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

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Workshop on SLM, EPFL, Lausanne, 27 October 2017
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
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
Is it possible to shape a coherent wave that would focus through a multiple scattering material?
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.
Focusing coherent light through opaque strongly scattering media

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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

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Figure of merit = enhancement $\eta$

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

Theoretical prediction:

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

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Figure of merit = enhancement $\eta$

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

Theoretical prediction:

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

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...)

- 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
Measurement of an optical transmission matrix through a strongly scattering medium

Image transmission through a complex medium with the transmission matrix

Additional conclusions on the ideal SLM for complex wavefront shaping

• Phase/amplitude modulation $\leftrightarrow$ Full control of input fields

• Large number $N$ of pixels $\leftrightarrow$ Large number of input patterns

• High refresh rate $\leftrightarrow$ Reasonable experiment time
Another technique using SLM: Digital Optical Phase Conjugation (DOPC)

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Reference beam

CCD
imaging plane

Focused spot

MMF

Readout beam

SLM
tilted imaging plane

Courtesy: Nicolino Stasio, PhD manuscript, EPFL 2017
Another technique using SLM: Digital Optical Phase Conjugation (DOPC)

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 $\leftrightarrow$ Fast digital phase conjugation
- Fast SLM-PC transfer rate
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 $\rightarrow$ DMD

DMD $\rightarrow$ Binary amplitude modulation

**Current workaround:** “conversion” of binary amplitude modulation to phase modulation

Binary amplitude off-axis holography

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
Conclusion: requirements for an ideal SLM for complex wavefront shaping

- Phase modulation (0-2\(\pi\))
- 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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