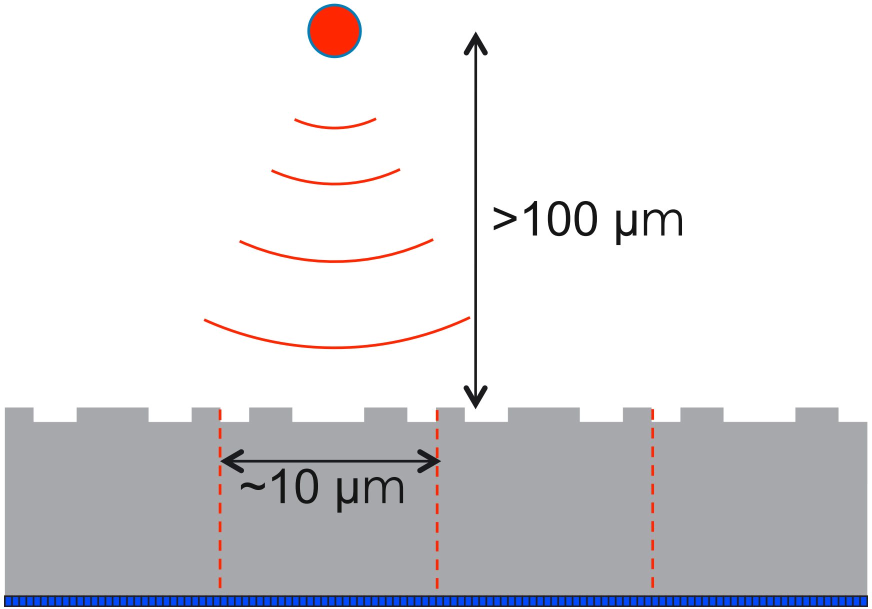
Depth of field depends on range of wavefront curvatures at entrance pupil



Differences in wavefront curvature lead to large depth of field

Typical lens-based imagers have depth of field of 5 diopters

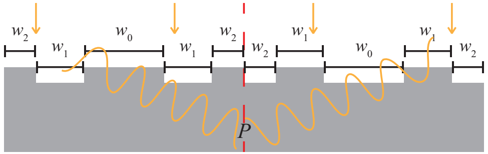
PicoCam has large depth of field

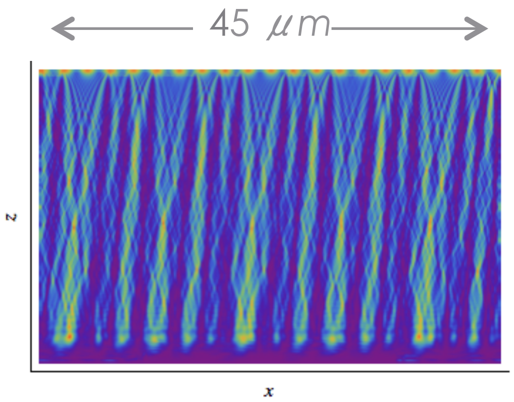


- Wavefront curvature over one grating half-period (effective pupil) is low, since period is small
- Depth of field: 100s of microns to infinity: ~1000 diopters

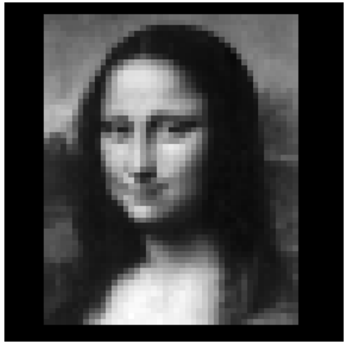
Summary: Lensless PicoCam technology

- Integrated diffractive optics with CMOS image sensor (lensless or lensed)



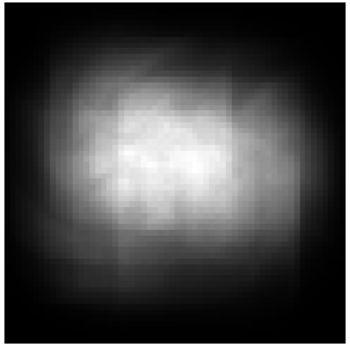


- Images and sensor decisions are not captured directly but instead *computed*

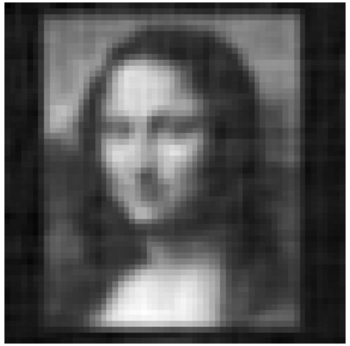


Input

Optical phase mask

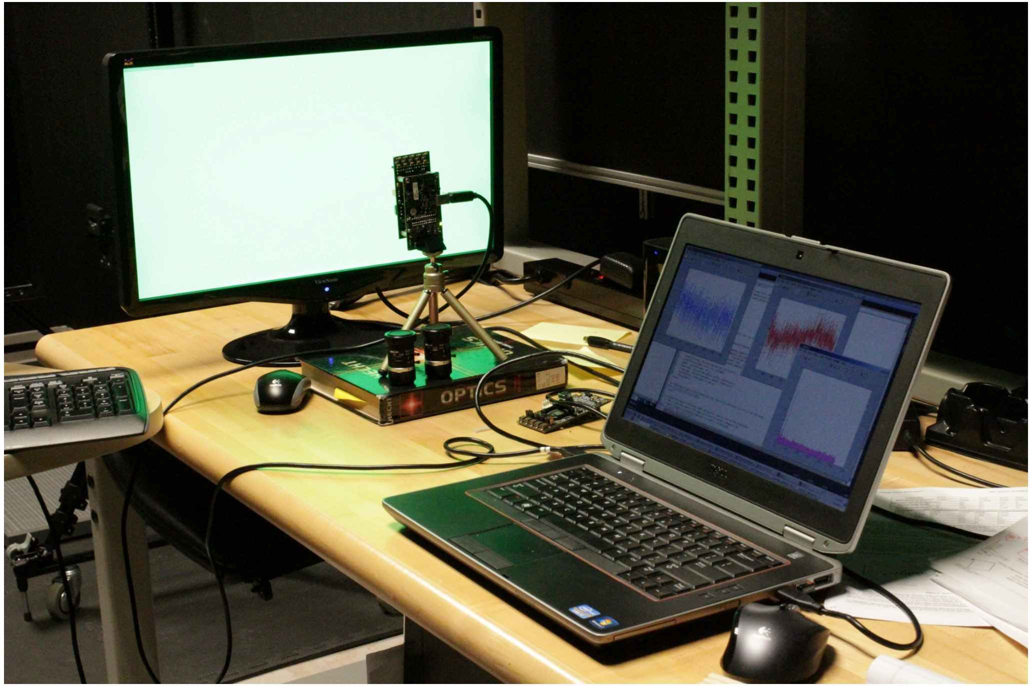


Sensor signals



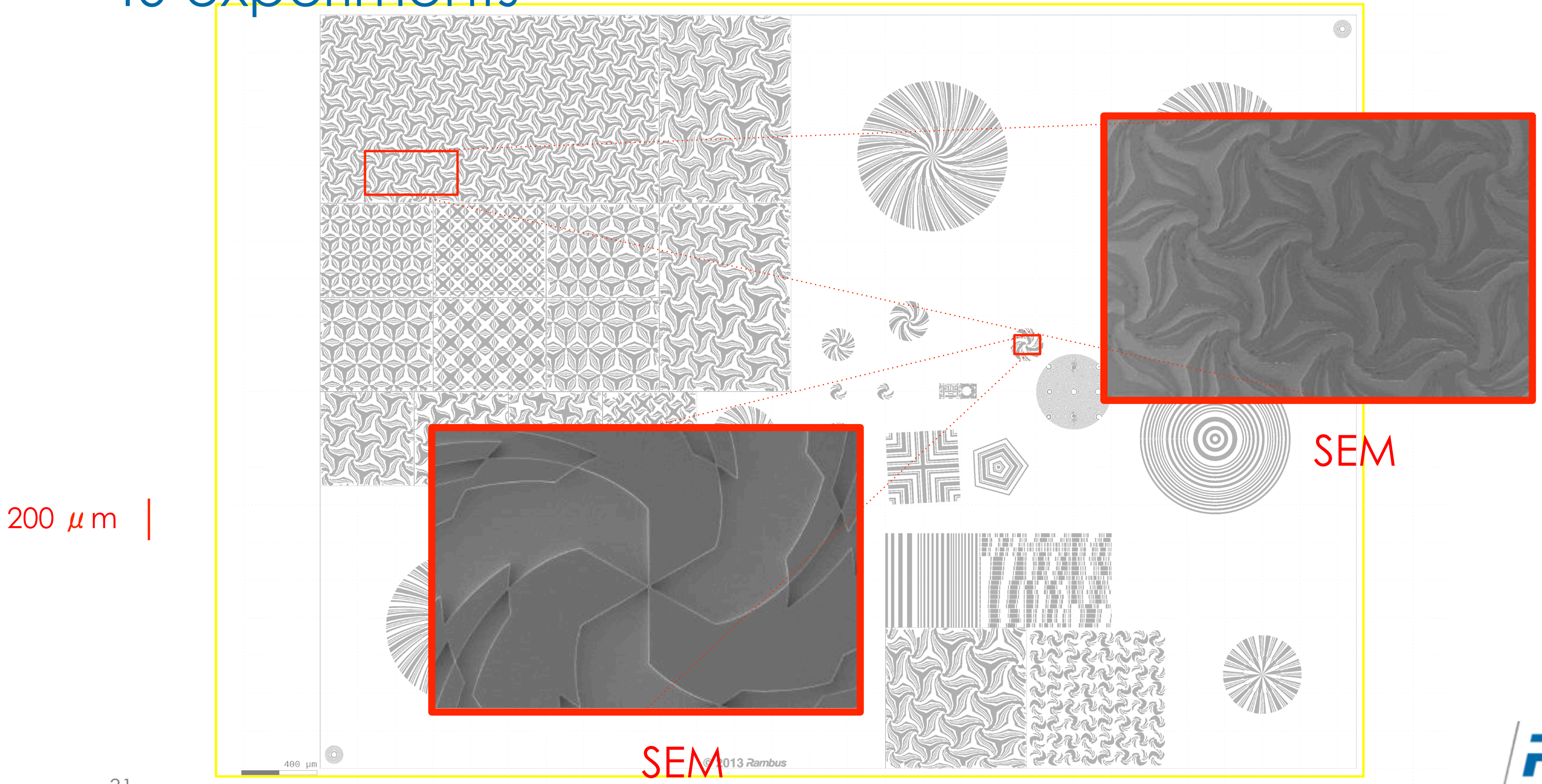
Computed image

PicoCam experimental prototype

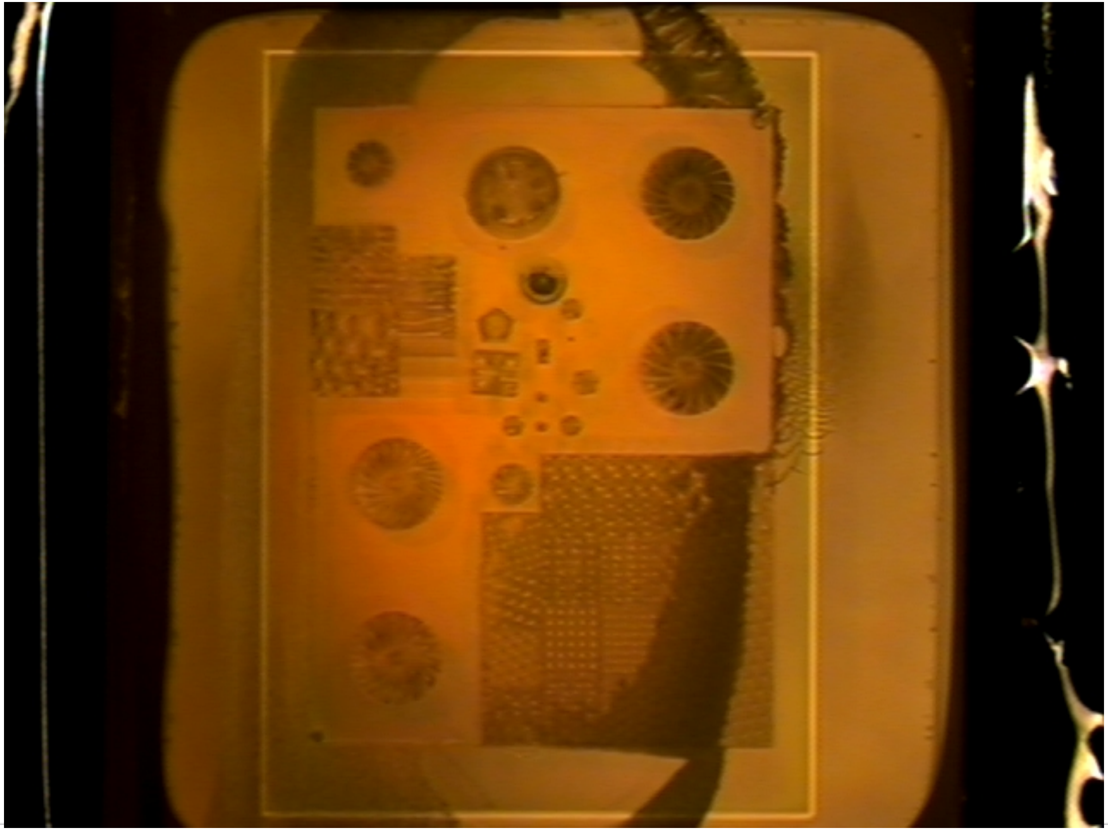


Commercial sensor with SDK

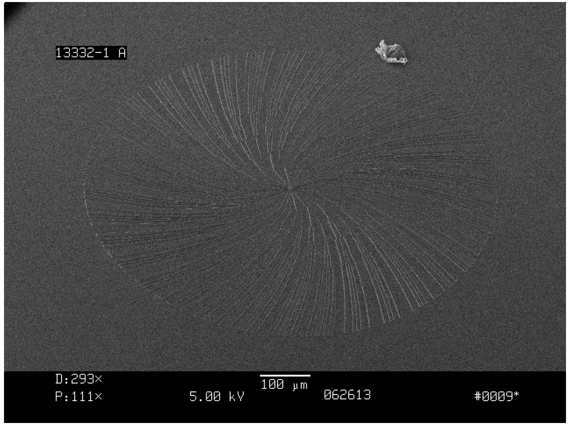
PicoCam experimental prototype phase mask: 40 experiments

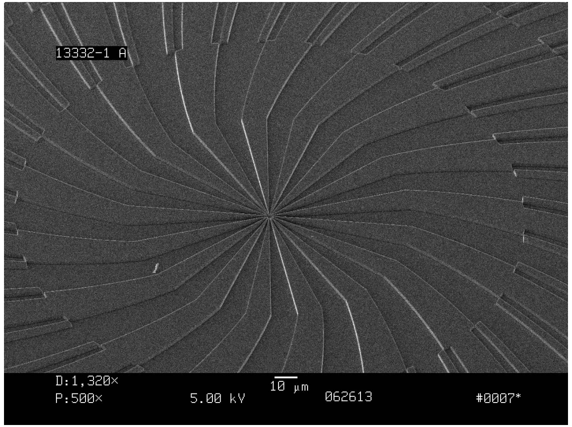


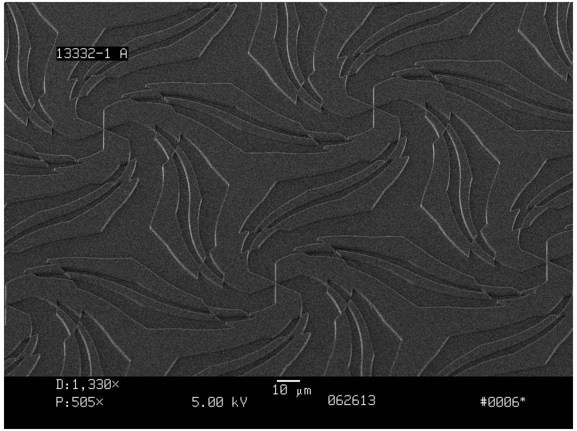
Phase gratings mounted on image sensor

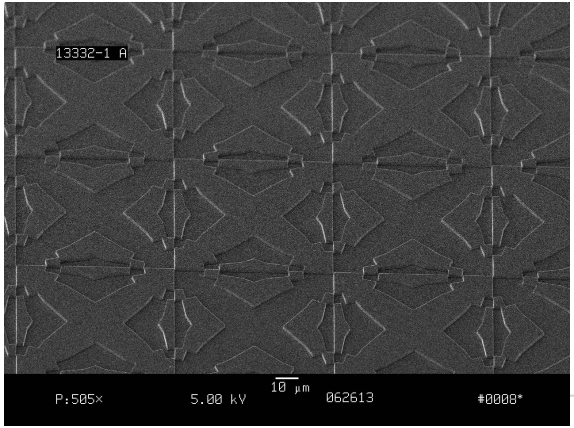


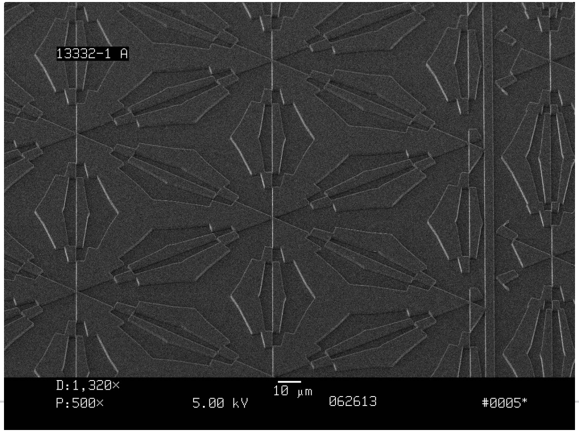
PicoCam experimental prototype phase mask



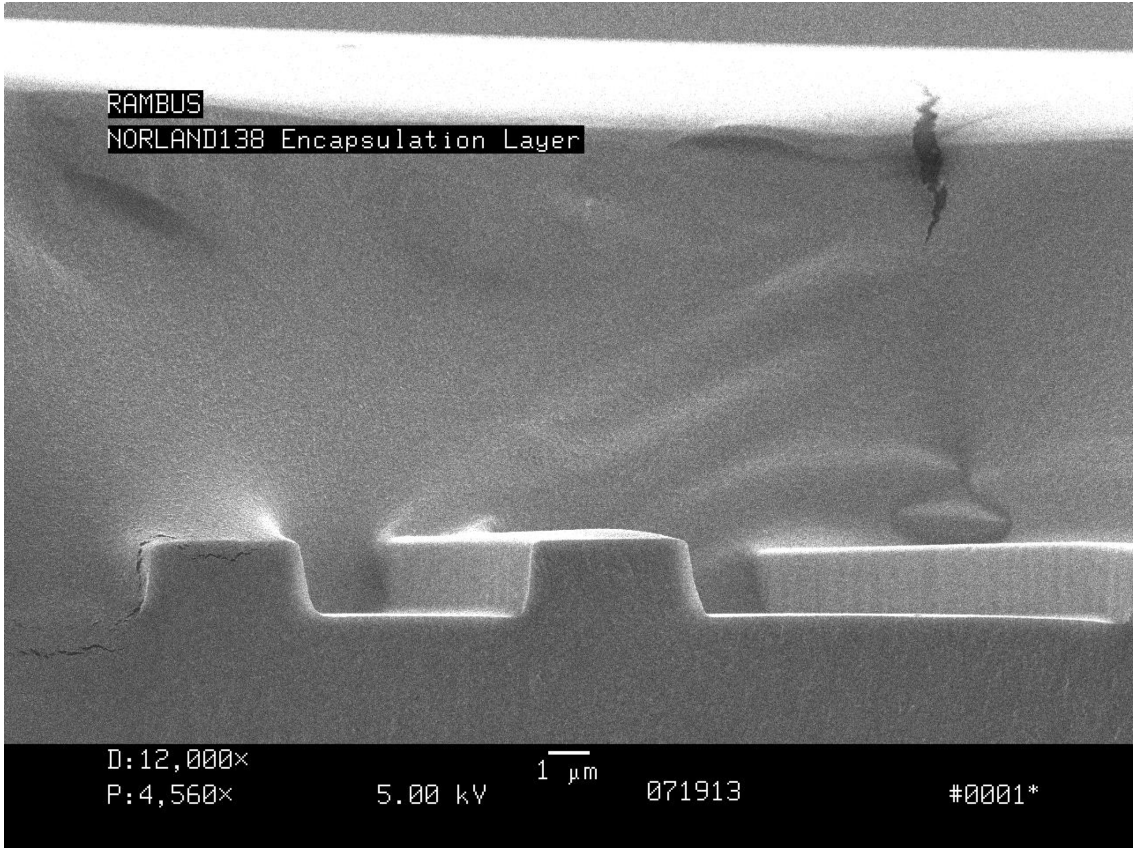




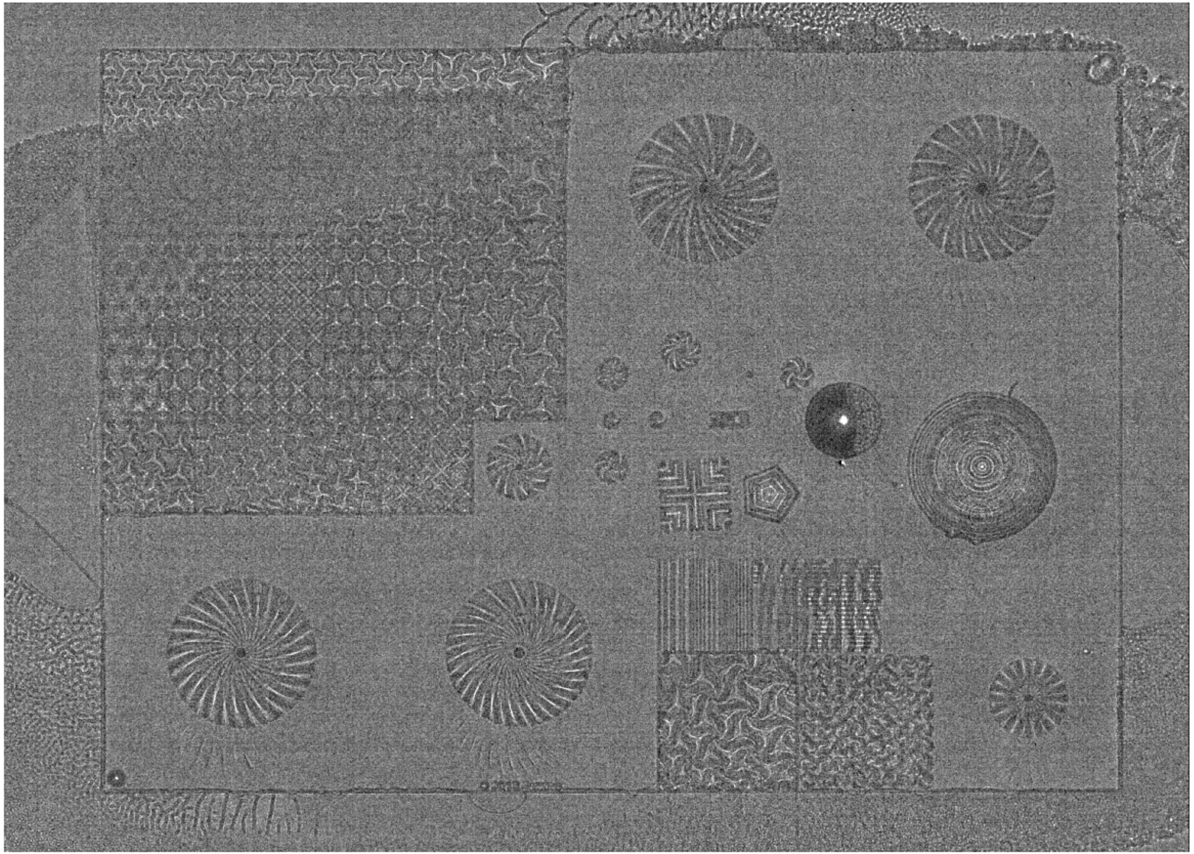




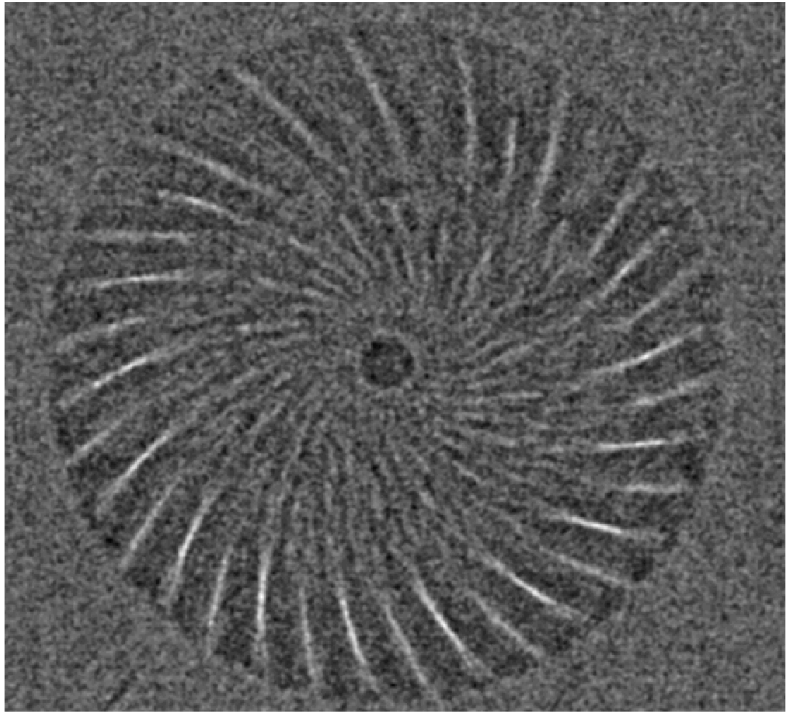
Phase grating with encapsulation layer

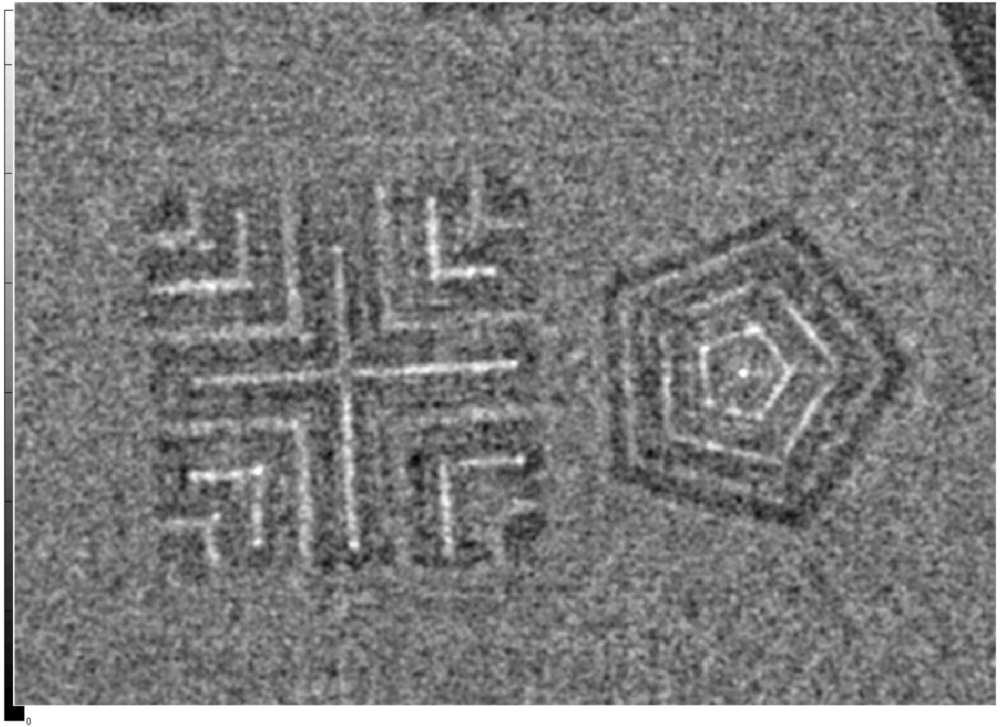


First PSFs!

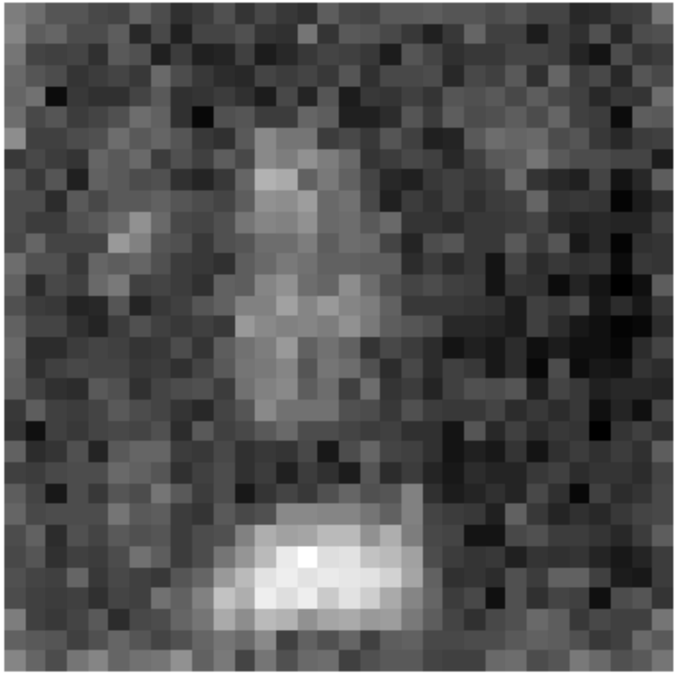


First PSFs!





First image! (not yet calibrated… so much to be done)



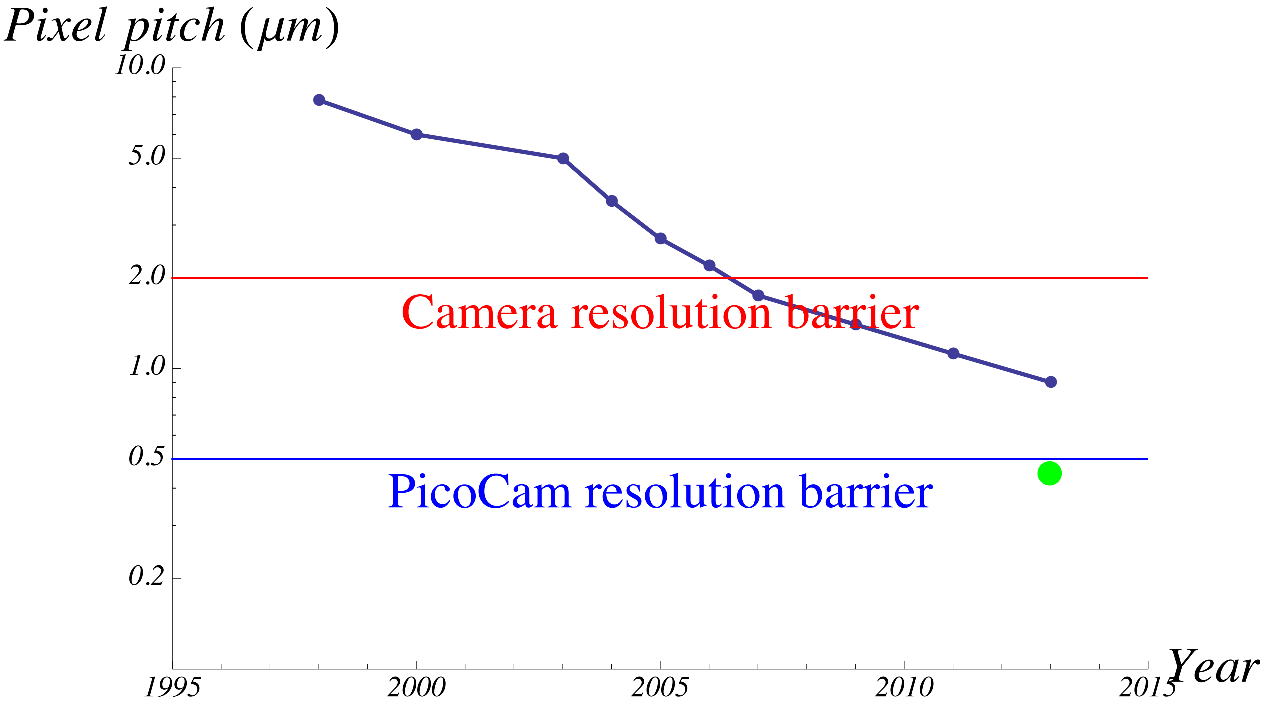
What about (non-imaging) sensing?

- The gratings and signal processing can be designed for a specific application
  - Bar-code reading
  - Face recognition
  - Motion estimation
  - Object tracking
  - …

Lensless PicoCam value propositions

- Very small (<.8 *mm* x .8 *mm*) sensor;1.3 *mm* x 1.4 *mm* with ADC, power, pads, etc. (current). Smaller in three years.
- Very thin (15 μm *on* 500 μm wafer)
- Very low mass (30 μg)
- Very inexpensive (15¢ for sensor alone in bulk) *sense for cents*
- Can be integrated with CMOS
- New form factors (shapes)
- Application-specific (motion, depth, occupancy, barcode, …)
- Can exploit small-pitch photodetector arrays

Sensor pixel pitch vs. year



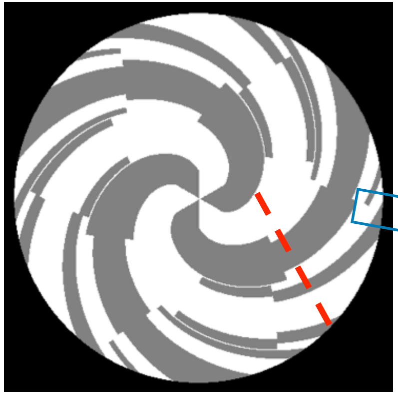
Lensless PicoCam technical challenges

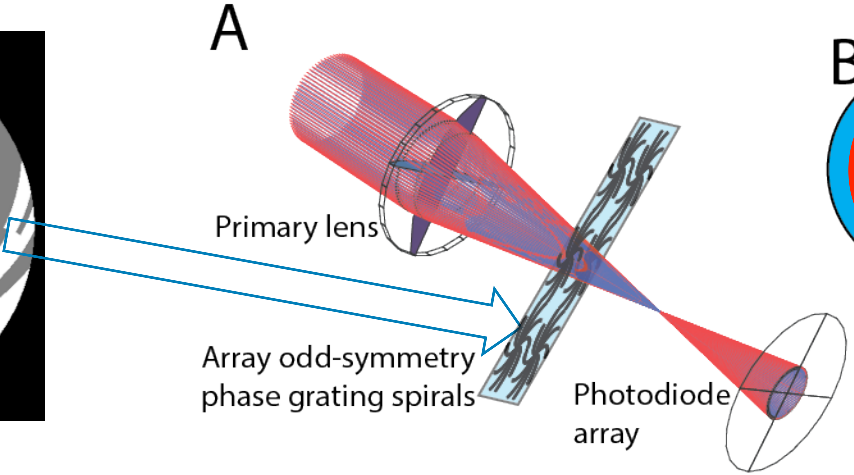
- Some applications (e.g., imaging) require more computing than traditional sensors.
  - But computation continues to become less expensive (Moore's Law) and can be done off chip or later.
- For some applications (e.g., imaging) the sensor data must be processed and converted to "traditional" formats.
  - But computation continues to become less expensive (Moore's Law)
- Only moderate low-light sensitivity (because small sensor)
  - But we're more sensitive than traditional cameras of the same aperture

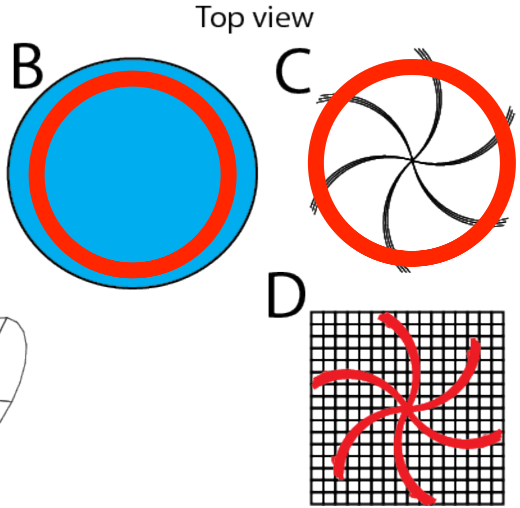
Lensed PicoCam

Spiral patterned gratings

Top view





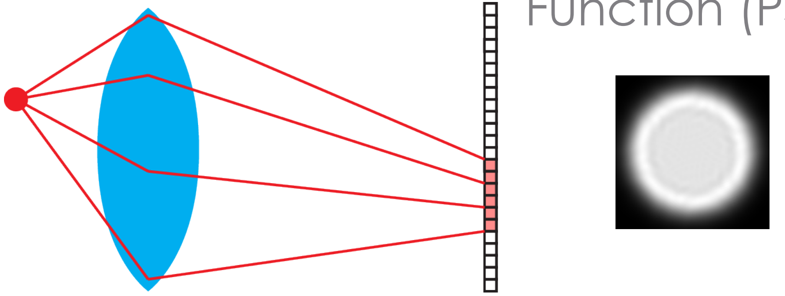


- Spiral patterns turn otherwise disk-like PSF into spirals
- Size of PSF is proportional to defocus
- Distinct PSFs for different ranges

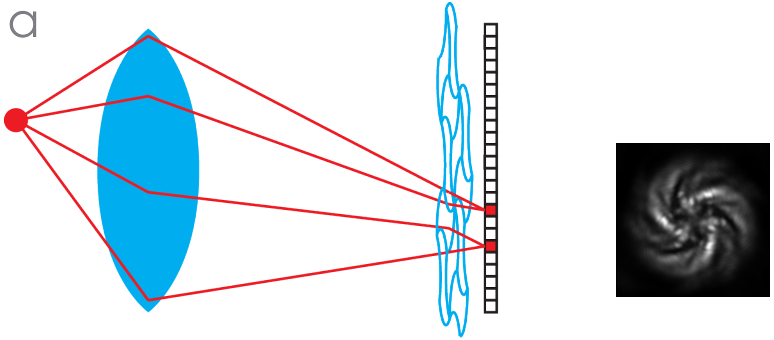
Imaging with imperfect focus

Point Spread Function (PSF)

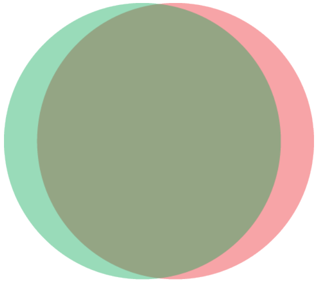
- Point sources not at conjugate focus cast light on many sensors
- Low-pass filter: destroys information



- Spiral phase grating perturbs PSF into a spiral
- Full-pass filter: preserves information
- In principle, recover as many image pixels as there are sensor pixels



Why do spirals in the optical path aid in image reconstruction?

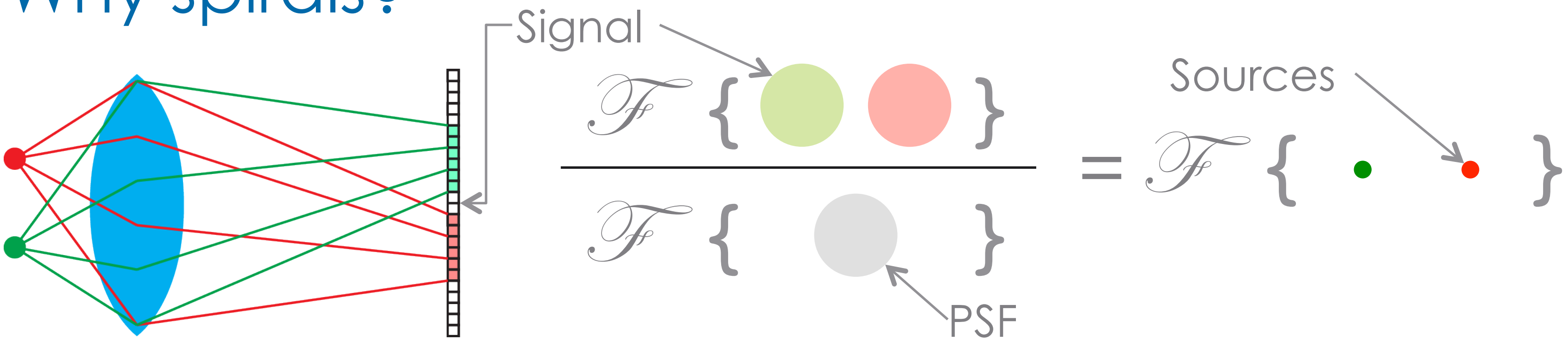


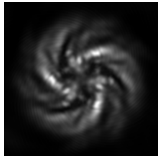
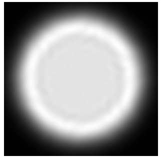
Cannot resolve

Can resolve

- Without spiral phase grating, two out-of-focus close points blend into one
- If separation of point sources is larger than the smallest feature of the PSF, then point sources resolvable

Why spirals?

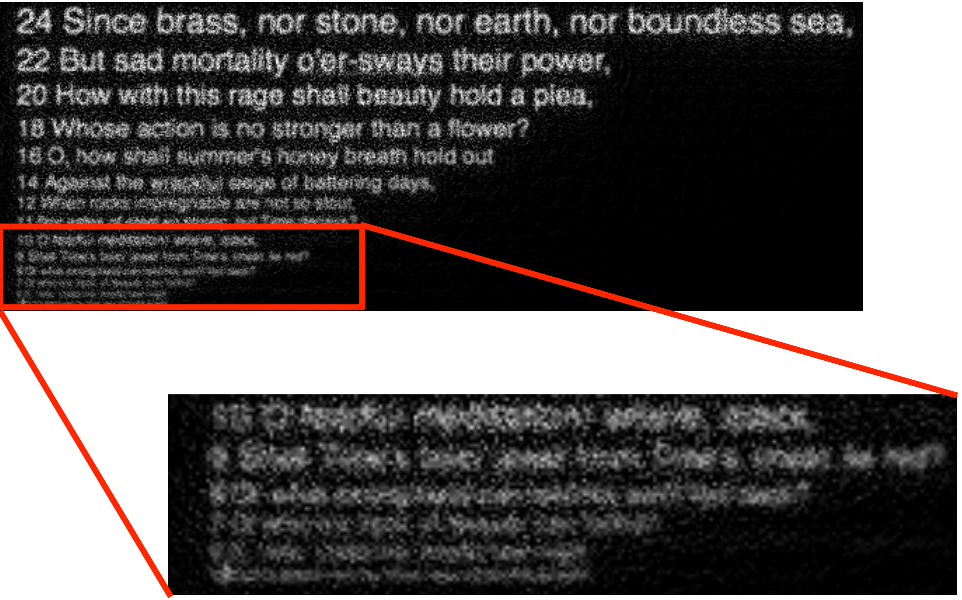


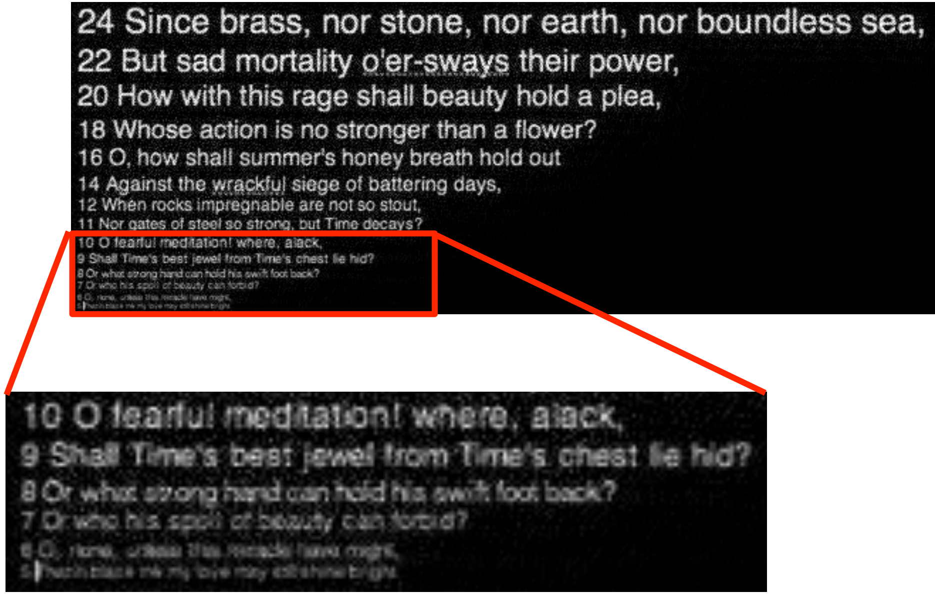
- Deconvolution equivalent to dividing by Fourier transform of PSF
- Want to avoid division by quantities close to 0
- Fourier transform of spirals has reasonable power at all spatial frequencies and orientations
- $\mathcal{F}\{$  $\}$ has better spectrum than $\mathcal{F}\{$  $\}$

Disk-like PSF

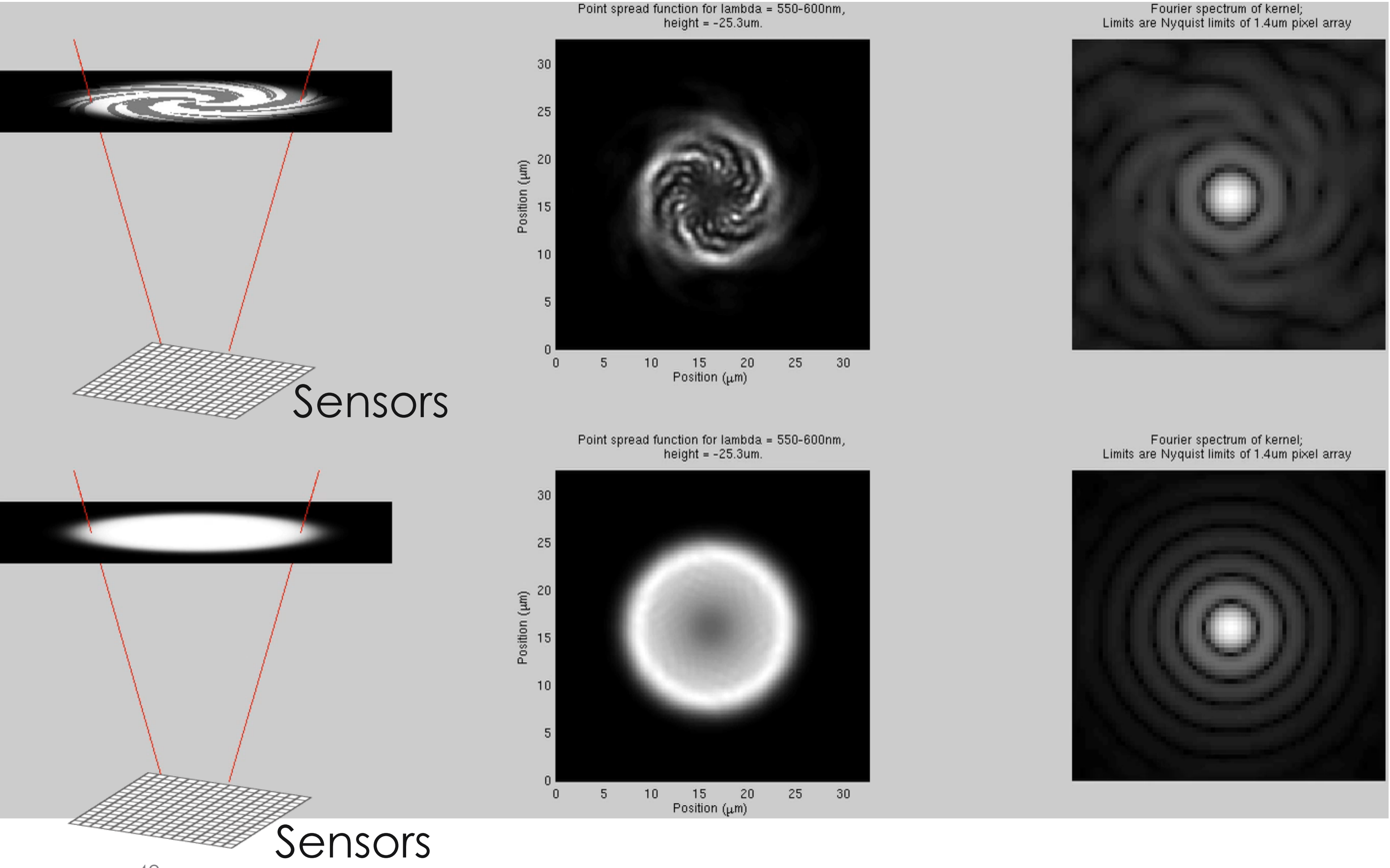
Spiral phase gratings

Computed reconstructions (0.1% noise)



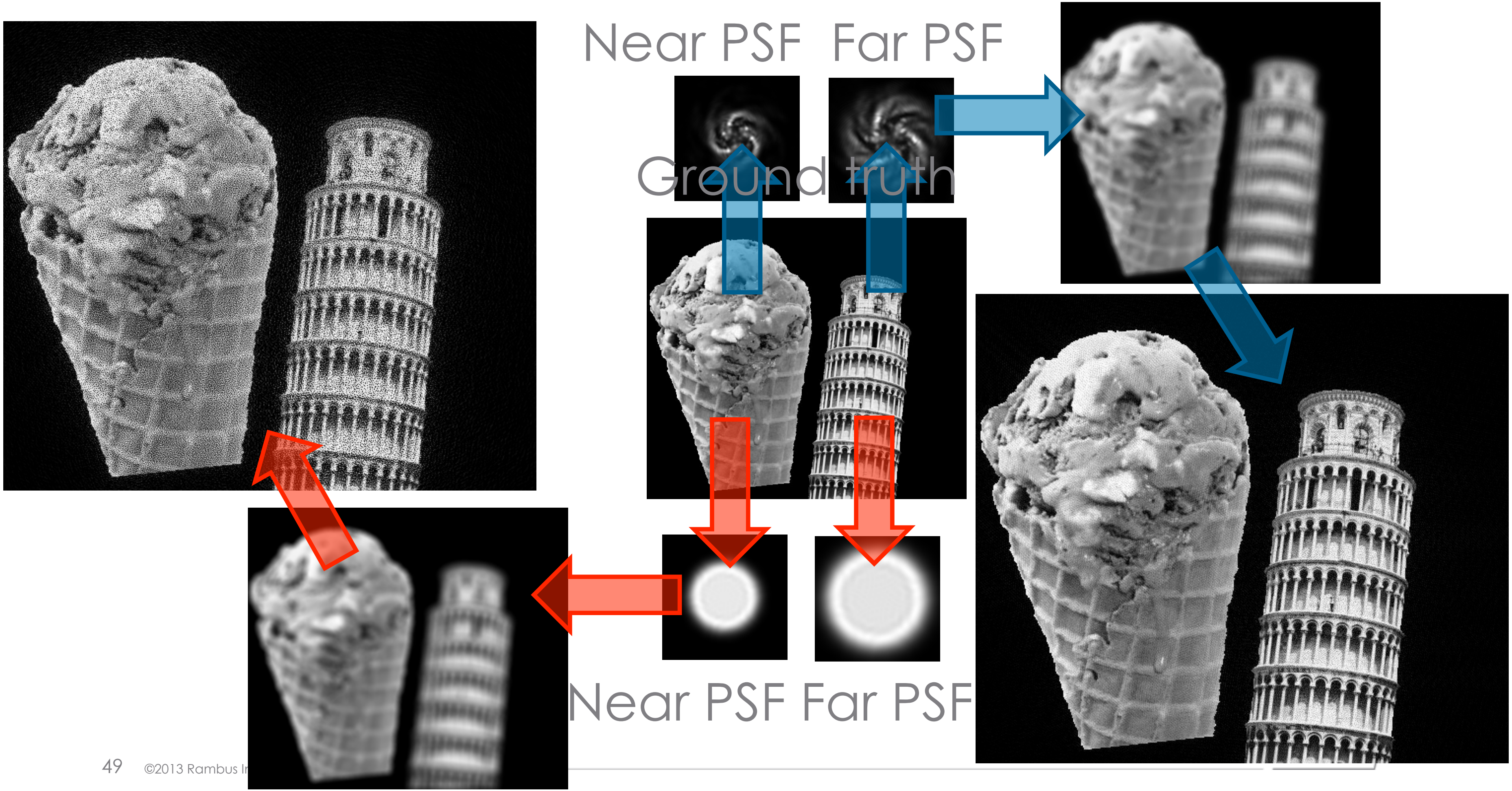


PSF as function of depth



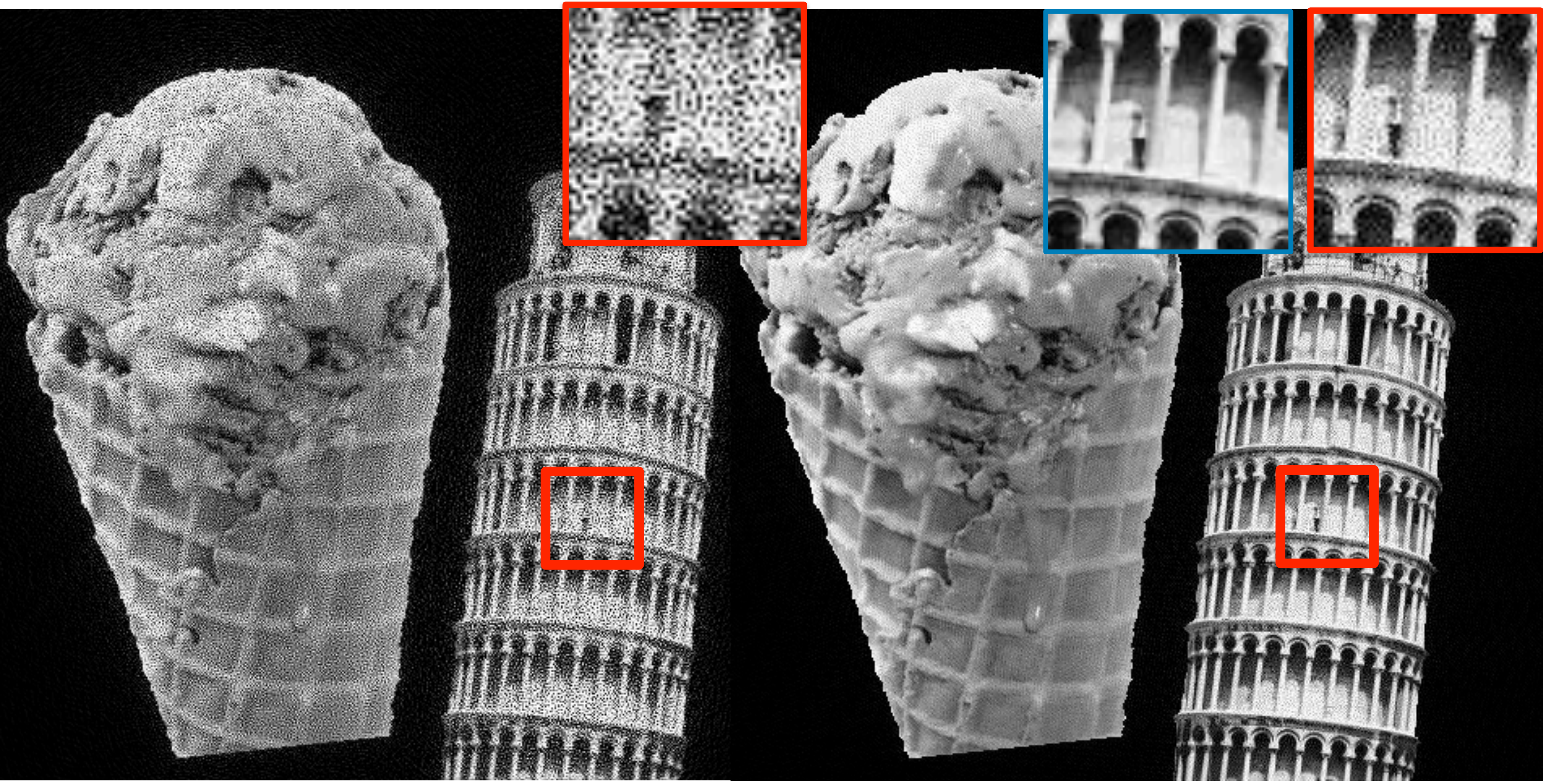
- Spiral PSFs are distinctive at each depth, and invertible
- Traditional PSFs have more Fourier zeros, inhibiting accurate reconstructions

Reconstructions



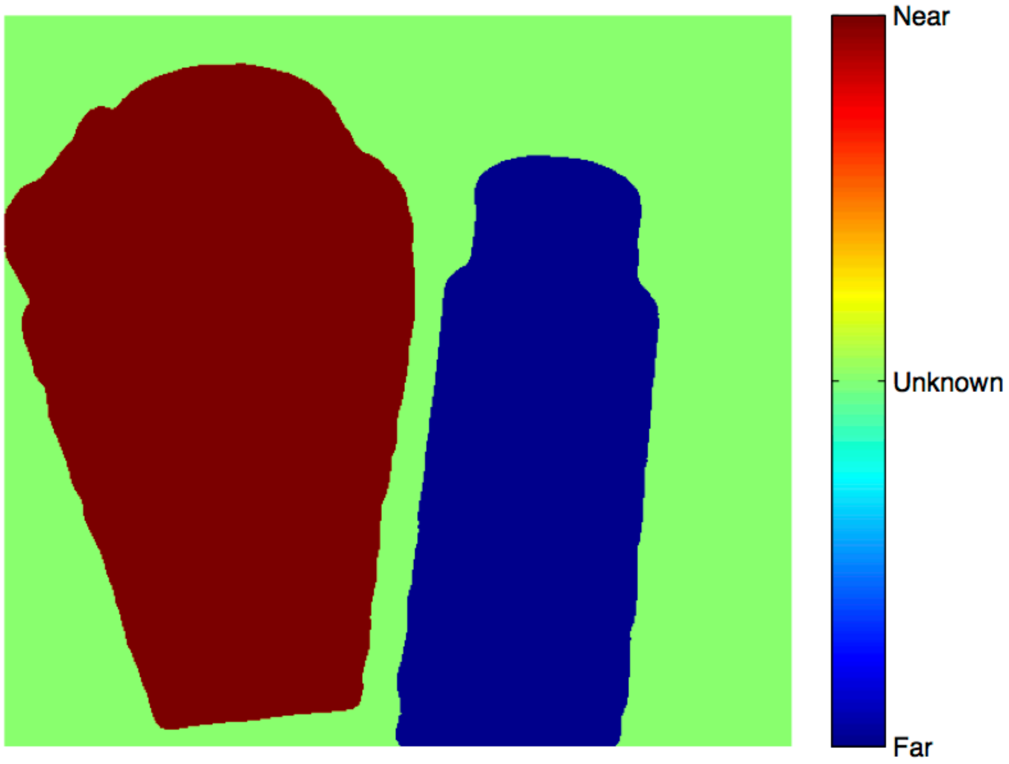
Disk-like PSF

Spiral phase gratings

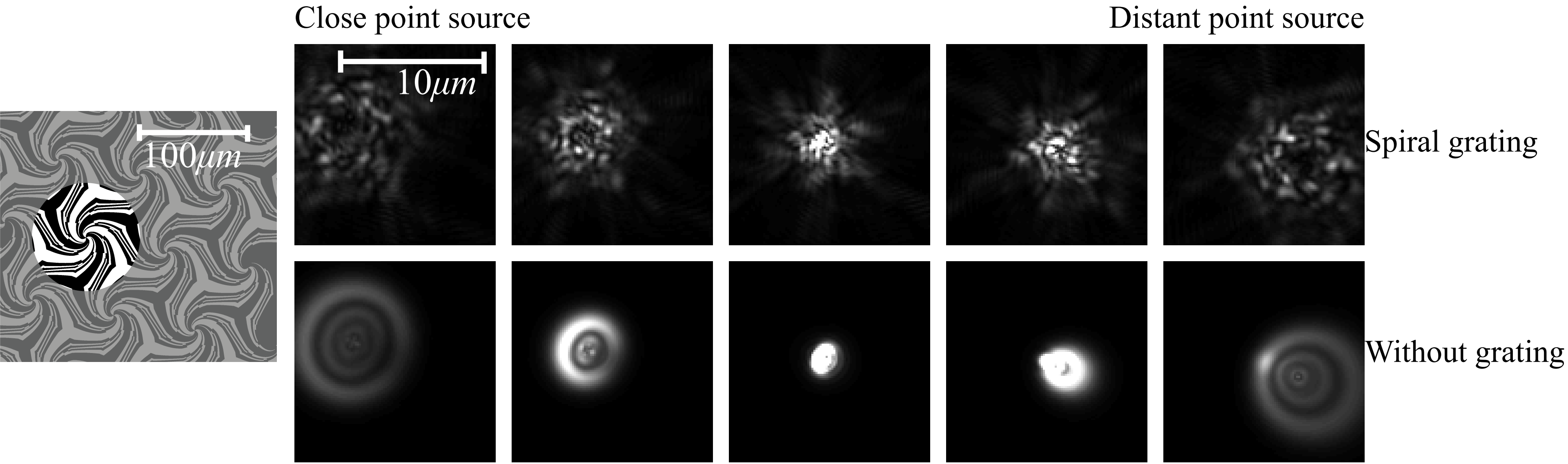


Range map

- PSF is distinctive for different depths
- Range can be inferred by Fourier "fingerprint" for objects with enough texture
- If not enough texture, image will be accurate, but depth unknown
- Incorrect depths ruled out, as they lead to spiral artifacts and (possibly) negative intensity

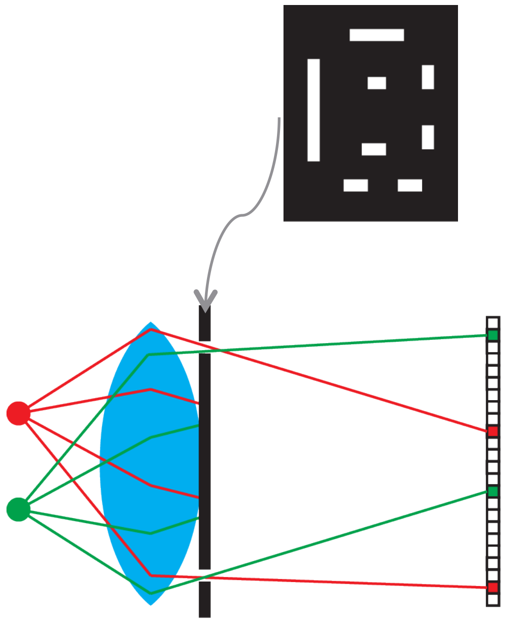


Aberration corrections



- Spiral PSF deconvolution can also remove known lens aberrations
- PSF diameter approximately 1/10th radius of illuminated grating pattern
- Convolution plus wrap-around

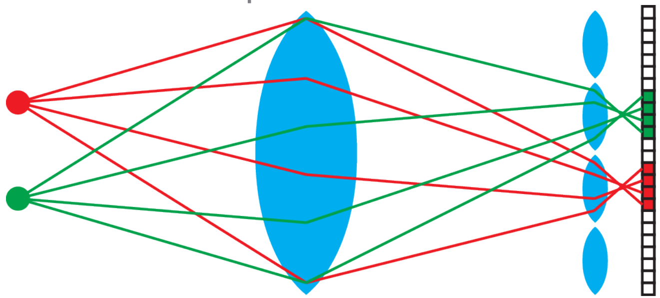
Comparison: coded aperture



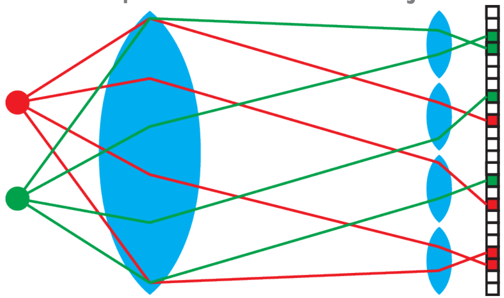
- Allow light only from certain coded regions of the lens
- PSF becomes scaled image of coded aperture
- To recover image, use similar techniques to spiral phase anti-symmetric camera
- Main drawback: light sensitivity

Comparison: plenoptic cameras

Plenoptic in focus



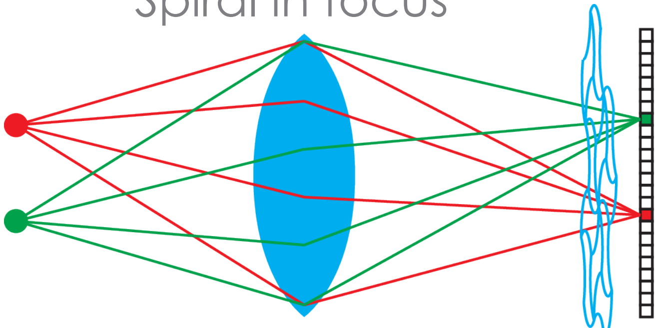
Plenoptic near object



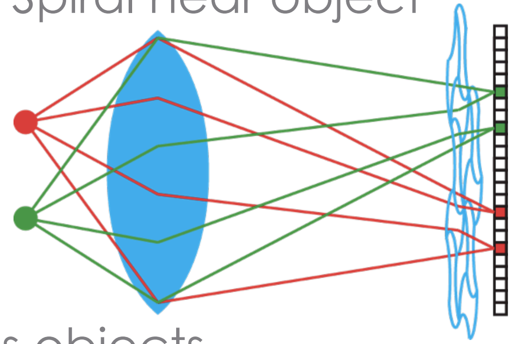
- Both have optical element close to image sensor
- Plenoptic cameras have resolution intermediate between the microlens pitch and the sensor pitch
- Limited NA of microlenses constrains form factor

No free lunch

Spiral in focus

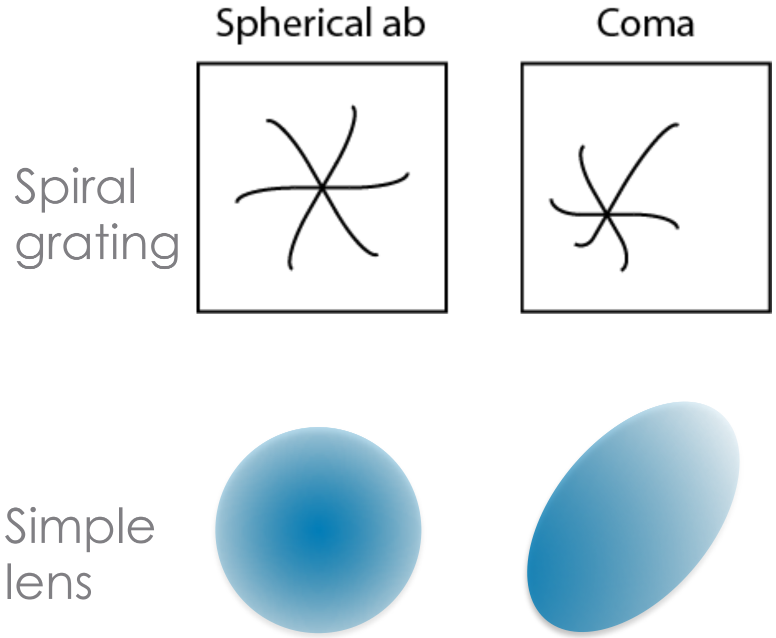


Spiral near object



- Deconvolution degrades SNR for out-of-focus objects
  - Approximately equivalent to a coded aperture
- Computation: perhaps 100 Gflops – 5 Tflops for video
- Spiral cameras use same data for range and image, so they can be fooled
  - Snowstorms and sparkles
  - In-focus images of maliciously-designed spiral patterns

Computationally correct for lens aberrations

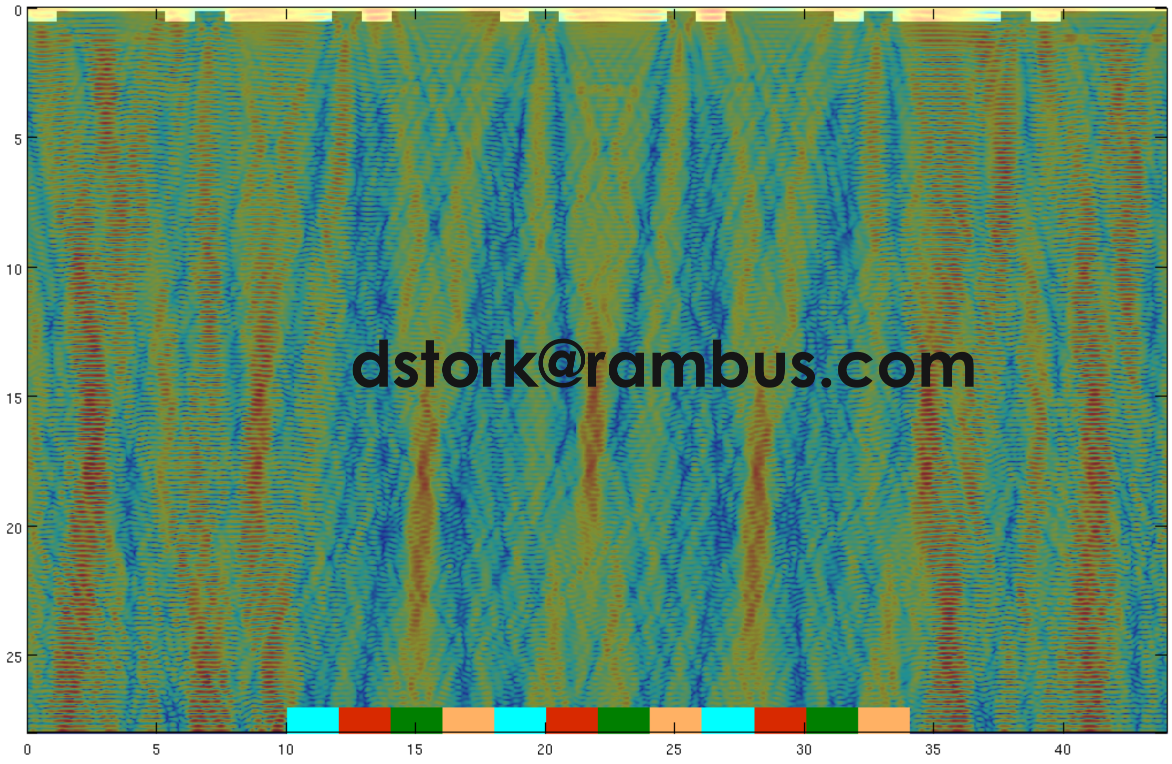


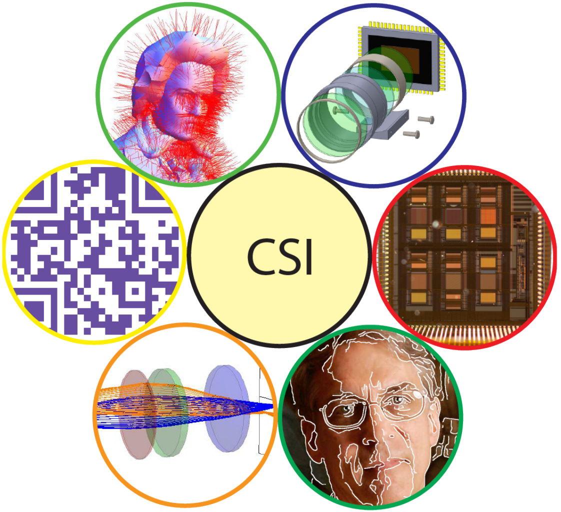
- Lens aberrations exist due to non-ideal (but sometimes optimal) lens shape
- In standard cameras, lens aberrations are minimized by complicated optics
- In our camera, aberrations warp the PSF, but the PSF is still invertible
- Our design can compensate for relatively large aberrations; may reduce system cost

Summary

- Introducing spiral phase anti-symmetric grating cameras
- Full (or close to full) resolution even for large defocus
- Better depth of field vs. low light performance than traditional cameras
- Better resolution and low-light performance than plenoptic cameras; less radical refocussing

Questions?





References

- "Phase gratings with odd symmetry for high-resolution lensless optical sensing," P. R. Gill and D. G. Stork, *OSA Computational Sensing and Imaging*, 2013
- "Digital camera with spiral odd-symmetry phase grating supports full-resolution computational refocusing," P. R. Gill and D. G. Stork, *OSA Sensors*, 2013
- "Odd-symmetry phase gratings produce optical nulls uniquely insensitive to wavelength and depth," P. R. Gill, *Applied Optics*, **38**(12):2074–2076, 2013
- "Lensless ultra-miniature CMOS computational imagers and sensors," D. G. Stork and P. R. Gill, *SensorComm 2013*

- *Supporting material to be available on Rambus.com in September*