Lighting Up Opaque Media

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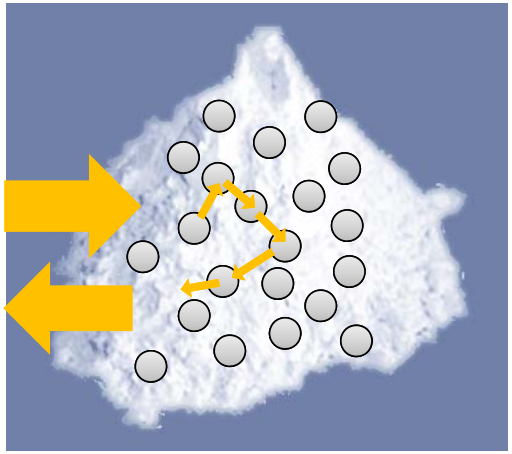
Opaque Media

Glass

Ground Glass



Strong Scattering Media

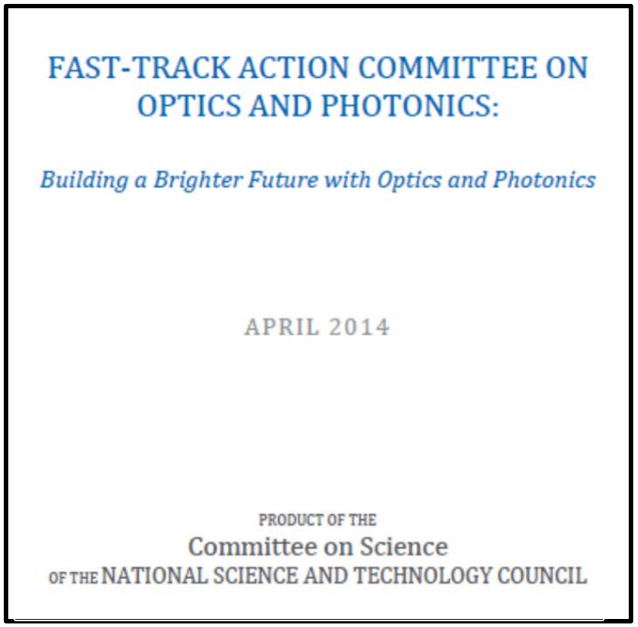
Cloud

Fog

Biological tissue

Sand Storm

National Photonics Initiative


FAST-TRACK ACTION COMMITTEE ON OPTICS AND PHOTONICS:

Building a Brighter Future with Optics and Photonics

APRIL 2014

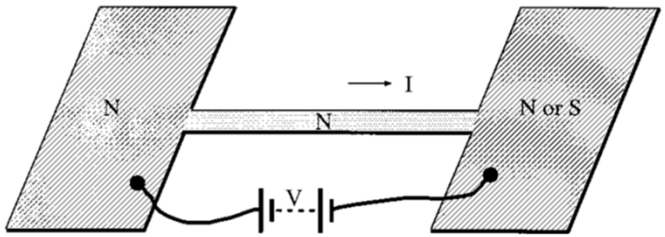
PRODUCT OF THE
Committee on Science
OF THE NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

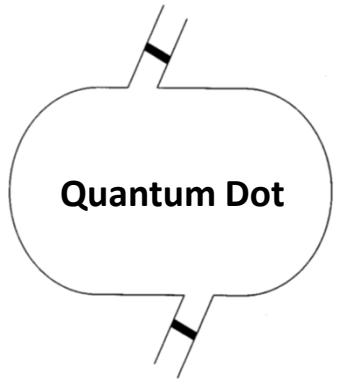
Four research opportunities of high priority

Imaging through complex media

To advance the science of light propagation and imaging through scattering, dispersive, and turbulent media

Mesoscopic Electron Transport





Interference of coherent electron wave

↓

Anderson localization

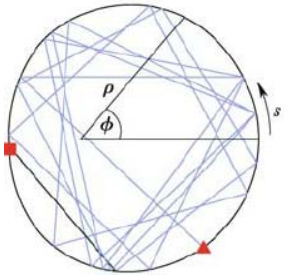
Universal conductance fluctuation

Mesoscopic Optics

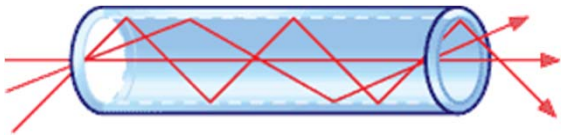
Classical wave: light, microwave, acoustic wave

Scattering medium

Chaotic cavity



Multi-mode fiber

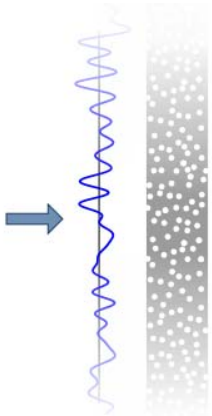


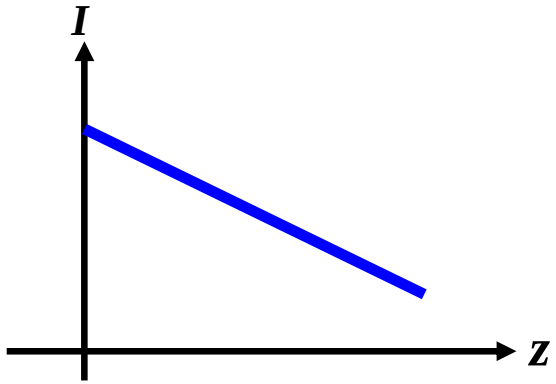
How to enhance light transmission through strong-scattering medium?

Diffusion Model

Diffusion equation $$\frac{\partial}{\partial t} I(r,t) = D\nabla^2 I(r,t)$$

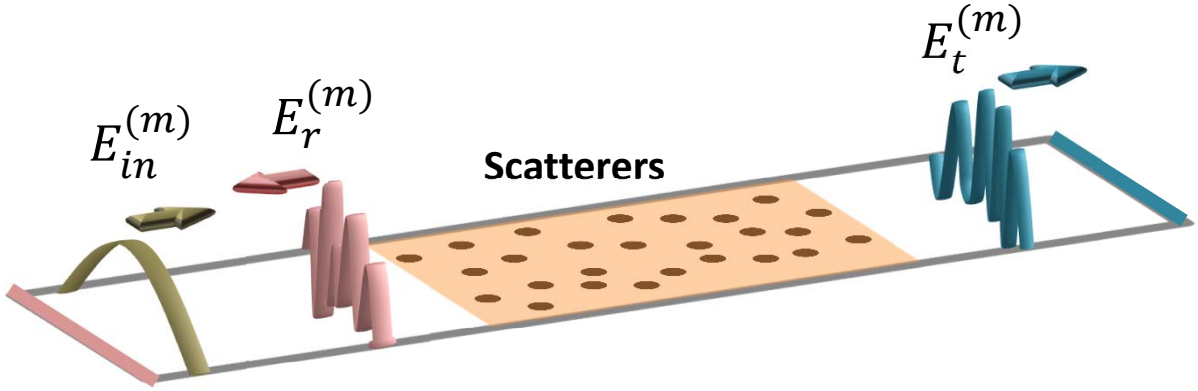
Diffusion coefficient $$D = \frac{v}{3} l_t$$





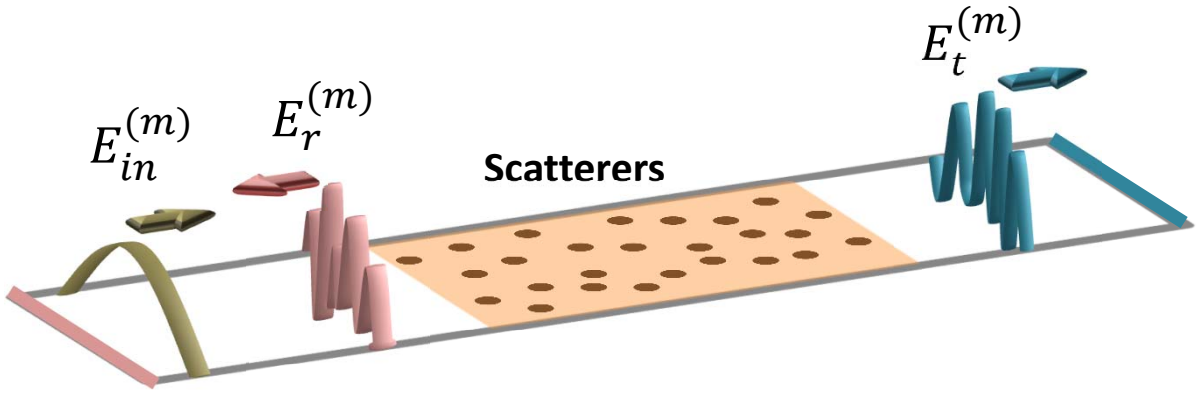
$$\langle T \rangle \approx \frac{l_t}{L} << 1$$

Transmission Matrix



Field transmission matrix $t = \begin{pmatrix} t_{11} & \cdots & t_{1N} \\ \vdots & \ddots & \vdots \\ t_{N1} & \cdots & t_{NN} \end{pmatrix}$

Transmission Matrix

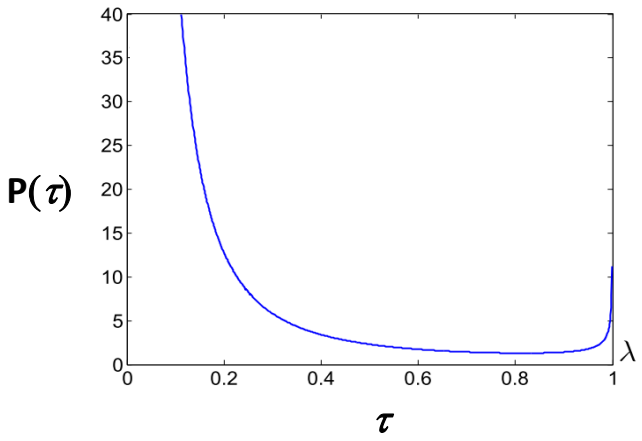


$$t = \begin{pmatrix} u_{11} & \cdots & u_{1N} \\ \vdots & & \vdots \\ u_{N1} & \cdots & u_{NN} \end{pmatrix} \begin{pmatrix} \sqrt{\tau_1} & & 0 \\ & \ddots & \\ 0 & & \sqrt{\tau_N} \end{pmatrix} \begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & & \vdots \\ v_{N1} & \cdots & v_{NN} \end{pmatrix}^{\dagger}$$

Transmission Eigenchannel

Bimodal distribution of transmission eigenvalues

$$\rho(\tau) \propto \frac{\langle \tau \rangle}{\tau\sqrt{1-\tau}}$$



$$\langle \tau \rangle \ll 1$$

Open channel $\tau \sim 1$

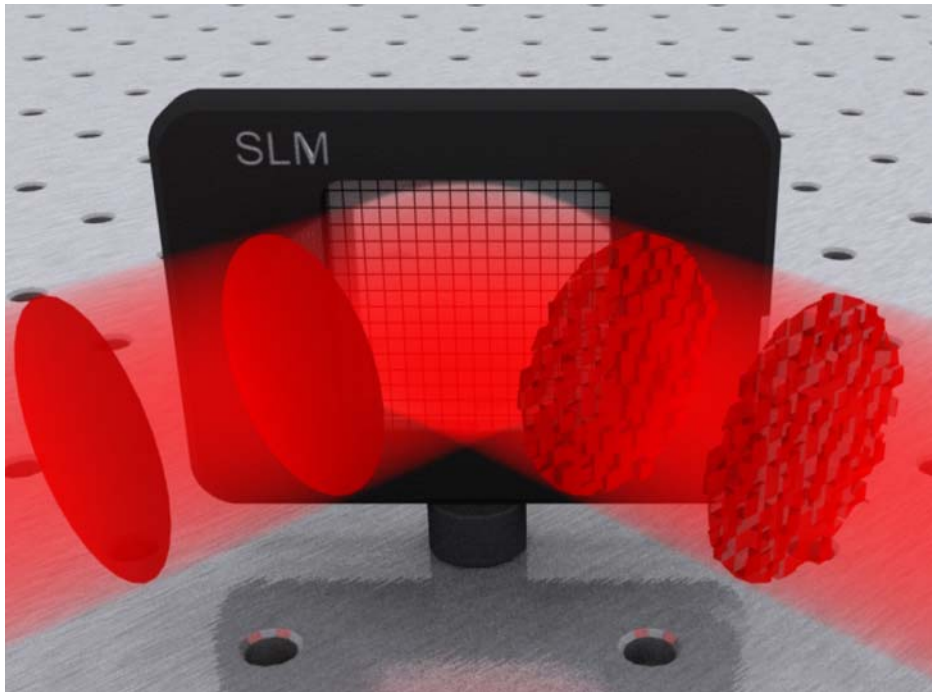
Closed channel $\tau \sim 0$

Dorokhov, *Solid State Commun*. **51**, 381 (1984)
Mello *et al. Ann. Phys.* **181**, 290 (1988)

Optical Wavefront Shaping

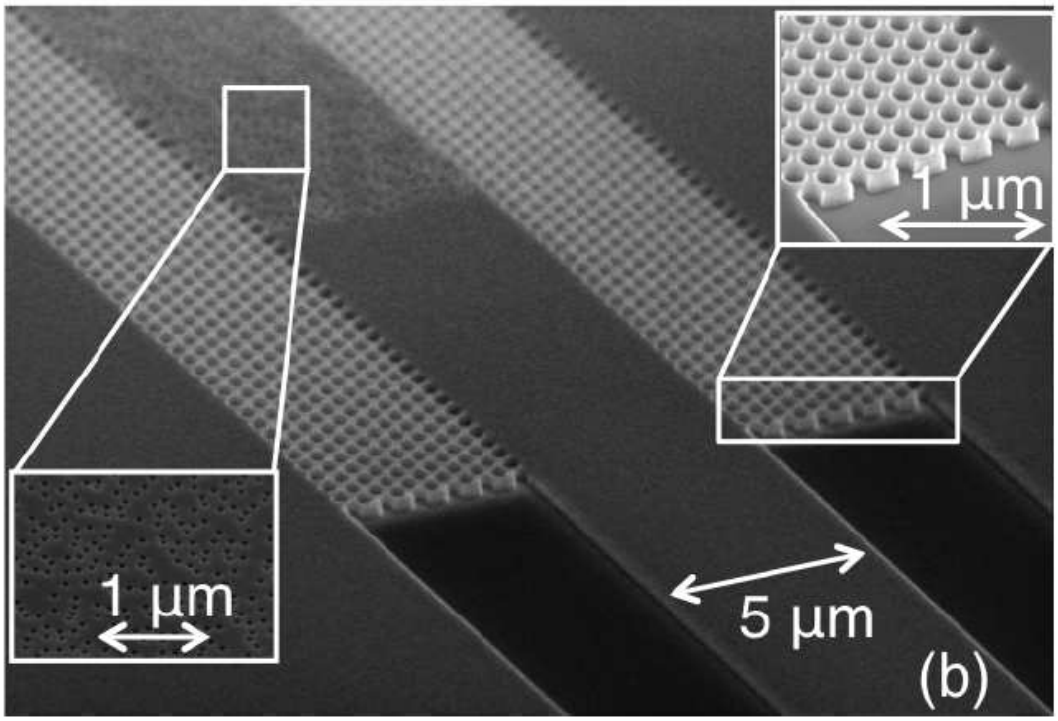
Spatial light modulator (SLM)

Flat phase in



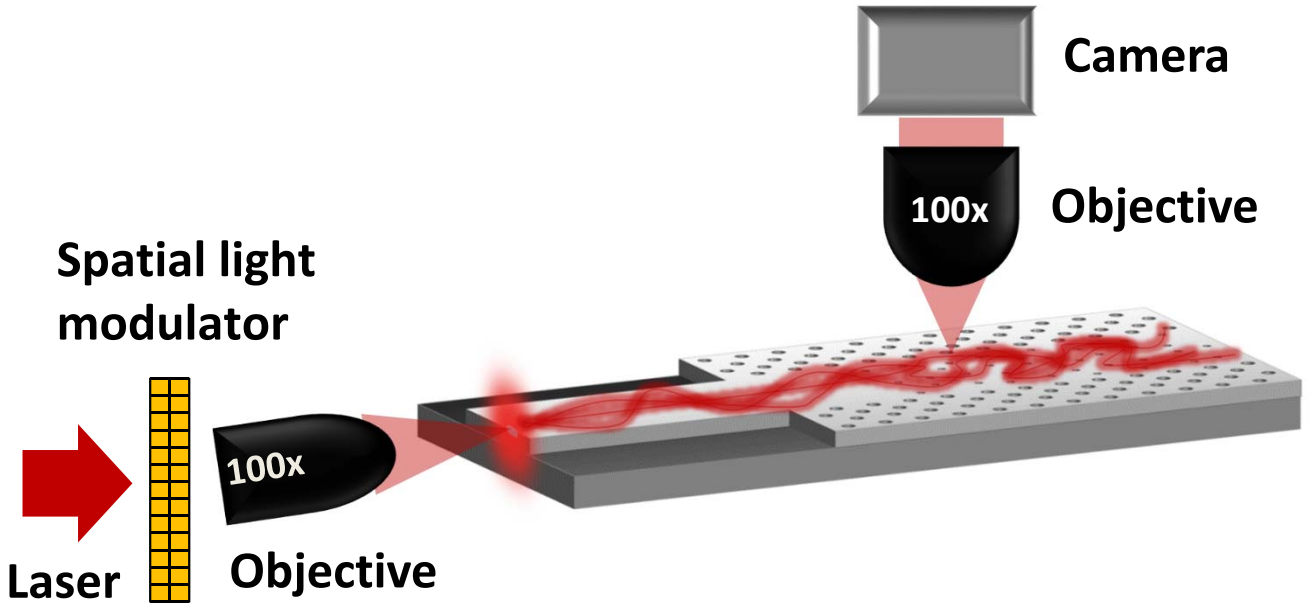
Structured phase out

Silicon Waveguide



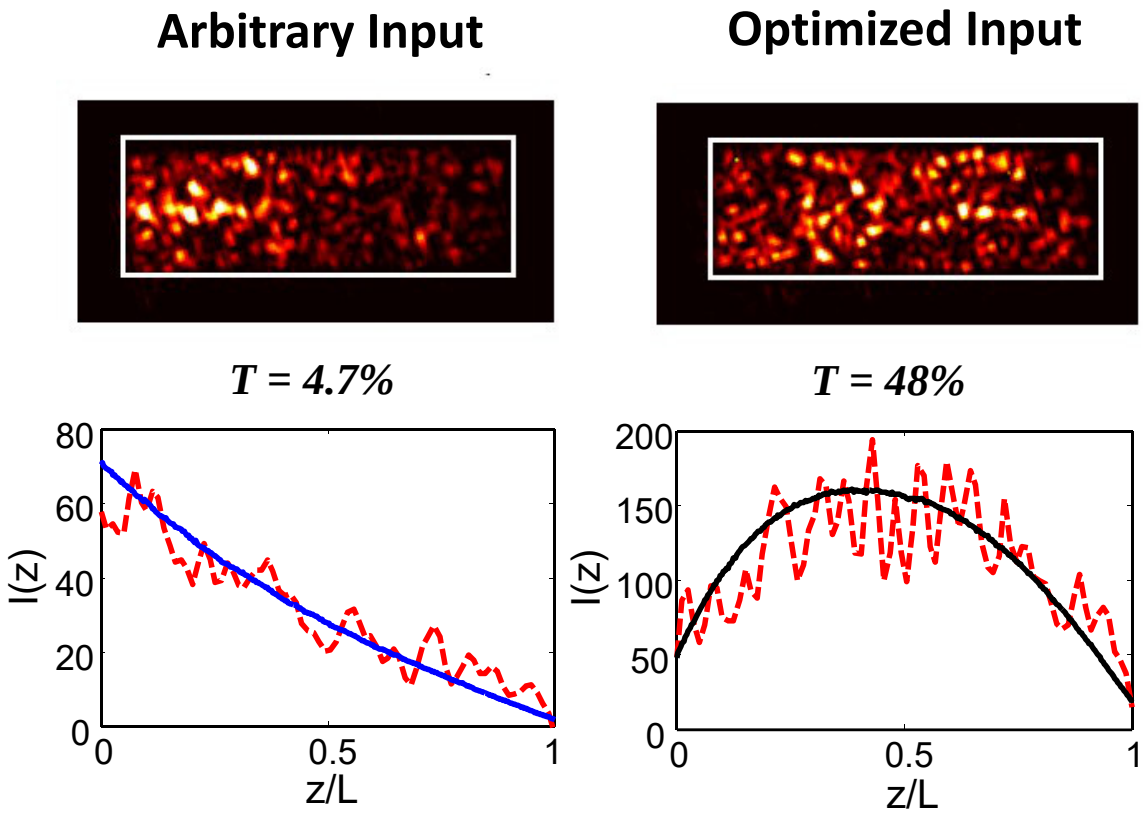
Yamilov *et al, Phys. Rev. Lett.* 112, 023904 (2014)

Direct Probing of Light Propagation inside quasi-2D Disordered Structure



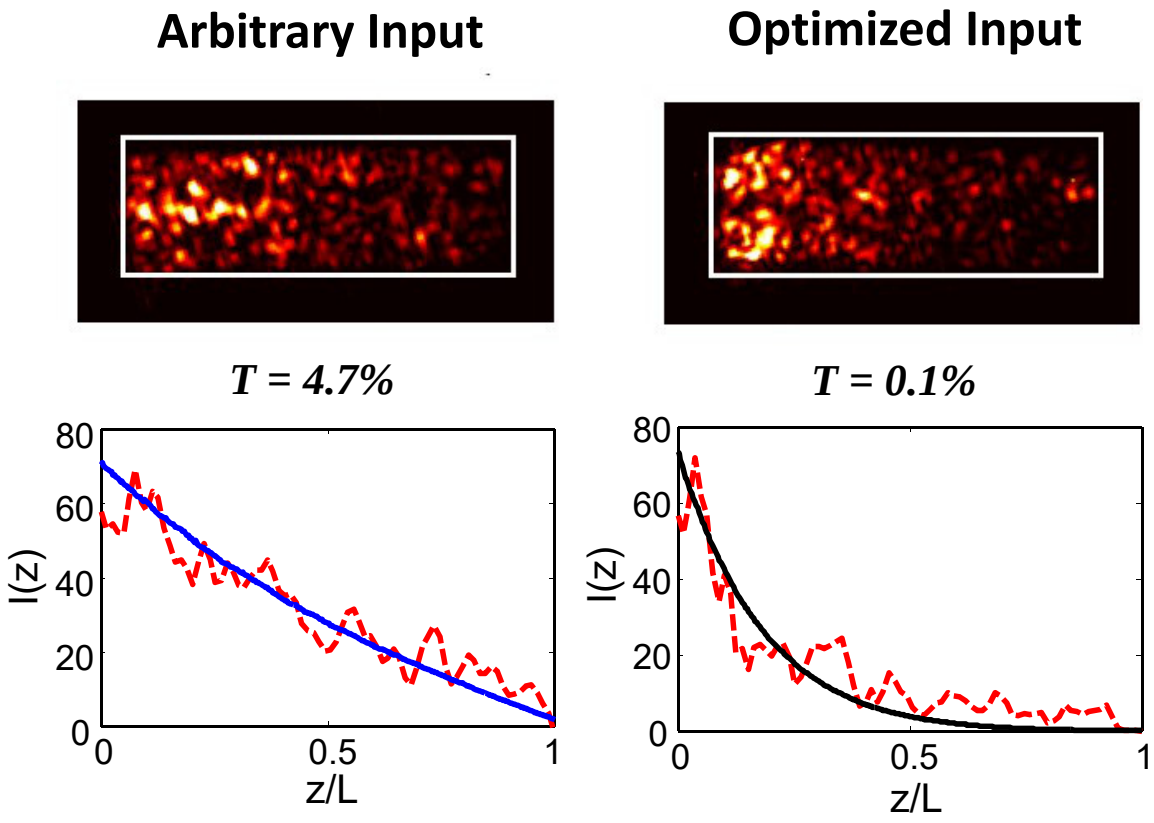
Yamilov *et al*, *Phys. Rev. Lett.* 112, 023904 (2014)

Maximizing Transmission



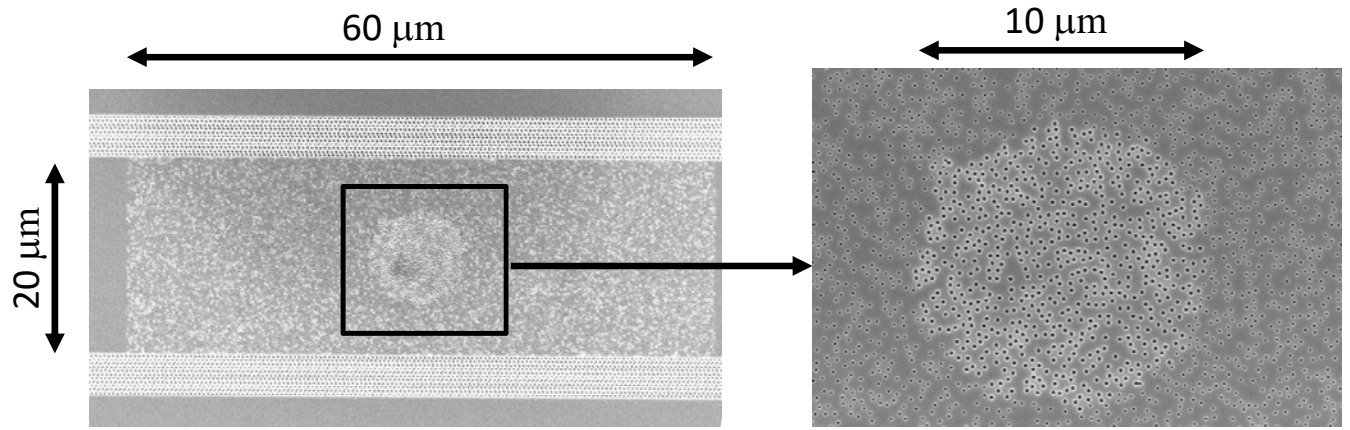
Sarma *et al*, *Phys. Rev. Lett.* 117, 086803 (2016)

Minimizing Transmission

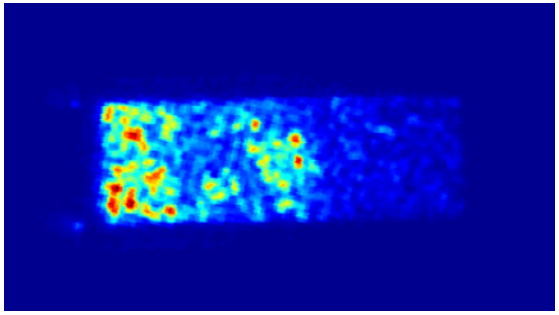


Sarma *et al*, *Phys. Rev. Lett.* 117, 086803 (2016)

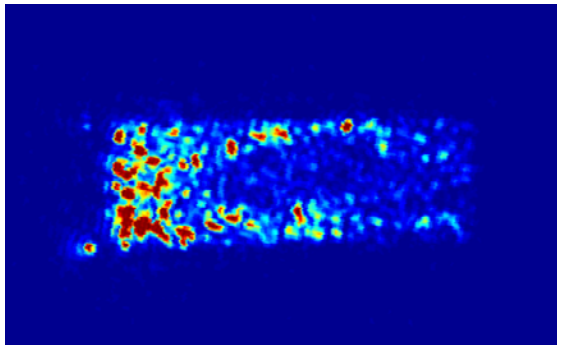
Inhomogeneous Scattering



Before optimization

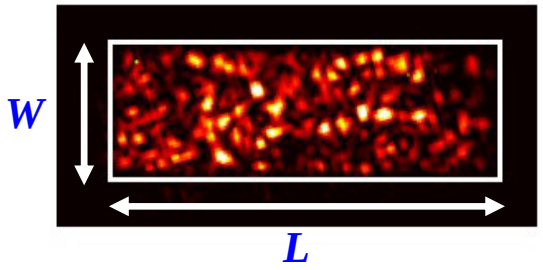


After optimization



Sarma *et al*, *Appl. Phys. Lett.* 110, 021103 (2017)

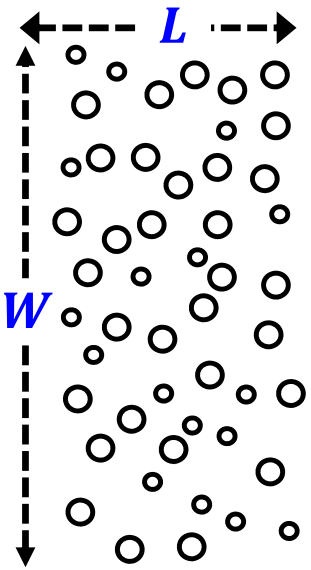
Quasi-1D waveguide, reflecting sidewall



$L >> W$

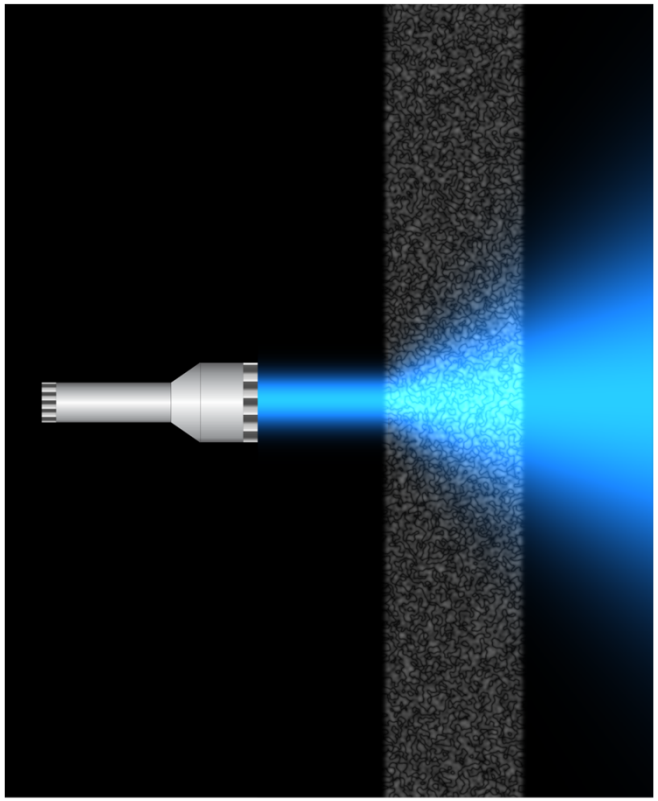
Wide slab, open boundary

$W >> L$

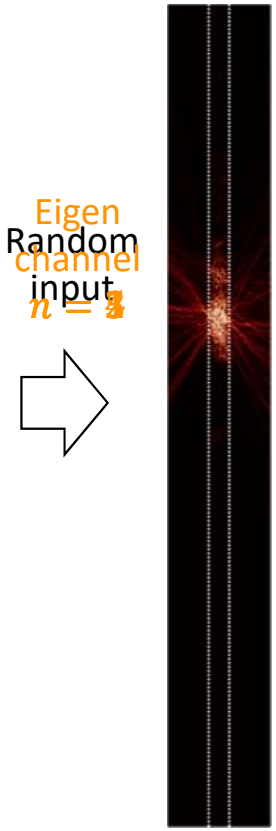


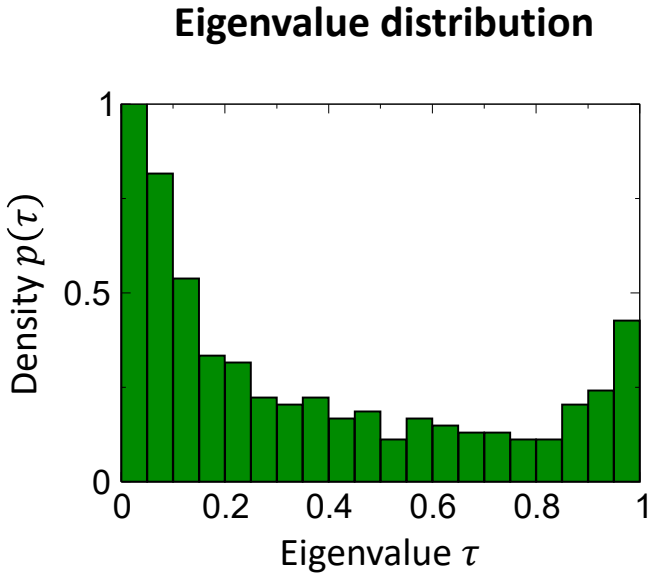
Choi et al, *Phys. Rev. B* **83**, 134207 (2011)
Ojambati et al, *Opt. Express* **24**, 18525 (2016)

Lateral Spreading of Light

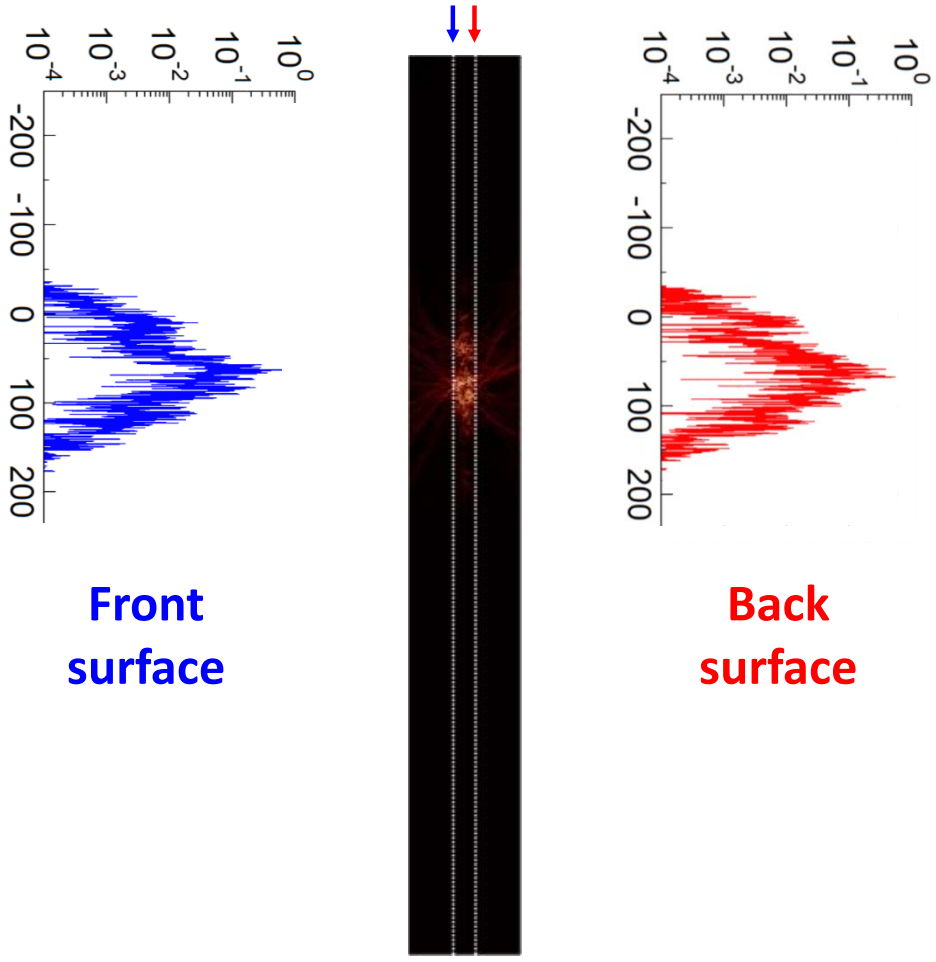


Transmission Eigenchannel





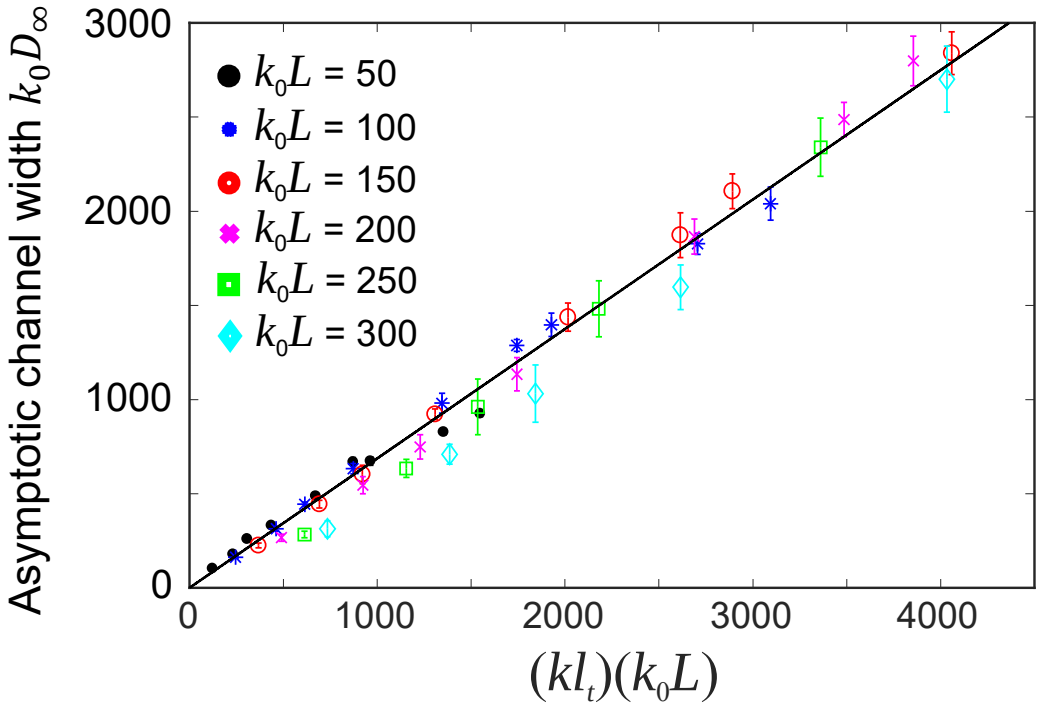
Yılmaz et al, *Nat. Photon.* 13, 352 (2019)



Yılmaz et al, *Nat. Photon.* 13, 352 (2019)

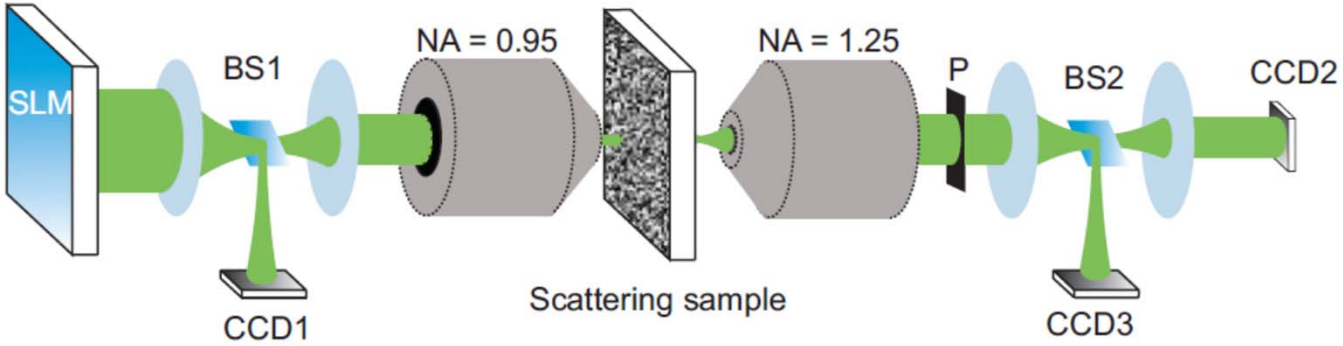
Channel Width

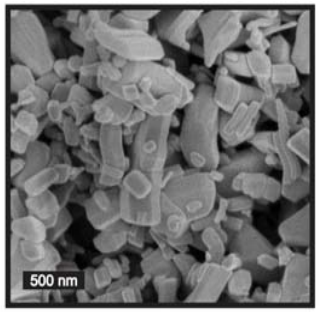
$$D \propto (kl_t)L$$



Yılmaz et al, *Nat. Photon.* 13, 352 (2019)

Experimental Setup

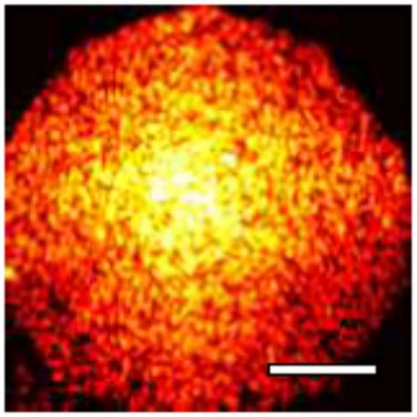




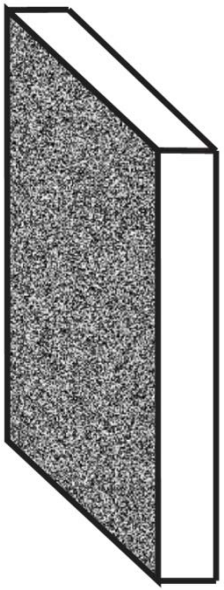
W = 1 cm
L = 10 µm
l_t = 1.5 µm

High Transmission Eigenchannel

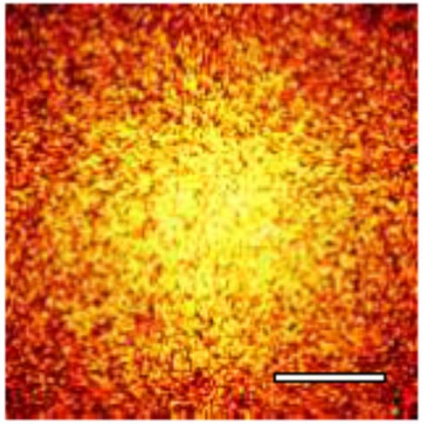
Front surface



$D_{in} \propto 10\ \mu m$



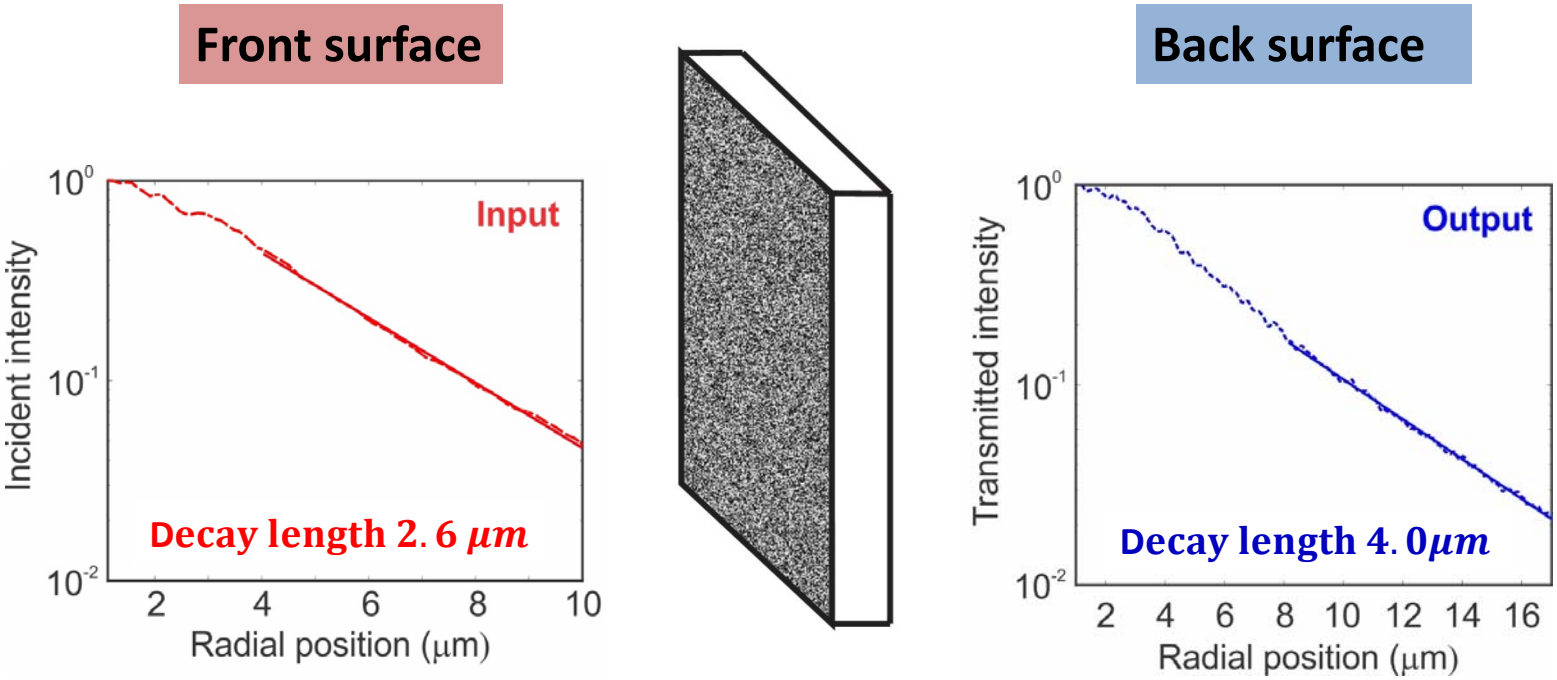
Back surface



$D_{out} \propto 14\ \mu m$

Yılmaz et al, *Nat. Photon.* 13, 352 (2019)

Transverse Localization



Yılmaz et al, *Nat. Photon.* 13, 352 (2019)

Intensity Enhancement

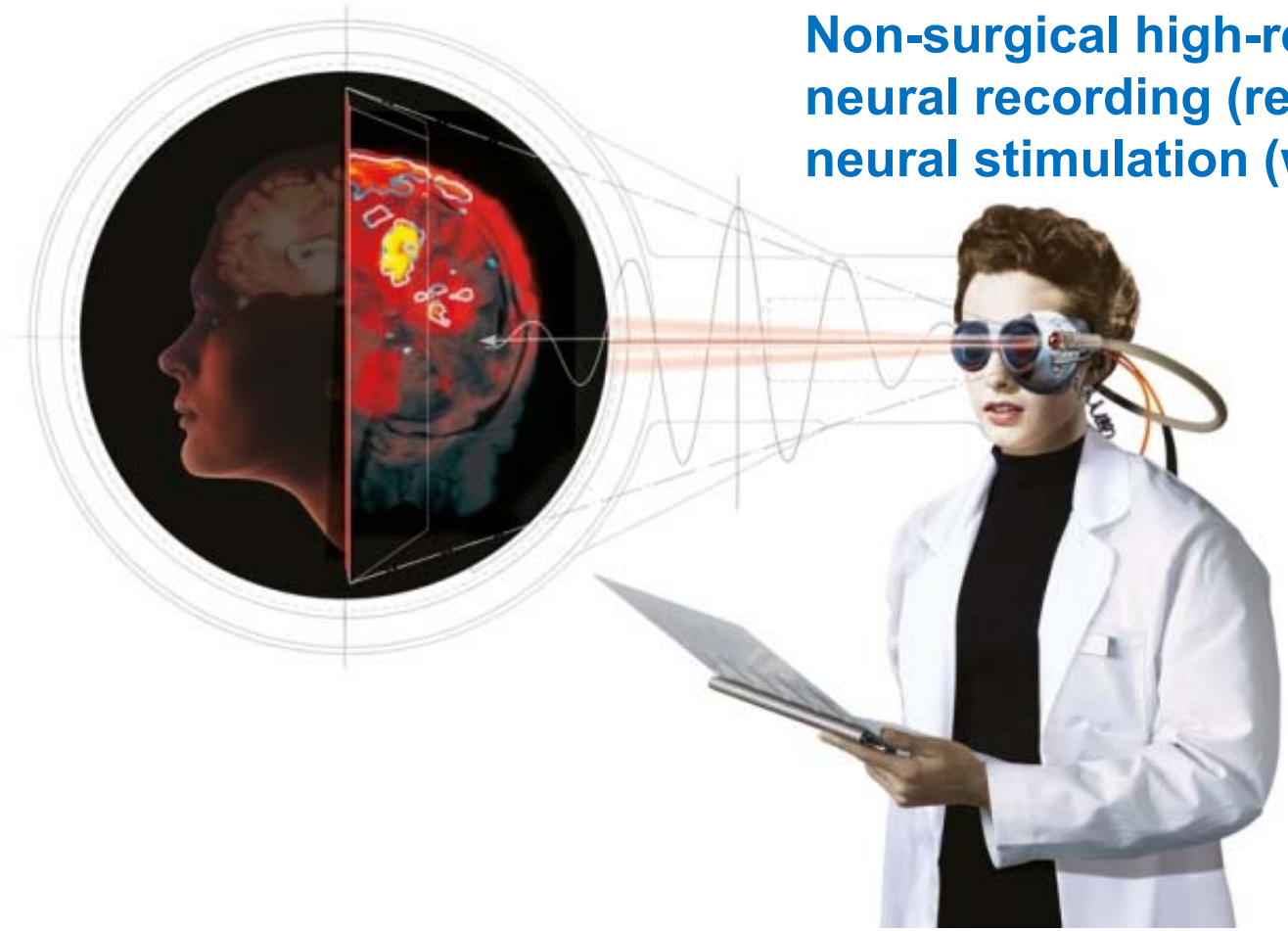
Random input (diffusion)

High transmission eigenchannel

$$\frac{\rho(E_{\text{high}})}{\rho(E_{\text{rand}})} = \frac{\tau_{\max} D_{\text{rand}}^2}{\langle \tau \rangle D_{\text{high}}^2} = 4.4$$

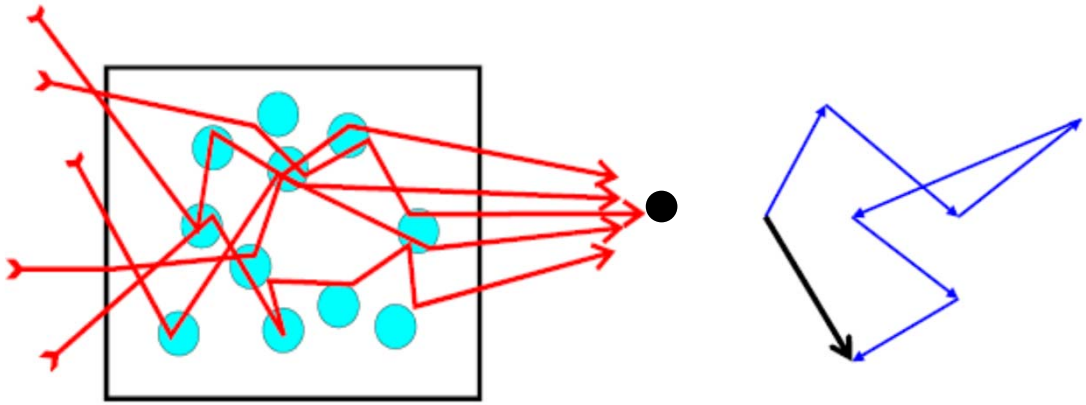
Yılmaz et al, *Nat. Photon.* 13, 352 (2019)

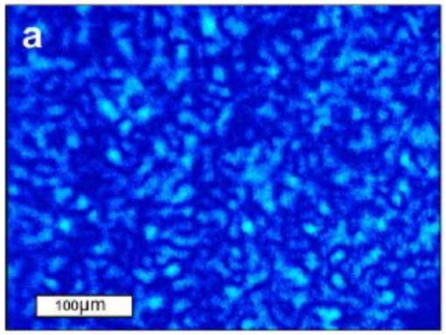
Non-surgical high-resolution neural recording (read out), neural stimulation (write in)



Merali, Nature 2015

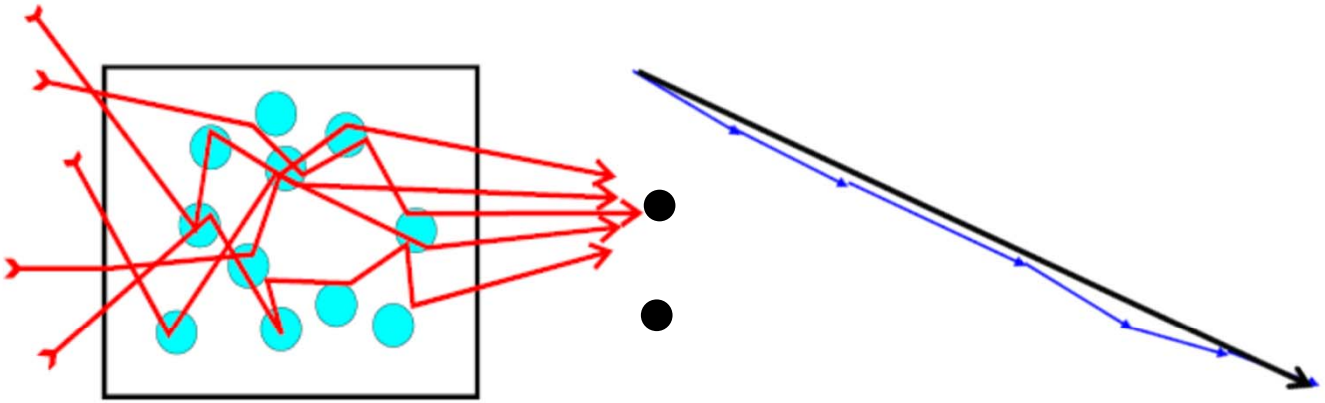
Focusing through Scattering Medium

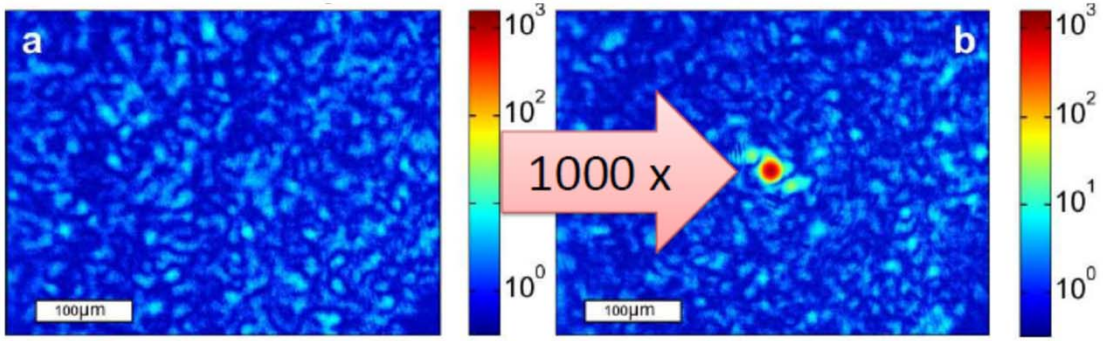




Vellekoop & Mosk, *Opt. Lett.* **32**, 2309 (2007)

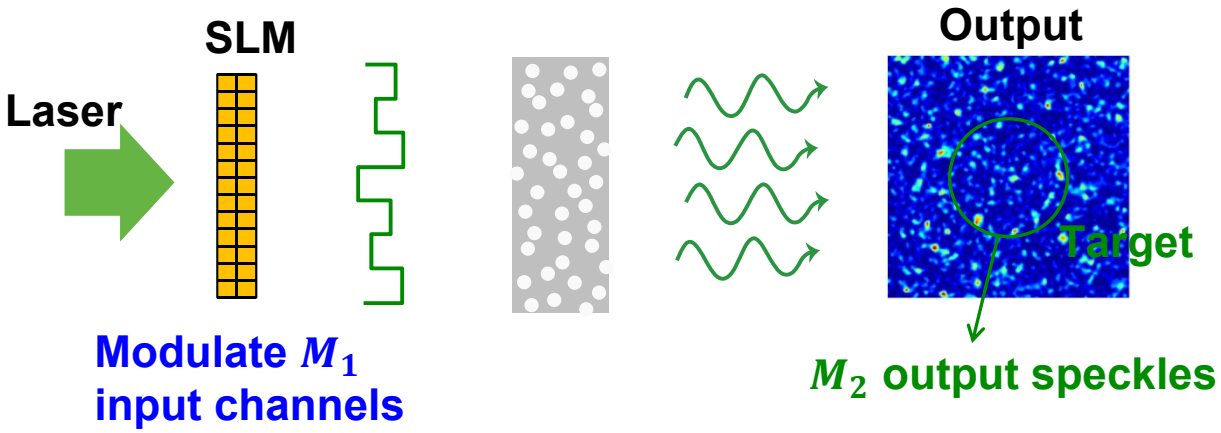
Focusing through Scattering Medium





Vellekoop & Mosk, *Opt. Lett.* **32**, 2309 (2007)

Focusing to Multiple Speckles



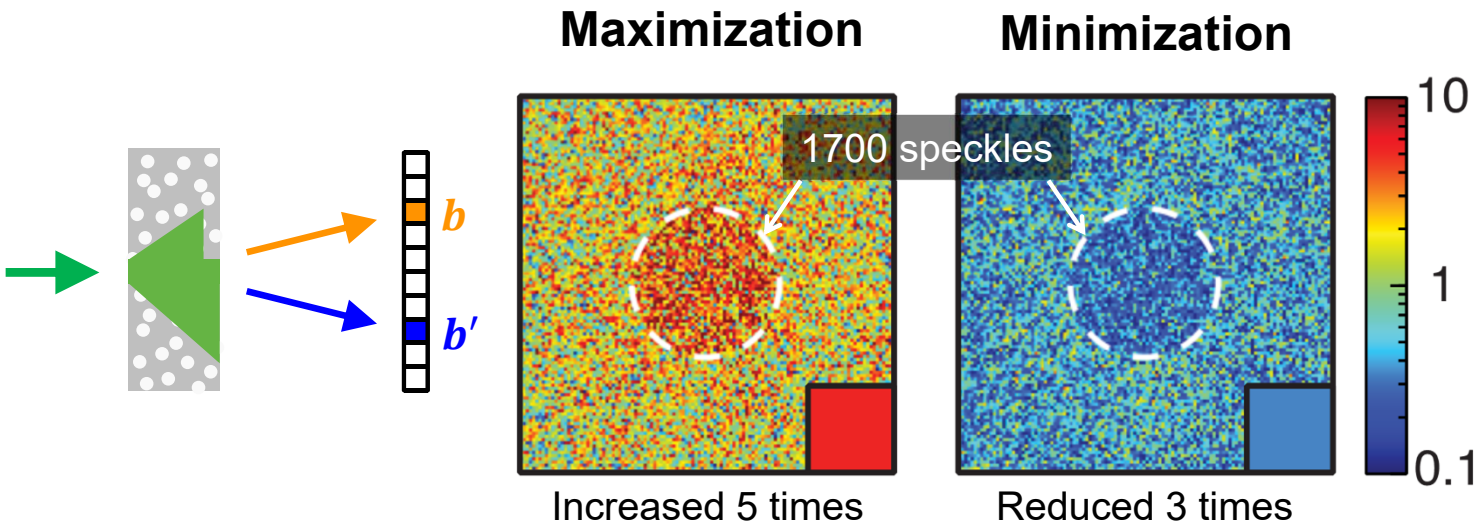
M_2 output speckles

$$|\psi_{\text{out}}\rangle = \tilde{t}|\psi_{\text{in}}\rangle$$

M_1 input channels

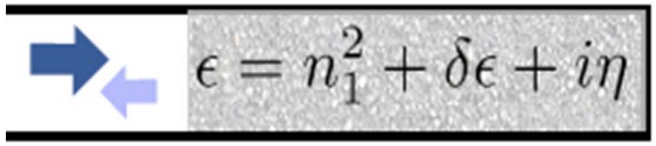
Hsu *et al*, *Nature Phys.* **13**, 497 (2017)

Correlation-Enhanced Focusing to Large Area



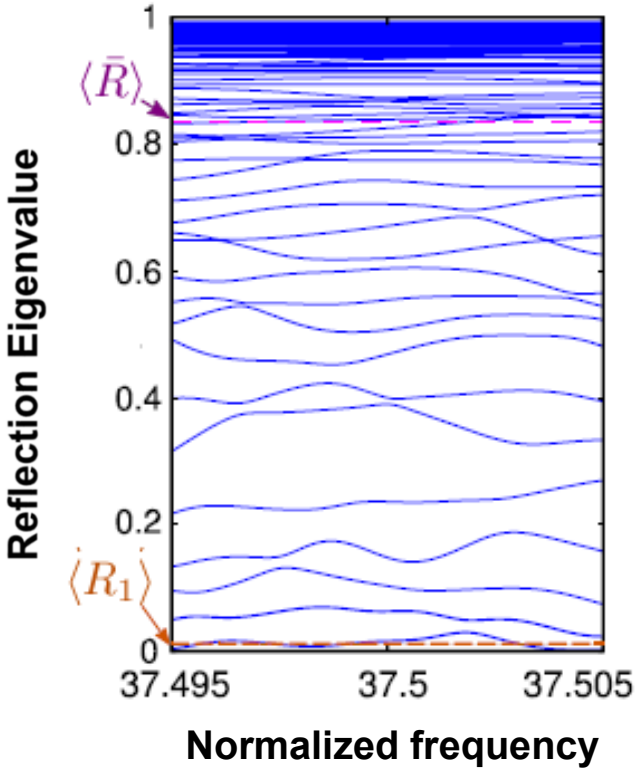
Hsu *et al, Nature Phys.* **13**, 497 (2017)

Coherent Control of Optical Absorption



Strong scattering

Weak absorption

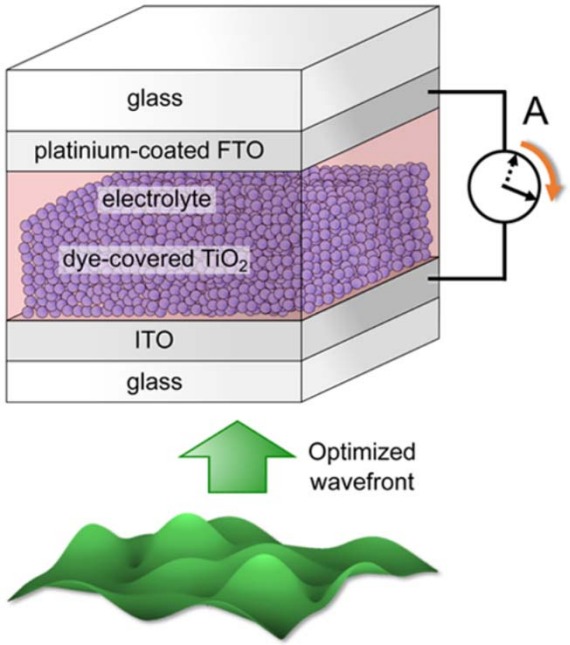


Chong & Stone, *Phys. Rev. Lett.* **107**, 163901 (2011)

Coherent Control of Optical Absorption

- **Scattering**
- **Absorption**

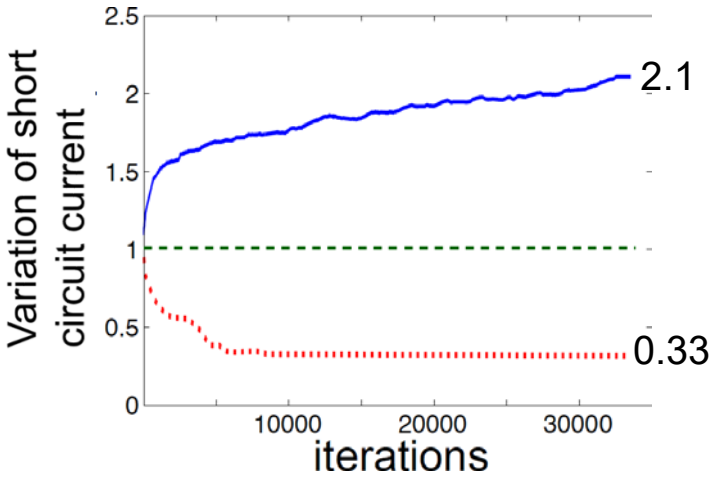
Dye-sensitized solar cell



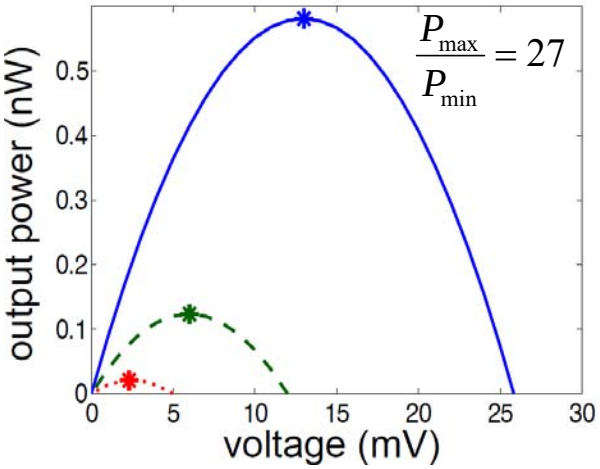
Liew *et al*, *ACS Photon.* 3, 449 (2016)

Coherent Control of Optical Absorption

Light-induced current



Light-induced electric power



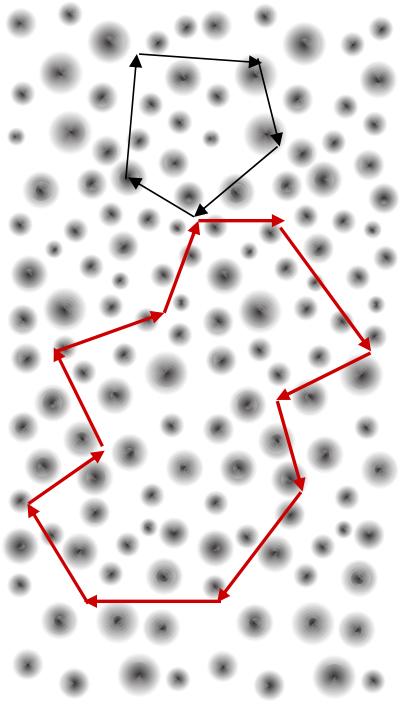
Liew et al, *ACS Photon.* 3, 449 (2016)

Light Amplification

Random medium with optical gain

Returning field $E = E_1 + E_2 + \ldots$

Coherent amplification enhances interference effect

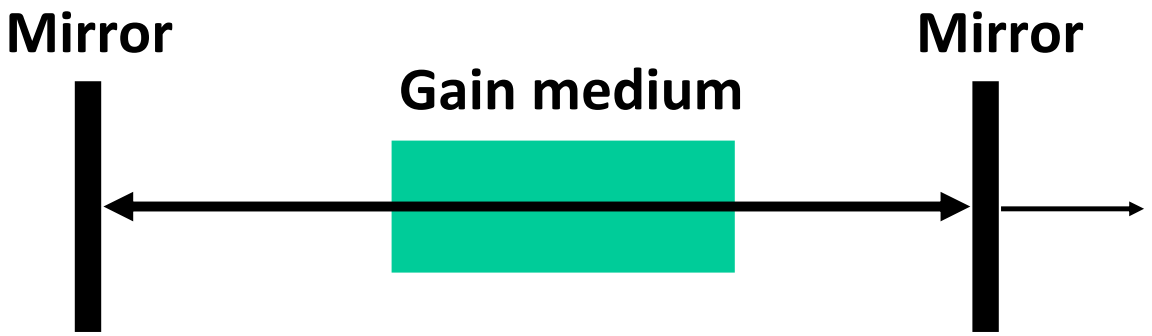


Yamilov et al, *Phys. Rev. E*, 70, 037603 (2004); *Phys. Rev. B* 71, 092201 (2005); *Phys. Rev. E* 74, 056609 (2006); *Physica B*, 405, 3012 (2010).

Conventional Laser

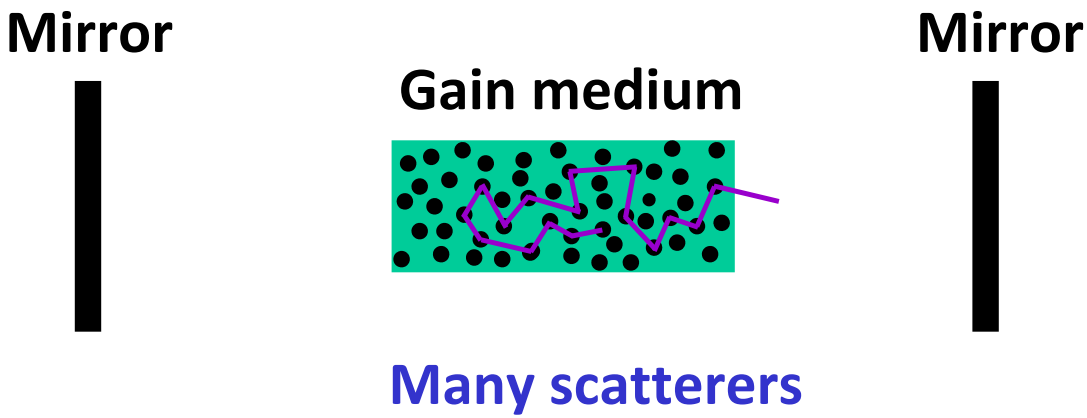
Essential components for a laser

- **Gain medium**
- **Cavity**



Multiple Scattering

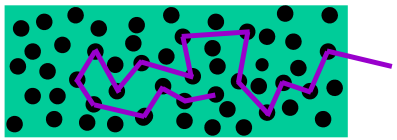
Multiple scattering increases pathlength of light inside gain medium, enhancing amplification



Mirrorless Laser

Light is trapped inside the gain medium without mirrors

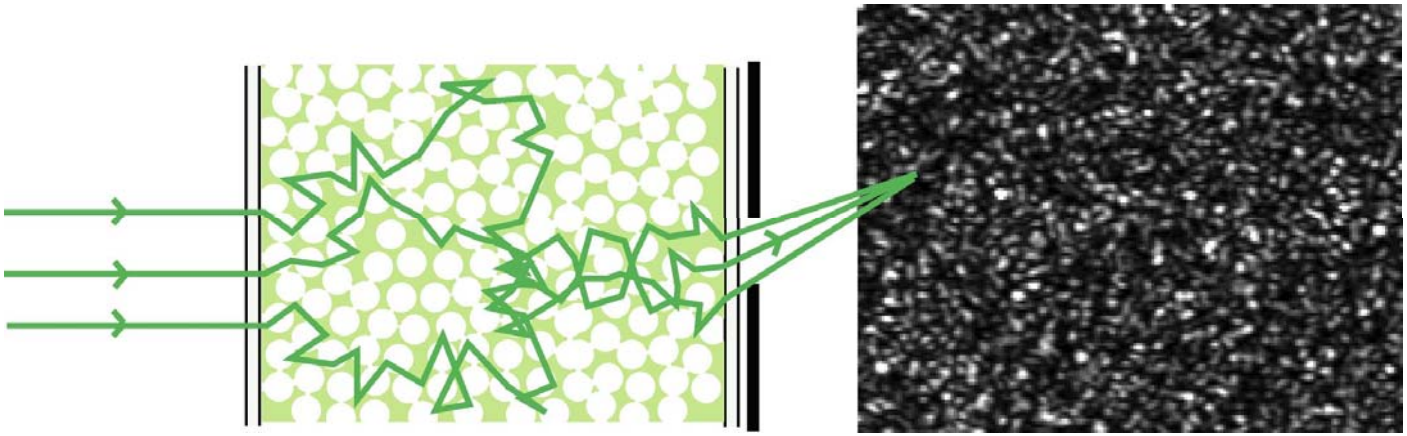
Gain medium



Michael Choma

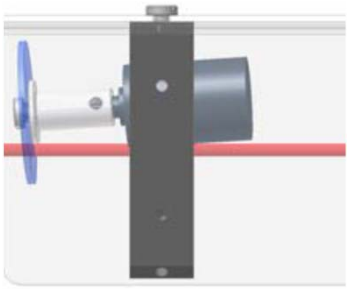
HC, *Progress in Optics* 45, 317 (2003)

Laser Speckle



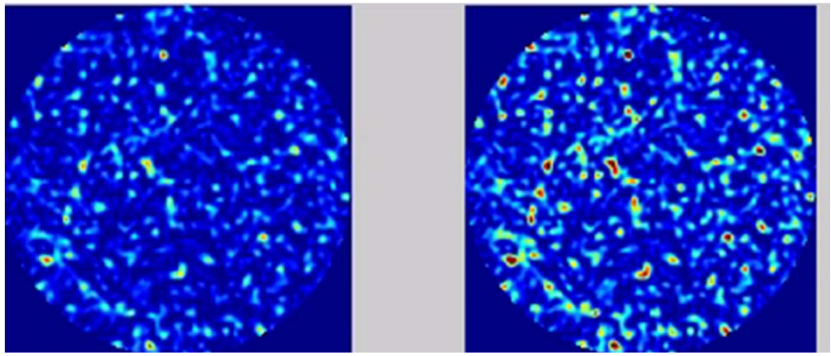
Averaging Out Speckle

Rotating diffuser

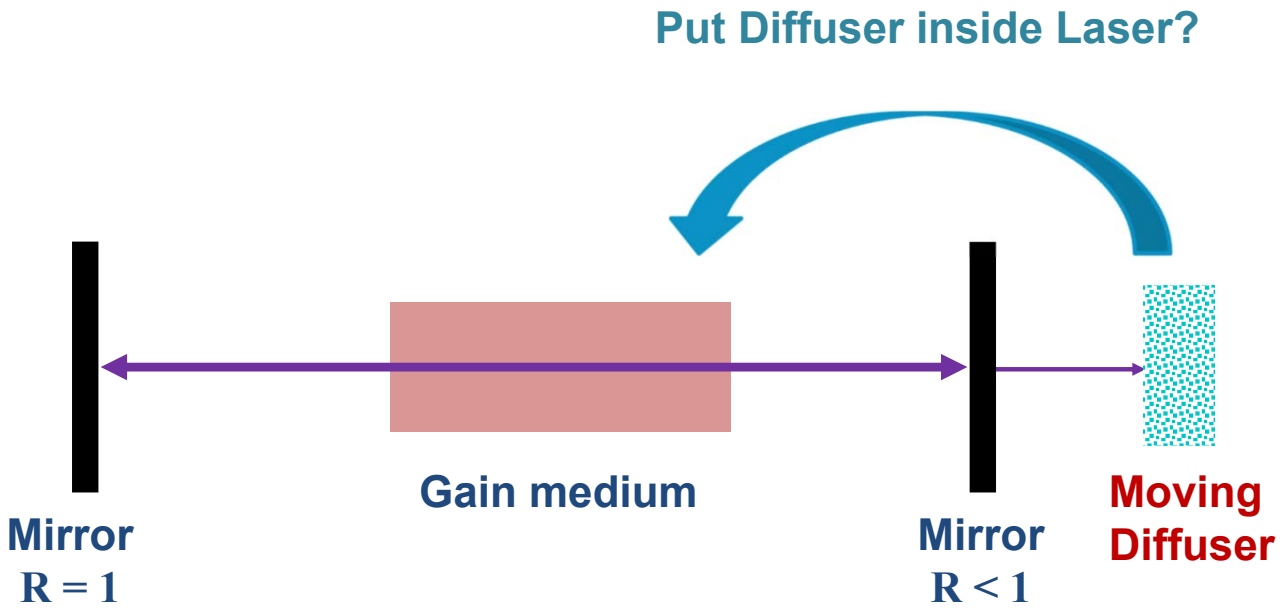


Speckle contrast

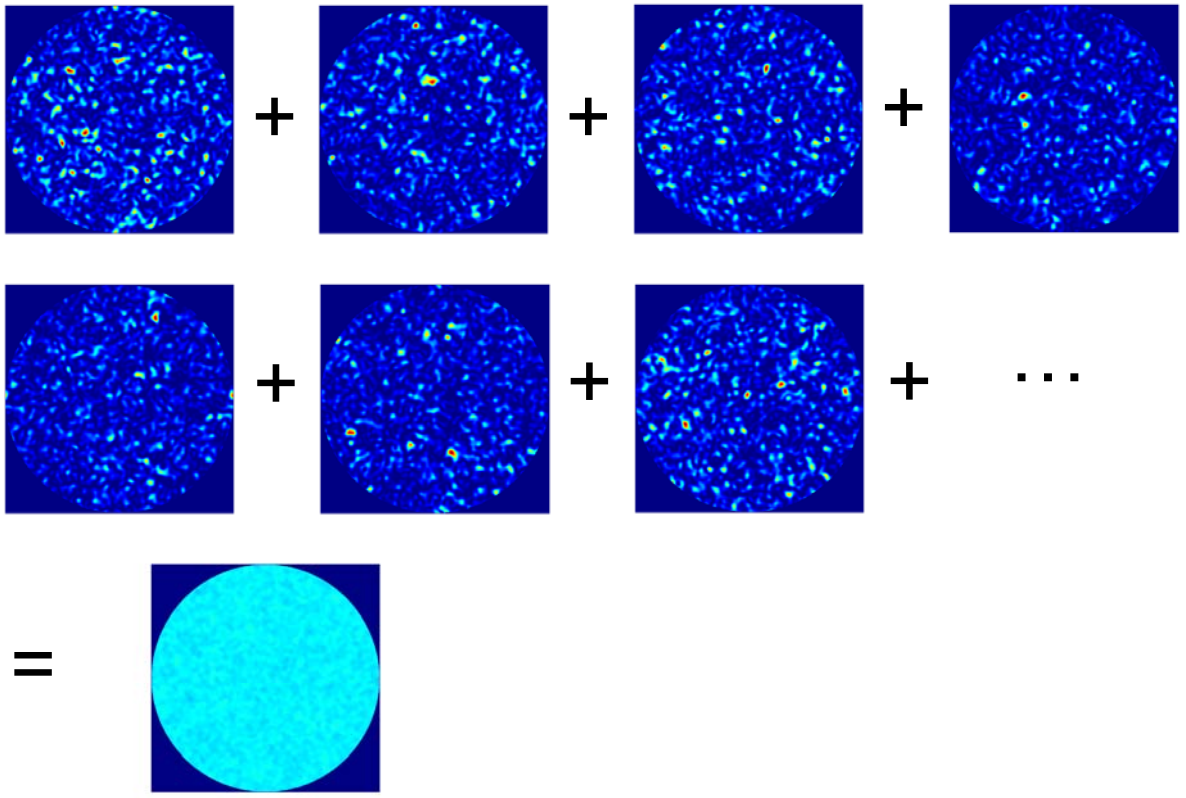
$$C \propto \frac{1}{\sqrt{N}}$$



Laser

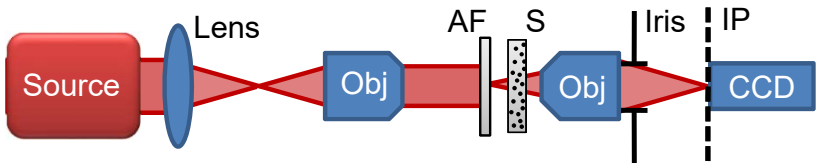

Put Diffuser inside Laser?
Mirror
R = 1
Gain medium
Mirror
R < 1
Moving
Diffuser

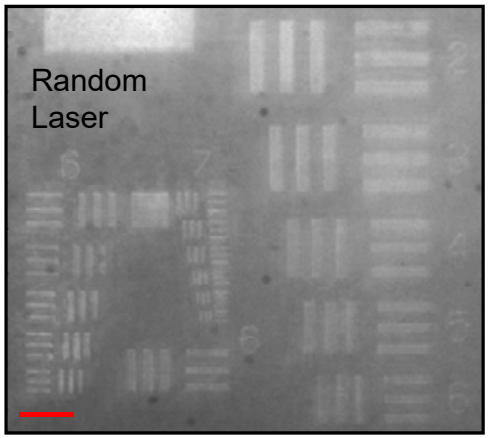
Many Random Lasing Modes

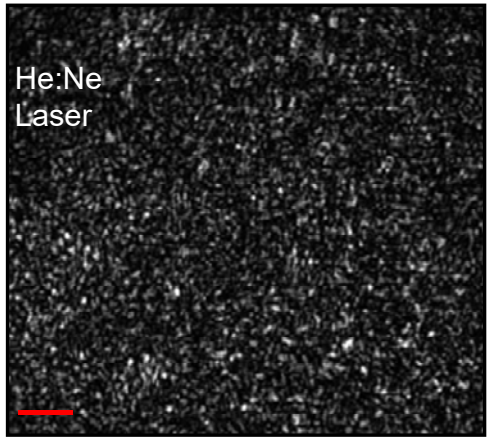


Redding *et al, Opt. Lett.* 36, 3404 (2011)

Speckle-free Full-Field Imaging

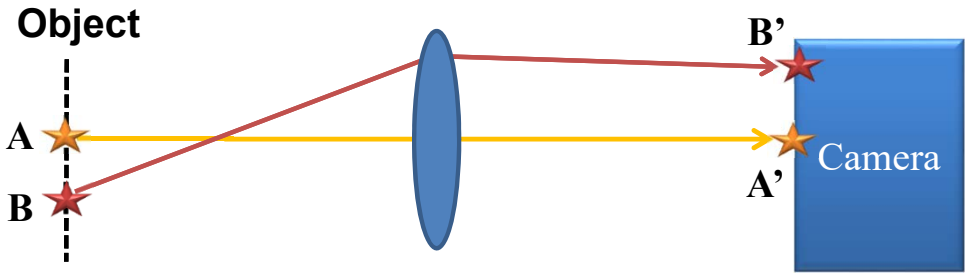


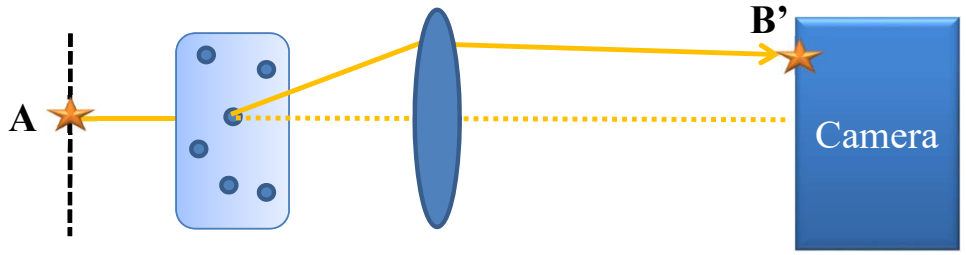




Redding *et al, Nature Photon*. 6, 355 (2012)

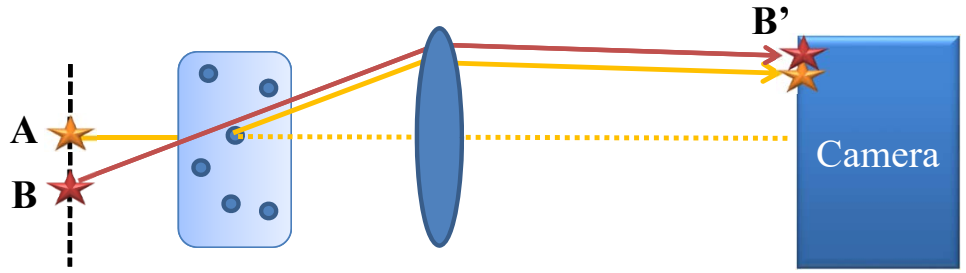
Full Field Imaging





Coherent illumination

$$I = |E|^2 = |E_0 + E_s|^2$$
$$= |E_0|^2 + |E_s|^2 + 2E_0E_s\cos(\theta)$$



Incoherent illumination

$$I = I_0 + I_s$$

Summary

Control light propagation and absorption in strong-scattering media by manipulating wave interference

Break the limit of incoherent diffusion to achieve extreme behaviour

Apply random laser to speckle-free full-field imaging

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