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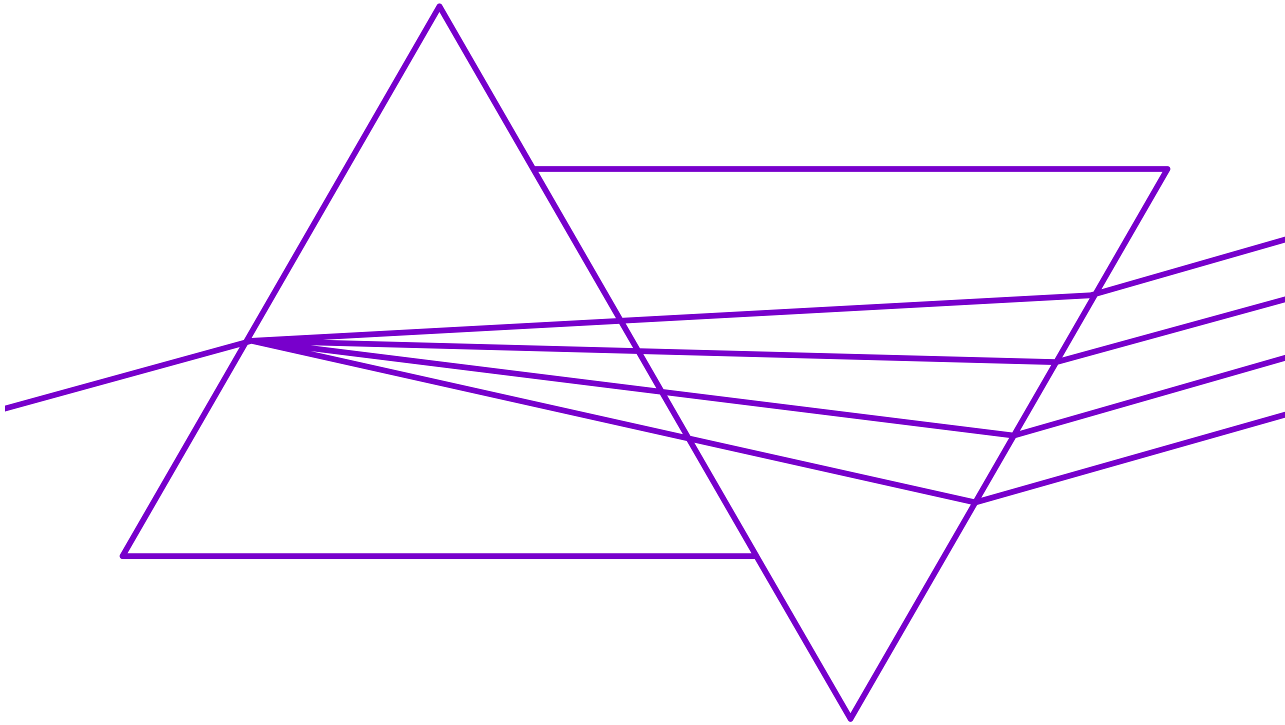
Advancing Optics and Photonics Worldwide

Technical Groups

Digital Holography with Single-Pixel Detection



Featuring Enrique Tajahuerce, Universitat Jaume I

14 December 2021

About Our Technical Group

Our technical group focuses on the design and implementation of holographic and diffractive-optic devices and systems for scientific, commercial, and other applications.

Our mission is to connect the 1000+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Digital Holographic Microscopy Techniques for Applications in Cytometry and Histology
- Structured Light with Digital Holograms
- Metasurface Holograms
- Real-Time Hologram Rendering from Optically-Acquired Interferograms

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/FH
- On LinkedIn at www.linkedin.com/groups/4826728
- On Facebook at www.facebook.com/groups/opticaholography
- Email us at TGactivities@optica.org

Today’s Speaker

Enrique Tajahuerce

Universitat Jaume I

Enrique Tajahuerce is an associate professor in the Department of Physics at Universitat Jaume I, Castelló, Spain. He has conducted his research at the Institute of New Imaging Technologies (INIT) there since 2010. He received his PhD in physics from Universidad de Valencia in 1998. He is co-author of more than 90 research papers and over 120 communications in international conference meetings. He has collaborated in the scientific committee and organization of international conferences sponsored by Optica, IEEE, and SPIE. In 2008, he received the IEEE Donald G. Fink Prize Paper Award. He is Fellow of Optica, Senior Member of SPIE and serves as topical editor for Optics Letters. Dr. Tajahuerce coordinates the Photonics Research Group (GROC·UJI) at University Jaume I. His research interests lie in the areas of diffractive optics, adaptive optics, optical security and encryption, digital holography, and computational imaging.

Digital holography with single-pixel detection

Enrique Tajahuerce

GROC·UJI, Institute of New Imaging Technologies (INIT), Universitat Jaume I, Castelló, Spain

The Photonics Research Group

GROC UJI
Photonics Research Group

UNIVERSITAT JAUME I

init
institute of new imaging technologies

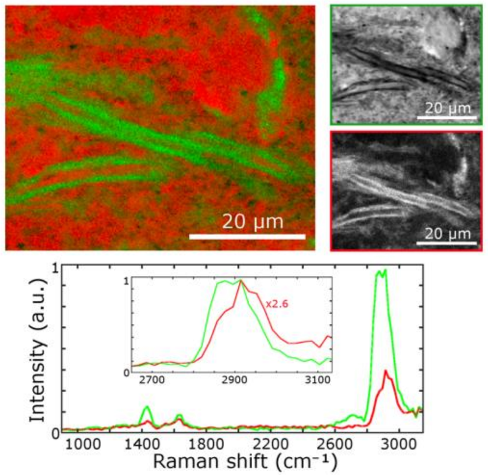
Research group

Jesús Lancis , Pedro Andrés, Vicent Climent,
Enrique Tajahuerce, Gladys Mínguez-Vega,
Lluís Martínez-León, Omel Mendoza, Pere Clemente,
Dani Torrent, Vicente Durán, Armin Lenz, Marc Martí,
Erick Ipus, Luis Ordóñez, Sergio Fernández, Francis Rey

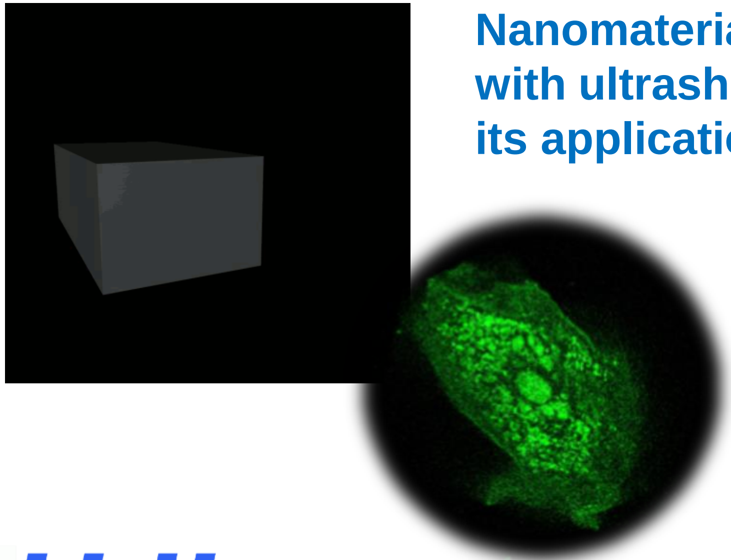
https://www.init.uji.es

@photonicsuji

Computational imaging and holography with structured illumination



Nanomaterial synthesized with ultrashort lasers and its applications



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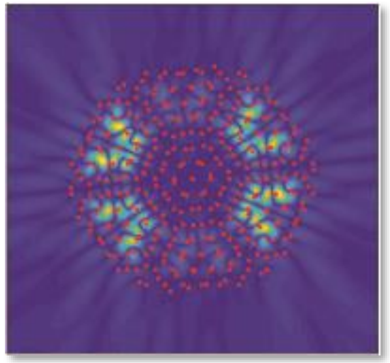
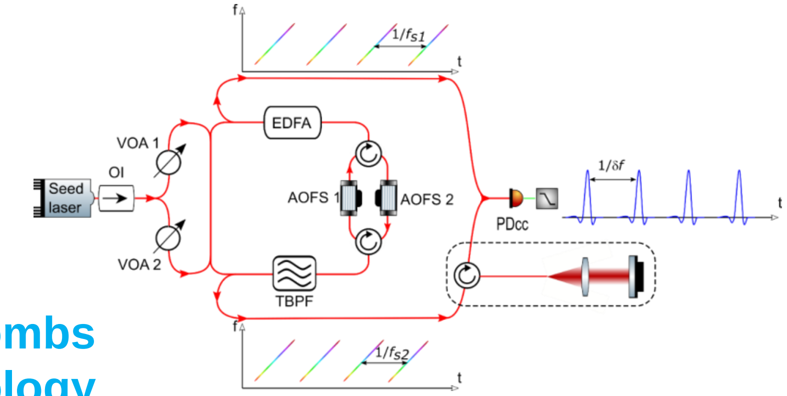
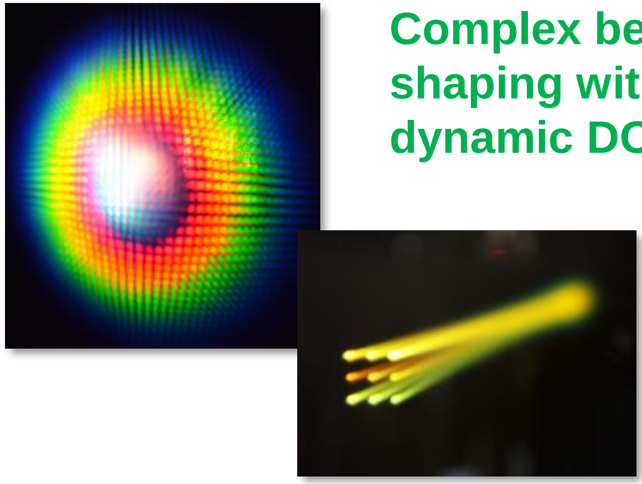
Control of the vibrational energy localized in thin elastic plates





Optical frequency combs for optical metrology applications



Complex beam shaping with dynamic DOEs

Outline

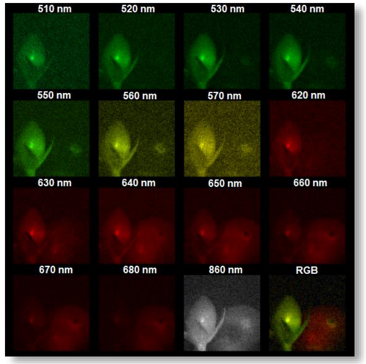
Description of **computational imaging techniques based on single-pixel detection** with microstructured illumination and compressive sensing.

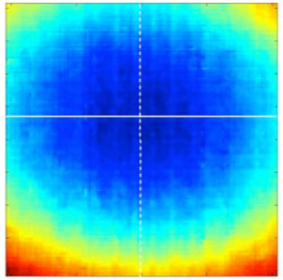
Application on **complex (amplitude and phase) imaging** with interferometric and non interferometric approaches.

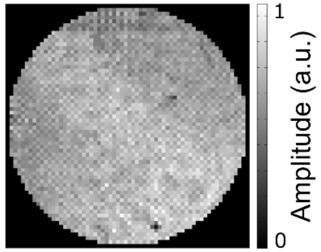
1. **The single-pixel camera**
2. **Multispectral imaging**
3. **Complex amplitude imaging**

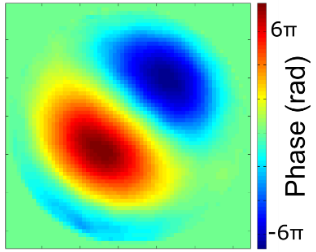
   Non-interferometric setups

   Interferometric setups



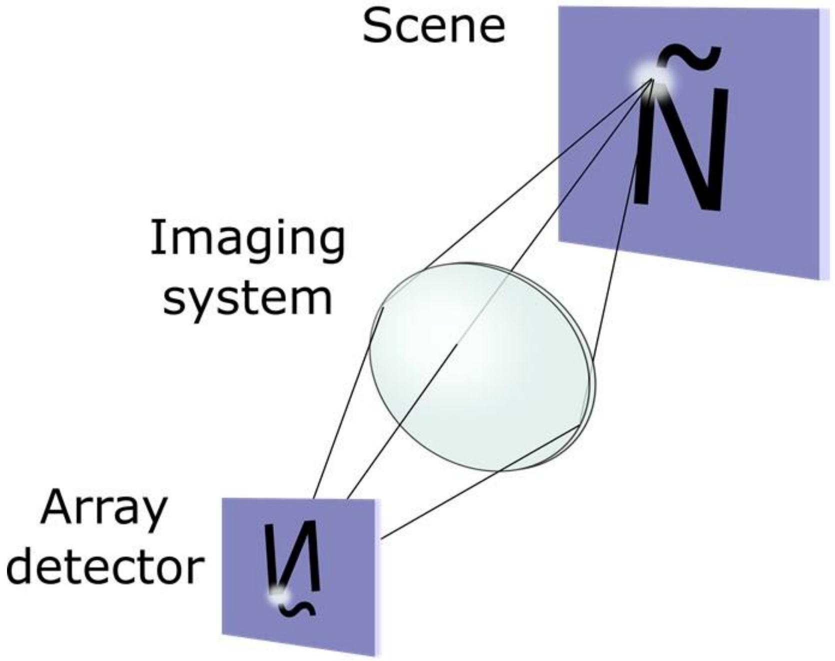






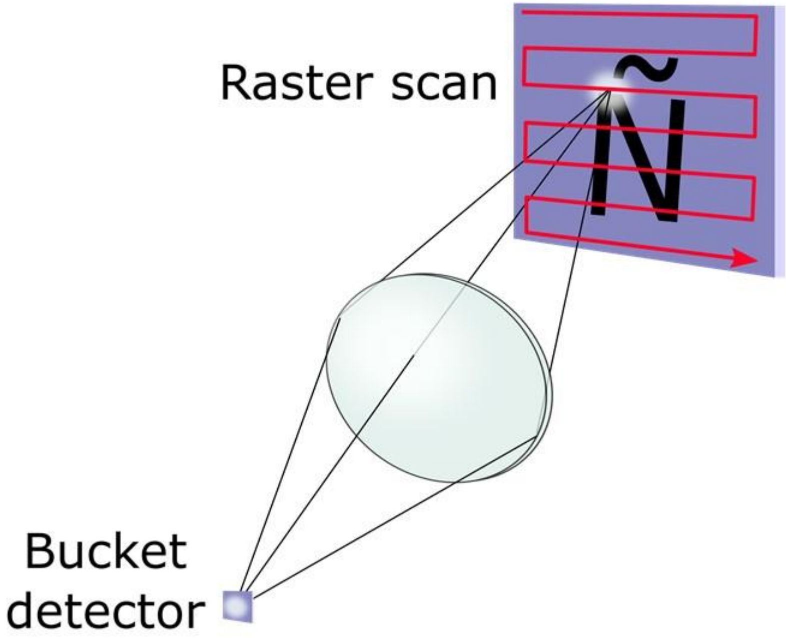
The single pixel camera

Conventional imaging

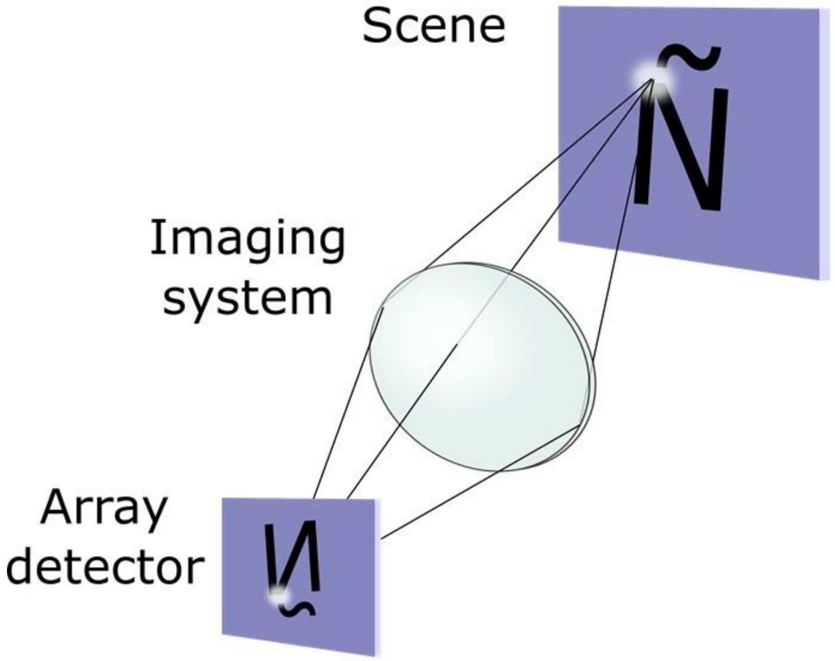


The single pixel camera

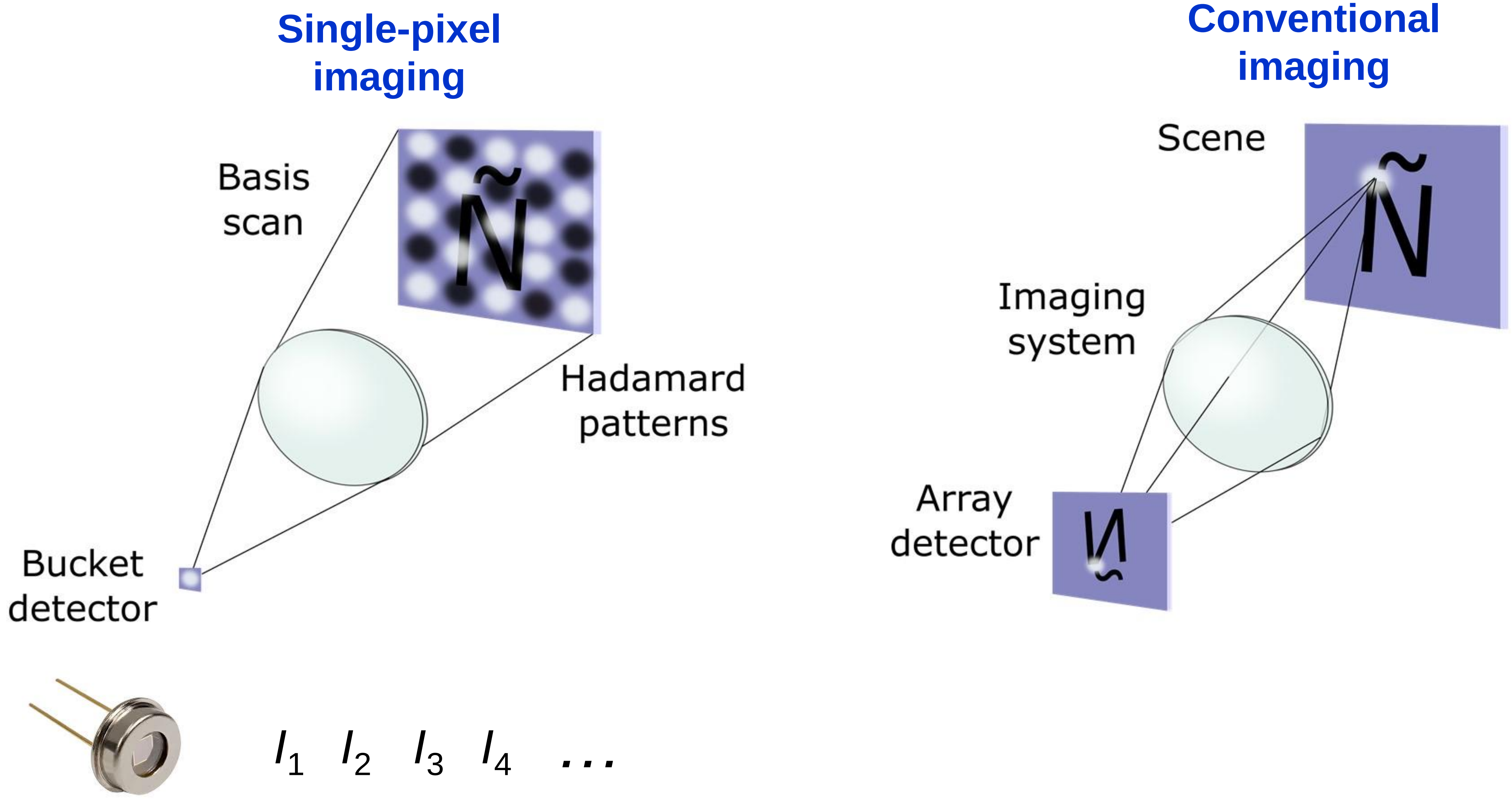
Raster scanning approach



Conventional imaging



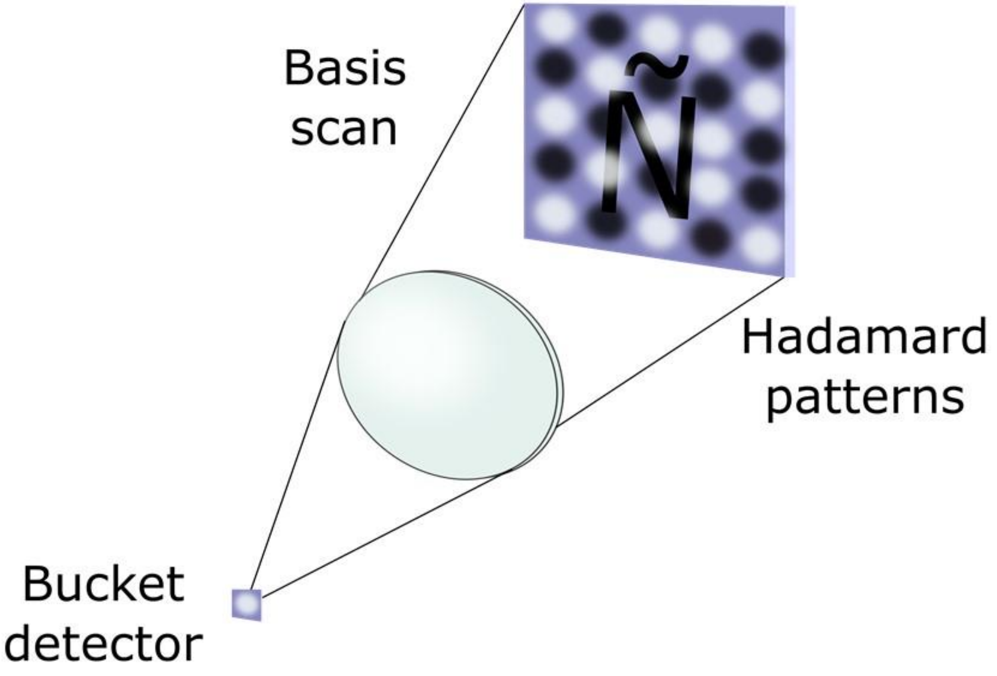
The single pixel camera



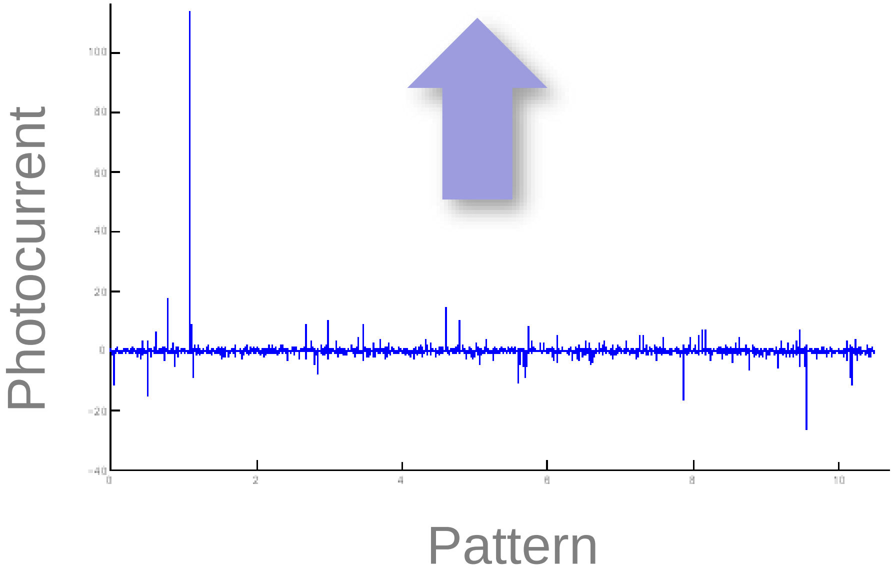
$I_1 \quad I_2 \quad I_3 \quad I_4 \quad \ldots$

The single pixel camera

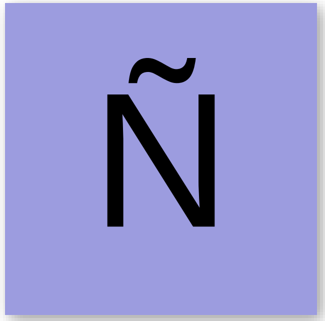
Single-pixel imaging



$I_1 \quad I_2 \quad I_3 \quad I_4 \quad \ldots$



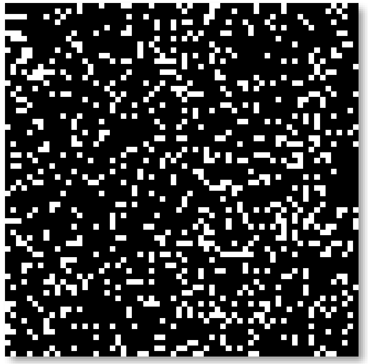
$$O(x,y) = \sum_{p=1}^{M} I_p \cdot H_p(x,y)$$



Sensing patterns

Random patterns

Binary or gray-level random patterns



Similar to
ghost imaging

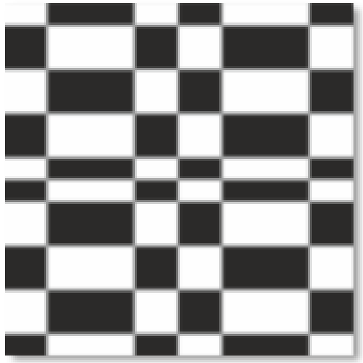
Deterministic patterns

Complete basis of functions such as:

Discrete Fourier

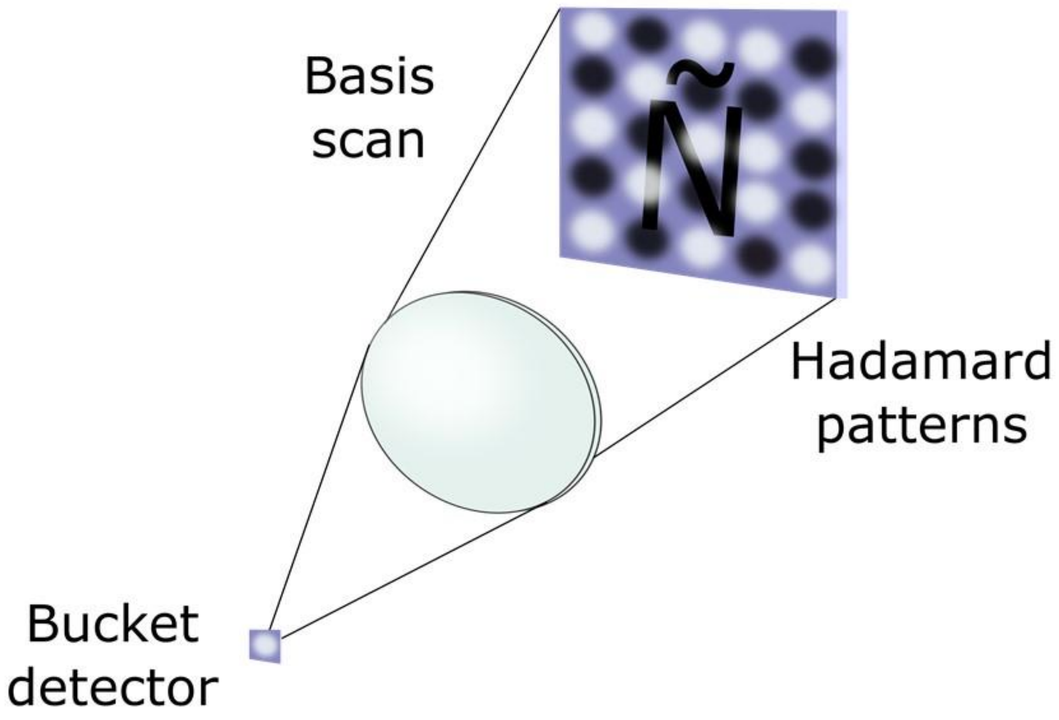
Discrete Cosine

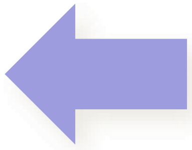
Walsh-Hadamard



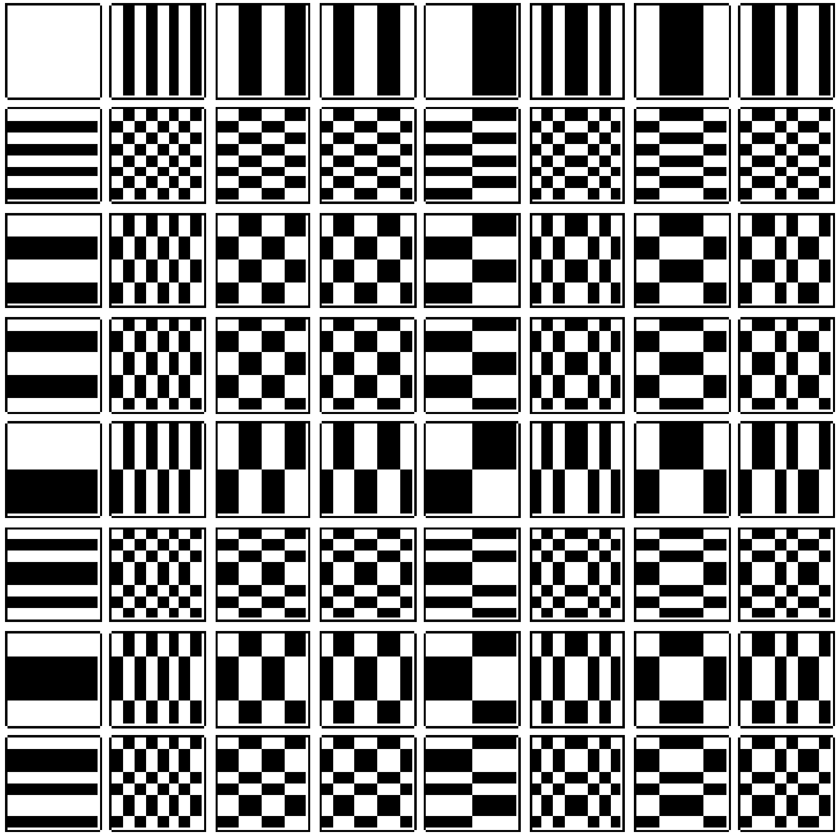
The single pixel camera

Sensing patterns





Matrix basis $\{+1, -1\}$



The single pixel camera

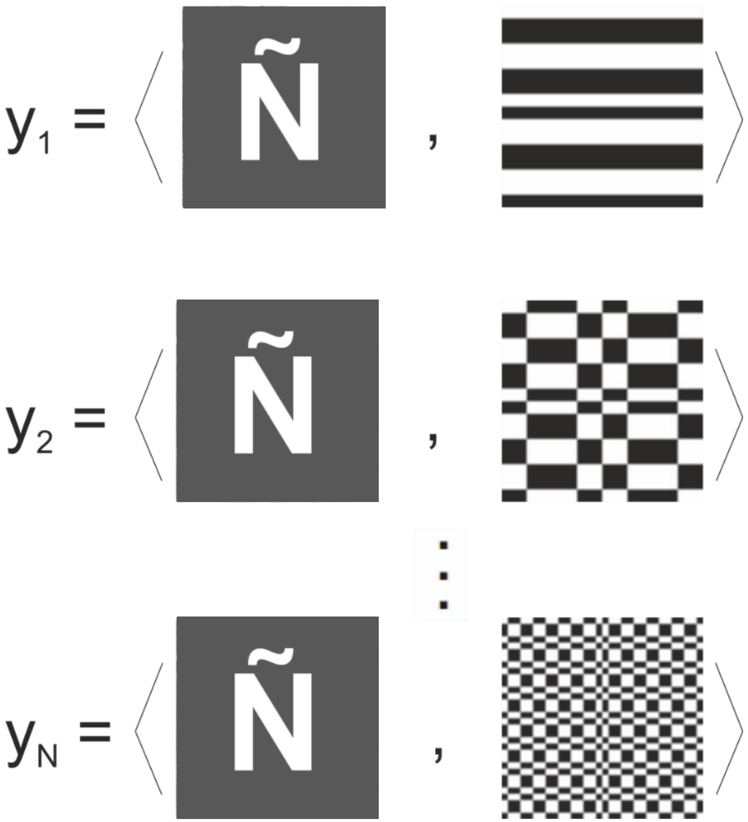
Sample

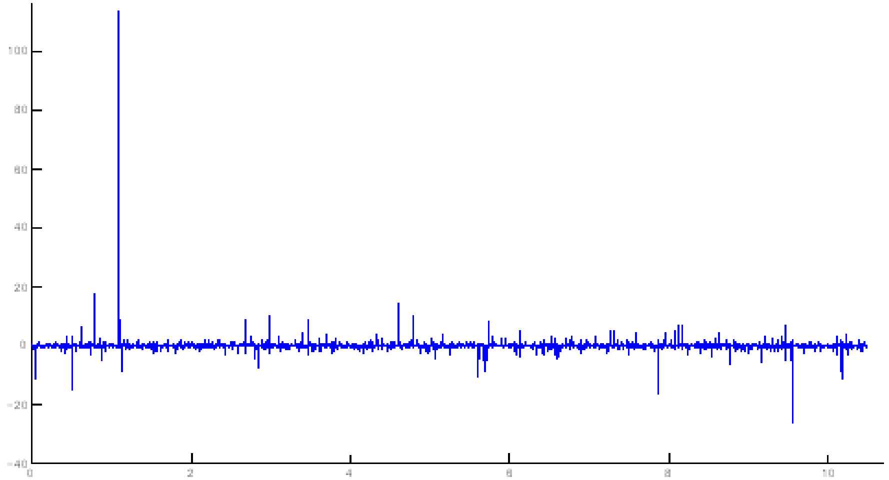
$O(x,y)$

N pixels

Projections with

$H_p(x,y)$



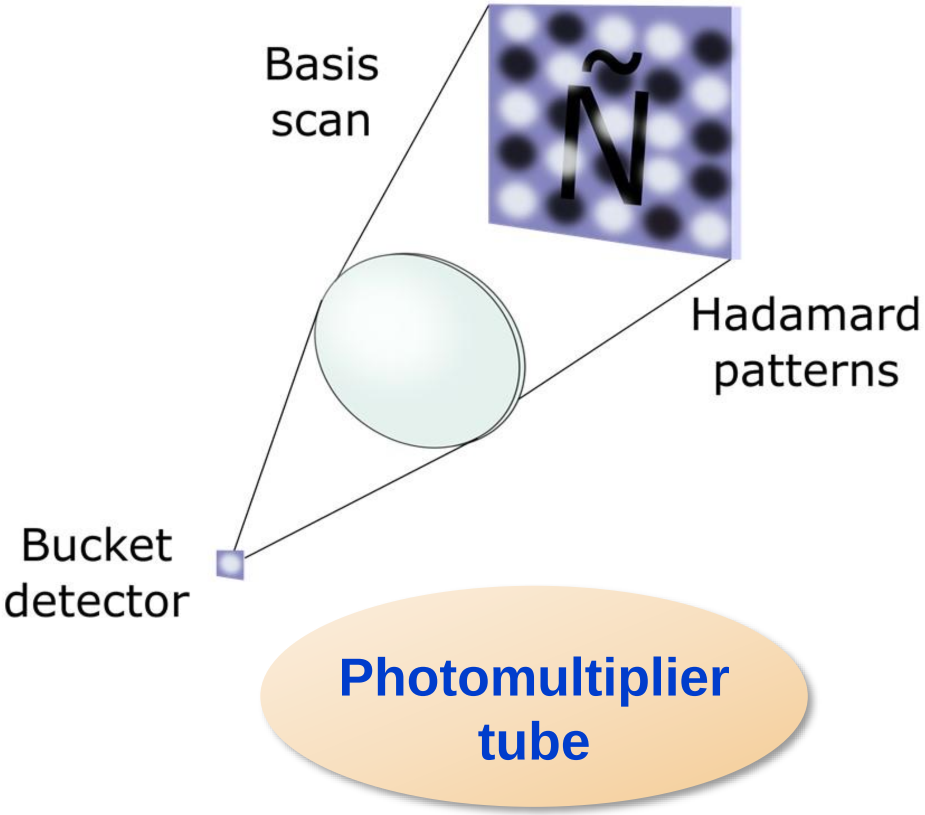


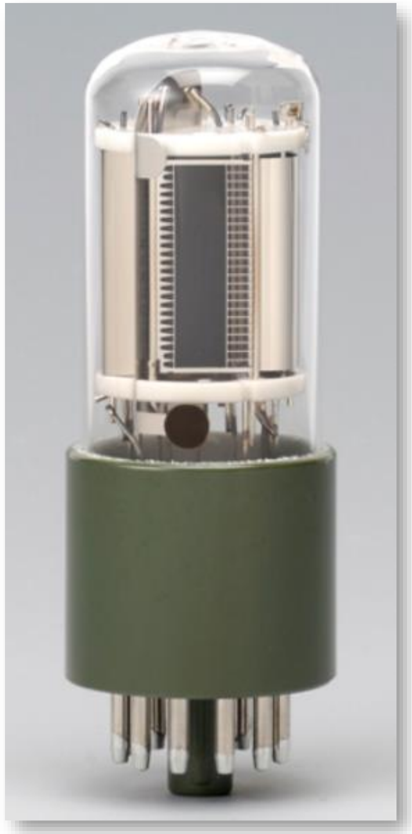
Inverse Hadamard transform

The single pixel camera

Advantages

Single-pixel detection can be more **efficient** and less expensive when light is scarce





The single pixel camera

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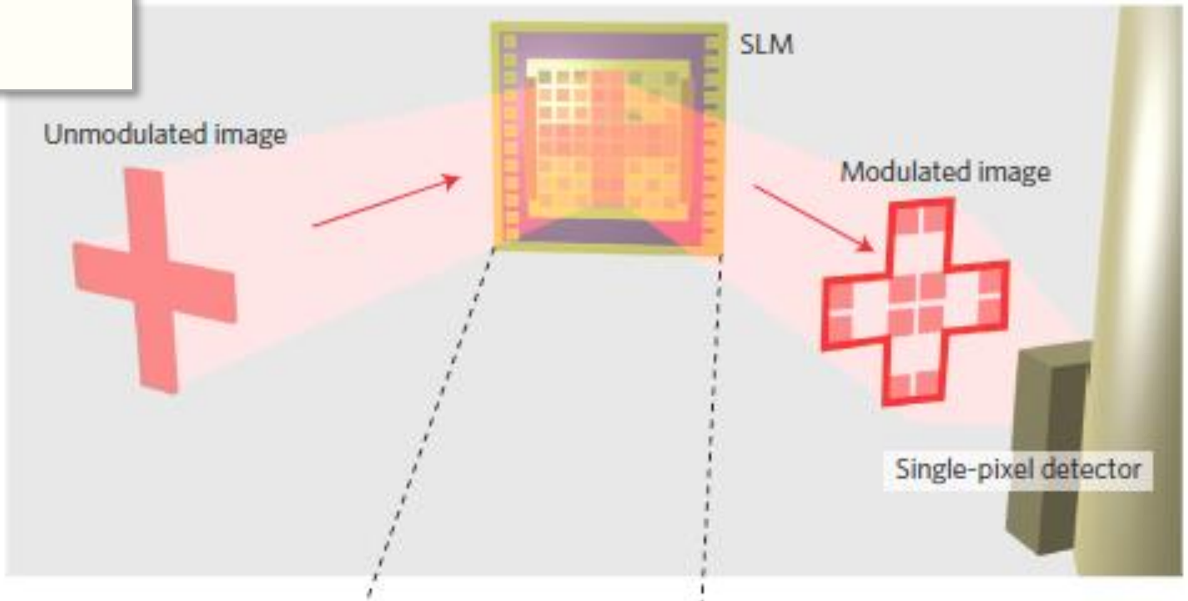
Advantages

Pixels are not cheap **when light is out of visible range**

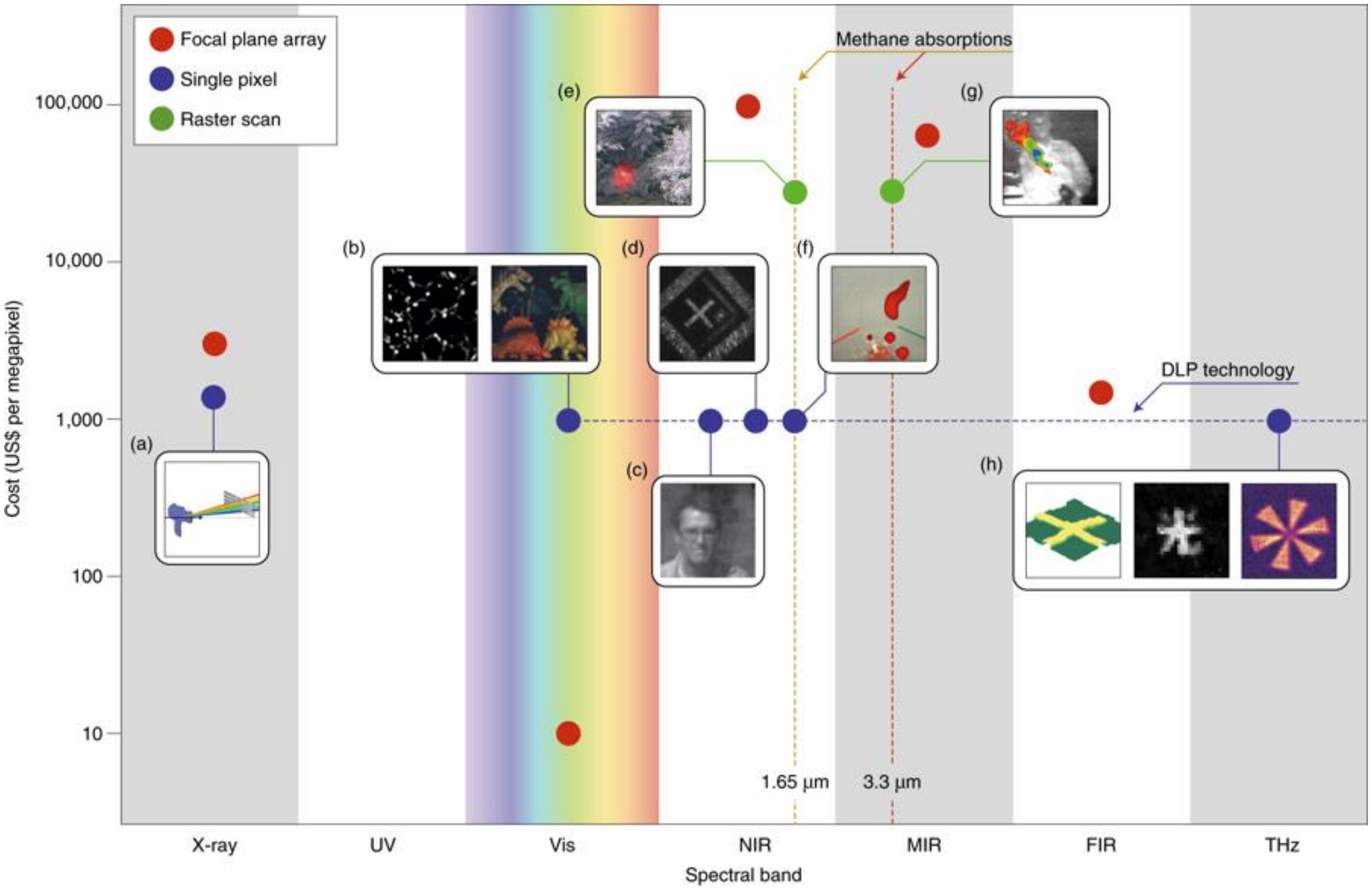
nature photonics | LETTERS
PUBLISHED ONLINE: 29 JUNE 2014 | DOI: 10.1038/NPHOTON.2014.139

Terahertz compressive imaging with metamaterial spatial light modulators

Claire M. Watts[1], David Shrekenhamer[1], John Montoya[2], Guy Lipworth[3], John Hunt[3], Timothy Sleasman[1], Sanjay Krishna[2], David R. Smith[3] and Willie J. Padilla[1]*



The single pixel camera




nature photonics

Review Article | Published: 03 December 2018

Principles and prospects for single-pixel imaging

Matthew P. Edgar, Graham M. Gibson & Miles J. Padgett

Nature Photonics **13**, 13–20 (2019) | Download Citation

Advantages

Single-pixel detectors can have **timing resolutions approaching picoseconds**

April 1987 / Vol. 12, No. 4 / OPTICS LETTERS 239

Coherent laser radar at 1.06 μm using Nd:YAG lasers

Thomas J. Kane,* W. J. Kozlovsky, and Robert L. Byer

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

Charles E. Byvik

NASA Langley Research Center, Hampton, Virginia 23665

Received December 16, 1986;

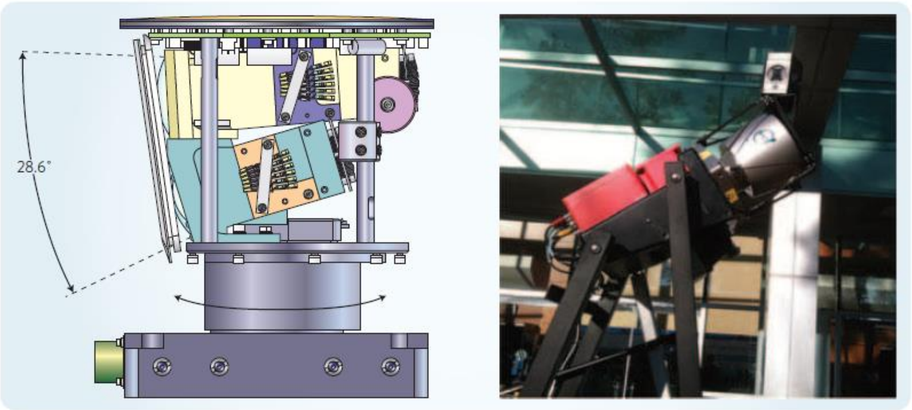
A coherent laser radar system operating at the 1.06-μm Nd:YAG laser wavelength has been built and operated. A laser-diode-pumped monolithic ring laser served as the master oscillator. A single flash-lamp-pumped zigzag slab amplified the oscillator output to a power of 2.3 kW. Single-mode optical fiber was used to collect and mix the return signal with the local-oscillator output. Signals from clouds at a range of 2.7 km and from atmospheric aerosols at a range of 600 m were detected.

LIDAR

Mapping the world in 3D

Brent Schwarz

NATURE PHOTONICS | VOL 4 | JULY 2010 | www.nature.com/naturephotonics



VELODYNE

Internal (left) and external (right) views of Velodyne's high-definition LIDAR. The sensor features a total of 64 semiconductor lasers and matched detectors, arranged into two sets (upper and lower) of linear arrays. The sensor head is spun at high speed during data collection to give the LIDAR system a complete 360° field-of-view.

Drawbacks

The light scanning process takes time

Image reconstruction process may require time

Solution

Use fast spatial light modulators for light structured illumination

Use efficient algorithms for image reconstruction

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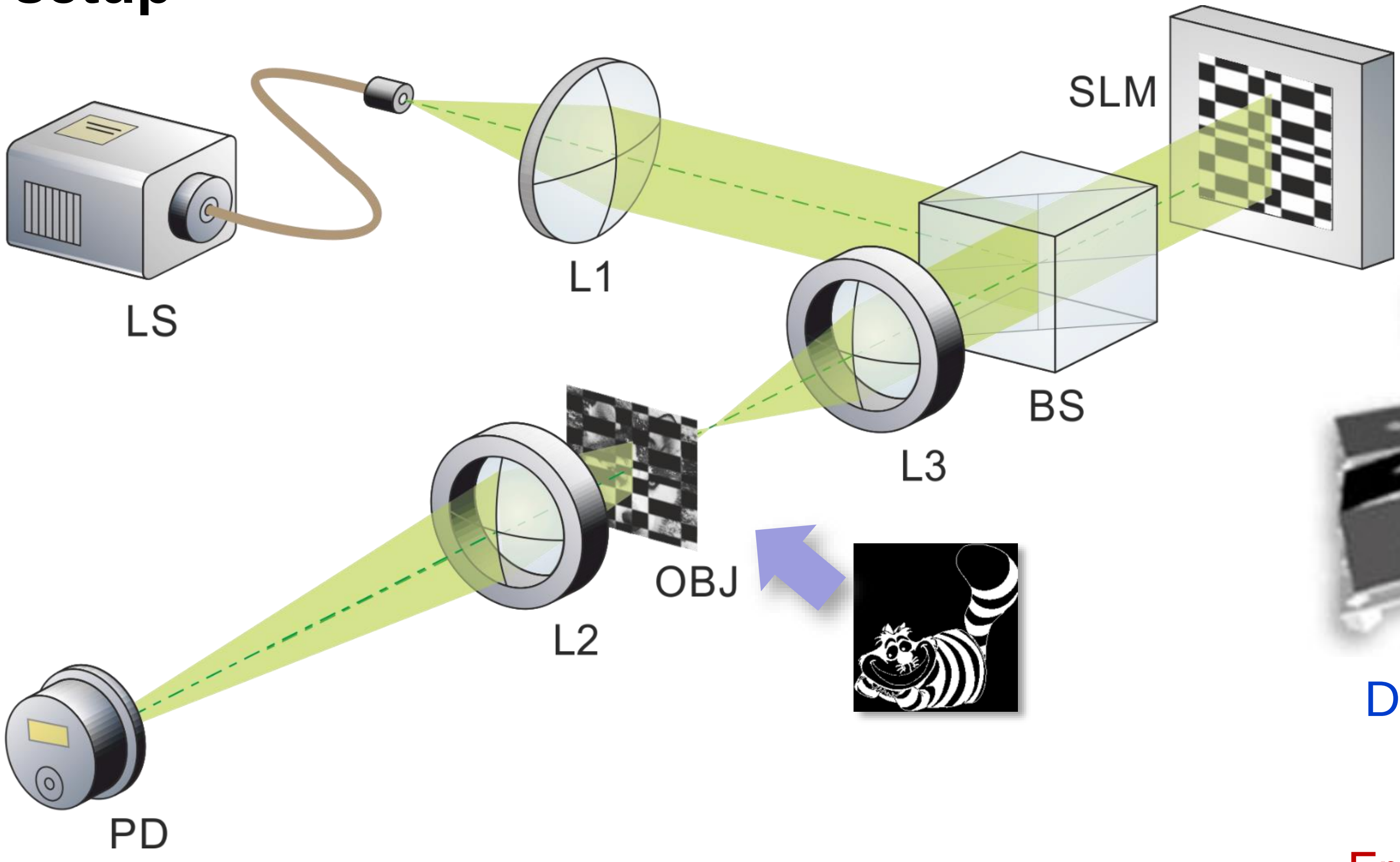
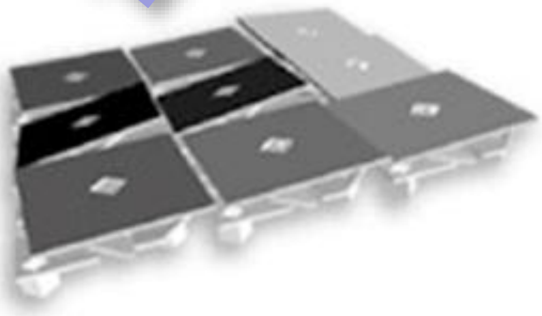
Experimental setup

Light source

Spatial light modulator





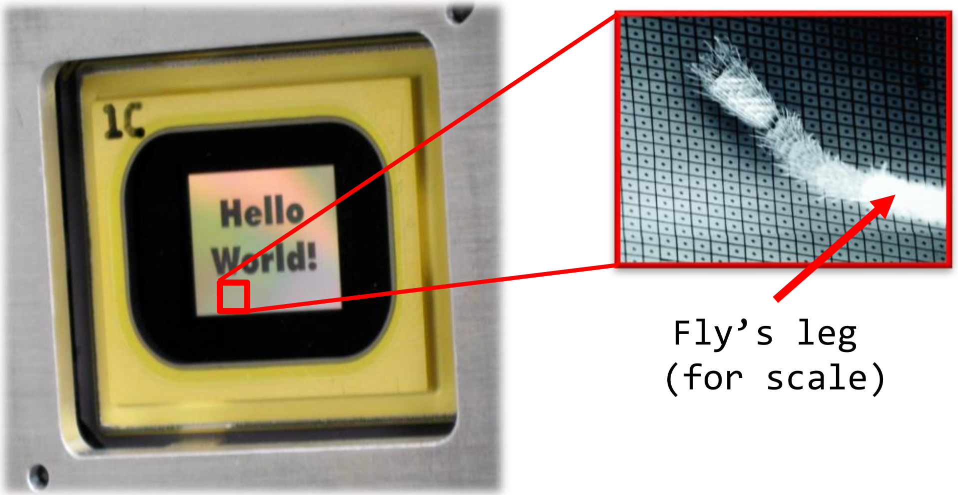
Light sensor

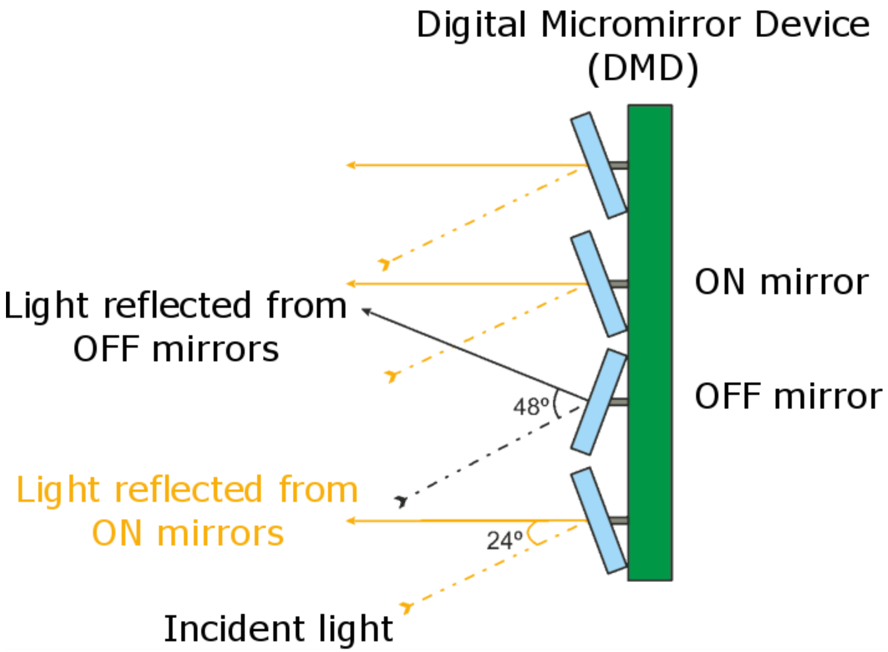
Digital micromirror device (DMD)

Frame rate ≤ 35 kHz

The single pixel camera

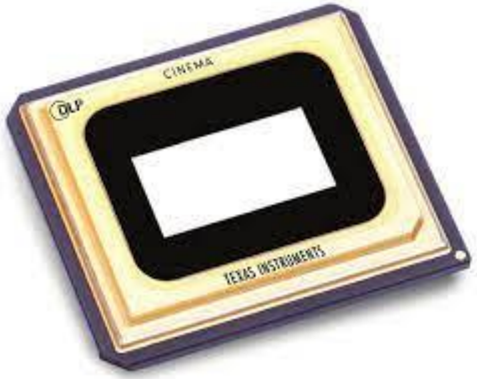
Digital micromirror device (DMD)



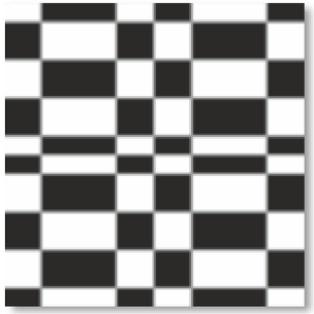


- Array of micrometric (~10 µm) mirrors with two possible orientations
- Fast refresh rate (~35 kHz)
- Binary intensity modulation

The single pixel camera

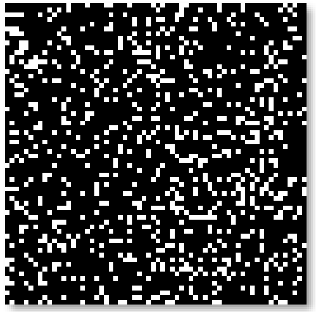


Algorithms



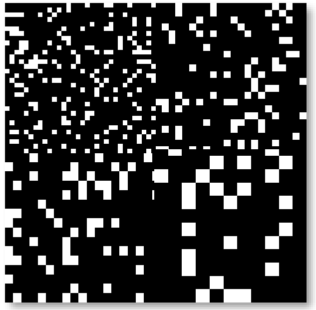
- Basis scan

Number of measurements equal to the number of pixels



- Compressive sensing or matrix completion

Number of measurements reduced to 10 – 20 %



- Adaptive algorithms

Number of measurements reduced by adapting the patterns to the image

Single-pixel camera with CS

Sample

$O(x,y)$

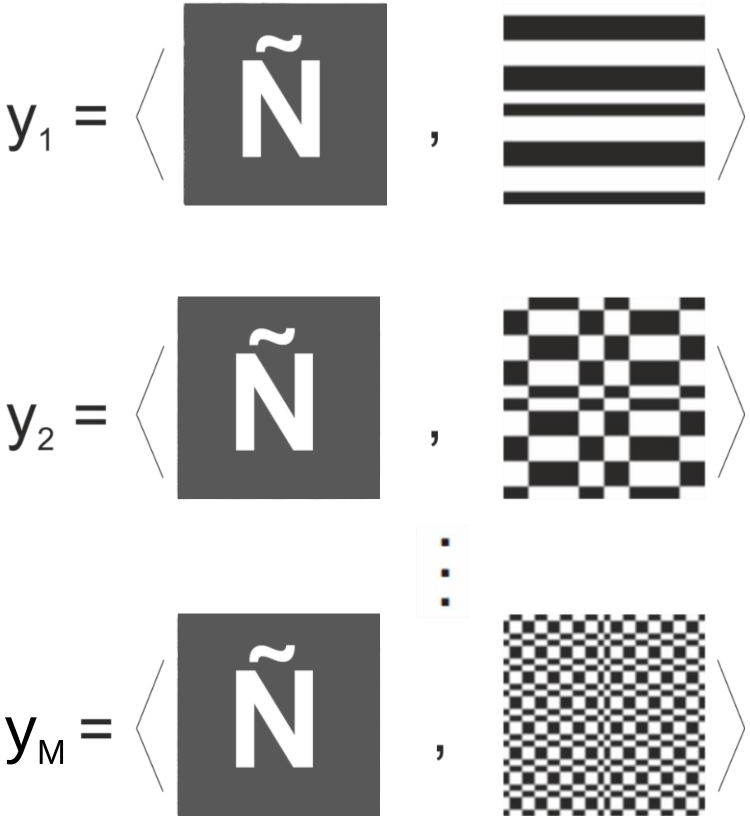
N pixels

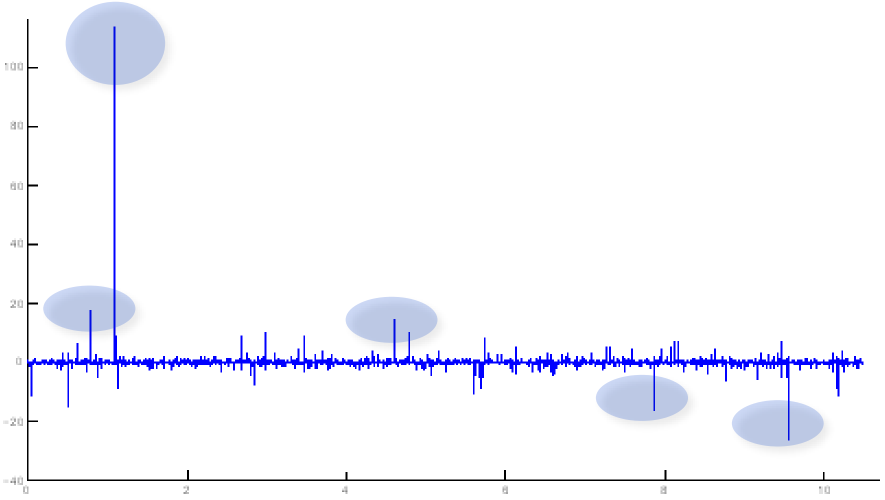
M measurements

M < N

Projections with

$H_p(x,y)$





S-sparse signal

Single-pixel camera with CS

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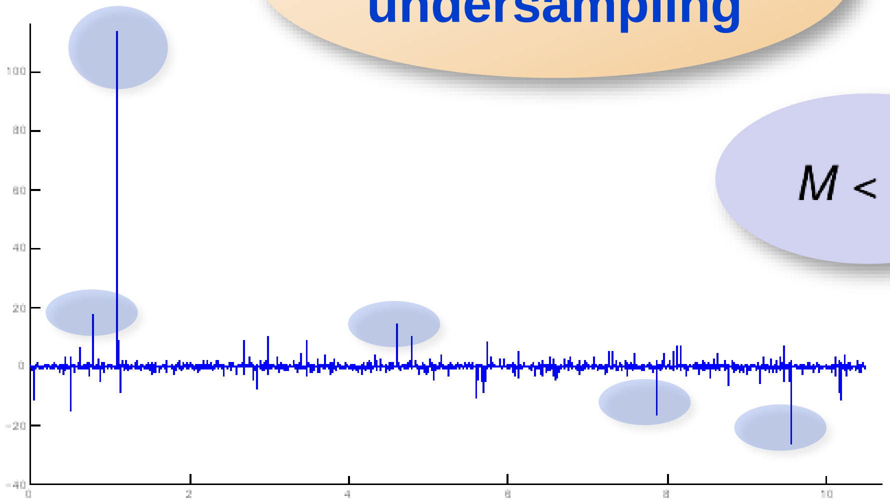
Sample

$O(x,y)$

N pixels

Random undersampling



$M < N$

Compressive algorithms

L1-magic, GSPR, or TwIST

The single pixel camera

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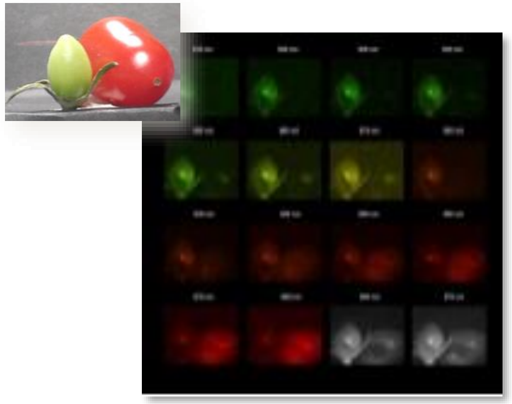
Multidimensional cameras

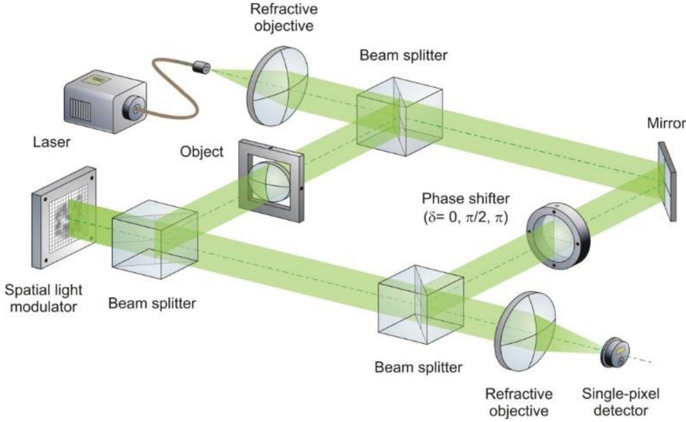


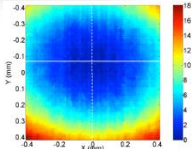
Microscopy

Ophthalmoscope

Imaging through scattering

Holographic cameras





Outline

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Photonics Research Group

Description of **computational imaging techniques based on single-pixel detection** with microstructured illumination and compressive sensing.

Application on multispectral imaging and **complex (amplitude and phase) imaging** with interferometric and non interferometric approaches.

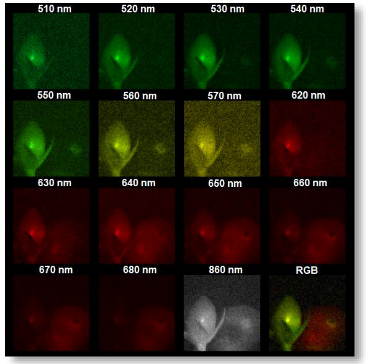
1. **The single-pixel camera**

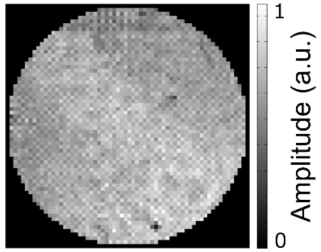
2. **Multispectral imaging**

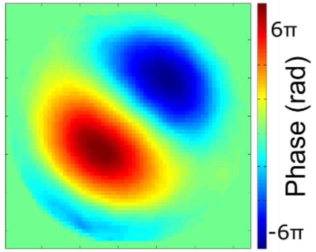
3. **Complex amplitude imaging**

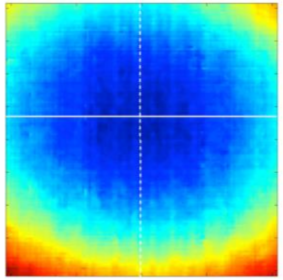
   Non-interferometric setups

   Interferometric setups





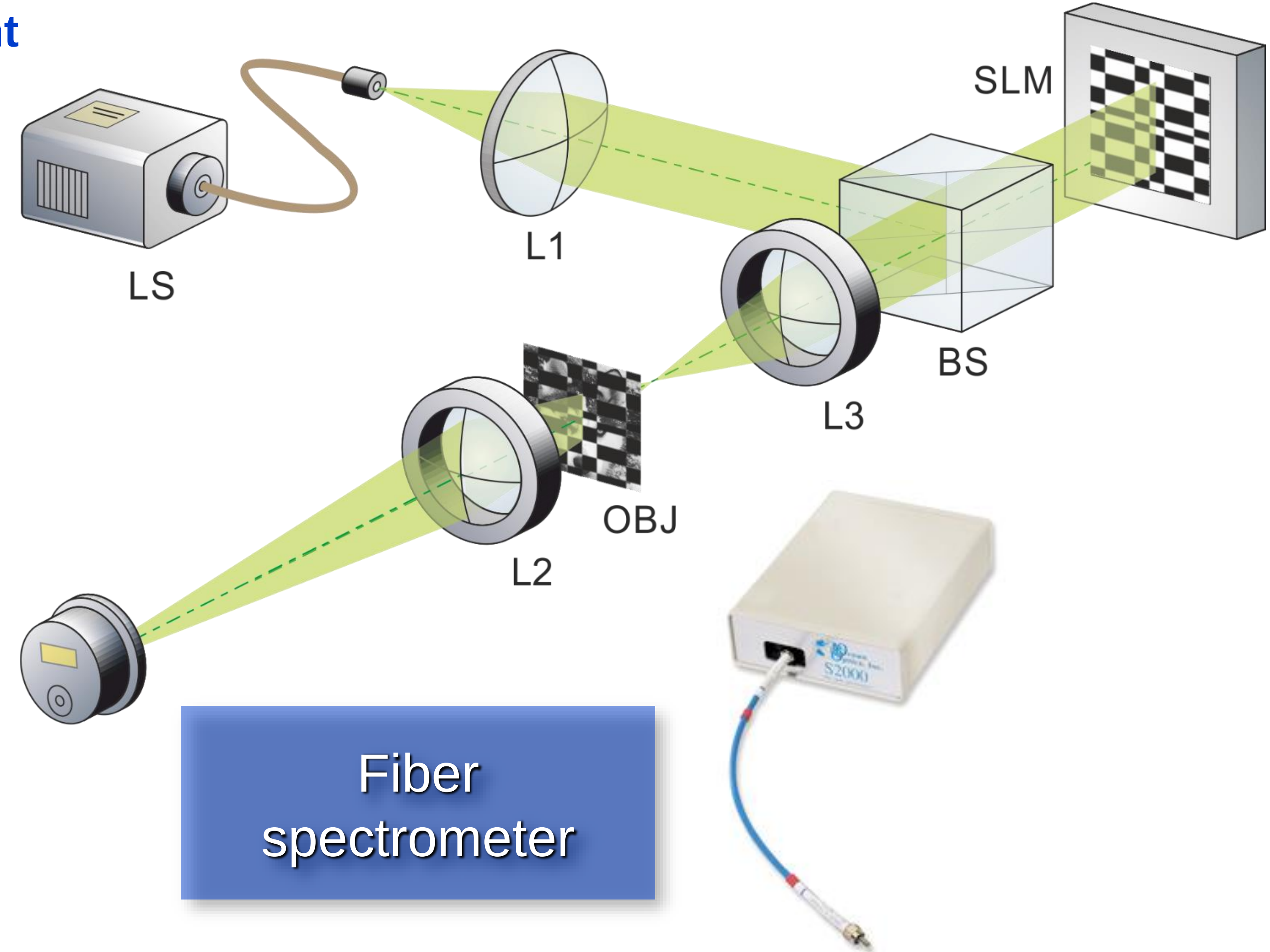




Multidimensional imaging

White-light source

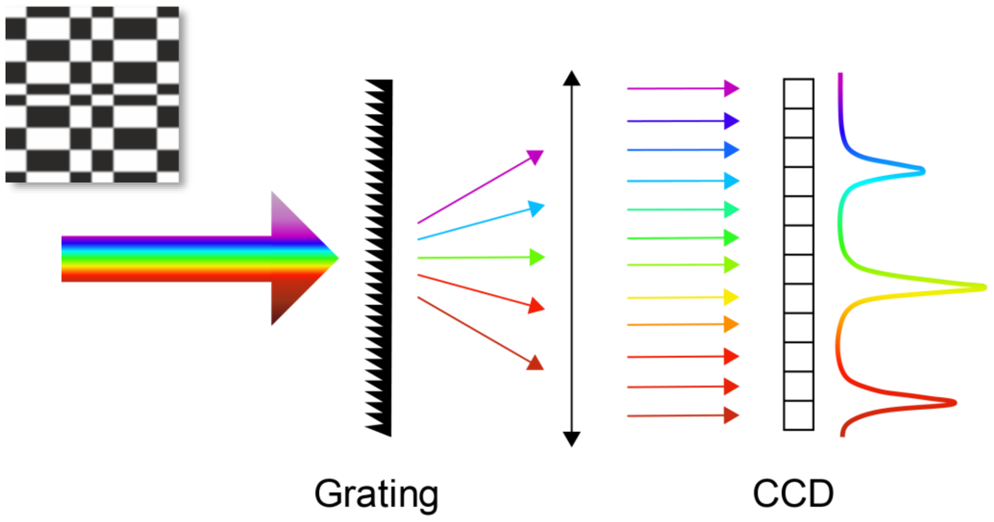
Spatial light modulator



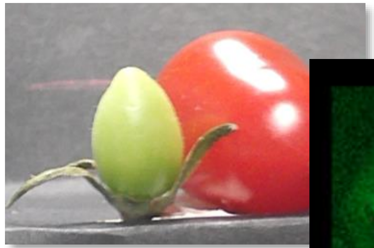
Fiber spectrometer

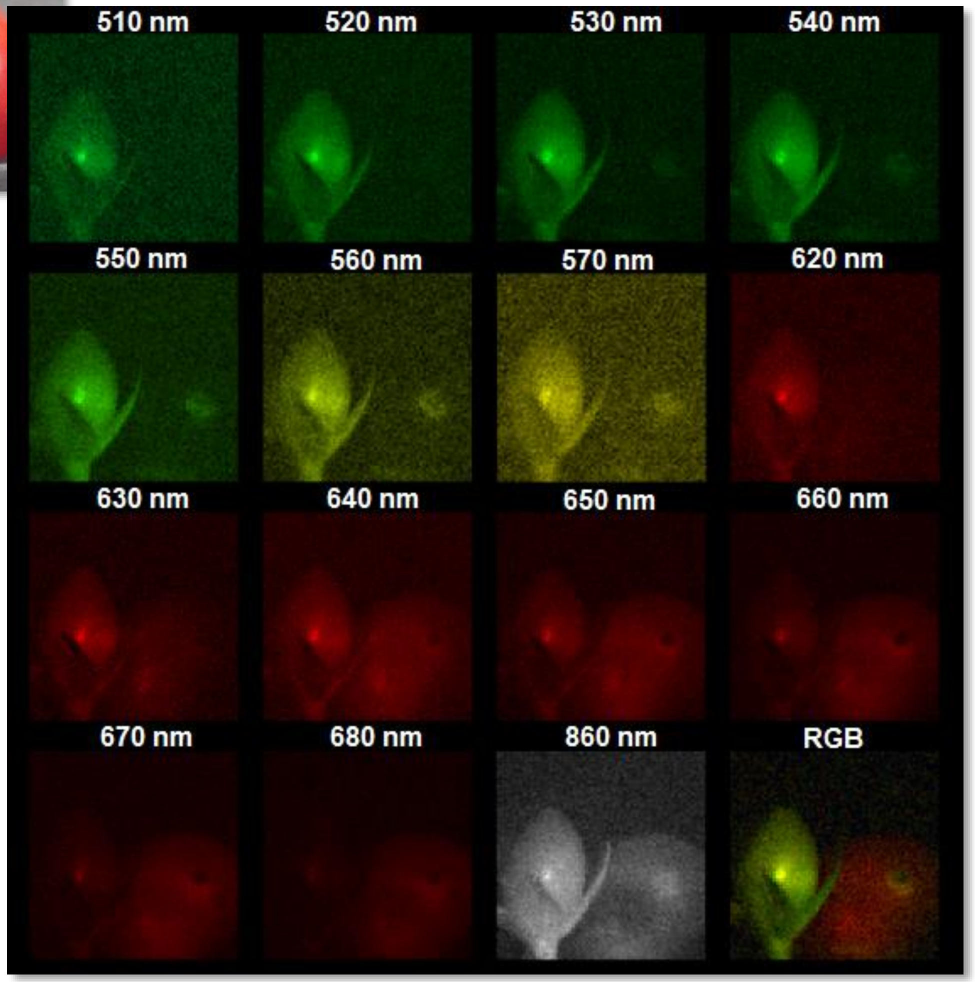
Multispectral imaging

Conventional spectrometer



- Single-shot
- CCD/CMOS based detector

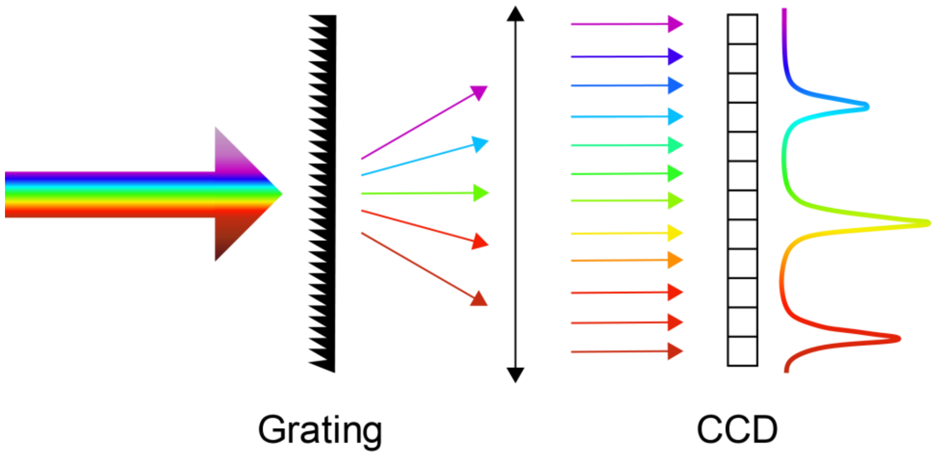




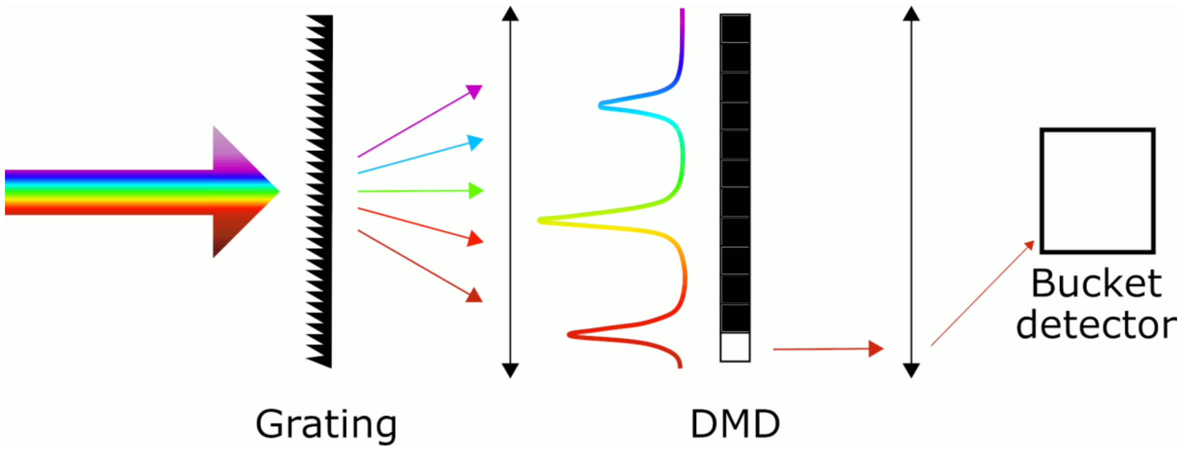
Fernando Soldevila et al, *Appl. Phys. B* (2013)

Multispectral imaging

Conventional spectrometer



Single-pixel spectrometer

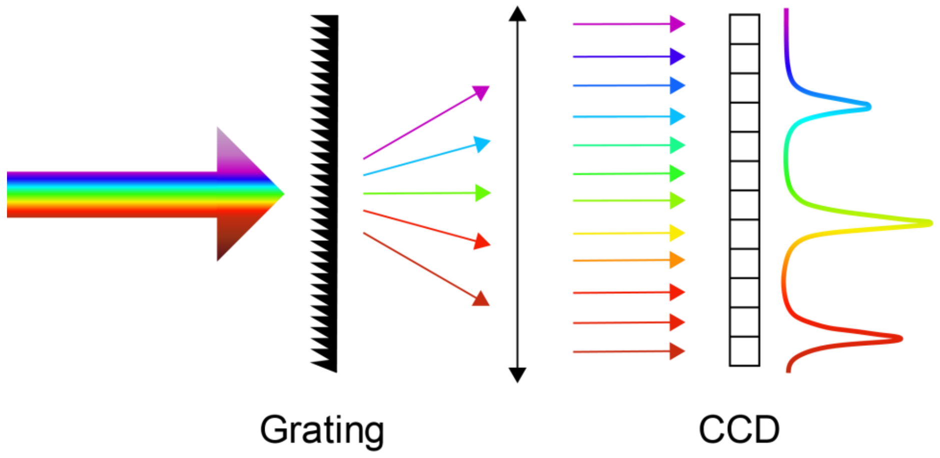


- Single-shot
- CCD/CMOS based detector

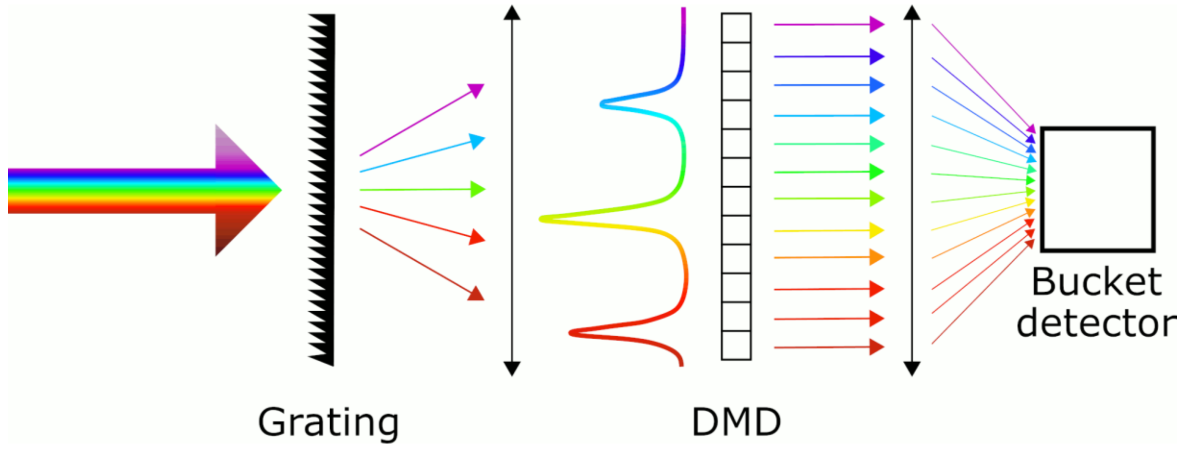
- Sequential measurement
- Single-pixel (PMT, SPAD, etc.)
- Programmable (CS, ML, MC, etc.)

Multispectral imaging

Conventional spectrometer



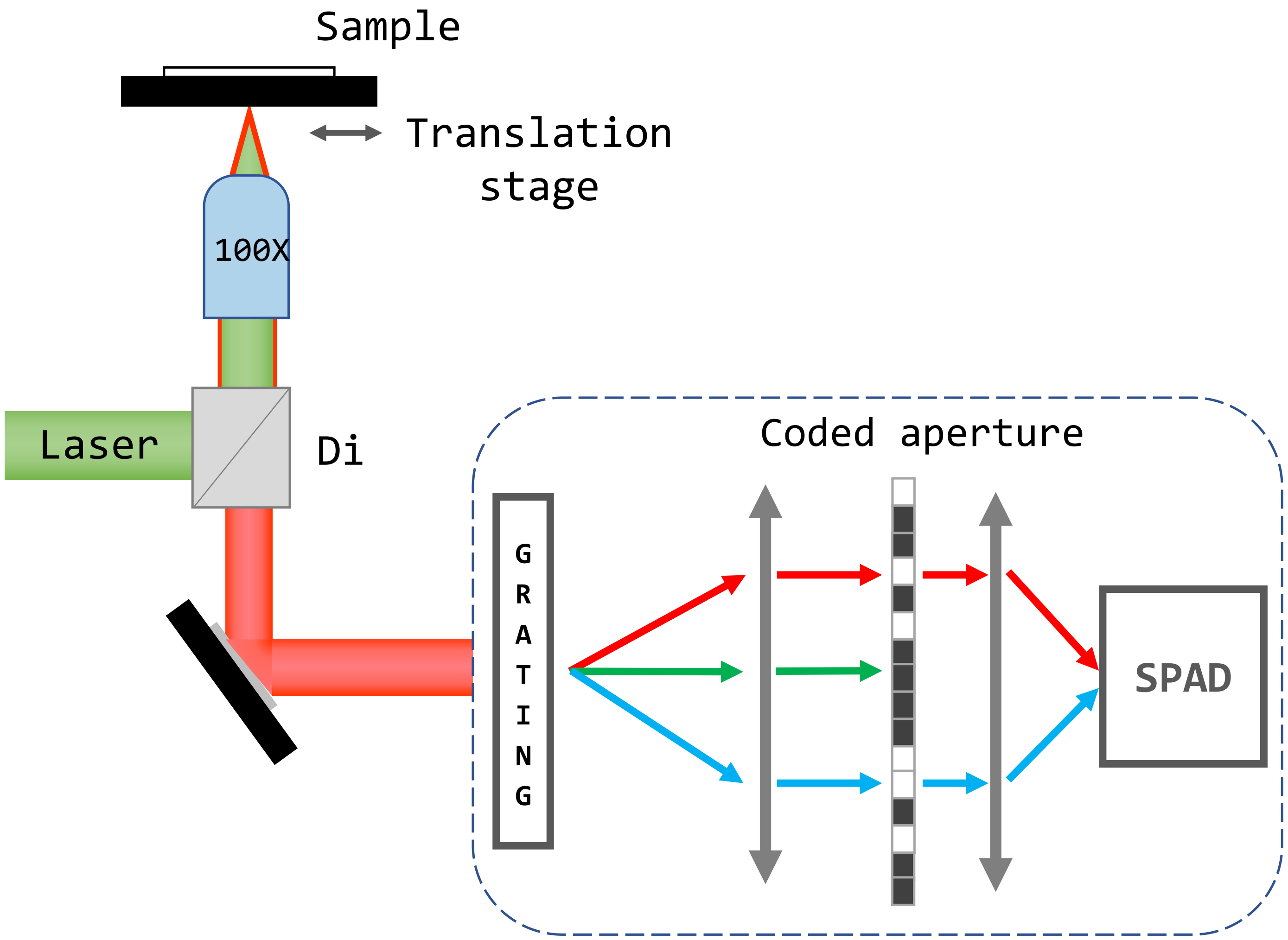
Single-pixel spectrometer

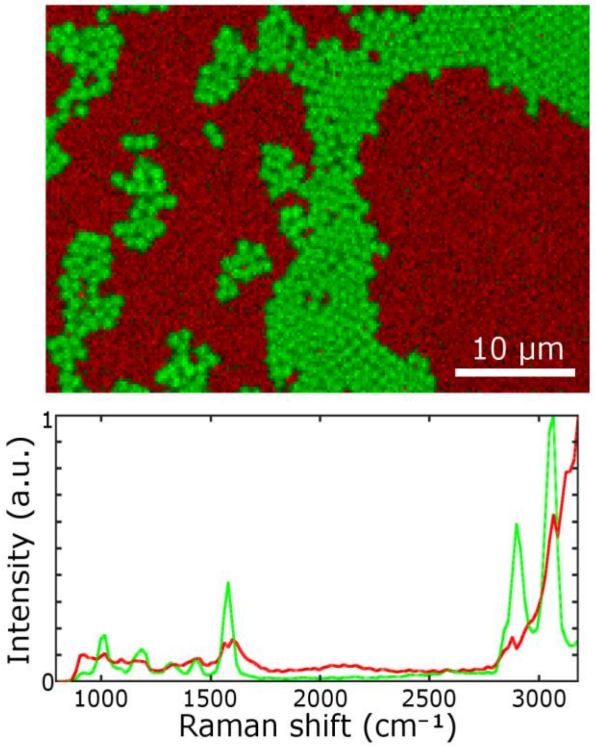


- Single-shot
- CCD/CMOS based detector

- Sequential measurement
- Single-pixel (PMT, SPAD, etc.)
- Programmable (CS, ML, MC, etc.)

Raman imaging via matrix completion



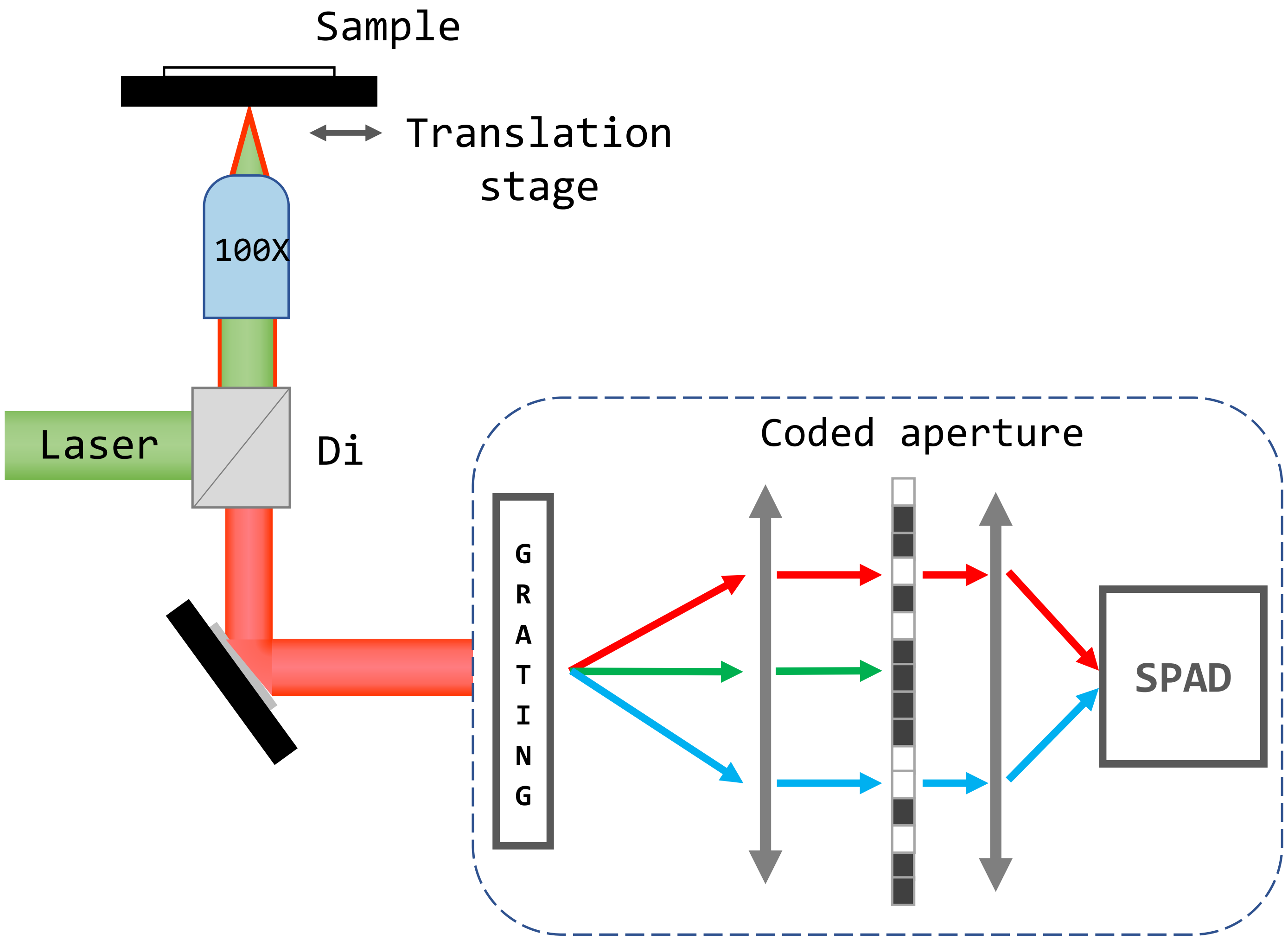


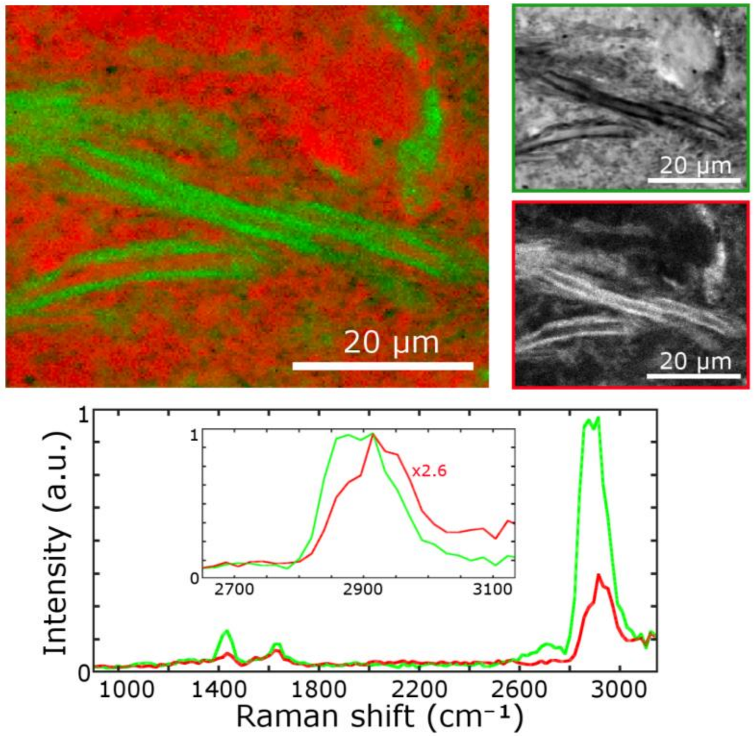
Polystyrene beads suspended in ***water***

(66% compression, 8 ms pixel dwell time)

F. Soldevila, J. Dong, E. Tajahuerce, S. Gigan, H. B. de Aguiar, *Optica* (2019)

Raman imaging via matrix completion





Myelin-rich tubular structures and ***protein-rich axons*** in a brain slice

(42% compression, 20 ms pixel dwell time)

F. Soldevila, J. Dong, E. Tajahuerce, S. Gigan, H. B. de Aguiar, *Optica* (2019)

Outline

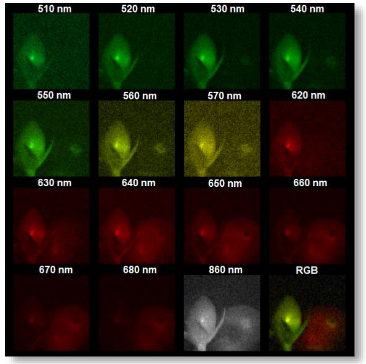
Description of **computational imaging techniques based on single-pixel detection** with microstructured illumination and compressive sensing.

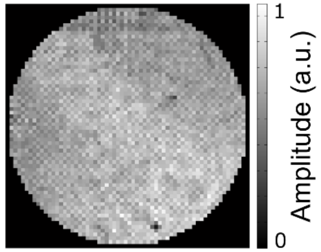
Application on multispectral imaging and **complex (amplitude and phase) imaging** with interferometric and non interferometric approaches.

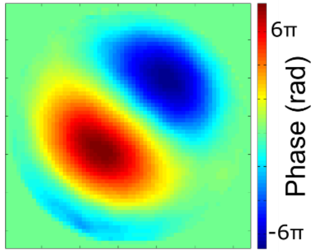
1. **The single-pixel camera**
2. **Multispectral imaging**
3. **Complex amplitude imaging**

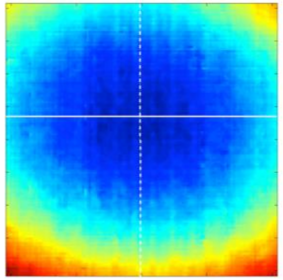
   Non-interferometric setups

   Interferometric setups





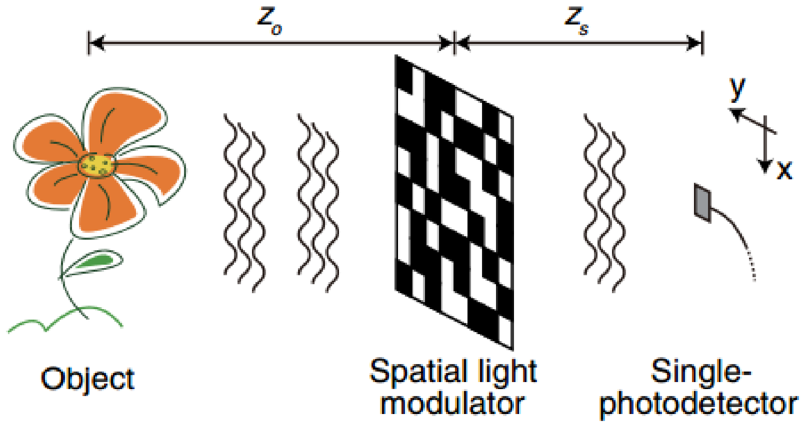


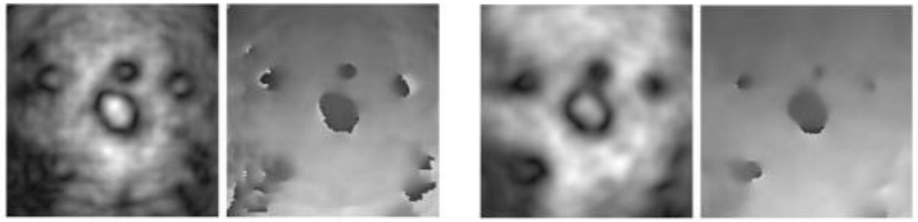


Single-pixel holographic cameras

Single-pixel camera by coherent diffraction imaging

Ryoichi Horisaki



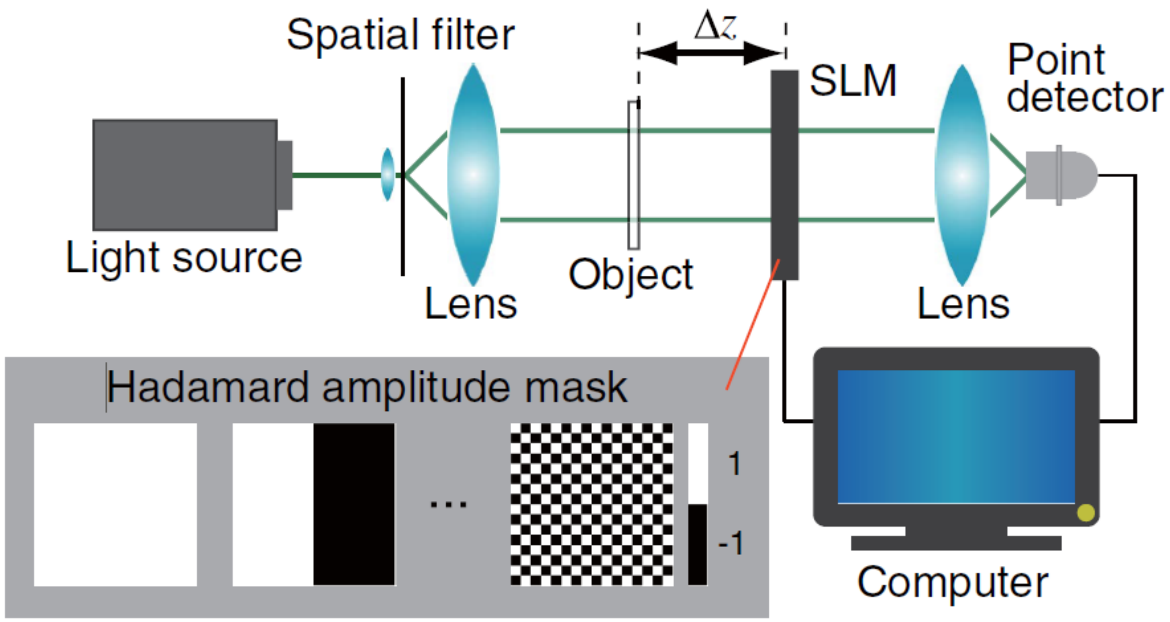


R. Horisaki et al. “Single-pixel compressive diffractive imaging”, Applied Optics 56, 1353 (2017)

Single-pixel holographic cameras

Transport-of-intensity single-pixel imaging

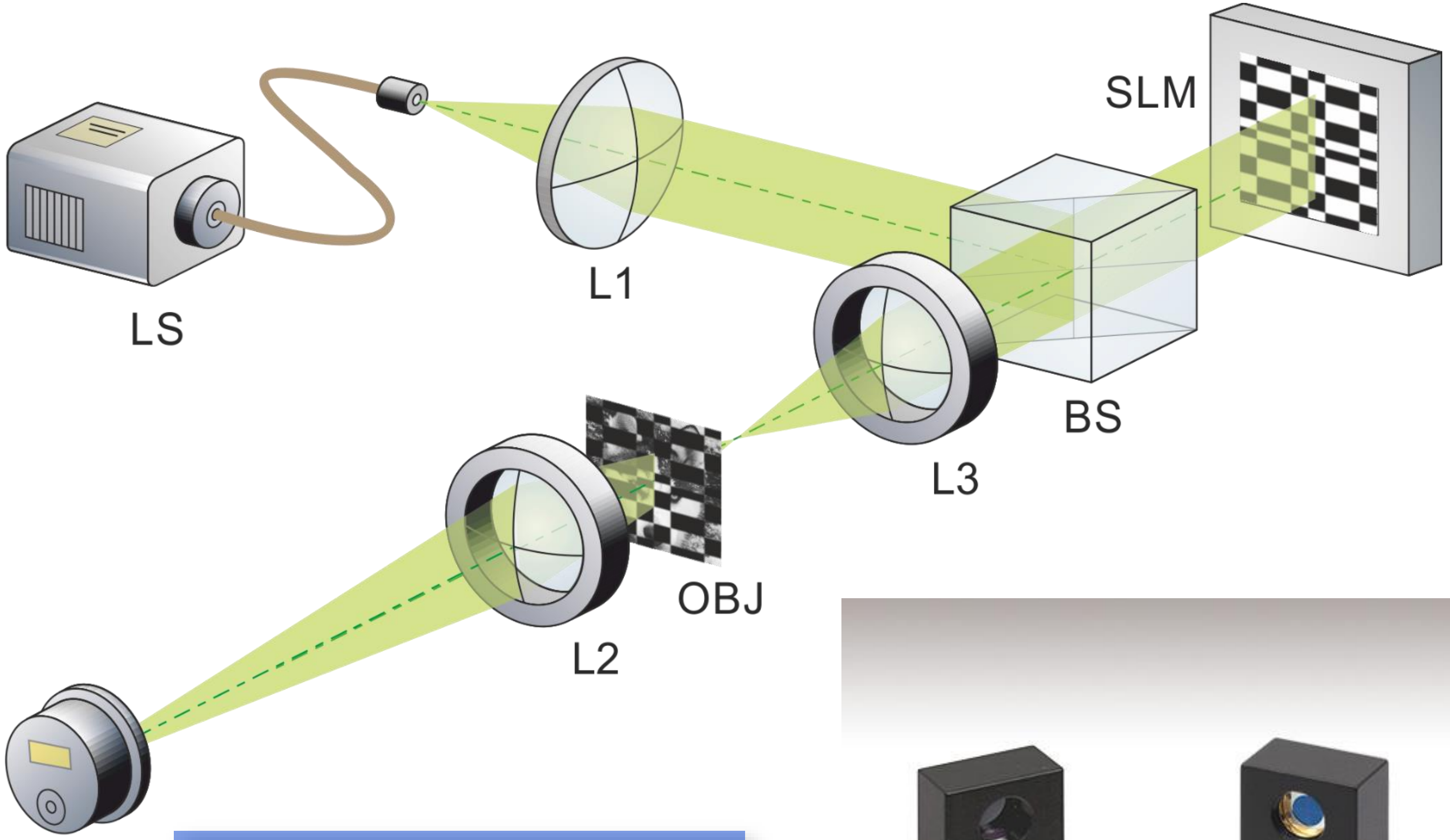
Takanori Nomura



Koshi Komuro, Yuya Yamazaki, and Takanori Nomura, "Transport-of-intensity computational ghost imaging," Appl. Opt. 57, 4451-4456 (2018)

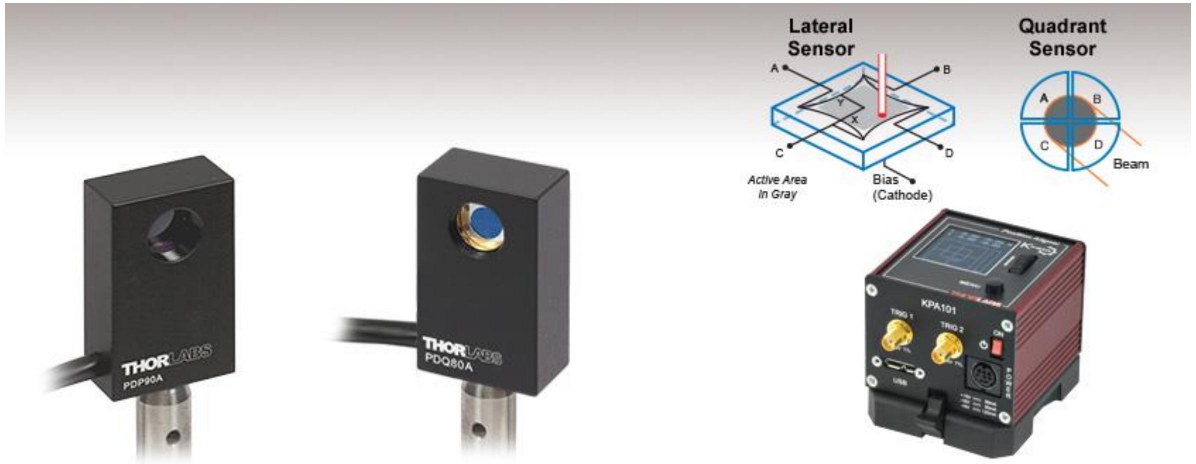
Single-pixel holographic cameras

Light source



Spatial light modulator

Position sensing detector

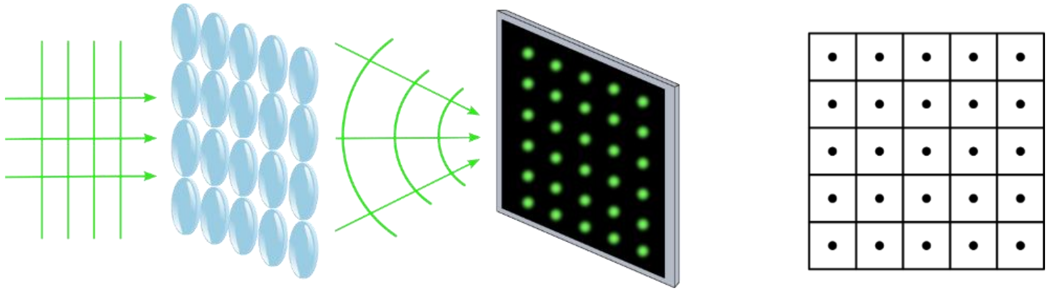


Single-pixel complex amplitude imaging

GROC UJI
Photonics Research Group

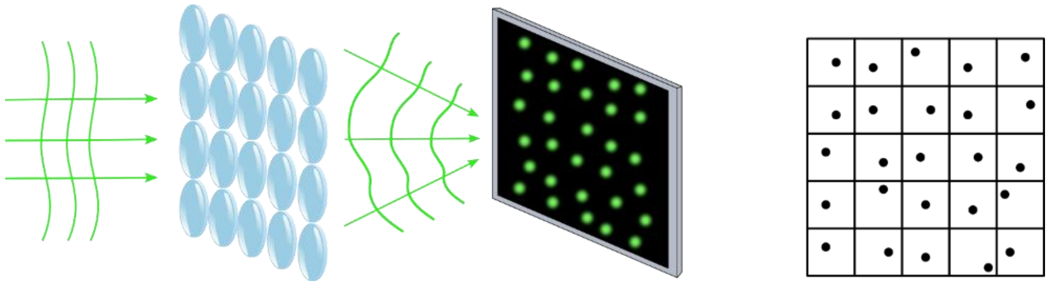
Shack-Hartmann wavefront sensing

For a plane wave the lenslet array generates a **regular distribution of focal spots**



If the wavefront presents **aberrations**, the spots change their **position**.

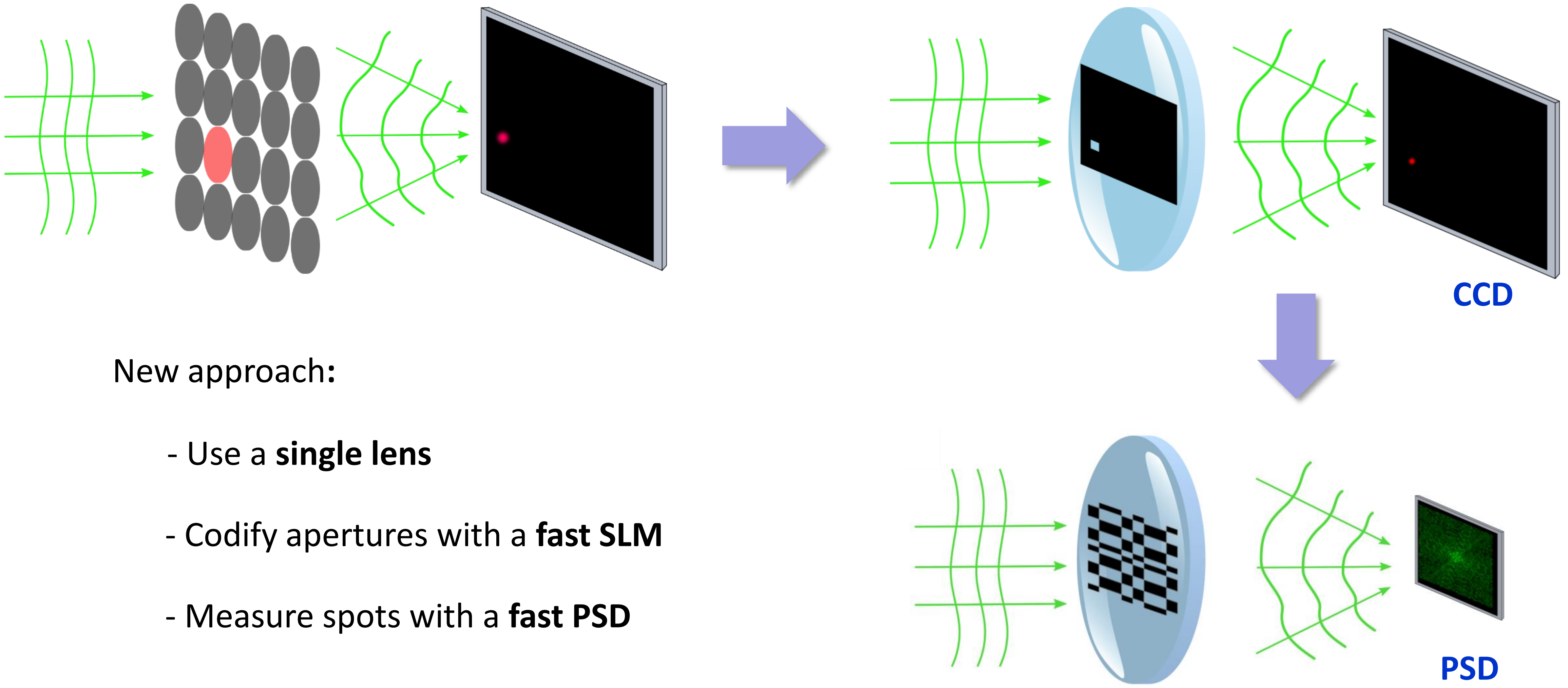
This change provides **phase information**



$$\vec{\Delta} = (\Delta x, \Delta y) = \frac{\lambda f}{2\pi} \vec{\nabla} \varphi$$

The Shack-Hartmann sensor can be used for complex amplitude imaging!

Single-pixel complex amplitude imaging



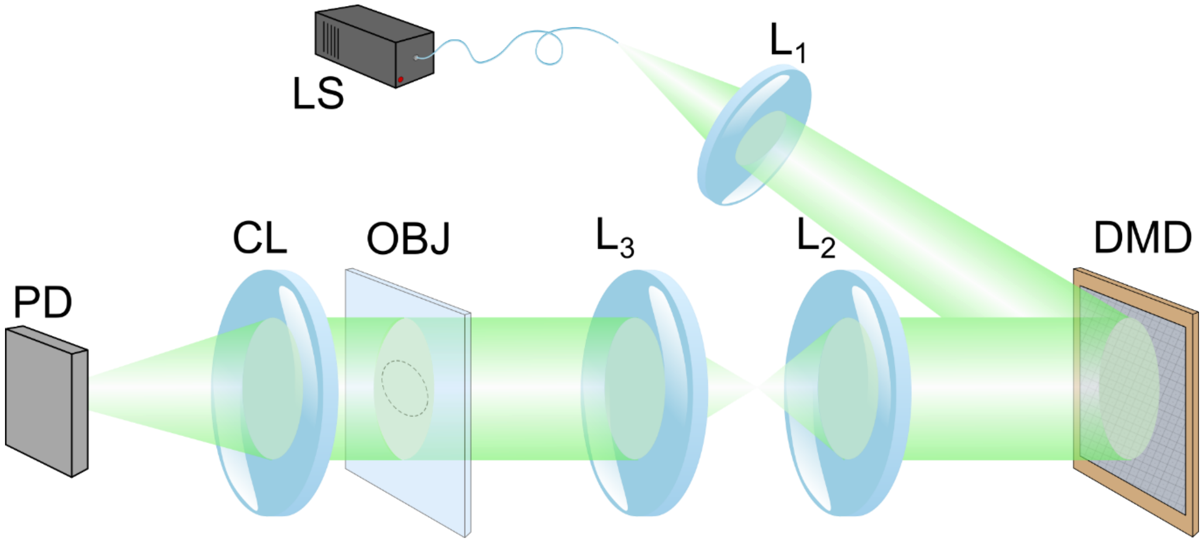
New approach:

- Use a **single lens**
- Codify apertures with a **fast SLM**
- Measure spots with a **fast PSD**

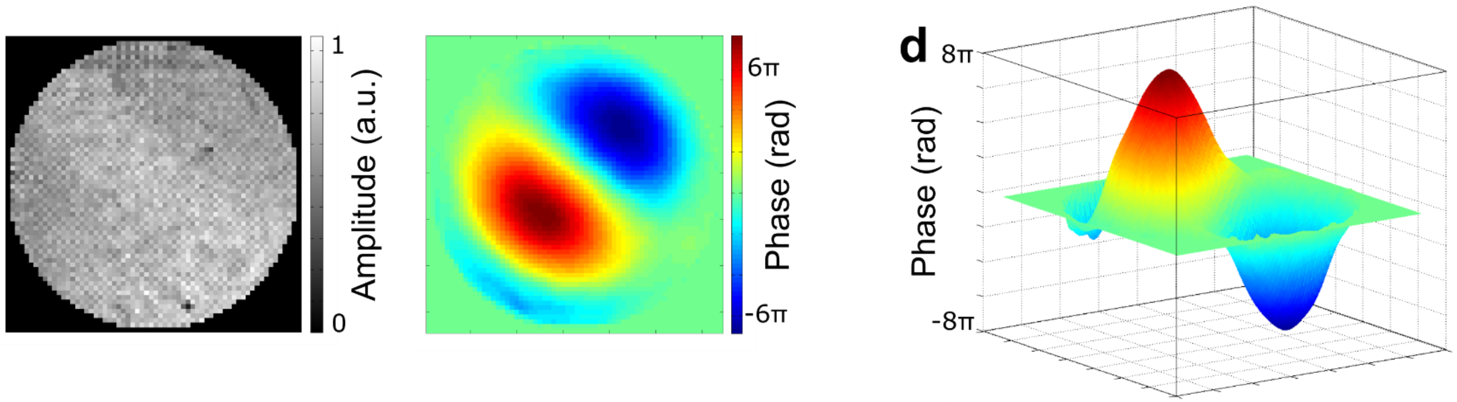
Single-pixel complex amplitude imaging

GROC UJI
Photonics Research Group

$$\vec{\Delta} = (\Delta x, \Delta y) = \frac{\lambda f}{2\pi}\vec{\nabla}\varphi$$

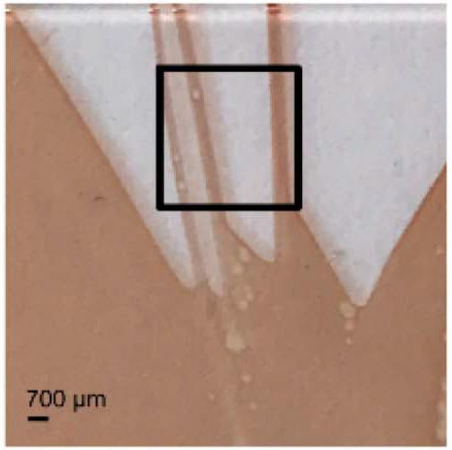


Object: **Coma aberration plate**
Size: 64×64 pixels (~80 µm pixel pitch)
Acquisition time: ~200 ms
(~22 kHz refresh rate)

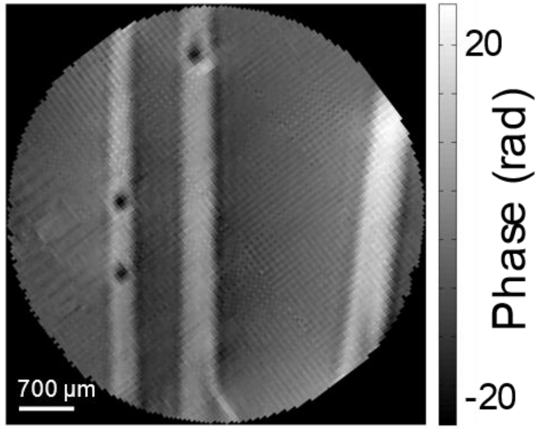


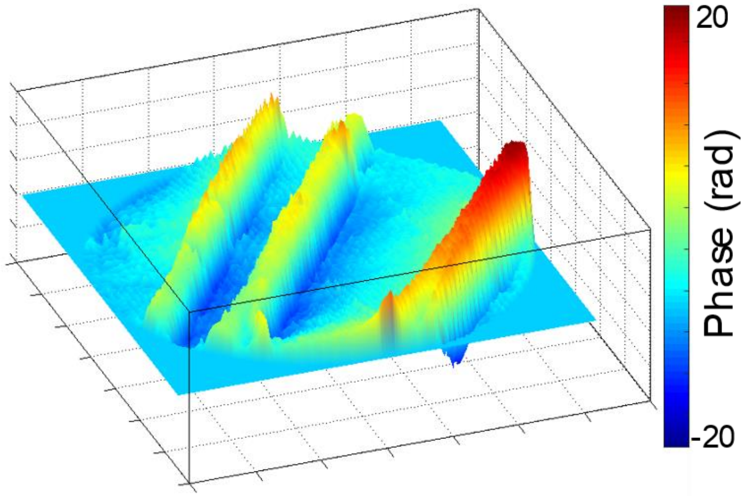
Fernando Soldevila et al., *Optica* (2018)

Single-pixel complex amplitude imaging



Object: Photoresist layer



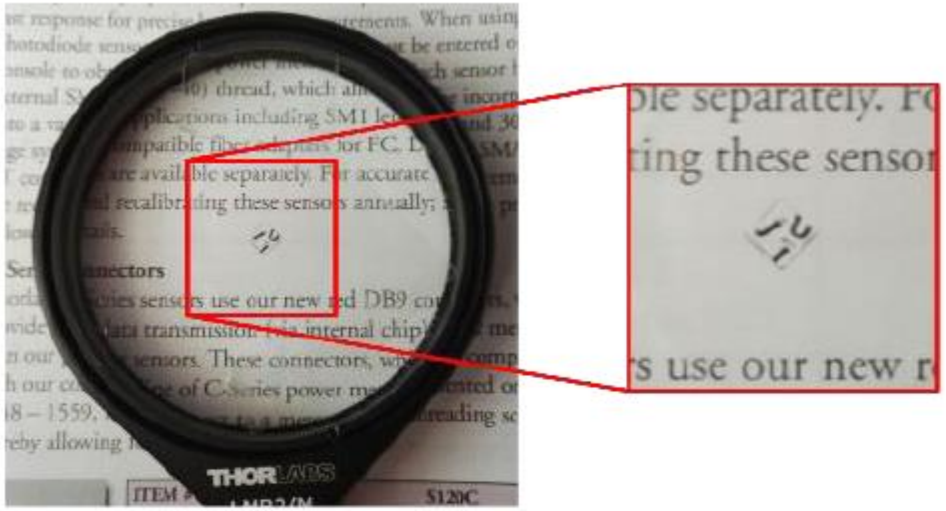


Size: 128×128 pixels (~40 µm pixel pitch)
Acquisition time: **~0.8 s**

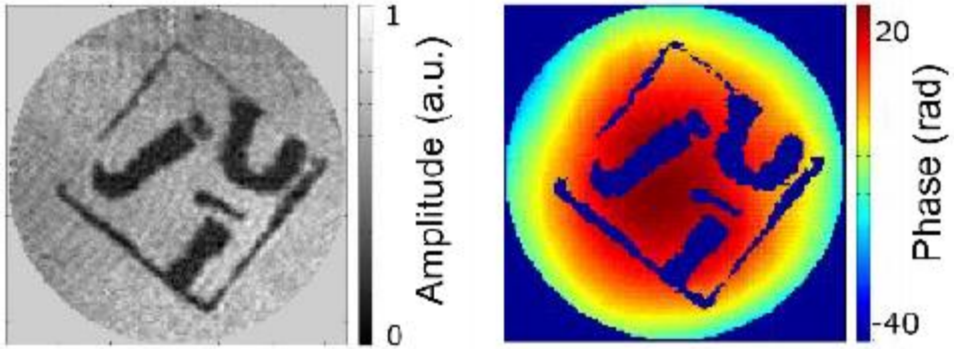
High detail can be recovered: small holes caused by air bubbles with ~80 µm diameter

Fernando Soldevila et al., *Optica* (2018)

Single-pixel complex amplitude imaging



Object: Lens with an amplitude mask

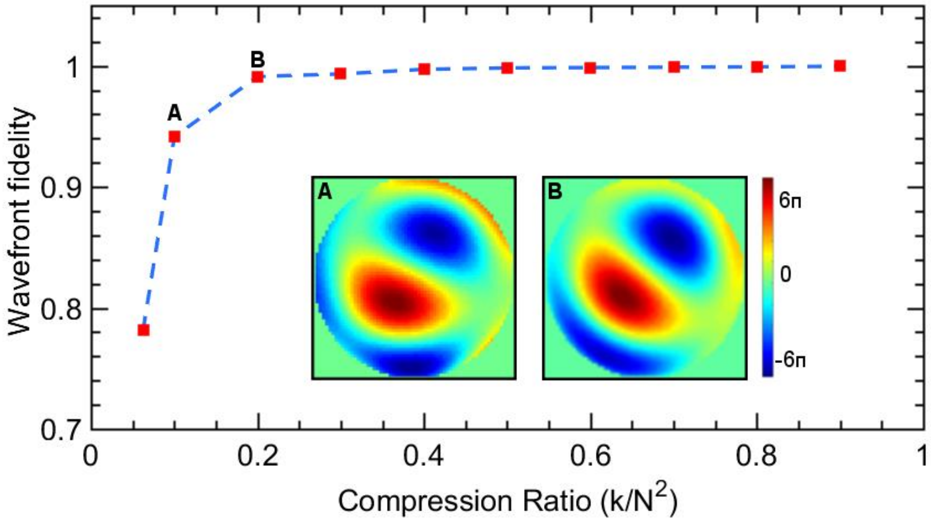


Size: 128×128 pixels (~40 µm pixel pitch)
Acquisition time: **~0.8 s**

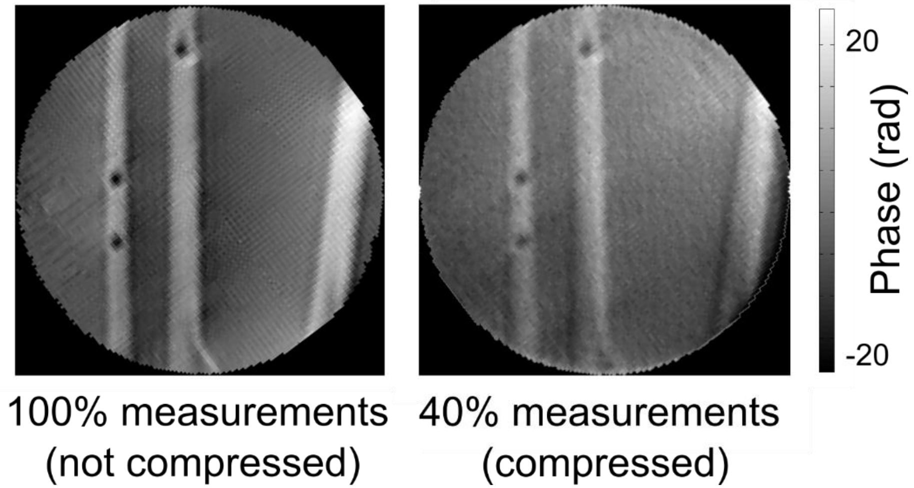
Fernando Soldevila et al., *Optica* (2018)

Single-pixel complex amplitude imaging

Speeding up: compressive sensing



Object: Coma aberration plate
Size: 64×64 pixels (~80 µm pixel pitch)
Acquisition time: **~10-20 ms** (at ~22 kHz)



Object: Photoresist layer
Size: 128×128 pixels (~40 µm pixel pitch)
Acquisition time: **~0.3 s** (at ~22 kHz)

Fernando Soldevila et al., *Optica* (2018)

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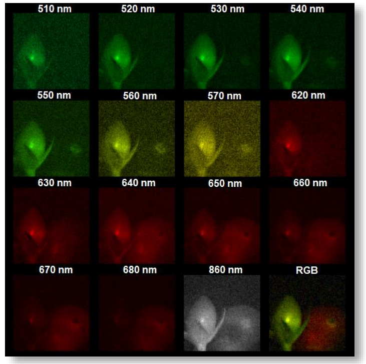
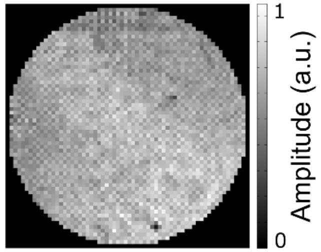
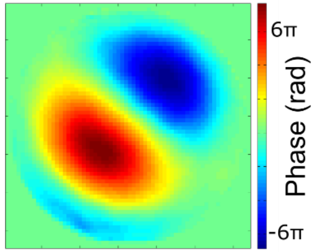
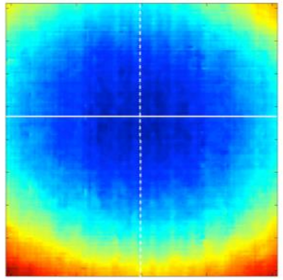




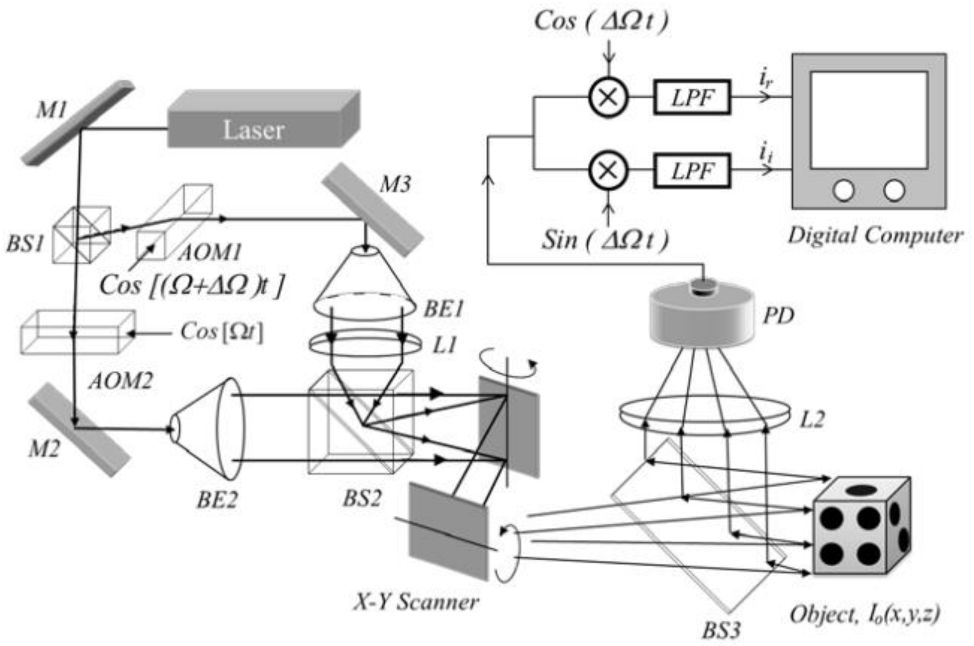




Single-pixel holographic cameras

Optical scanning holography (OSH)

Ting-Chung Poon



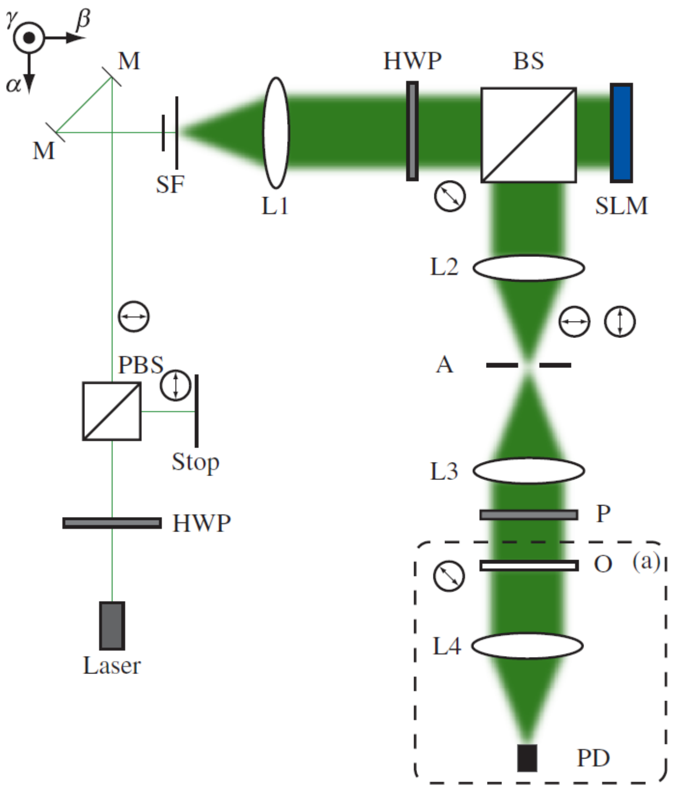
Y. S. Kim et al. “Speckle-free digital holographic recording of a diffusely reflecting object”, Opt. Express 21, 8183 (2013)

J. P. Liu et al., “Coherence-Experiments-Single-Pixel-Digital-Holography”, Opt. Lett. 40, 2366 (2015)

Single-pixel holographic cameras

Motionless optical scanning holography

Takanori Nomura

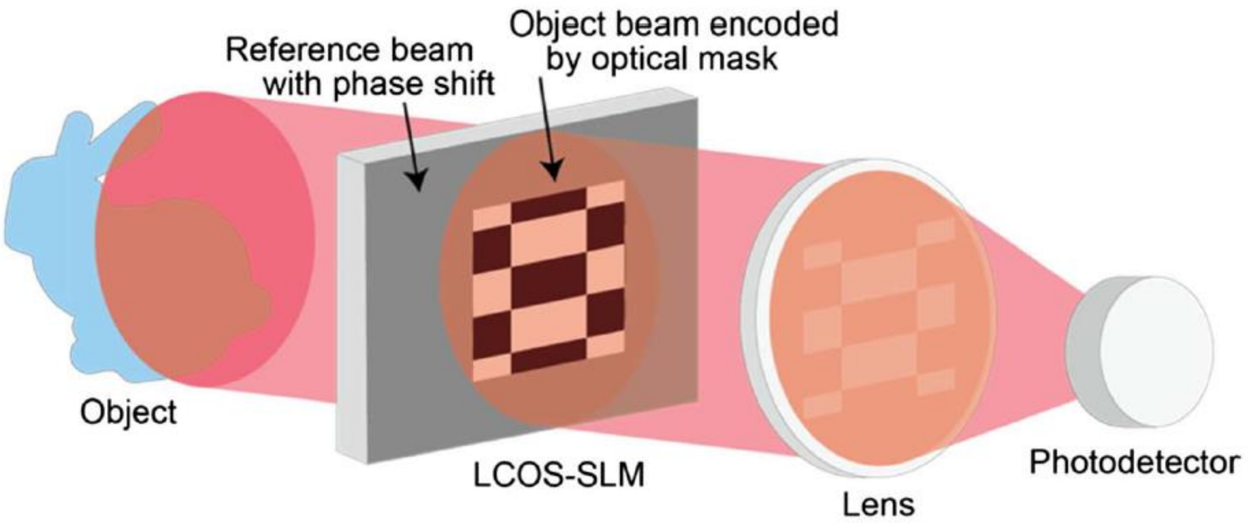


Naru Yoneda, Yusuke Saita, and Takanori Nomura, Motionless optical scanning holography, Opt. Lett. 45, 3184-3187 (2020)

Single-pixel holographic cameras

Complex amplitude single-pixel imaging with a common-path interferometer

Yoshio Hayasaki

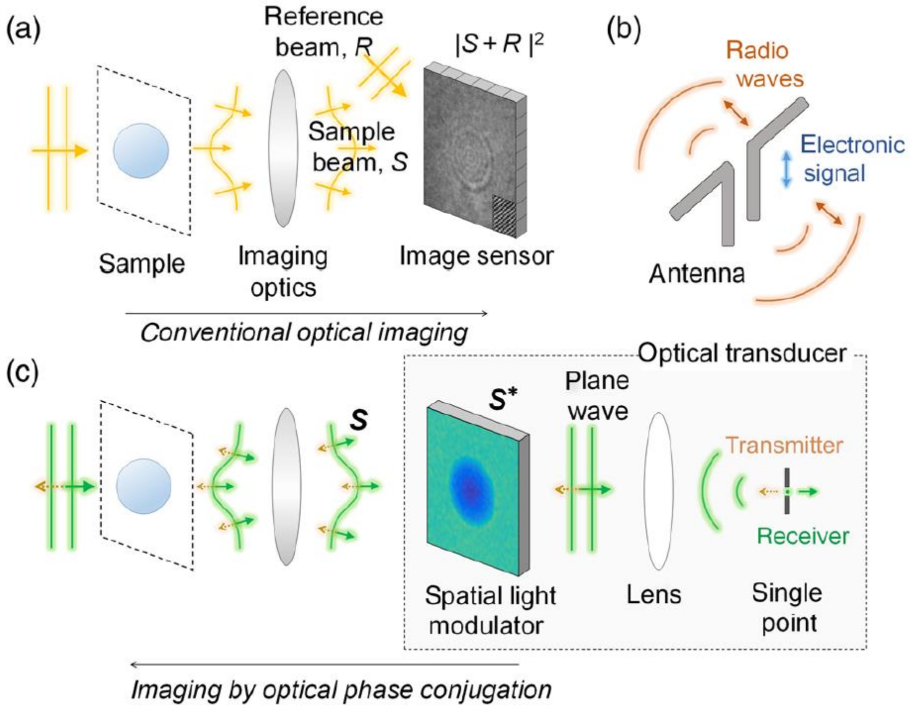


Kazuki Ota and Yoshio Hayasaki, "Complex-amplitude single-pixel imaging," Opt. Lett. 43, 3682-3685 (2018)

Single-pixel holographic cameras

Reference-free single-pixel holographic imaging

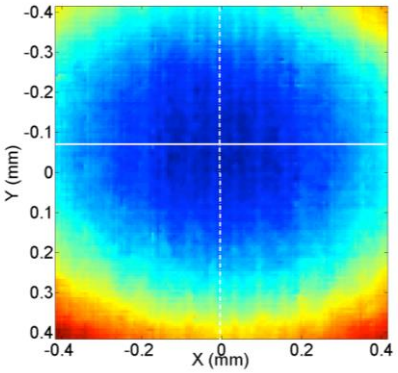
YongKeun Park



Seungwoo Shin, KyeoReh Lee, YoonSeok Baek, and YongKeun Park, "Reference-free single-point holographic imaging and realization of an optical bidirectional transducer," Phys. Rev. Appl. 9, 044042 (2018)

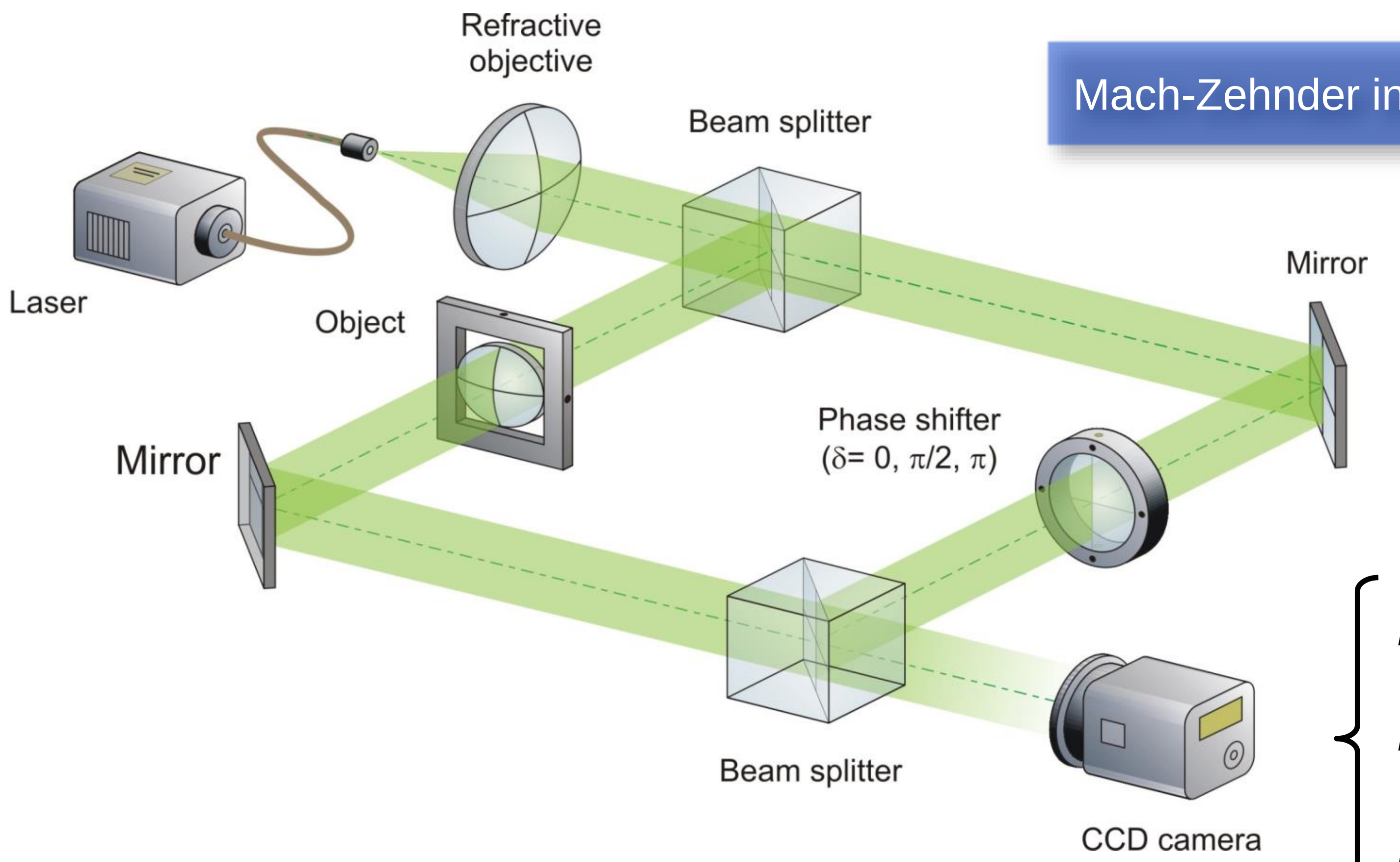
Single-pixel holographic camera

Phase image



Fresnel propagation

Mach-Zehnder interferometer



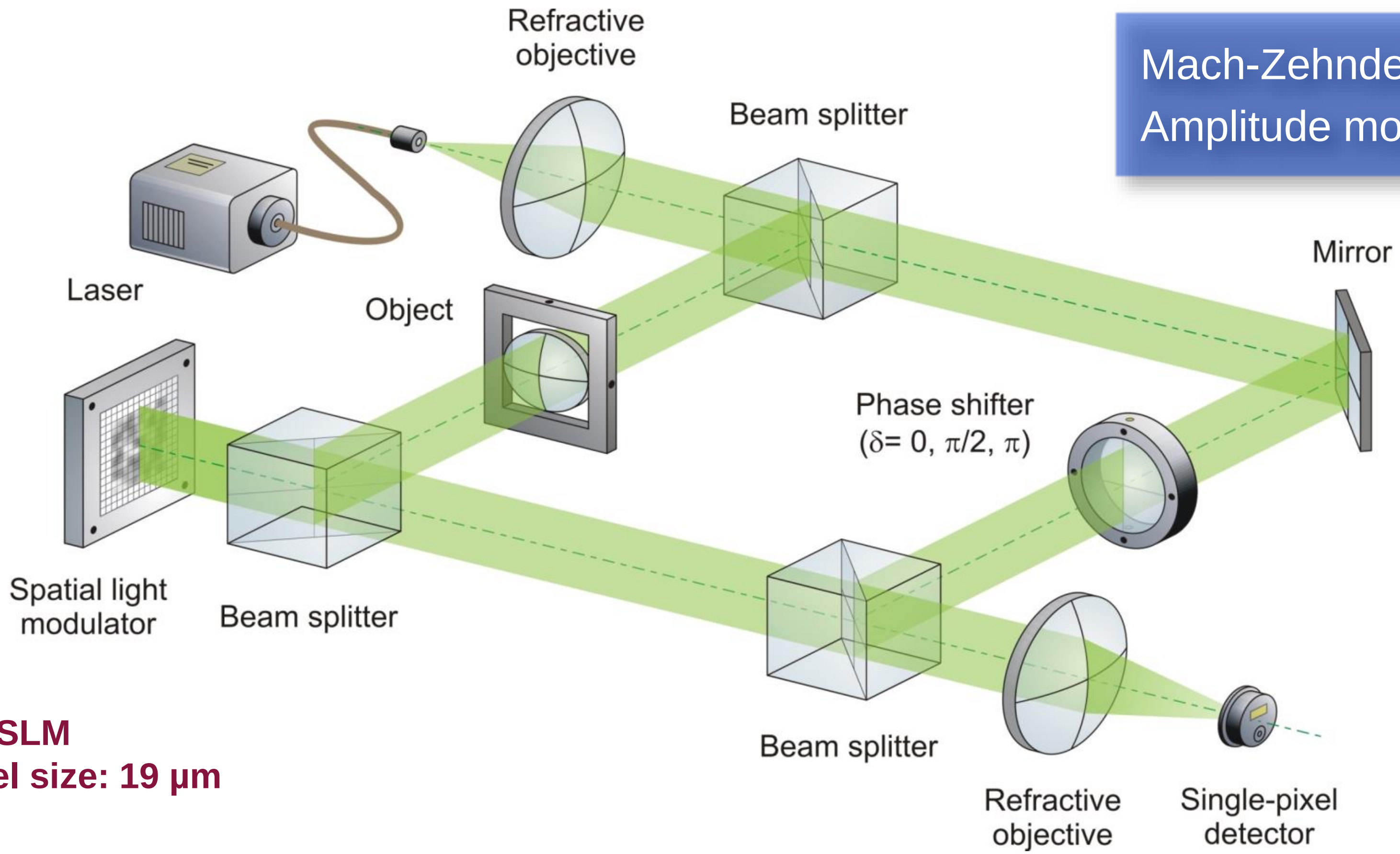
$$\begin{cases} I_0(x,y) \\ I_{\frac{\pi}{2}}(x,y) \\ I_\pi(x,y) \end{cases}$$

$$H(x,y) = \frac{1}{4}\left[I_0(x,y) - I_\pi(x,y)\right] + \frac{j}{4}\left[2I_{\frac{\pi}{2}}(x,y) - I_0(x,y) - I_\pi(x,y)\right]$$

Phase shifting

Single-pixel holographic camera

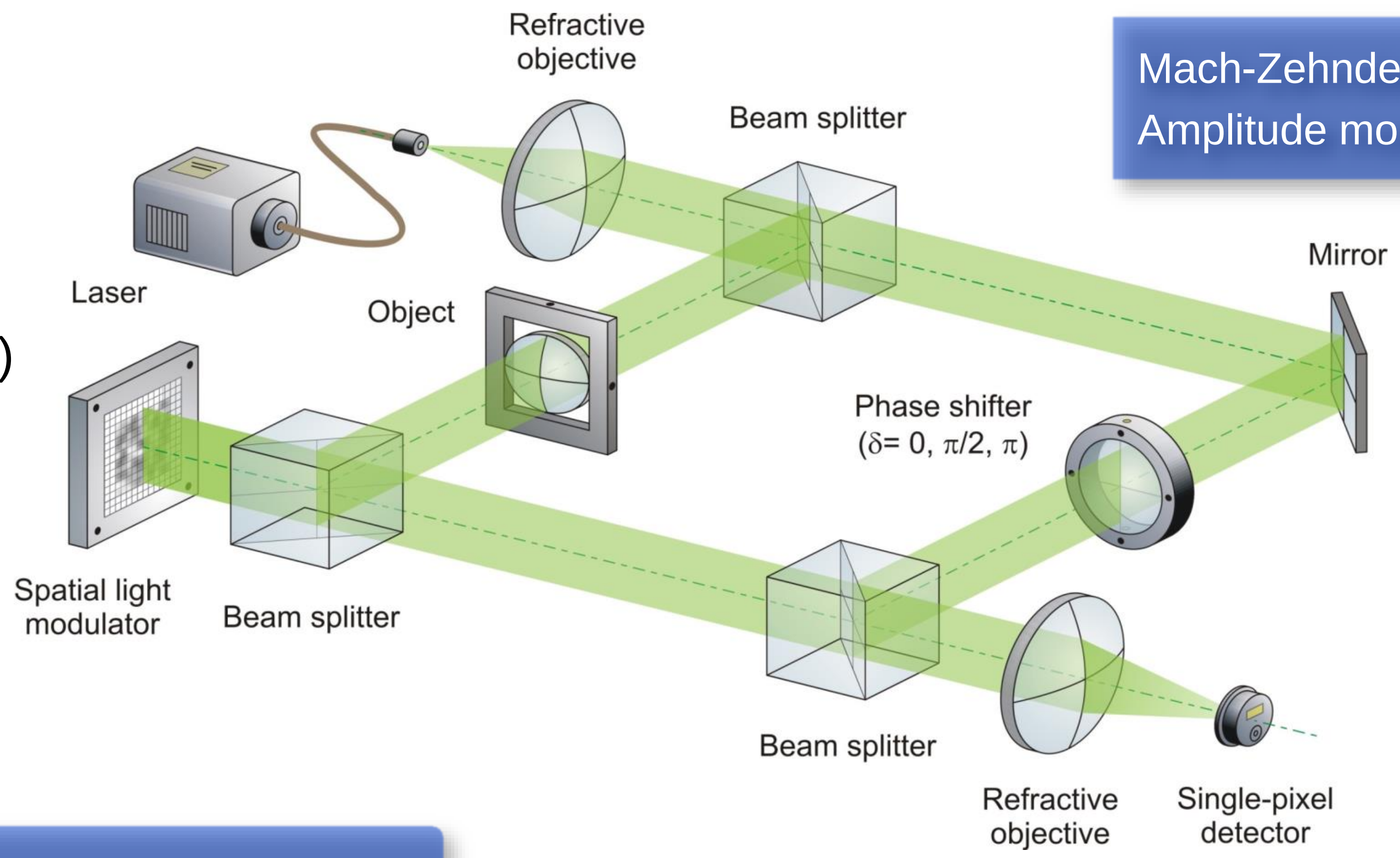
Mach-Zehnder interferometer
Amplitude modulation



LC-SLM
Pixel size: 19 µm

P. Clemente et al.
Optics Letters 38, 2524 (2013)

Single-pixel holographic camera



Mach-Zehnder interferometer
Amplitude modulation

$H_p(x,y)$

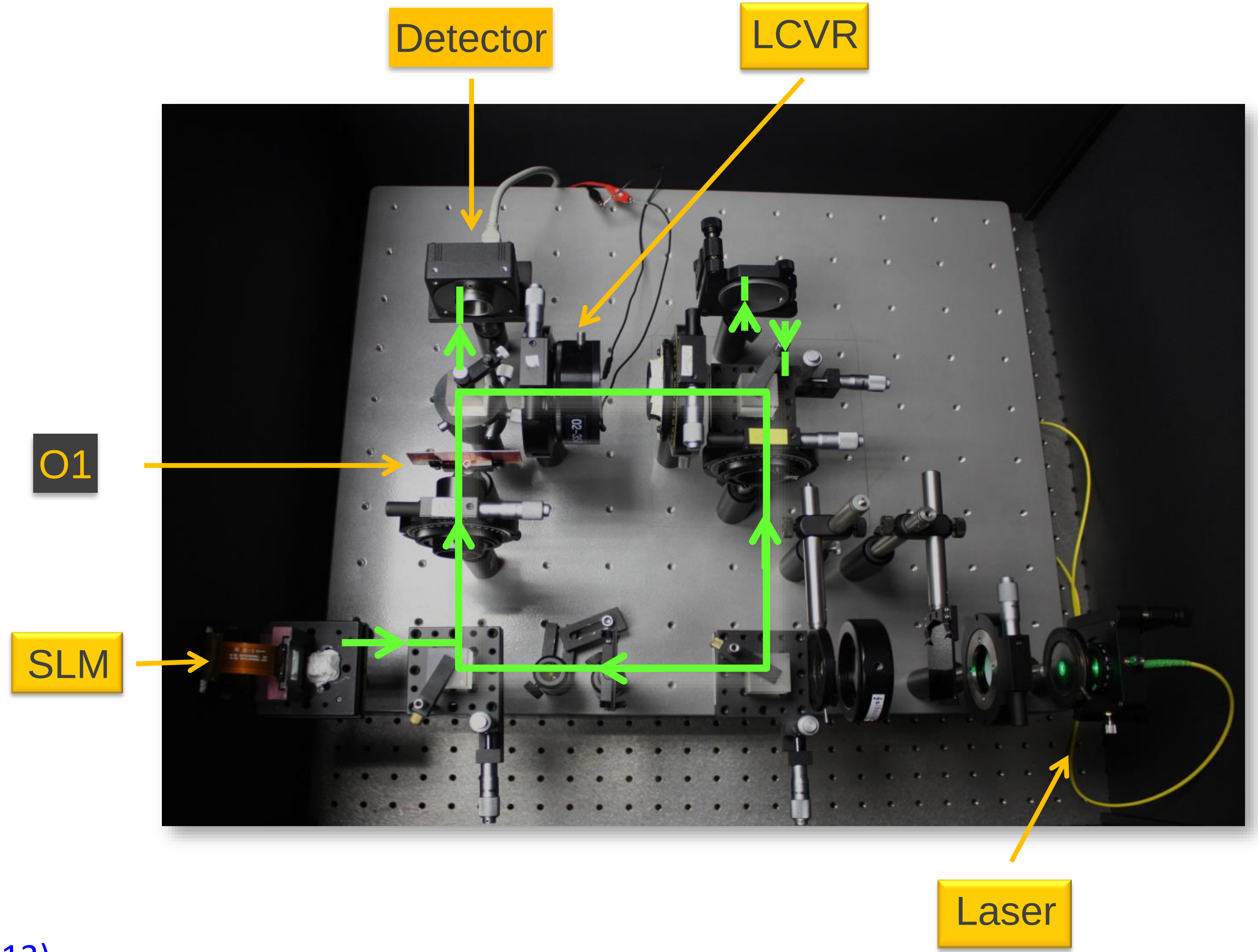
$$\begin{cases} I_{p,0} \\ I_{p,\pi/2} \\ I_{p,\pi} \end{cases}$$

Reconstruction algorithm

$$H(x,y) = \sum_{p=1}^{M} y_p \cdot H_p(x,y)$$

$$y_p = \frac{1}{4}\left[I_{p,0} - I_{p,\pi}\right] + \frac{j}{4}\left[2I_{p,\pi/2} - I_{p,0} - I_{p,\pi}\right]$$

Single-pixel holographic camera



P. Clemente et al.
Optics Letters 38, 2524 (2013)

Single-pixel holographic camera

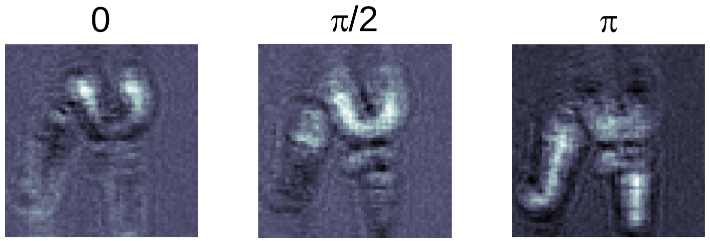
Amplitude object

Size: 4,864 x 4,864 mm^2

Resolution: 38 μm

Propagated distance: 253 mm

Compression ratio: 5:1

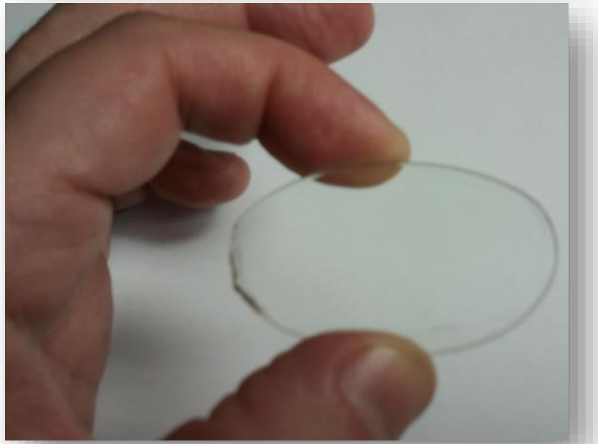


Phase-shifted Interferograms

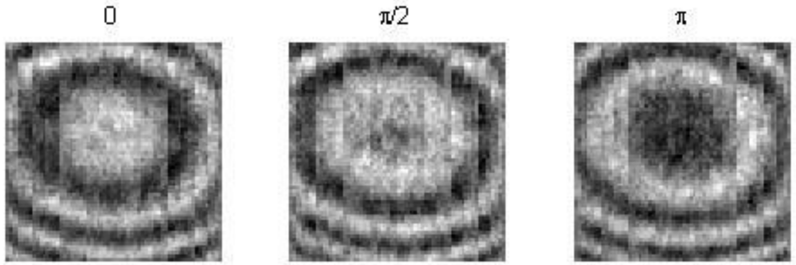
Reconstructed object

P. Clemente et al.
Optics Letters 38, 2524 (2013)

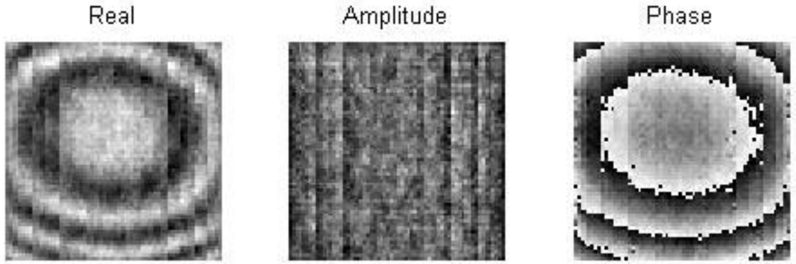
Single-pixel holographic camera



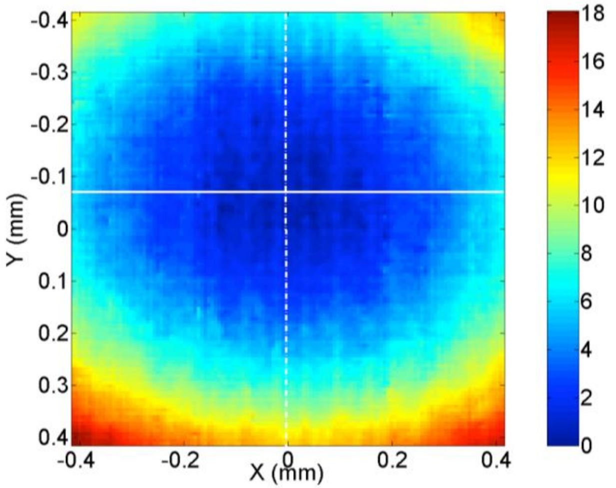
Phase object



Phase-shifted Interferograms



Reconstructed phase



Size : 128 x 128 pixels

Resolution : 19 µm

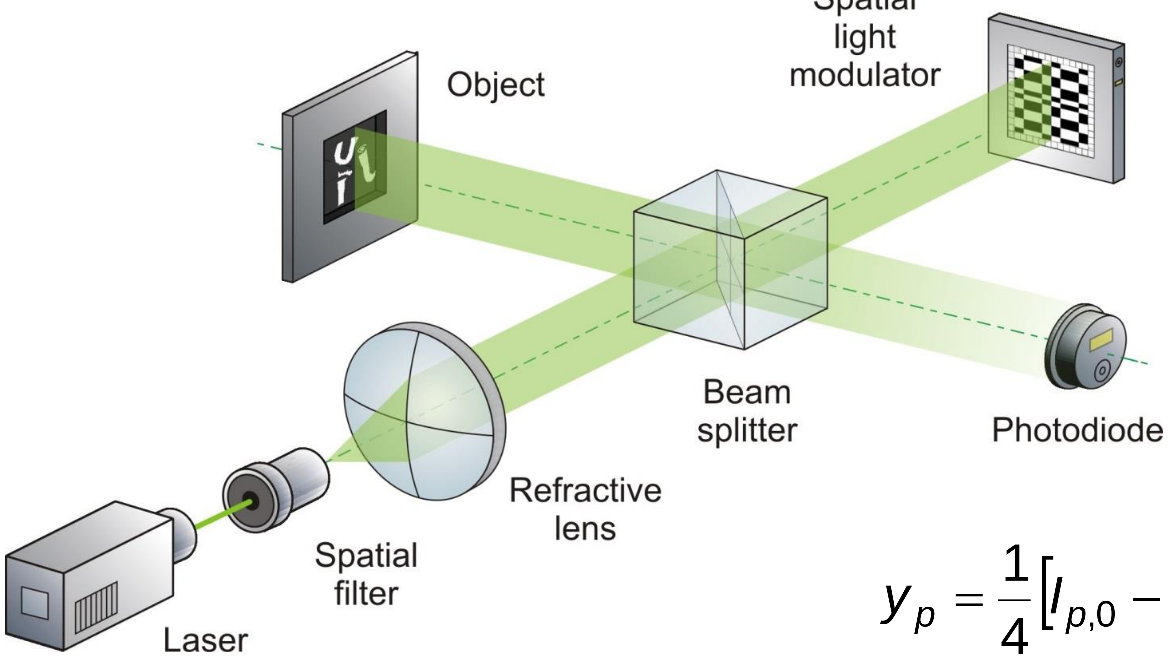
Prop. distance: -153 mm

Compression ratio: 5:1

P. Clemente et al.
Optics Letters 38, 2524 (2013)

Single-pixel holographic camera with phase patterns

Michelson interferometer
Phase-only modulation



$H_p(x,y)$ Microstructured phase patterns

Sampling patterns encoded in the reference beam

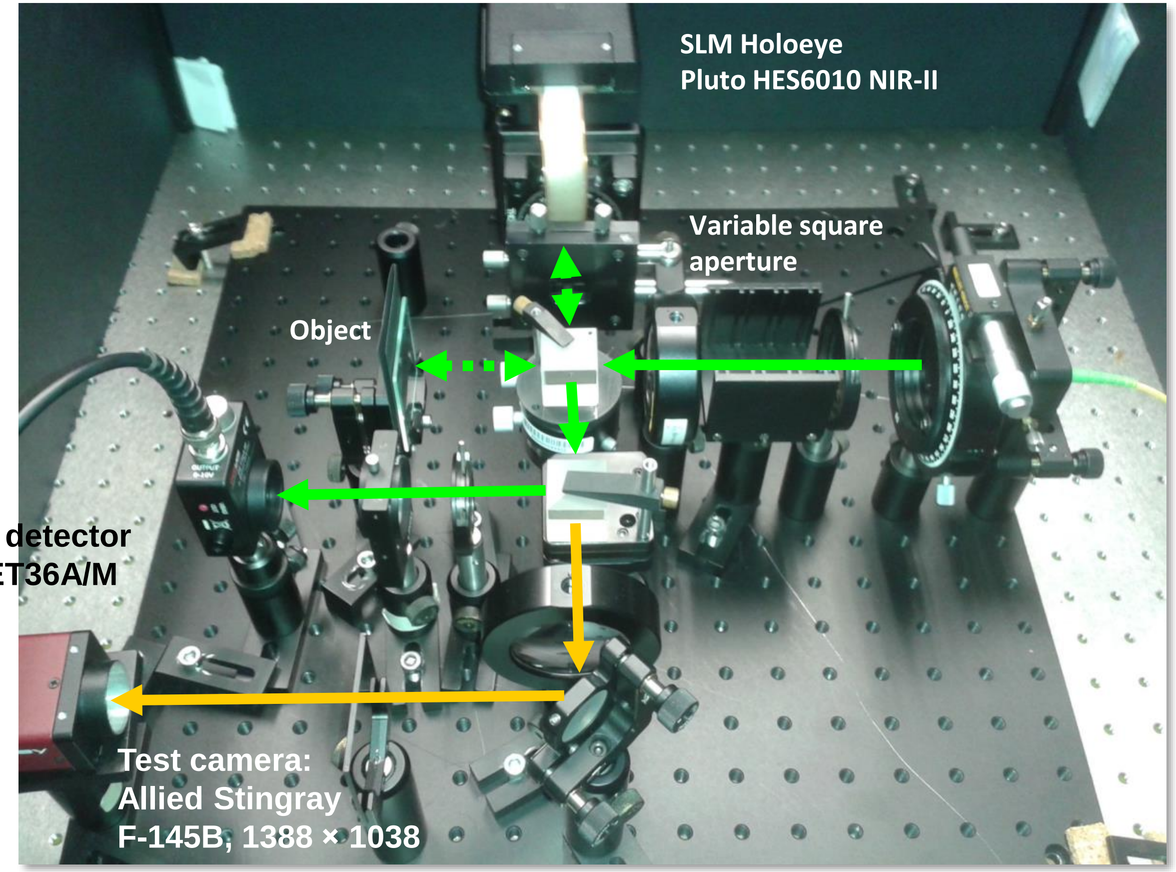
$$y_p = \frac{1}{4}\left[I_{p,0} - I_{p,\pi}\right] + \frac{j}{4}\left[2I_{p,\pi/2} - I_{p,0} - I_{p,\pi}\right]$$

$$O(x,y) = \frac{1}{N}\sum_{p=1}^{M} I_p \cdot H_p(x,y)$$

Ll. Martínez-León et al.
Optics Express 25, 4975 (2017)

Single-pixel holographic camera with phase patterns

To card
NI cDAQ-9171

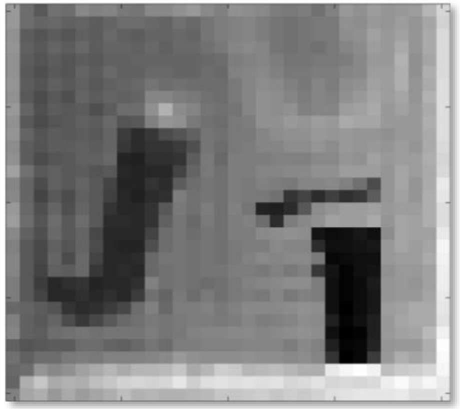


Single-pixel detector
Thorlabs DET36A/M

From laser
Oxxius, 532 nm

Single-pixel holographic camera with phase patterns

Amplitude hologram reconstruction,
(1600 patterns)



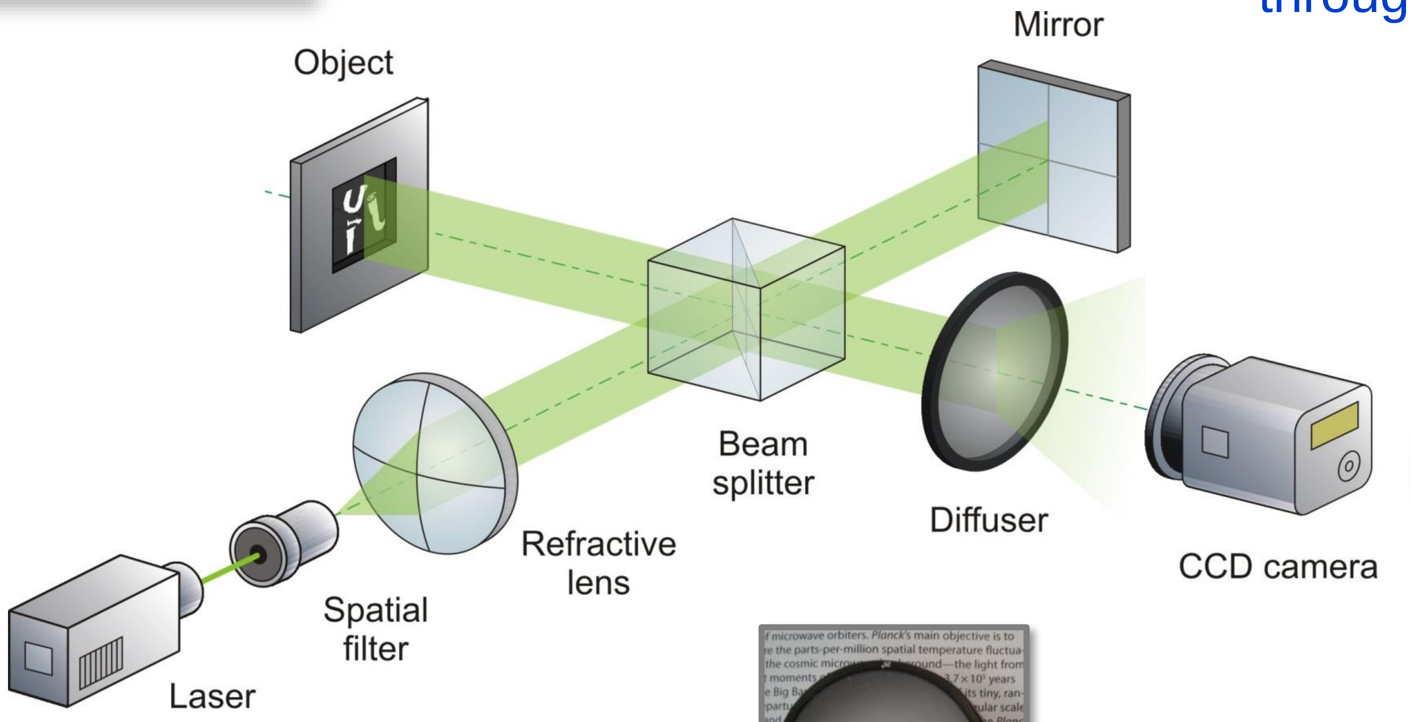
Phase hologram reconstruction by
single-pixel holography
(784 patterns)

Single-pixel holographic camera with phase patterns

GROC UJI Photonics Research Group

Conventional phase-shifting Michelson interferometer

Complex amplitude imaging through scattering

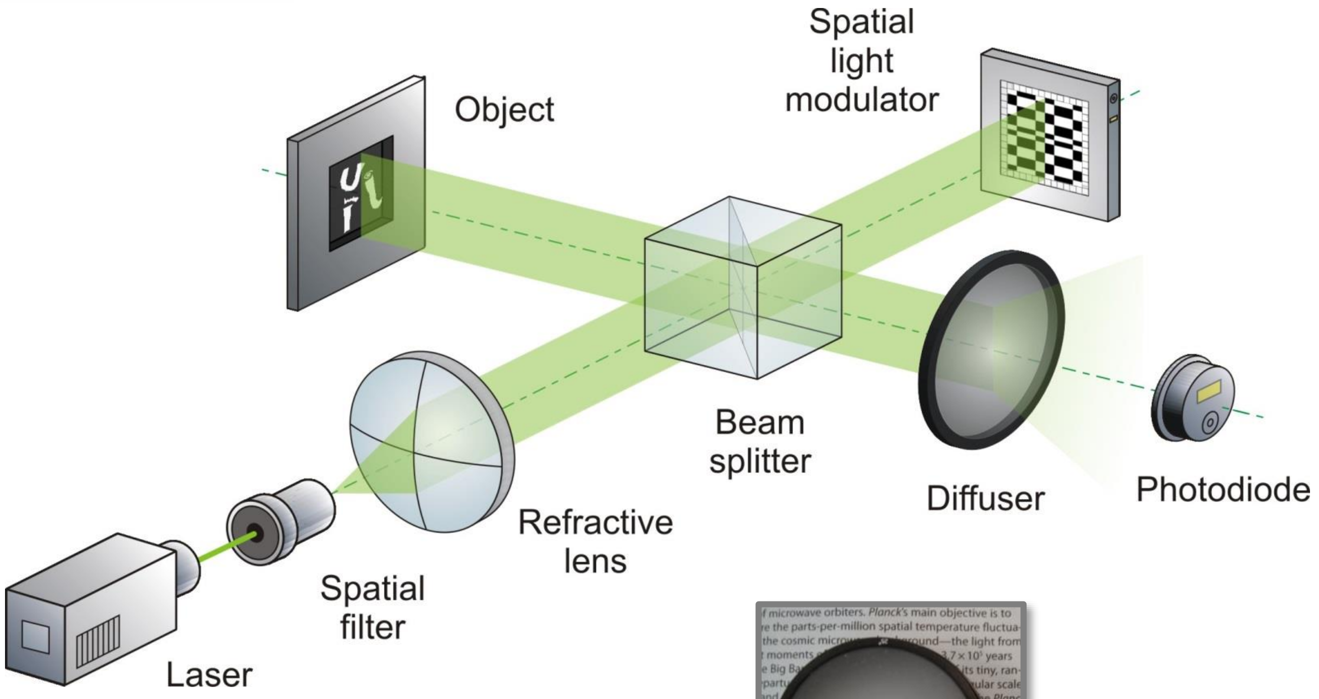


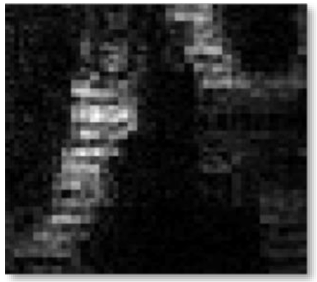
Single-pixel holographic camera with phase patterns

GROC UJI
Photonics Research Group

Michelson interferometer
Phase-only modulation

Complex amplitude imaging through scattering

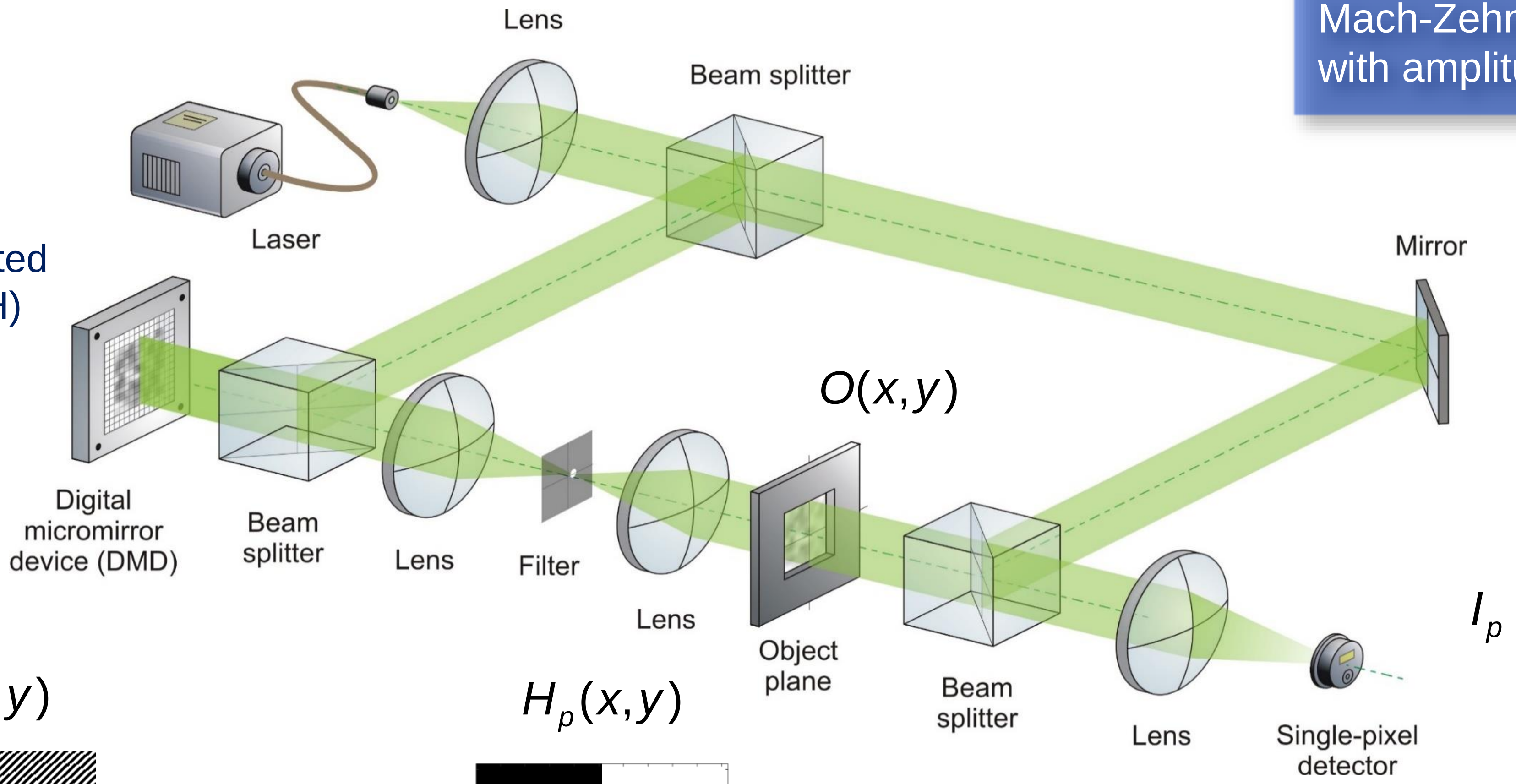




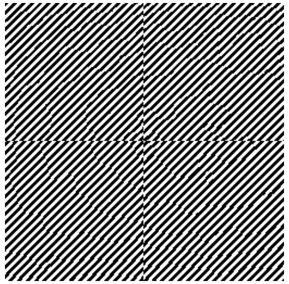
Single-pixel holographic camera with DMD

Mach-Zehnder interferometer with amplitude-only SLM

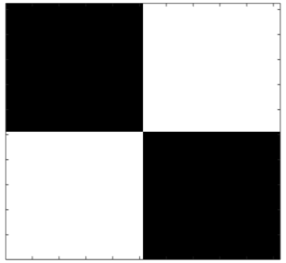
Computer generated holograms (CGH)



$C_p(x,y)$



$H_p(x,y)$



Single-pixel holographic camera with DMD

Mach-Zehnder interferometer with amplitude-only SLM

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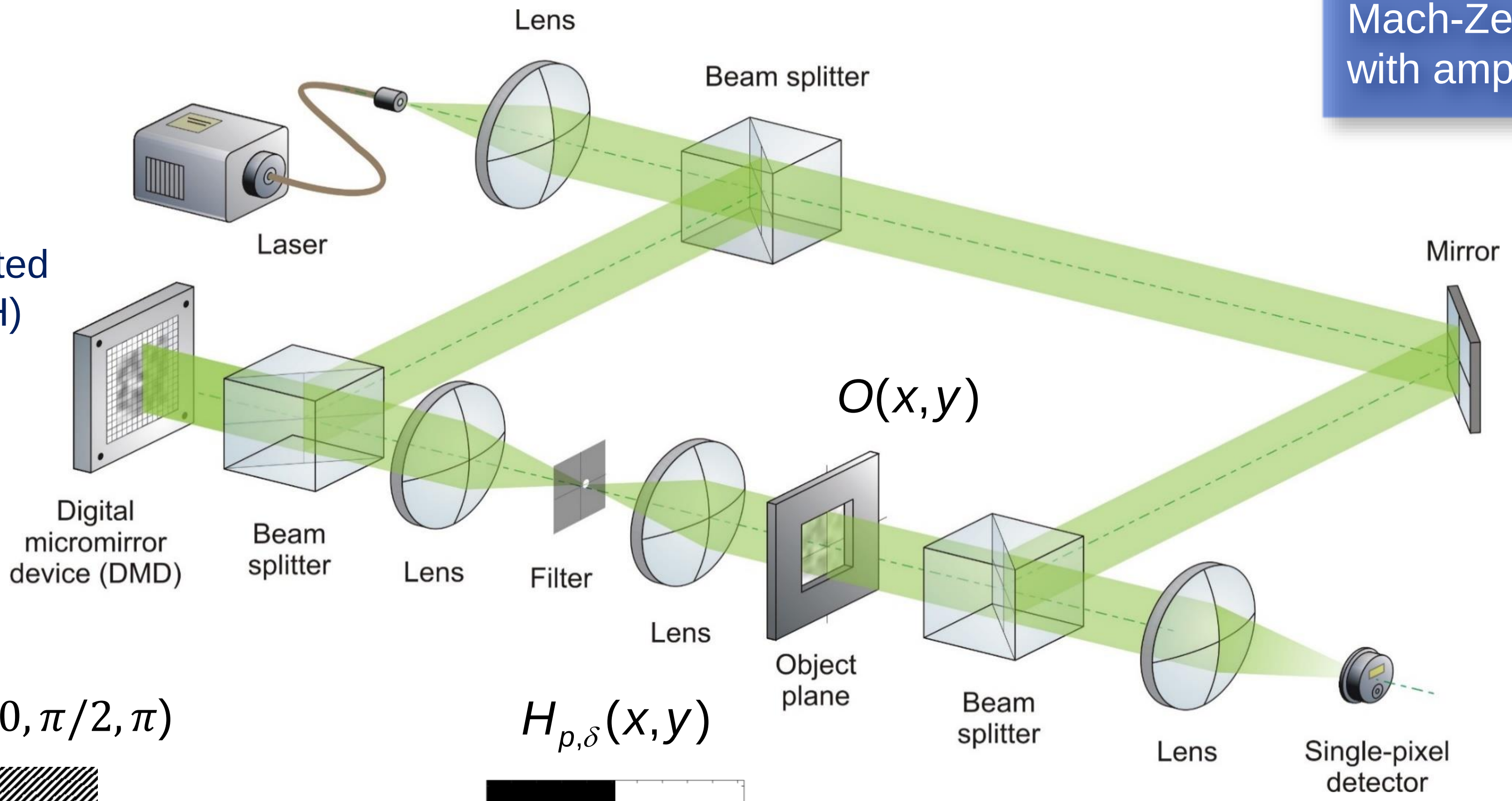
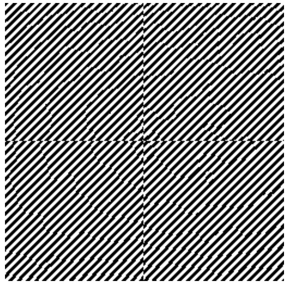
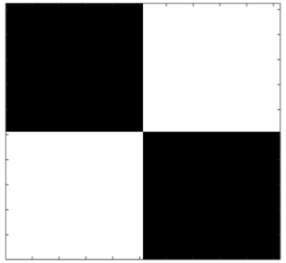


$$\begin{cases} I_{p,0} \\ I_{p,\pi/2} \\ I_{p,\pi} \end{cases}$$

$C_p(x,y) + \delta(0,\pi/2,\pi)$



$H_{p,\delta}(x,y)$



$$y_p = \frac{1}{4}\left[I_{p,0} - I_{p,\pi}\right] + \frac{j}{4}\left[2I_{p,\pi/2} - I_{p,0} - I_{p,\pi}\right]$$

Single-pixel holographic camera with DMD

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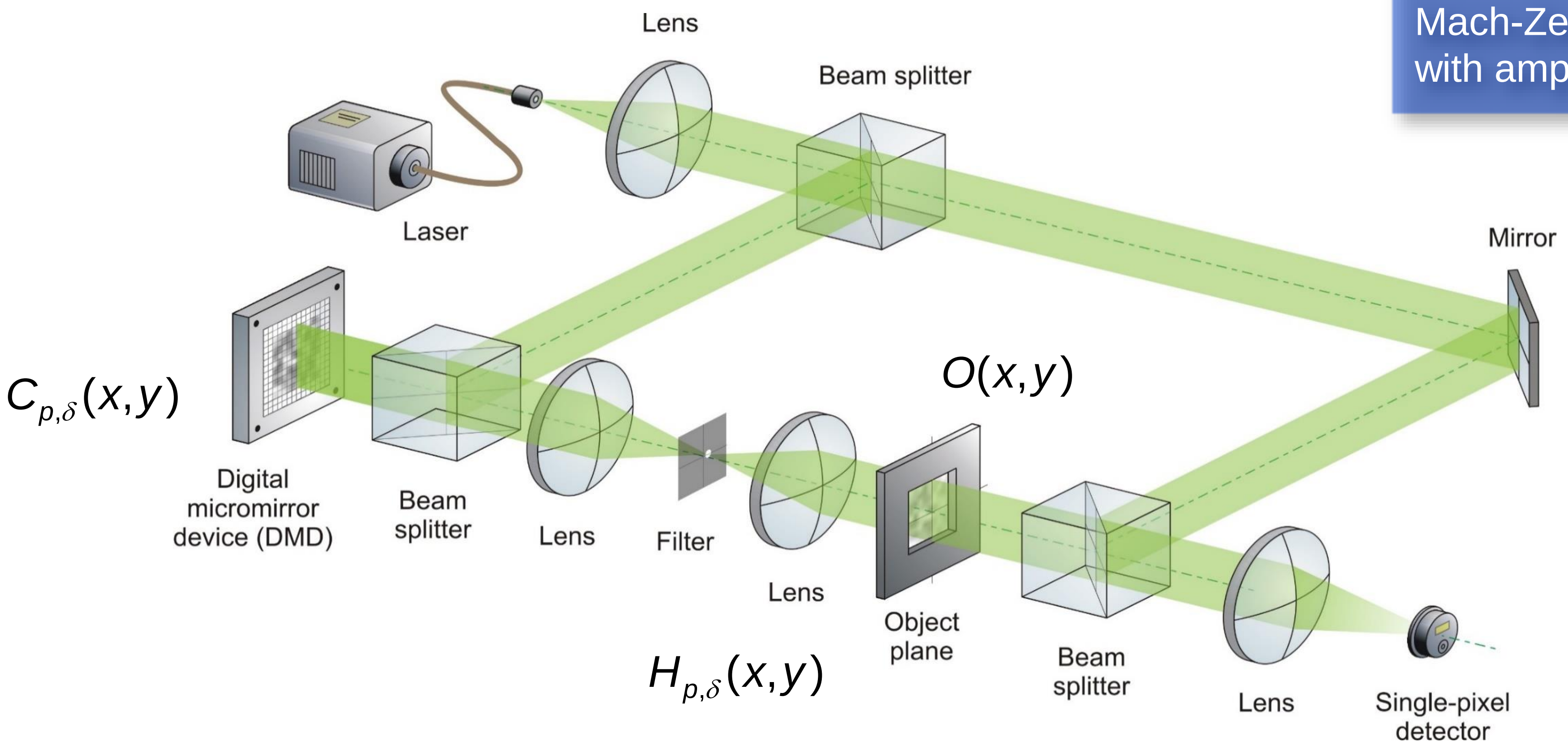
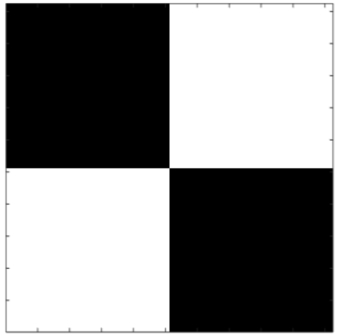
Mach-Zehnder interferometer with amplitude-only SLM



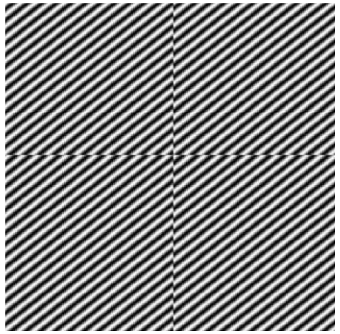
$$O(x,y) = \frac{1}{N}\sum_{p=1}^{M} y_p \cdot H_p(x,y)$$

$$y_p = \frac{1}{4}\left[I_{p,0} - I_{p,\pi}\right] + \frac{j}{4}\left[2I_{p,\pi/2} - I_{p,0} - I_{p,\pi}\right]$$

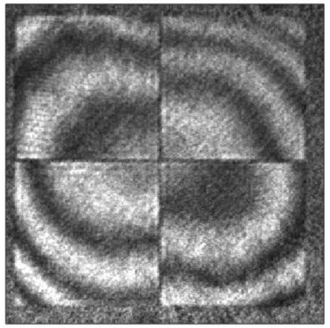
Single-pixel holographic camera with DMD



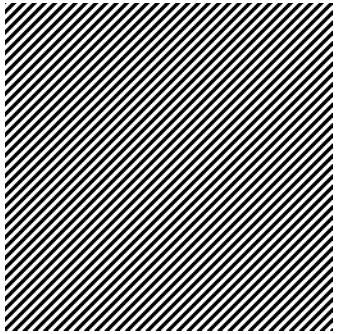
Hadamard pattern
to be codified



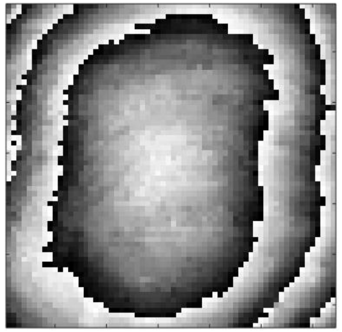
Hadamard pattern
CGH



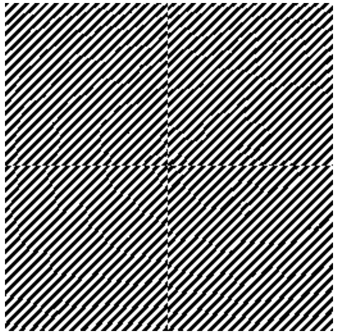
Interference pattern
(at the object plane)



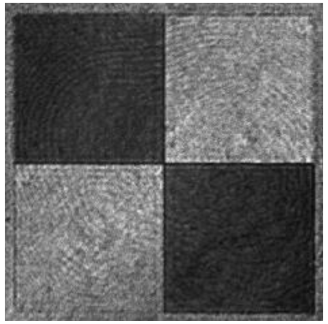
Plane wave
CGH



Phase aberration



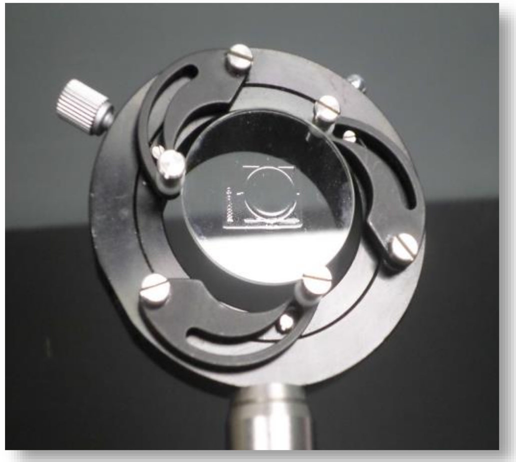
Corrected
Hadamard pattern
CGH



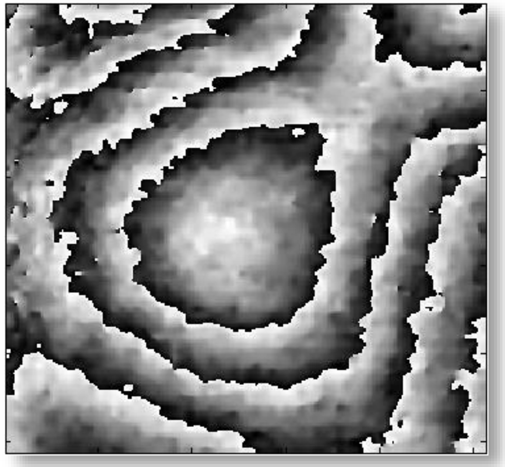
Interference pattern
corrected

Single-pixel holographic camera with DMD

Image of a photoresist layer simulating an aberration



Phase object

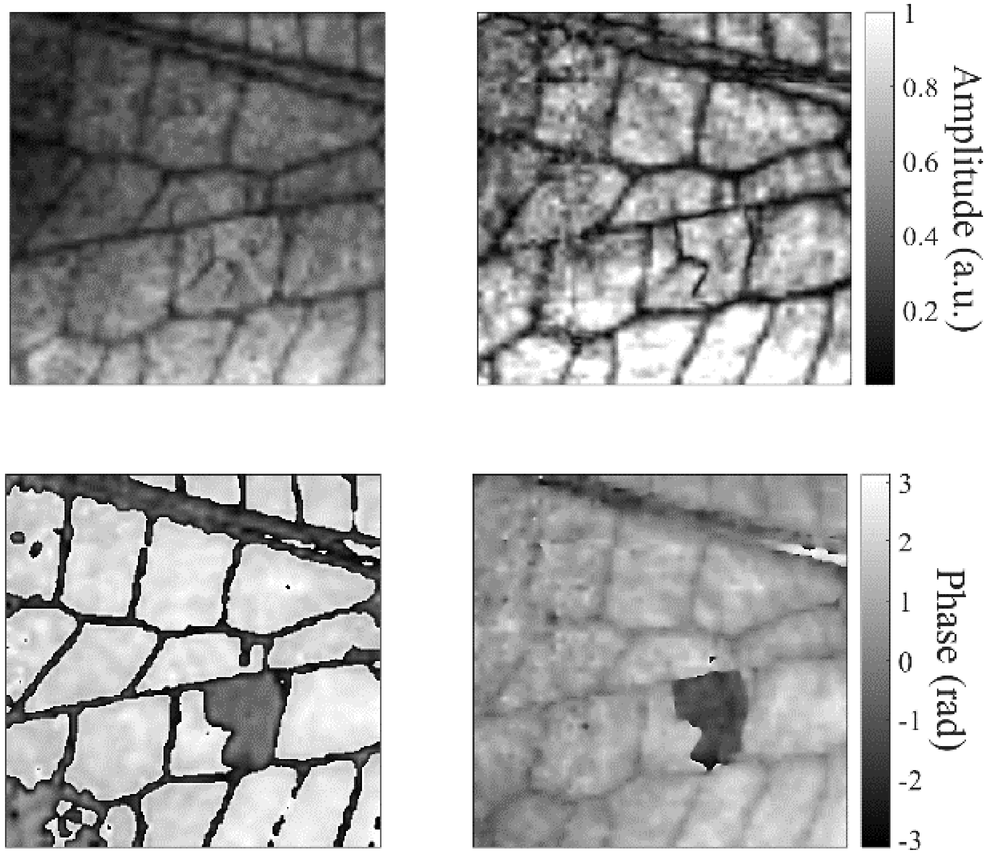


Phase image

H. González et al.,
Optics Express 26, 20342 (2018)

Single-pixel holographic camera with DMD

Object



Conventional holography

Single-pixel holography

H. González et al.,
Optics Express 26, 20342 (2018)

Concluding remarks

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We have described **computational imaging techniques based on single-pixel detection** with microstructured illumination and compressive sensing.

We have shown several applications on **complex (amplitude and phase) imaging**.

Advantages:

Simplicity of the sensor

Efficient light sensors

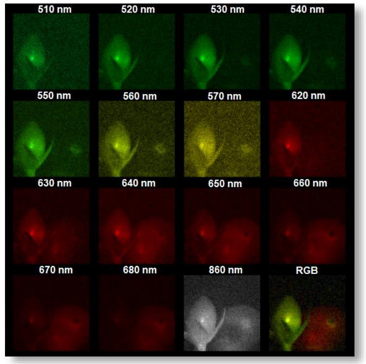
Broad spectral range

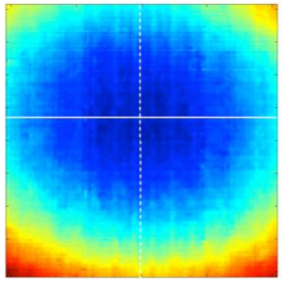
Measure multiple optical parameters

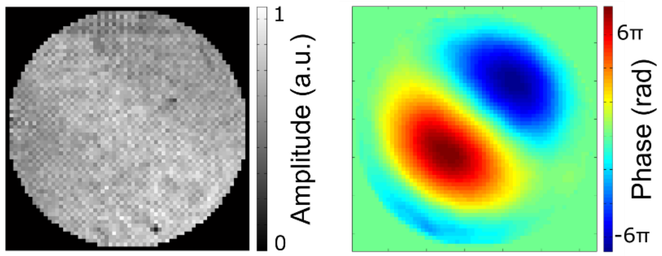
Challenge:

Faster sampling methods

Smart reconstruction algorithms







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Photonics Research Group

Research group

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