Spatial Light Modulators: what are the needs for (complex) optical wavefront shaping through complex media

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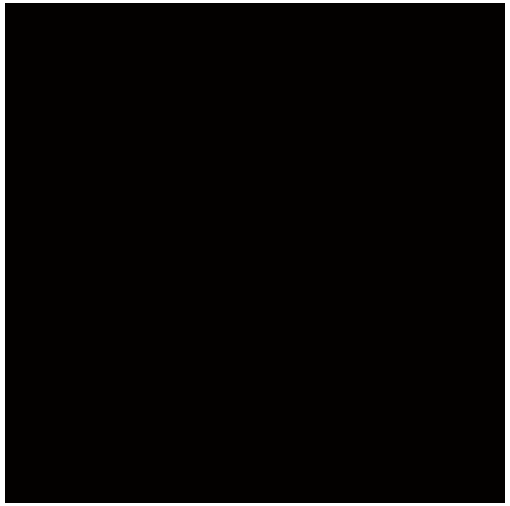
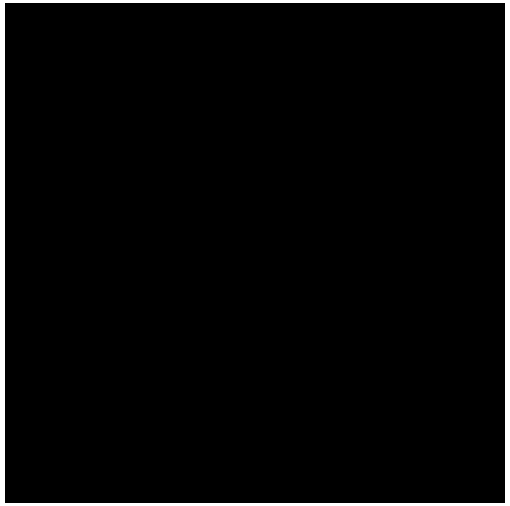
UNIVERSITÉ Grenoble Alpes

Workshop on SLM, EPFL, Lausanne, 27 October 2017

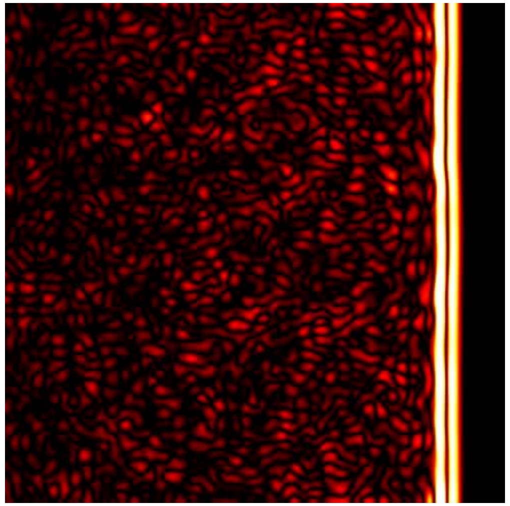
LiPhy Laboratoire interdisciplinaire de Physique

Propagation of coherent waves in complex media

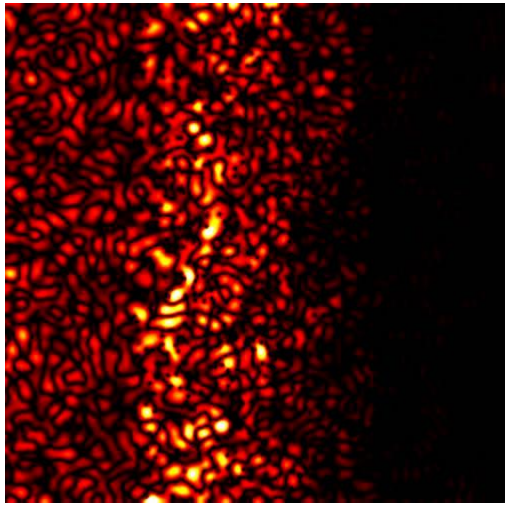




Propagation of coherent waves in complex media

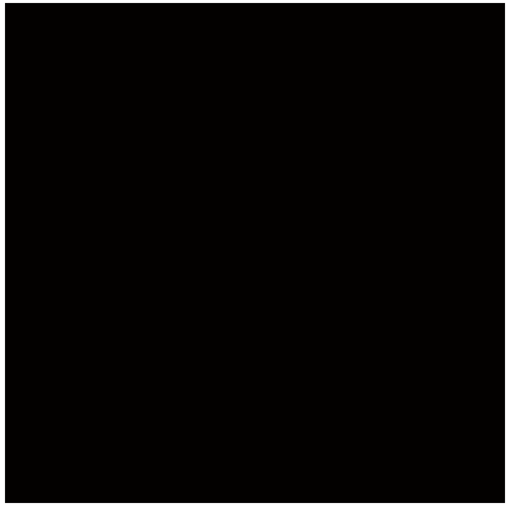


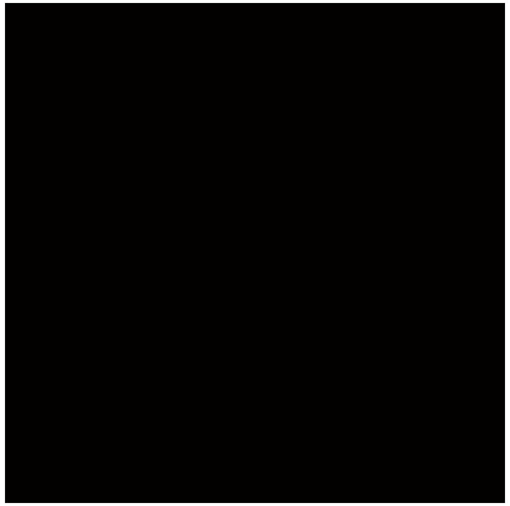
Visible light in tissue at depth < 100-200 µm



Visible light in tissue at depth > a few mm

Propagation of coherent waves in complex media





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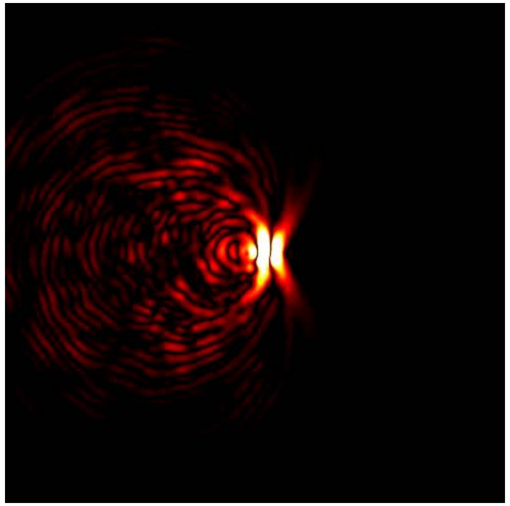

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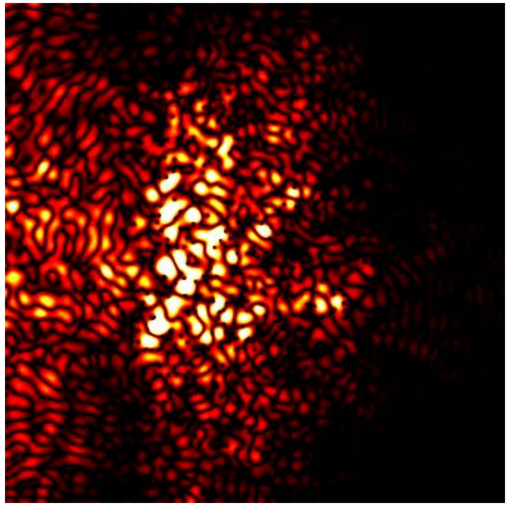
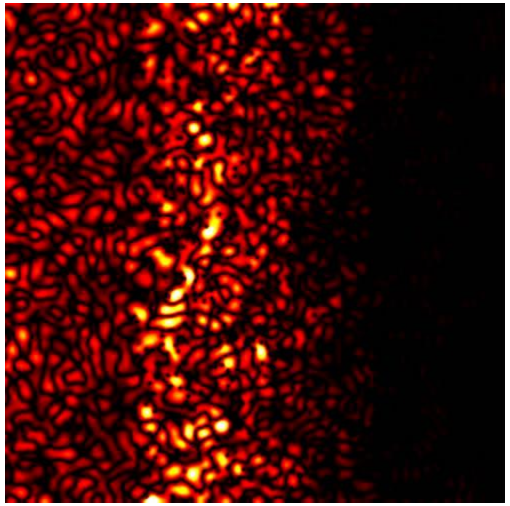
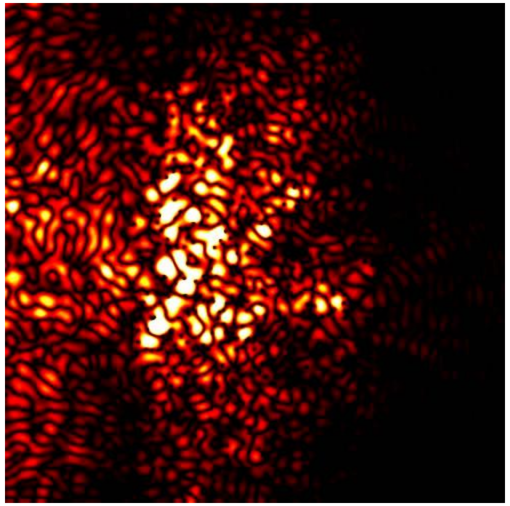


Visible light in tissue at depth > a few mm

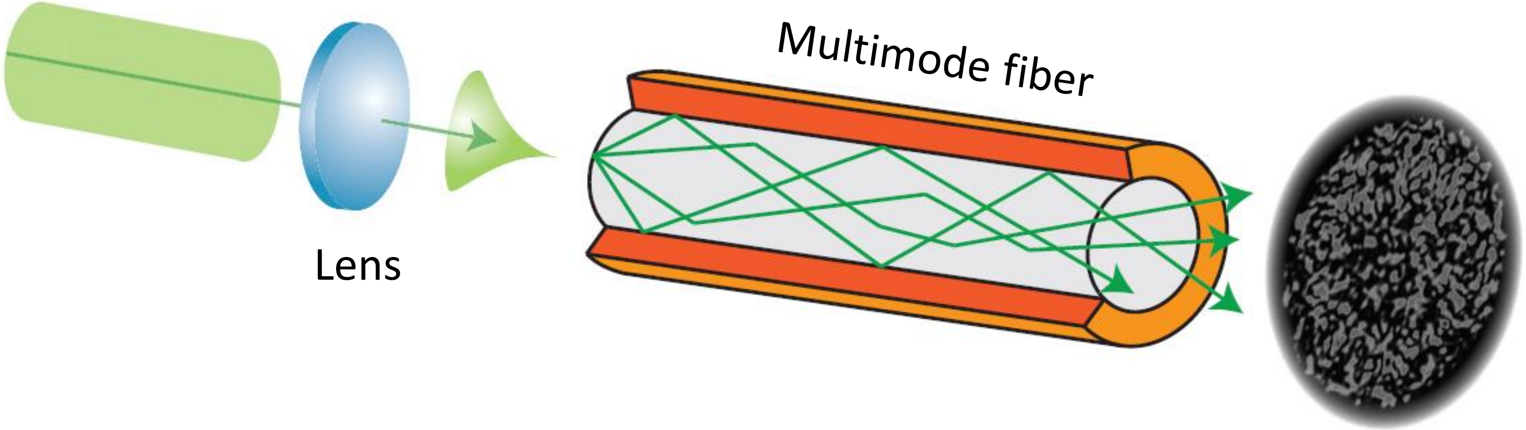
Propagation of coherent waves in complex media





Is it possible to shape a coherent wave that would focus through a multiple scattering material ?

Propagation of coherent waves in a multi-mode fiber



Is it possible to shape a coherent wave that would focus through a multi-mode fiber ?

Is it possible to shape a coherent wave that would focus through a complex medium ?

The answer is : YES, by using spatial light modulators

"The" pioneer experiment: optimization-based focusing through turbid media

August 15, 2007 / Vol. 32, No. 16 / OPTICS LETTERS

Focusing coherent light through opaque strongly scattering media

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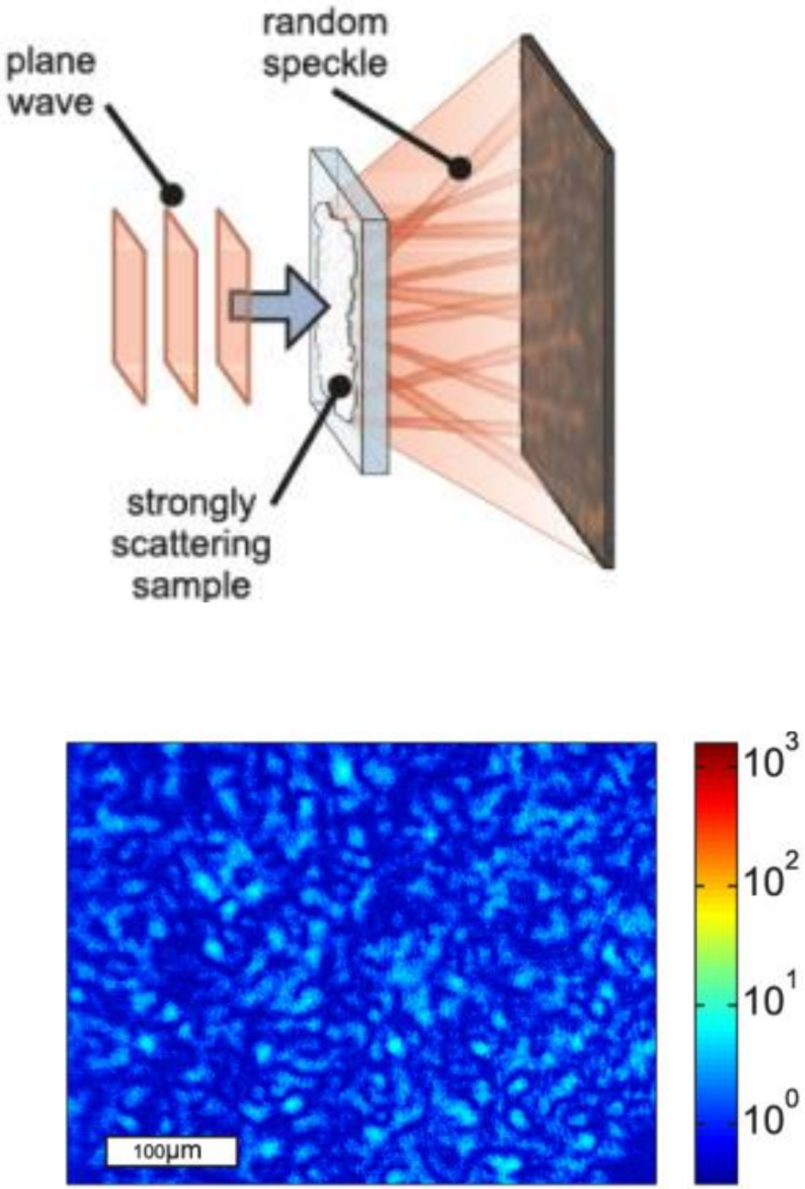
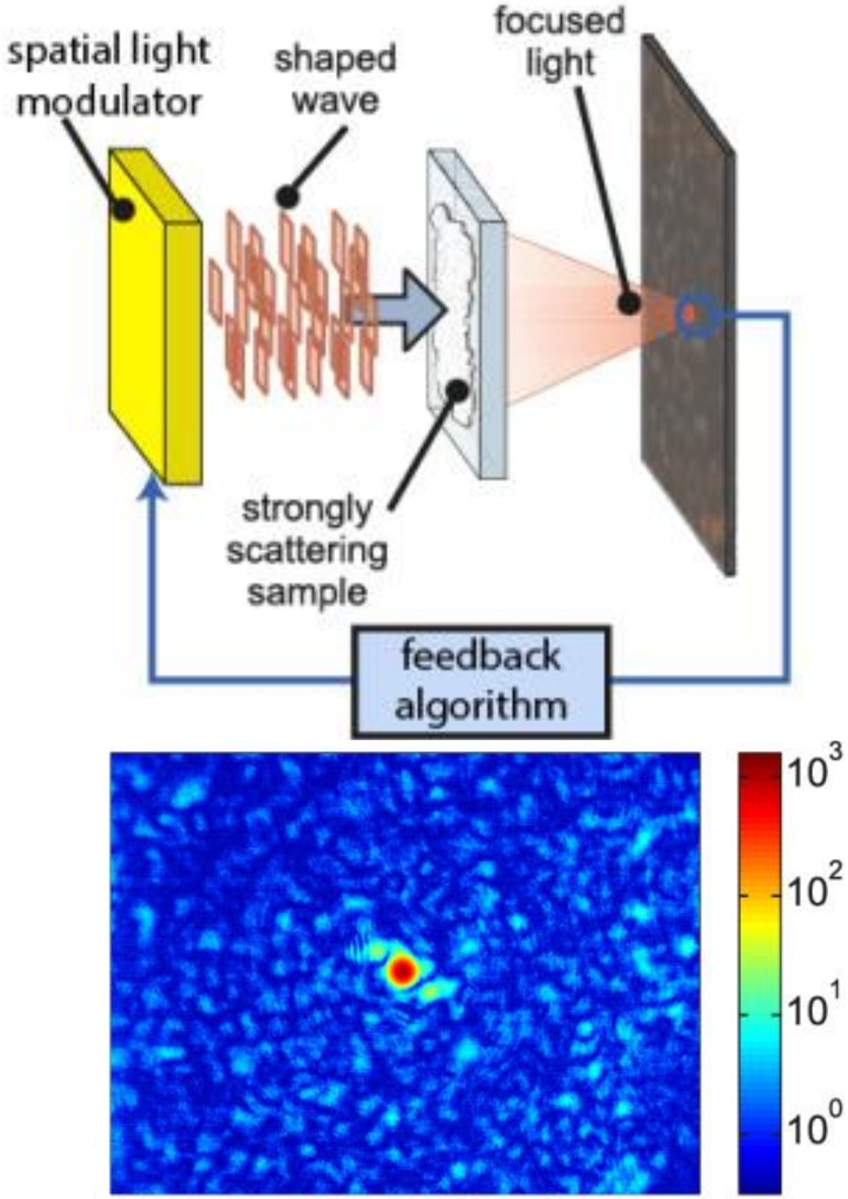
Complex Photonic Systems, Faculty of Science and Technology and MESA+ Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

**Corresponding author: i.m.vellekoop@utwente.nl*

We report focusing of coherent light through opaque scattering materials by control of the incident wavefront. The multiply scattered light forms a focus with a brightness that is up to a factor of 1000 higher than the brightness of the normal diffuse transmission. © 2007 Optical Society of America

The pioneer experiment: optimization-based focusing through turbid media





Vellekoop & Mosk Focusing coherent light through opaque strongly scattering material, Opt. Lett, 32(16),2007.

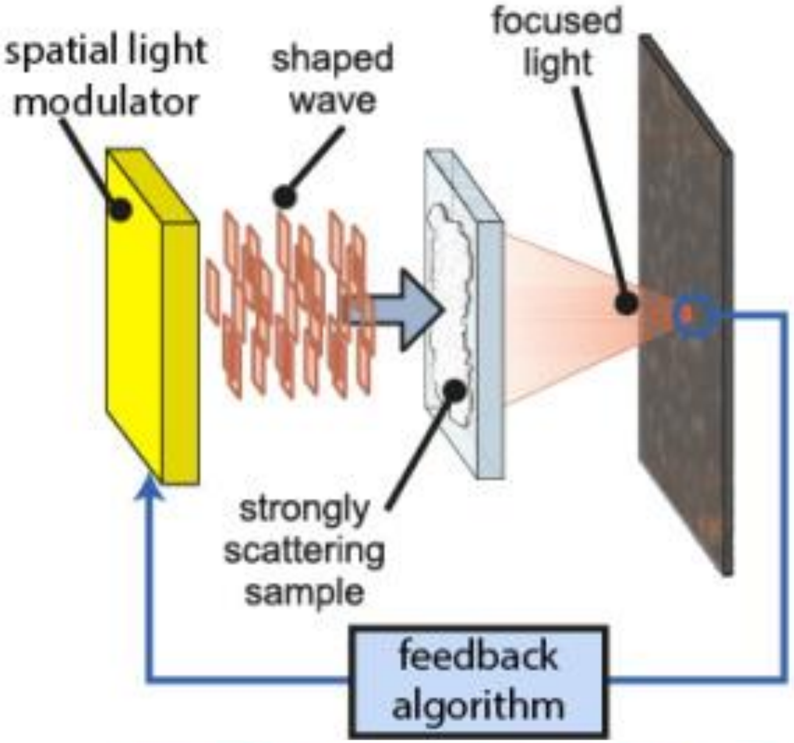
The pioneer experiment: optimization-based focusing through turbid media

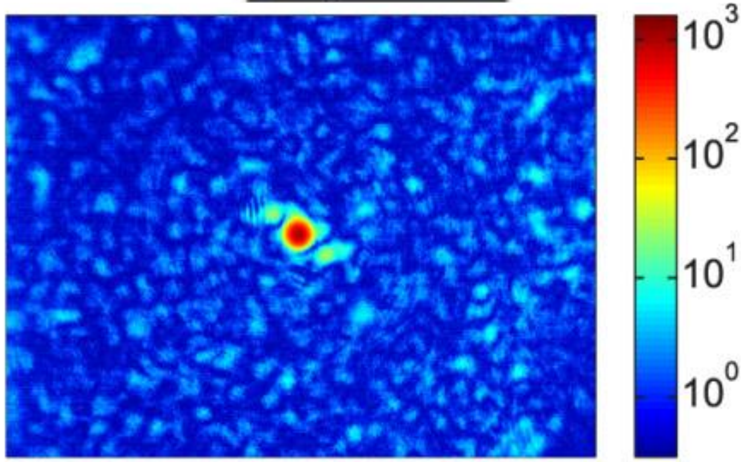
Figure of merit = enhancement η

$$\eta = \frac{I_{focus}}{\langle I_{reference} \rangle}$$

Theoretical prediction:

$$\eta \propto N_{SLM\ pixels}$$





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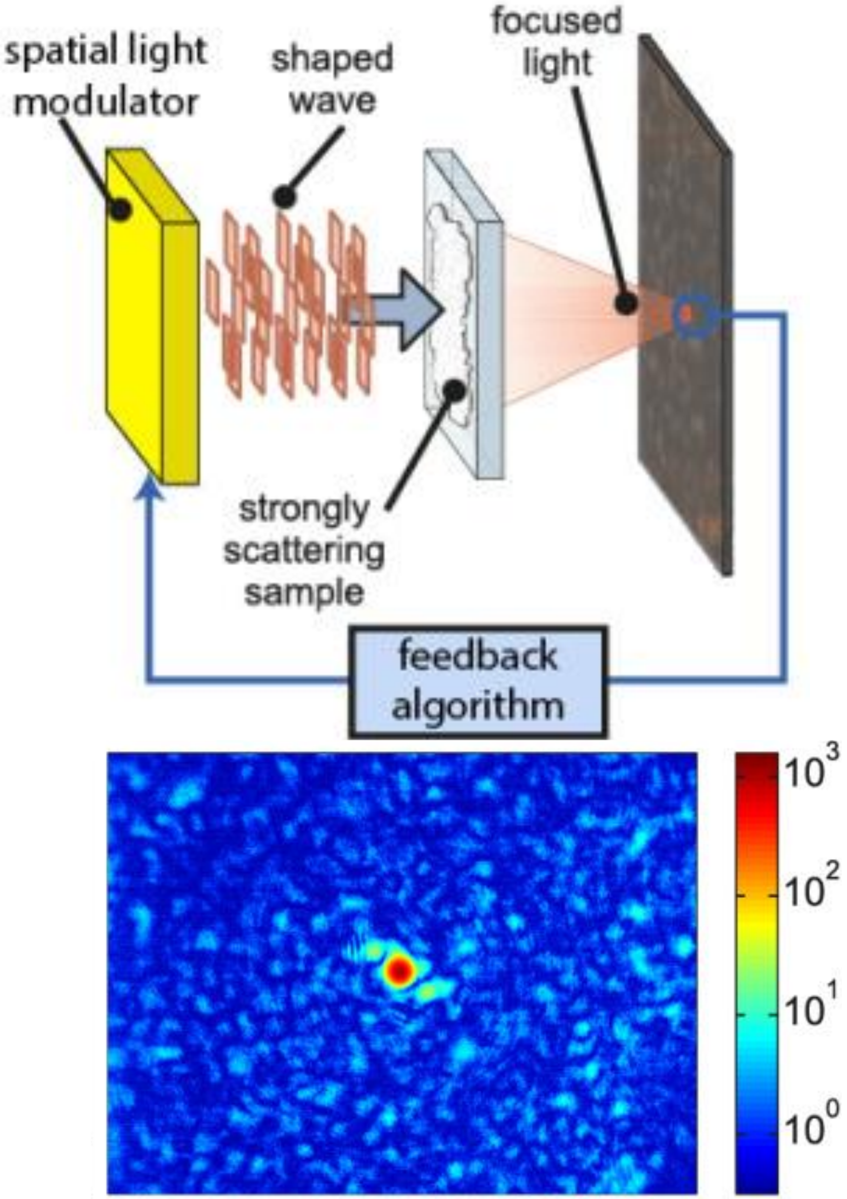
The pioneer experiment: optimization-based focusing through turbid media

Figure of merit = enhancement η

$$\eta = \frac{I_{focus}}{\langle I_{reference} \rangle}$$

Theoretical prediction:

$$\eta \propto \frac{N_{SLM\ pixels}}{M_{speckle\ grain}}$$

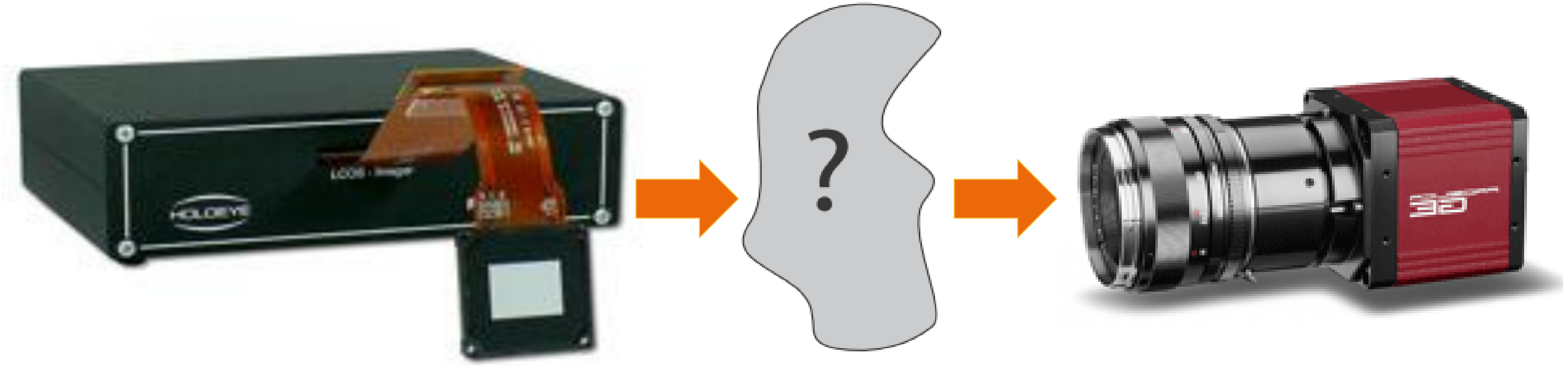


Vellekoop & Mosk Focusing coherent light through opaque strongly scattering material, Opt. Lett, 32(16),2007.

Straightforward conclusions on the ideal SLM for complex wavefront shaping

- **Phase modulation** ↔ Control of interference state
- **Large number N of pixels** ↔ Control of N-wave interference
- **High refresh rate** ↔ Reasonable experiment time

Another approach using SLM: transmission matrix of linear media (including complex media…)



SLM : array of pixels

Linear system

camera CCD : arrays of pixels

- N input "modes"
- M output "modes"

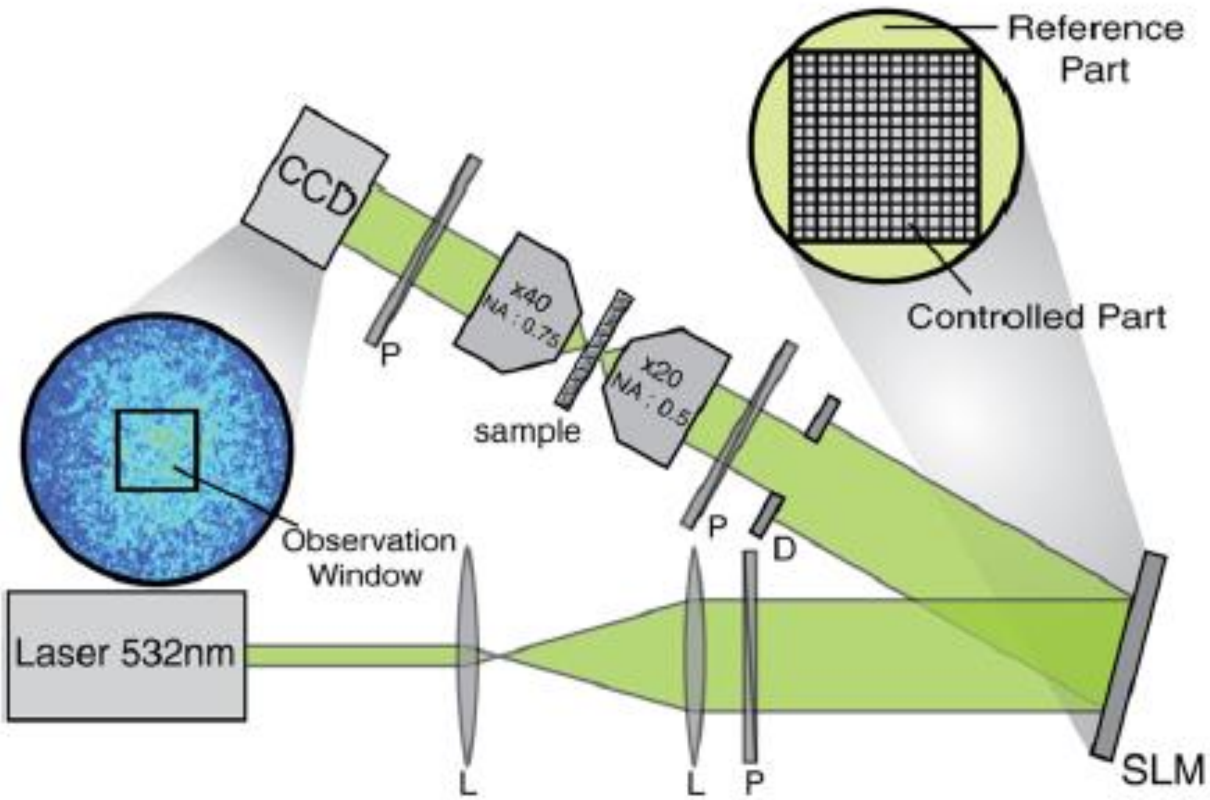
$$E_\beta^{out} = \sum_{\alpha=1}^{N} h_{\beta\alpha} E_\alpha^{in}$$

Measurement of an optical transmission matrix through a strongly scattering medium

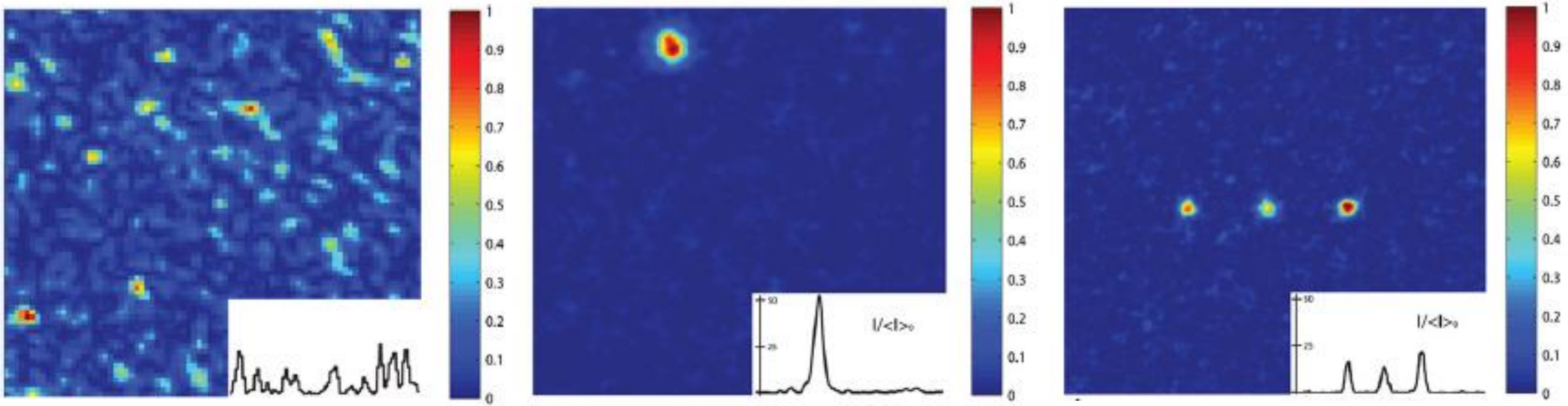
PRL **104,** 100601 (2010) PHYSICAL REVIEW LETTERS 12 MARCH 2010

Measuring the Transmission Matrix in Optics: An Approach to the Study and Control of Light Propagation in Disordered Media

S. M. Popoff, G. Lerosey, R. Carminati, M. Fink, A. C. Boccara, and S. Gigan
Institut Langevin, ESPCI ParisTech, CNRS UMR 7587, ESPCI, 10 rue Vauquelin, 75005 Paris, France

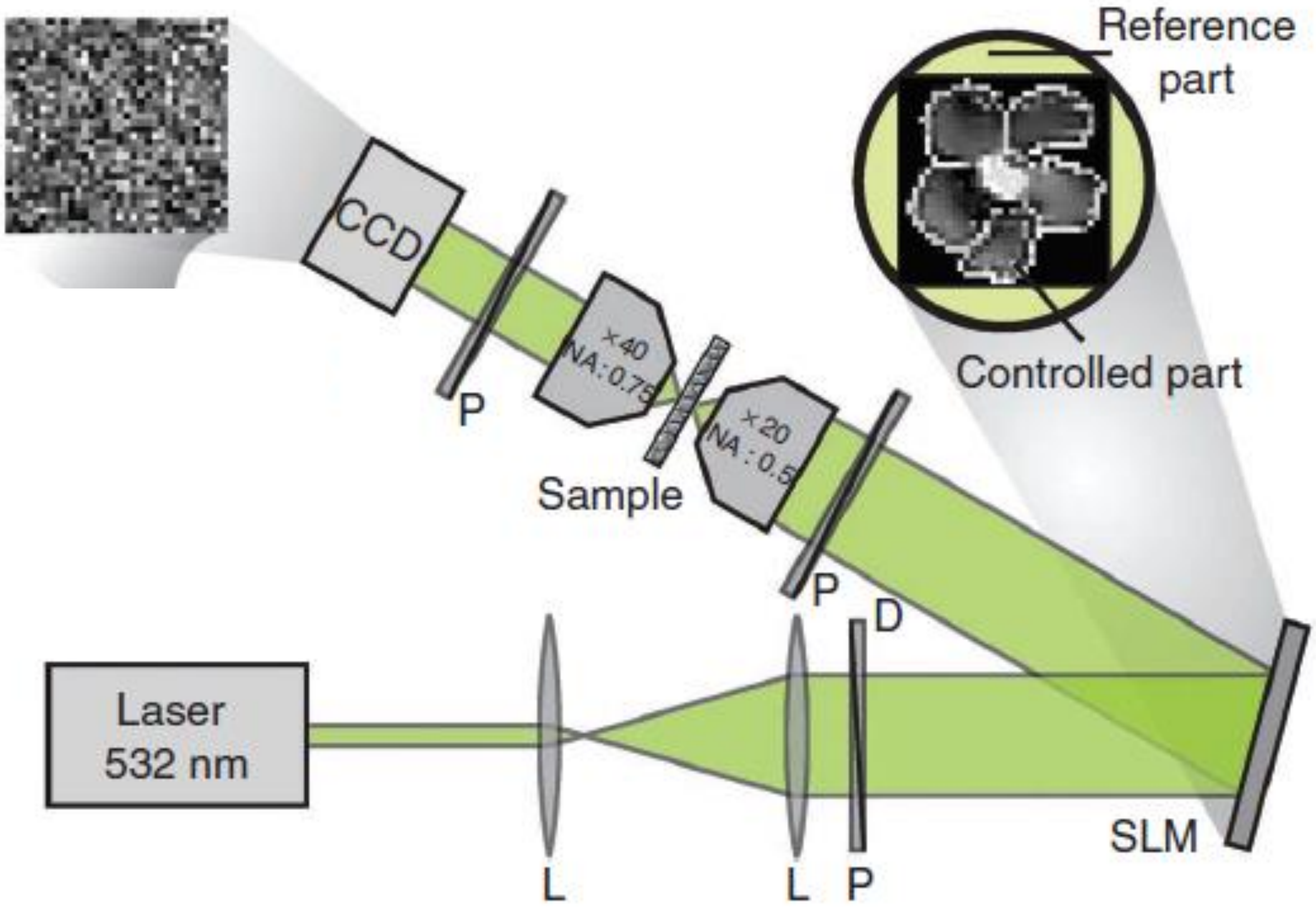


Measurement of an optical transmission matrix through a strongly scattering medium



Popoff et al. Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media. PRL, 104(10), 2010.

Image transmission through a complex medium with the transmission matrix

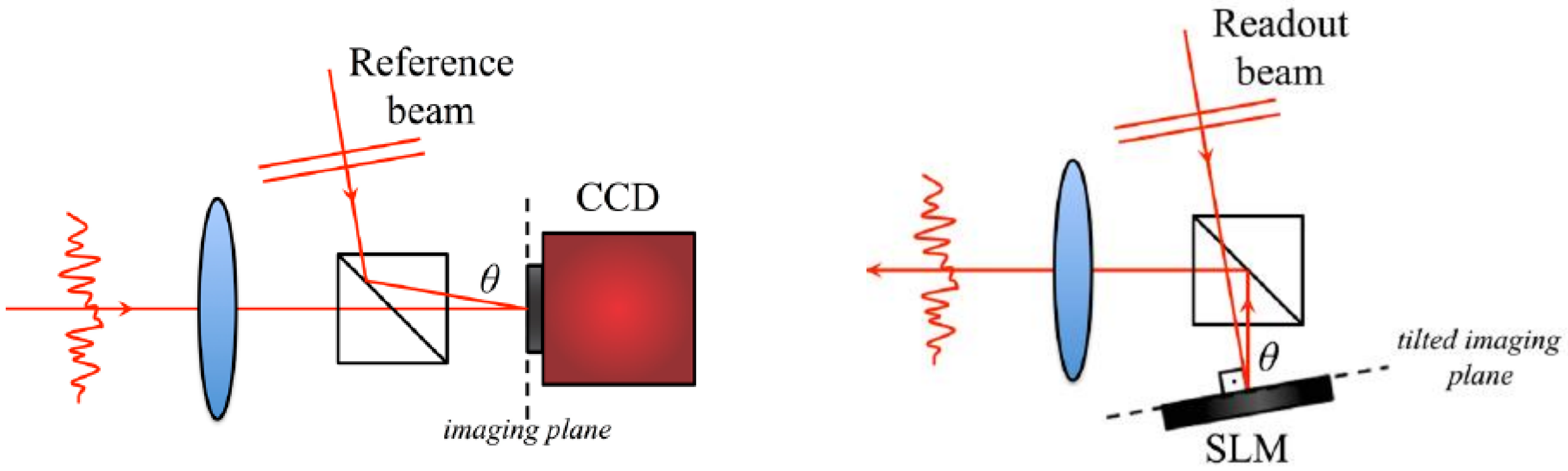


Popoff et al, "Image transmission through an opaque material", Nat. Comm, 1(81), 2010.

Additional conclusions on the ideal SLM for complex wavefront shaping

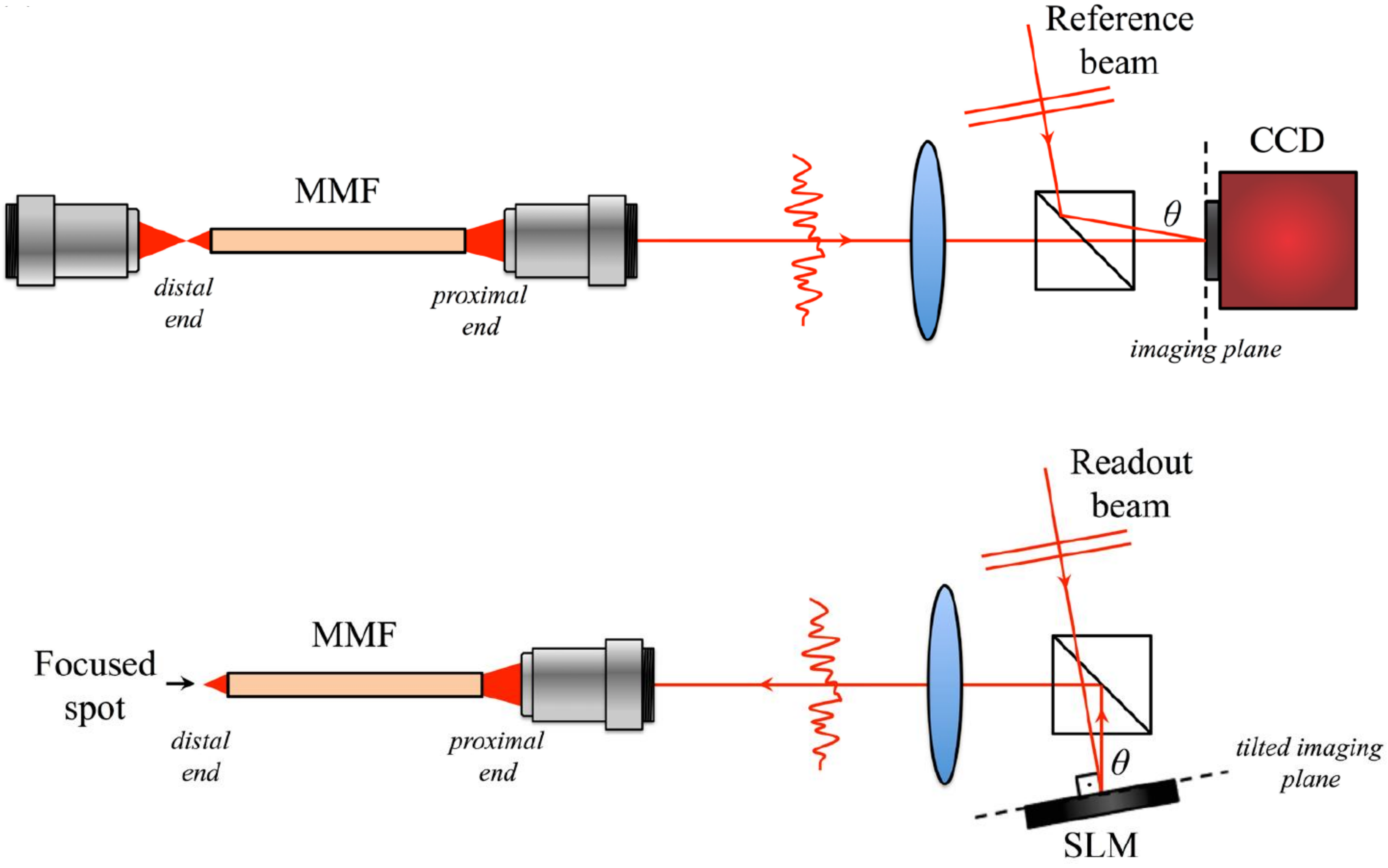
- **Phase/amplitude modulation** ↔ Full control of input fields
- **Large number N of pixels** ↔ Large number of input patterns
- **High refresh rate** ↔ Reasonable experiment time

Another technique using SLM: Digital Optical Phase Conjugation (DOPC)



Cui, M., & Yang, C. Implementation of a digital optical phase conjugation system and its application to …. *Optics express*, *18*(4), 2010.

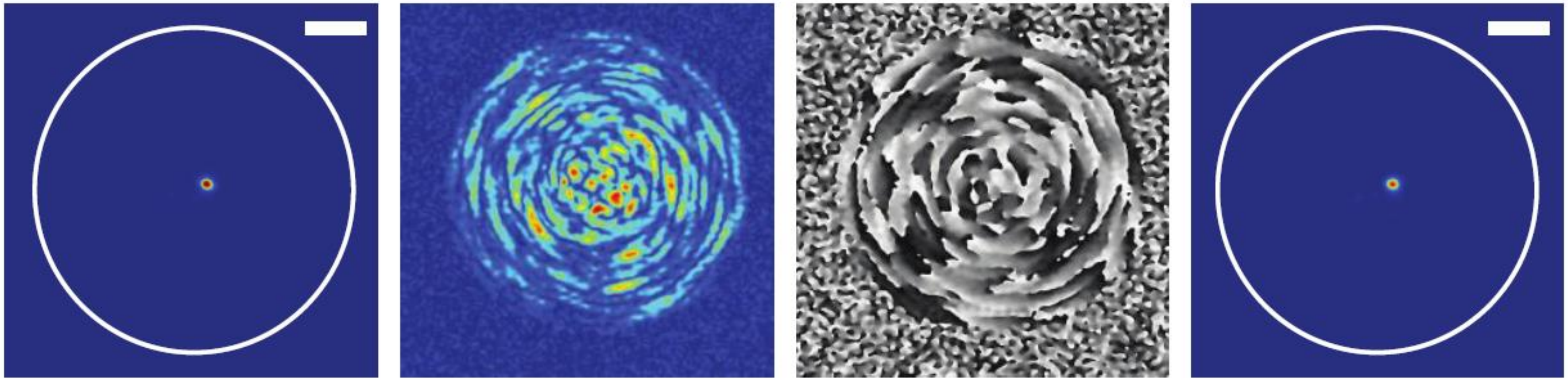
Another technique using SLM: Digital Optical Phase Conjugation (DOPC)



Courtesy: Nicolino Stasio, PhD manuscript, EPFL 2017

Another technique using SLM: Digital Optical Phase Conjugation (DOPC)

Reference pattern at the input side	Intensity pattern at the output side	Phase pattern at the output side	Input side after phase conjugation at the output side



Papadopoulos et al, *Focusing and scanning light through a multimode optical fiber using digital phase conjugation*, Opt. Exp., 20(10), 2012

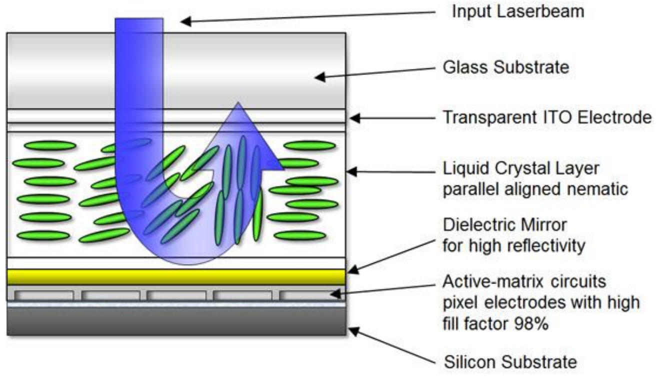
Additional conclusions on the ideal SLM for complex wavefront shaping

- **Phase/amplitude modulation** $\leftrightarrow$ Full control of input fields
- **Large number N of pixels** $\leftrightarrow$ Good spatial sampling of field
- **High refresh rate**
- **Fast SLM-PC transfer rate**

$\leftrightarrow$ Fast digital phase conjugation

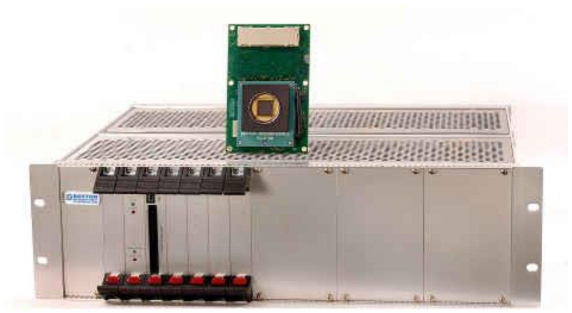
Typical commercial spatial light modulators:

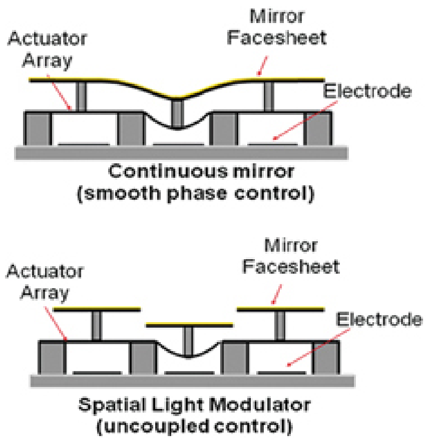
Liquid-crystal SLM



- Modulate phase or amplitude
- Megapixels
- Slow (~ < 100 Hz)
- Relatively "cheap" (20k€)

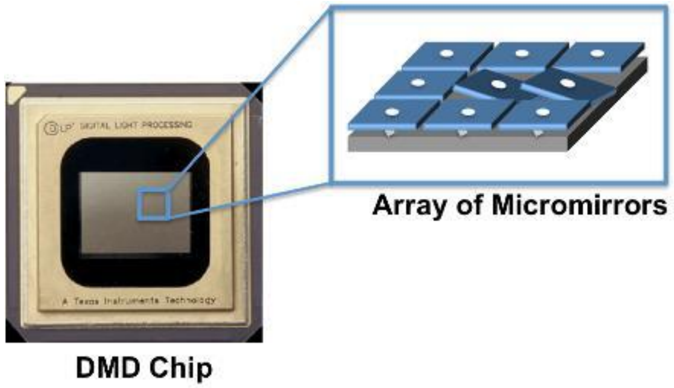
Deformable mirrors





- Modulate phase
- Kilopixels
- Fast (up to 22kHz)
- Very Expensive (~100k€)

Digital micromirrors devices



- Binary amplitude modulation
- Megapixels
- Fast (up to 22kHz)
- "Cheap" (15K€)

Current status:

Fast + Mega pixel → **DMD**

DMD → **Binary amplitude modulation**

<u>Current workaround</u>: "conversion" of binary amplitude modulation to phase modulation

Binary amplitude off-axis holography

Conkey et al., *High-speed scattering medium characterization with application to focusing light through turbid media*. *Opt. Exp.*, *20*(2), 2012.

Super-pixel approaches

Goorden et al, *Superpixel-based spatial amplitude and phase modulation using a DMD*. *Optics Express* 22(15), 2014

Binary amplitude modulation to binary phase modulation

Hoffmann et al, *Kilohertz binary phase modulator for pulsed laser sources using a DMD*, arXiv:1710.06936

Conclusion: requirements for an ideal SLM for complex wavefront shaping

- Phase modulation (0-2π)
- Large number of pixels (≥ millions of pixels)
- High refresh rate (≥ tens of KHz)
- Fast SLM-PC transfer rate (≥ GB/s, USB 3.0)

Thank you for your attention

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