# Mesoscopic Optics

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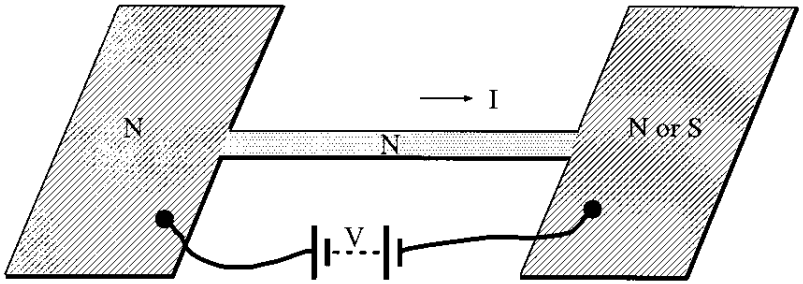
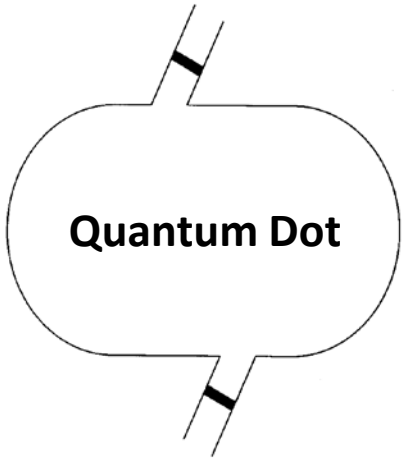
*Univ Twente, Netherlands*

# Mesoscopic Electron Transport




**Interference of coherent electron wave**

↓

**Anderson localization**

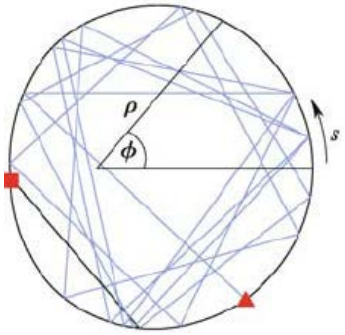
**Universal conductance fluctuation**

# Mesoscopic Optics

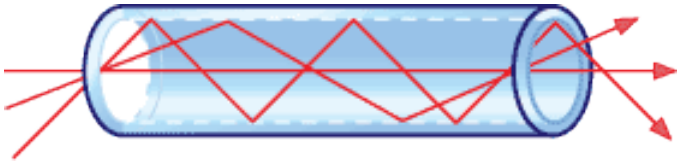
**Classical wave: light, microwave, acoustic wave**

**Scattering medium**

**Chaotic cavity**




**Multi-mode fiber**



# Strong Scattering Media

## Cloud

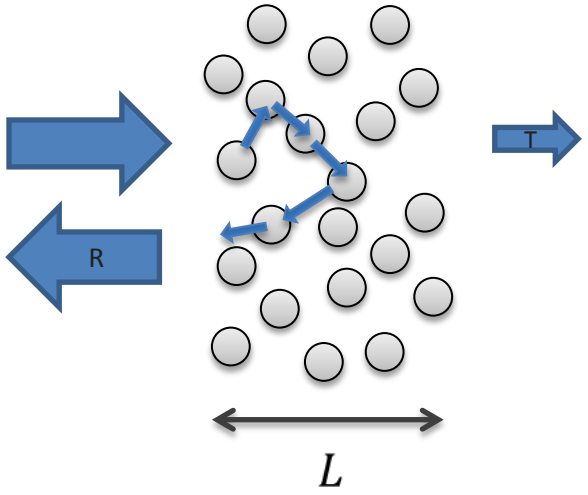
## Fog

## Biological tissue

## Sand Storm

# Transmission Through a Diffusive Medium

Sample thickness $L$ >> Transport mean free path $l_t$




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

**How to enhance wave transmission?**

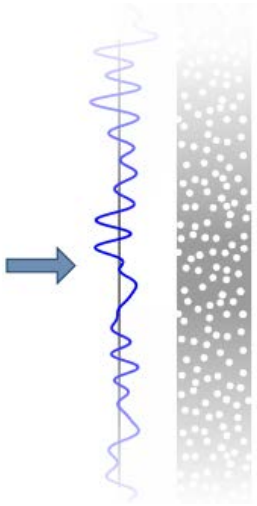
# Diffusion Model

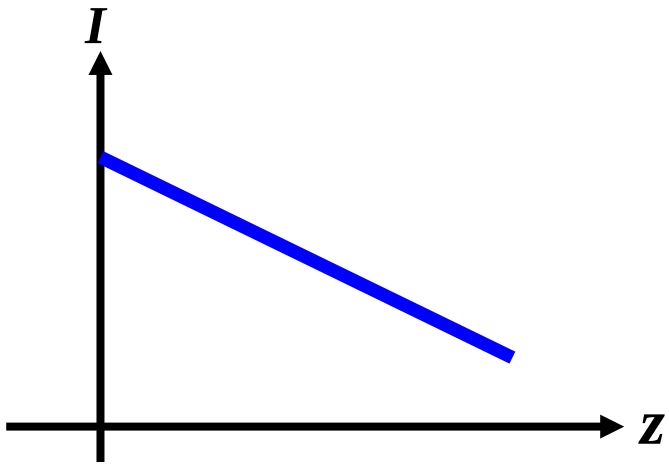
**Diffusion equation**

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

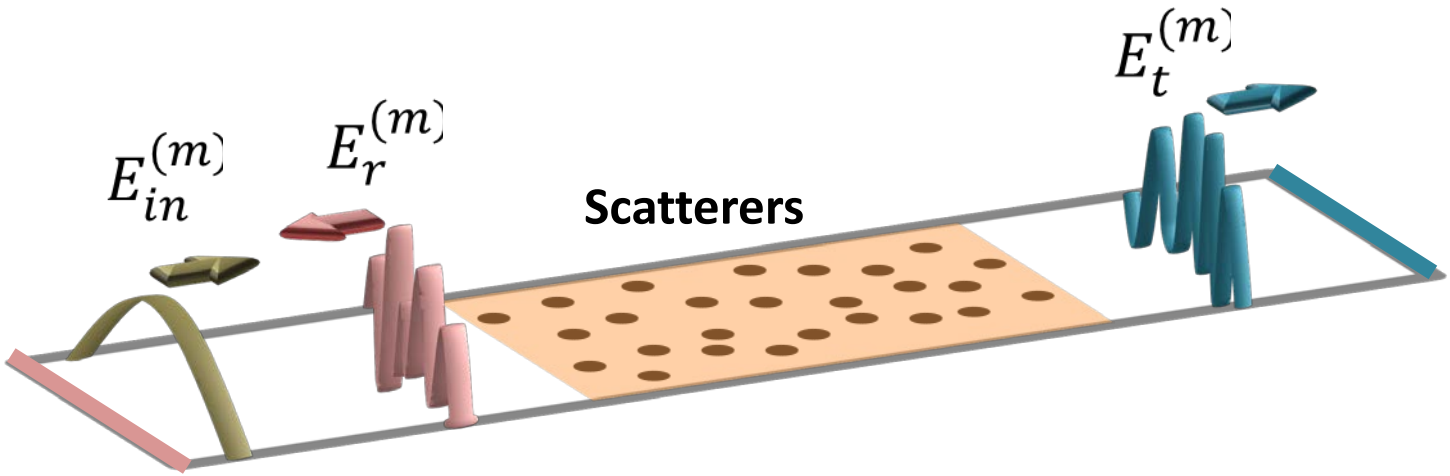
**Diffusion coefficient**

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





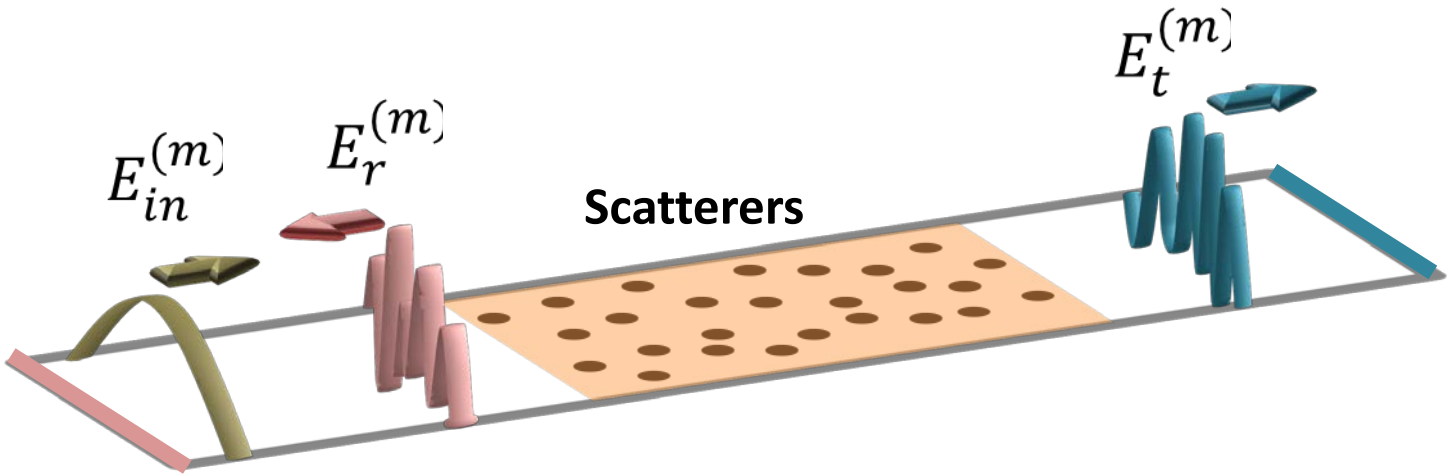
# Transmission Matrix




**Field transmission matrix**

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

# Transmission Matrix



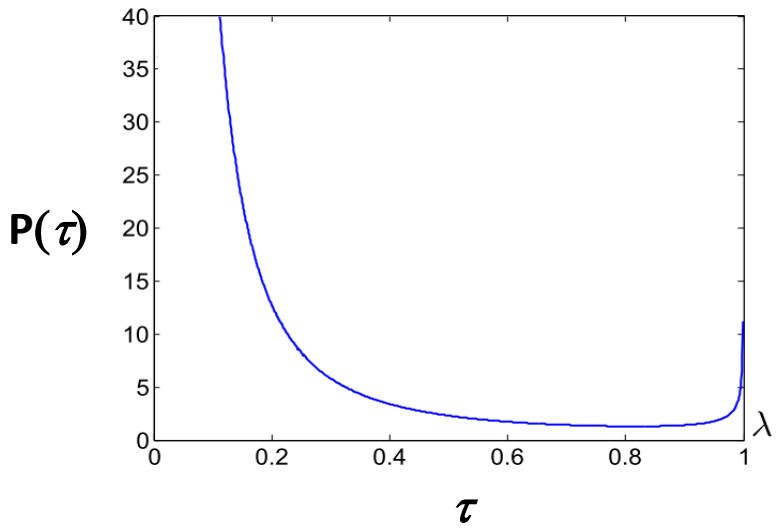

$$t = \begin{pmatrix} u_{11} & \cdots & u_{1N} \\ \vdots & \ddots & \vdots \\ u_{N1} & \cdots & u_{NN} \end{pmatrix} \begin{pmatrix} \sqrt{\tau_1} & & 0 \\ & \ddots & \\ 0 & & \sqrt{\tau_N} \end{pmatrix} \begin{pmatrix} v_{11} & \cdots & v_{1N} \\ \vdots & \ddots & \vdots \\ v_{N1} & \cdots & v_{NN}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

# Transmission Eigenchannel

**Bimodal distribution of transmission eigenvalues**

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

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



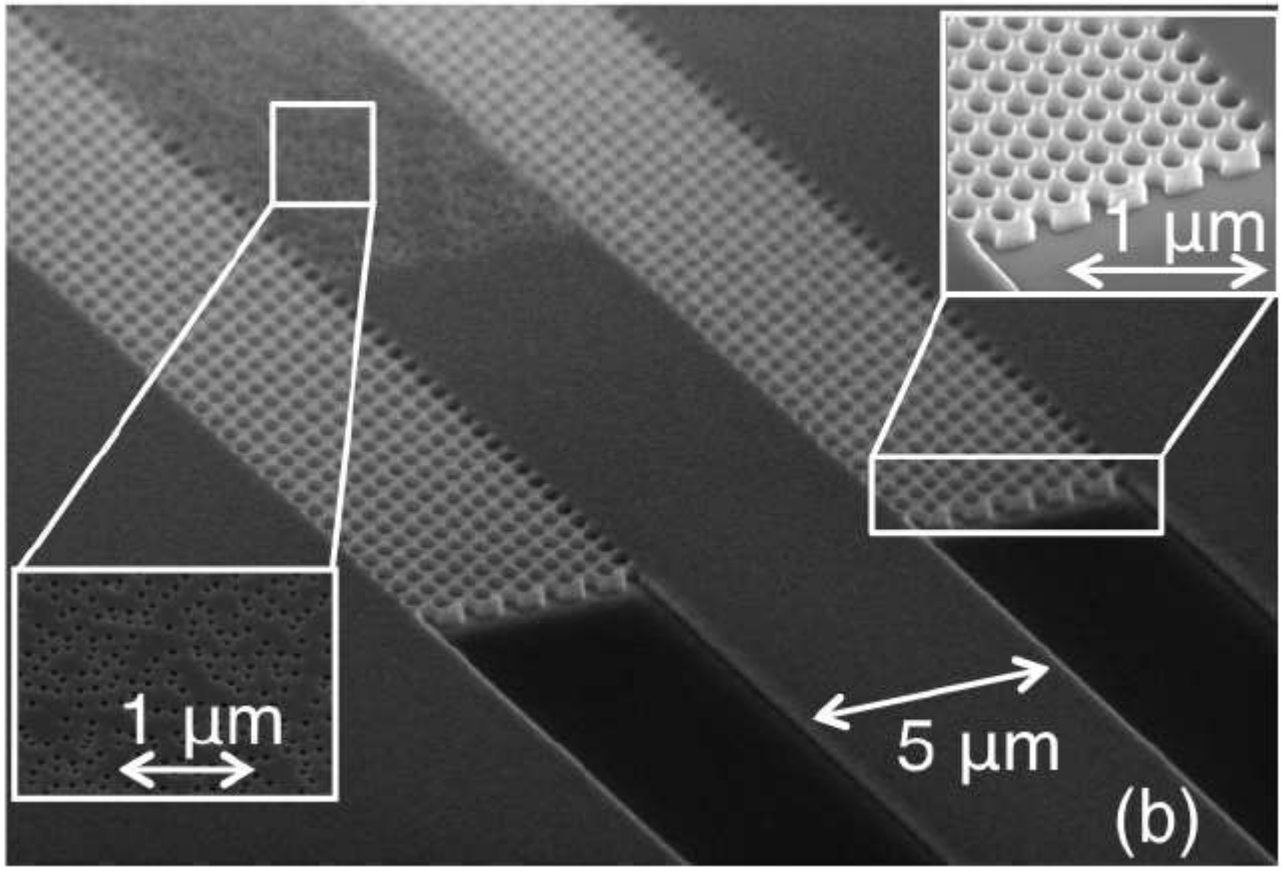

**Open channel $\tau \sim 1$**

**Closed channel $\tau \sim 0$**


Dorokhov, Solid State Commun. **51**, 381 (1984)

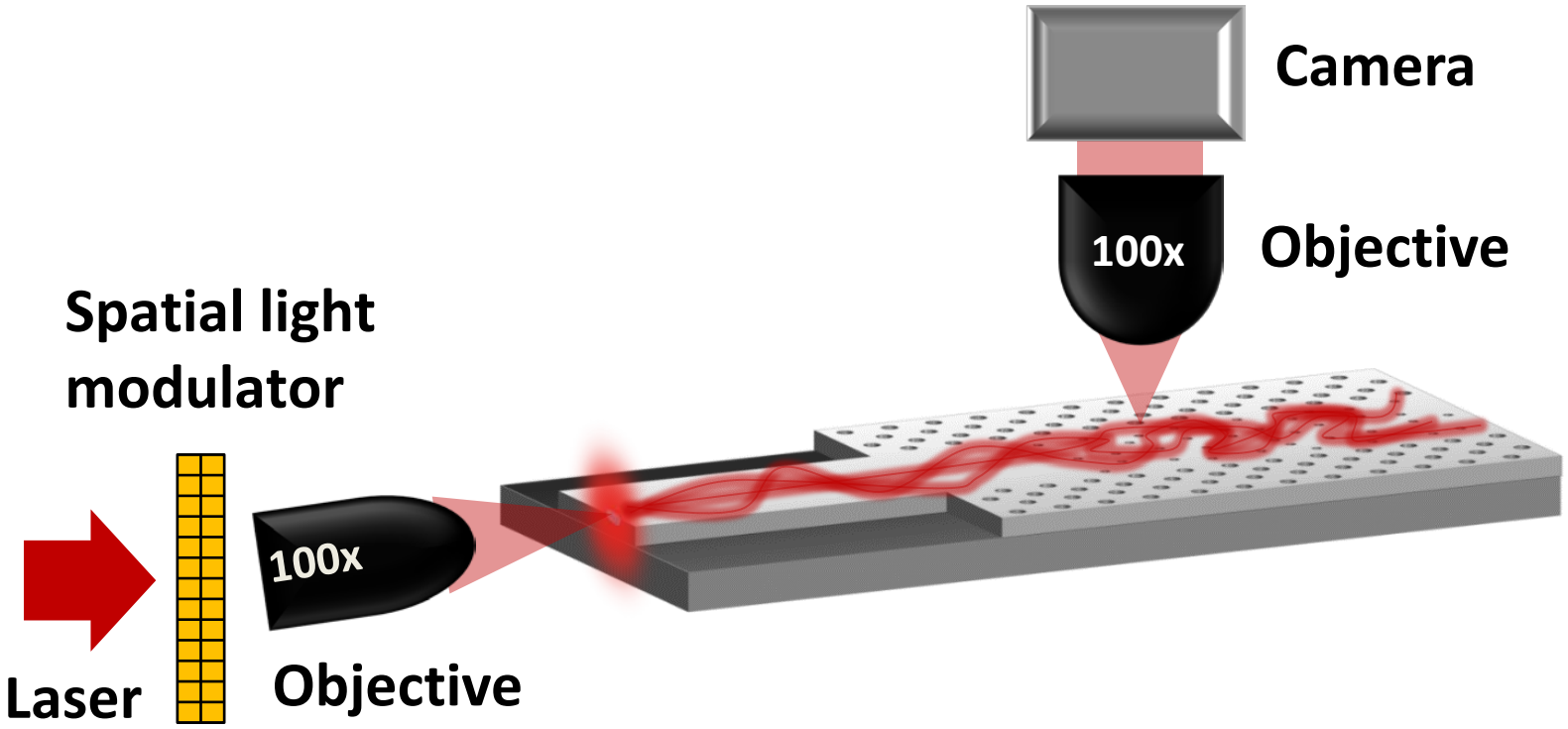
Mello *et al. Ann. Phys.* **181**, 290 (1988)

# Silicon Waveguide




Yamilov, Sarma, Redding, Payne, Noh, & HC, Phys. Rev. Lett. 112, 023904 (2014)

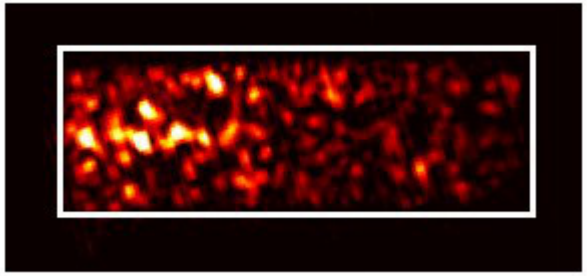
# Direct Probing of Light Propagation inside quasi-2D Disordered Structure



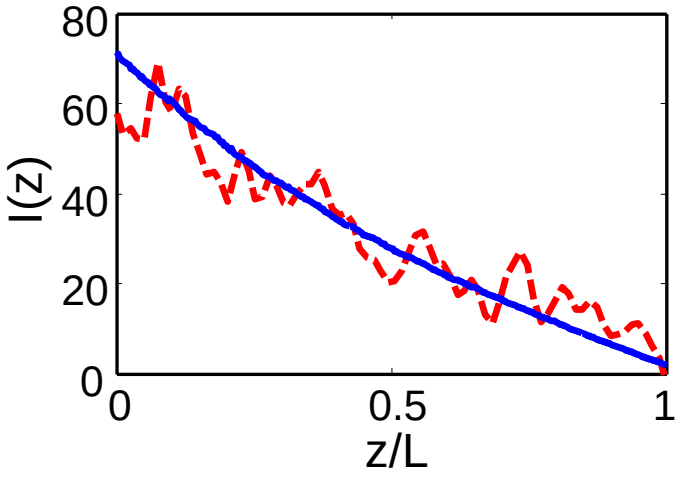

Yamilov, Sarma, Redding, Payne, Noh, & HC, Phys. Rev. Lett. 112, 023904 (2014)

# Maximizing Transmission

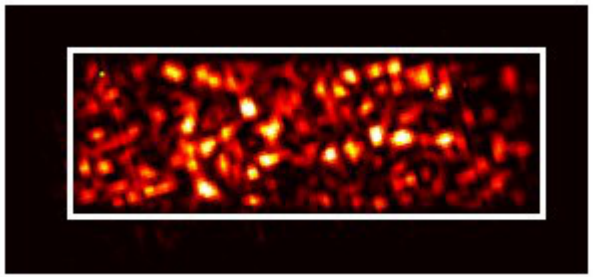
**Arbitrary Input**



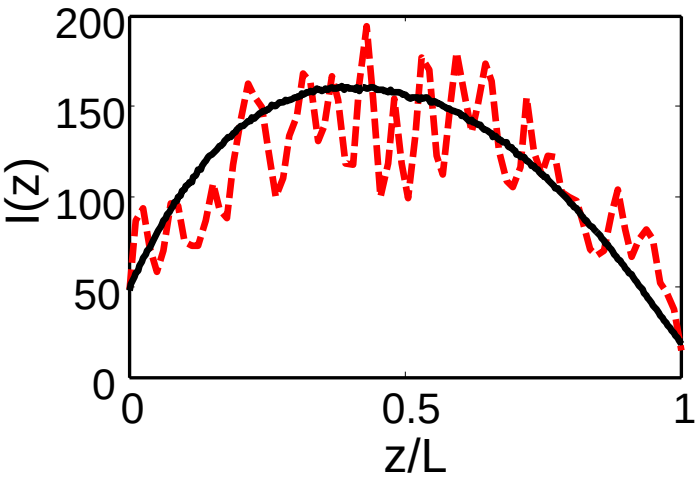
$T = 4.7\%$




**Optimized Input**



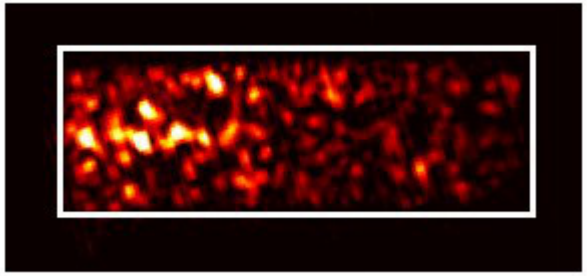
$T = 48\%$



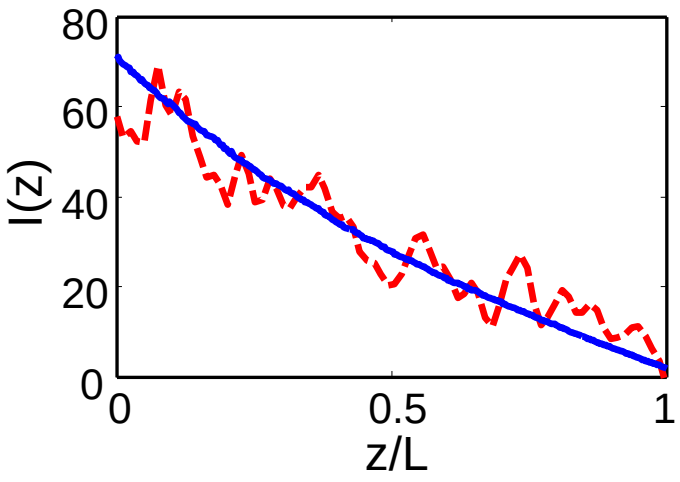

Sarma, Yamilov, Petrenko, Bromberg & HC, *Phys. Rev. Lett.* 117, 086803 (2016)

# Minimizing Transmission

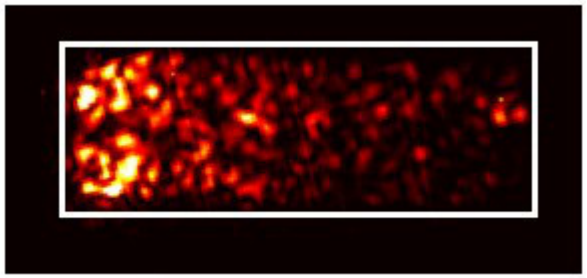
**Arbitrary Input**



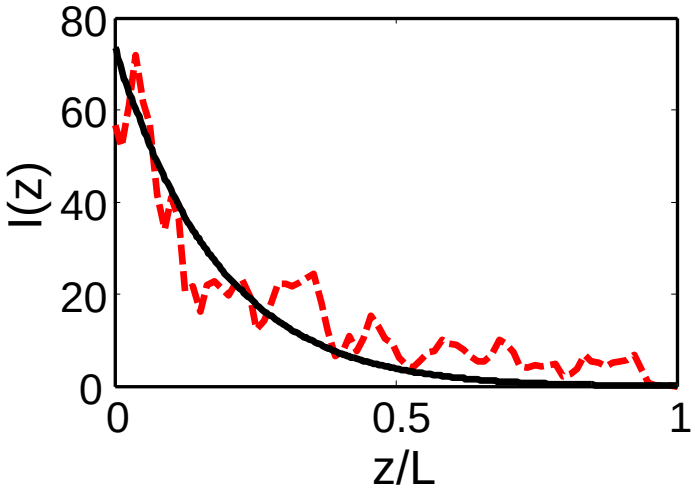
$T = 4.7\%$




**Optimized Input**

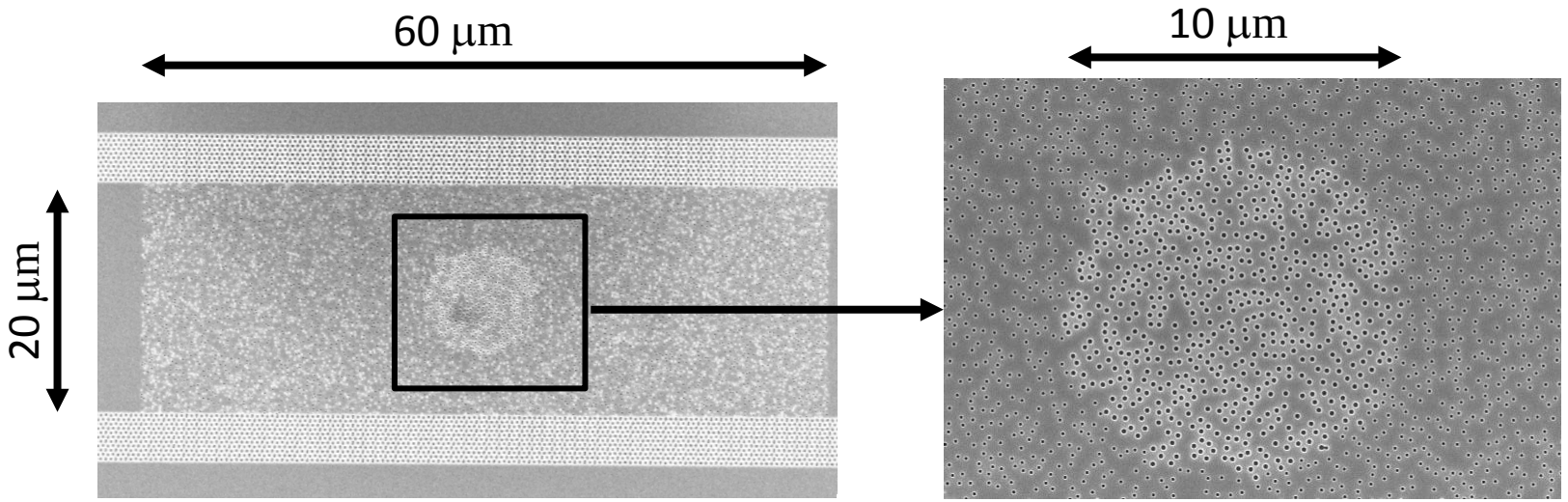


$T = 0.1\%$

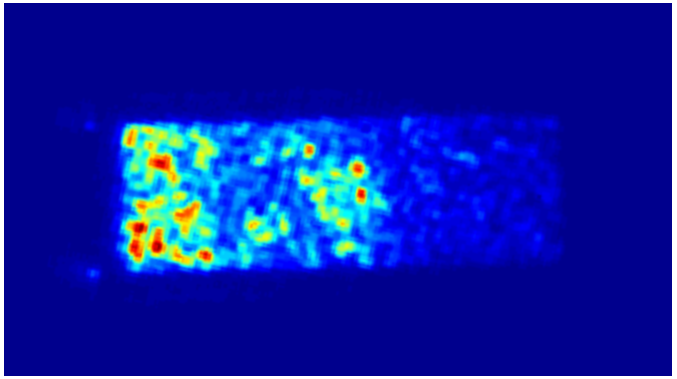



Sarma, Yamilov, Petrenko, Bromberg & HC, *Phys. Rev. Lett.* 117, 086803 (2016)

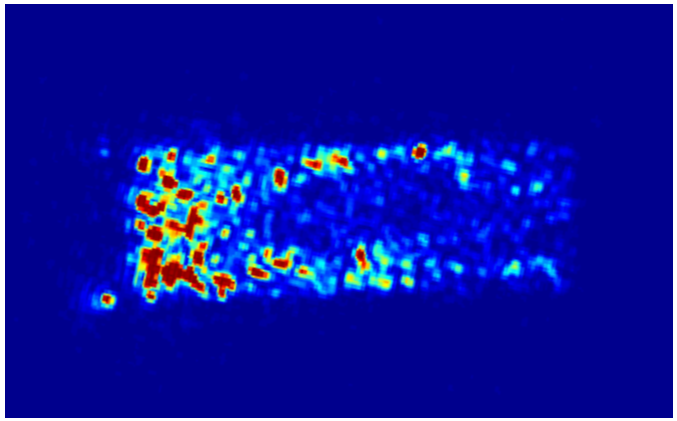
# Inhomogeneous Scattering




**Before optimization**



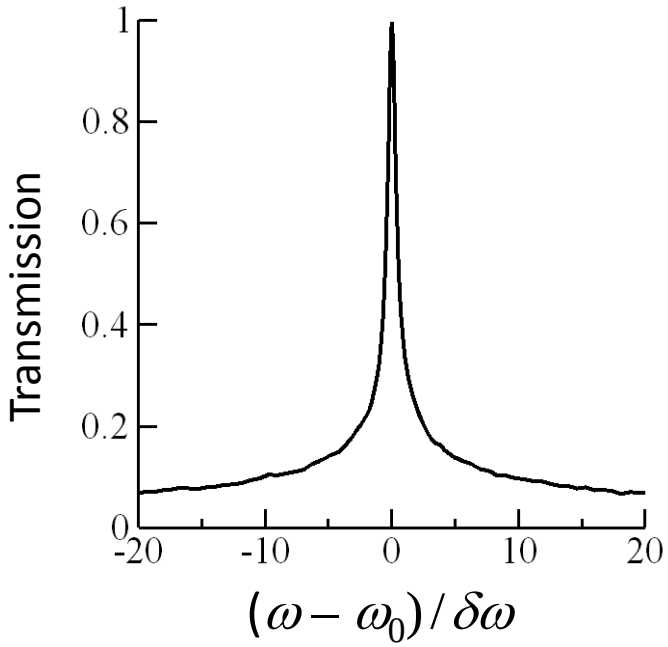
**After optimization**



Sarma, Yamilov & HC, *Appl. Phys. Lett.* 110, 021103 (2017)

# Spectral Bandwidth

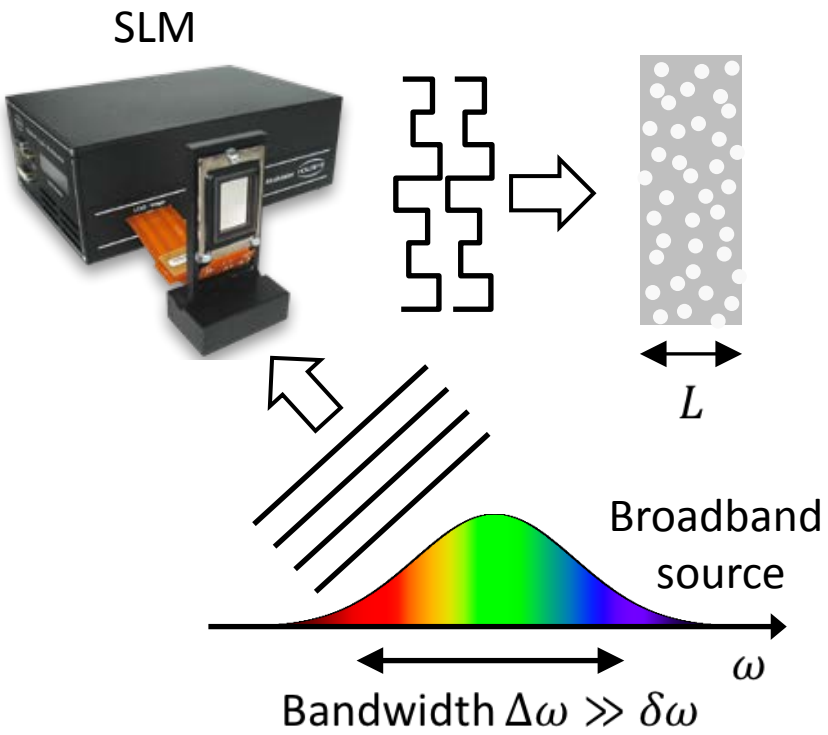
**Open channel at $\omega_0$**




**Correlation width**

$$\delta\omega \sim 1/\Delta t \sim D/L^2$$

# Coherent Control of Broadband Light



# Broadband Transmission

**Number of independent spectral channels**

$$M_S \sim \frac{\Delta\omega}{\delta\omega} + 1$$

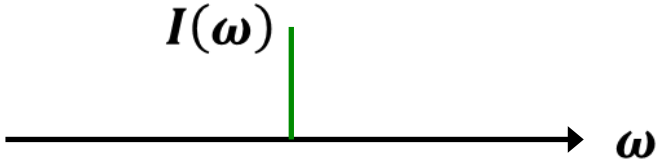
**Total transmission**

$$T_0 \sim \frac{1 + \bar{T}(M_S - 1)}{M_S}$$

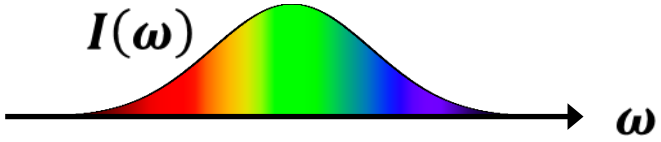
$$M_S >> 1 \qquad T_0 \to \bar{T}$$

# Broadband Transmission

**Monochromatic light**




**Broadband light**




$$T = \frac{\langle \psi_{in} | \tilde{t}^{\dagger} \tilde{t} | \psi_{in} \rangle}{\langle \psi_{in} | \psi_{in} \rangle} \quad \Rightarrow \quad T = \frac{\langle \psi_{in} | A | \psi_{in} \rangle}{\langle \psi_{in} | \psi_{in} \rangle}$$

$$A = \int d\omega \, I(\omega) \tilde{t}^{\dagger}(\omega) \tilde{t}(\omega)$$

**Maximum transmission**

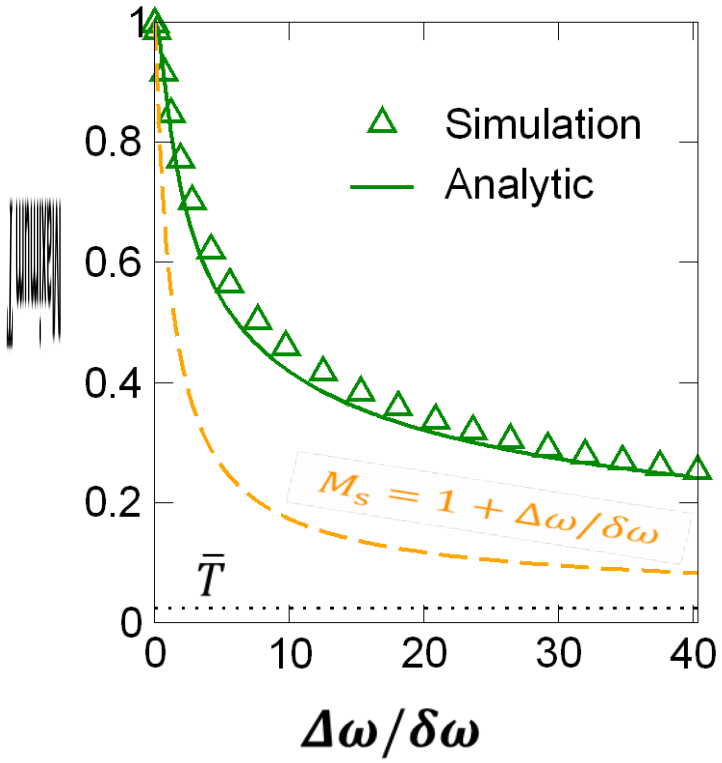
⇕

**Largest eigenvalue of $A$**

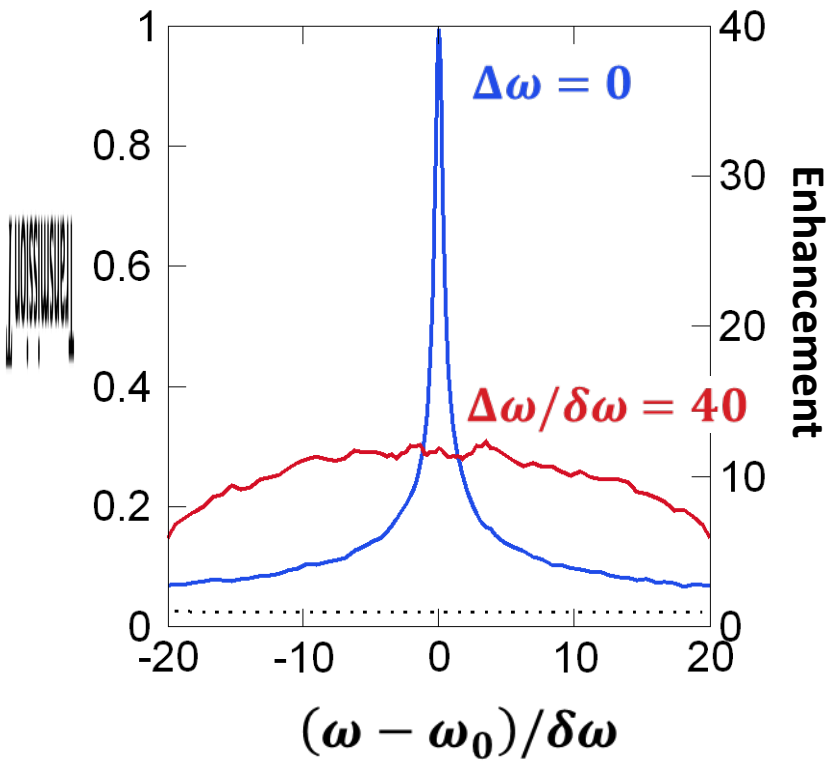
Hsu, Goetschy, Bromberg, Stone & HC, Phys. Rev. Lett. 115, 223901 (2015)

# Broadband Open Channel

## Maximal transmission




## Broadband transmission

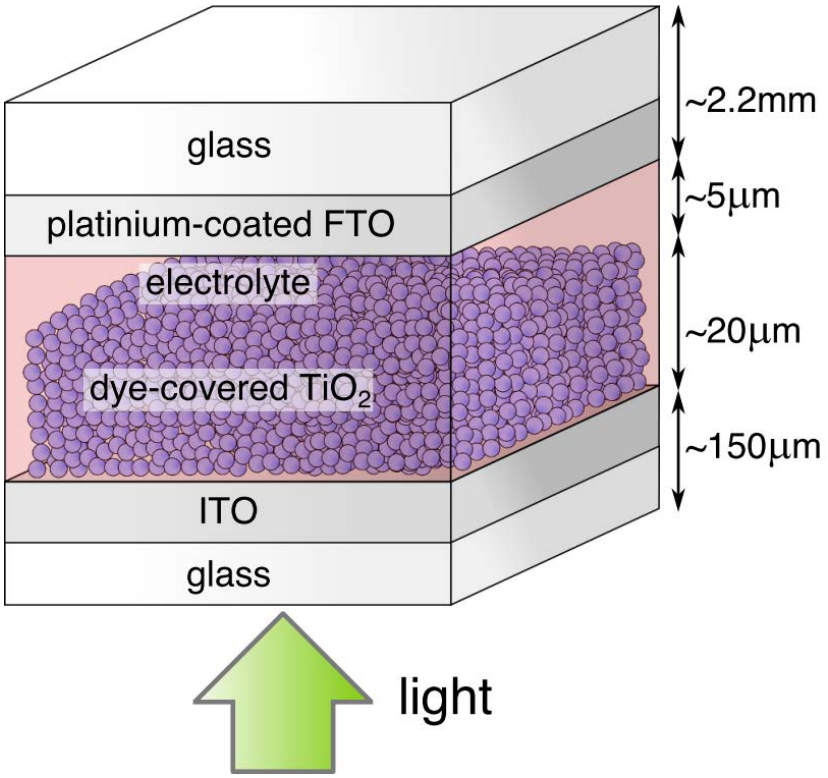



Hsu, Goetschy, Bromberg, Stone & HC, Phys. Rev. Lett. 115, 223901 (2015)

# Coherent Control of Optical Absorption

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

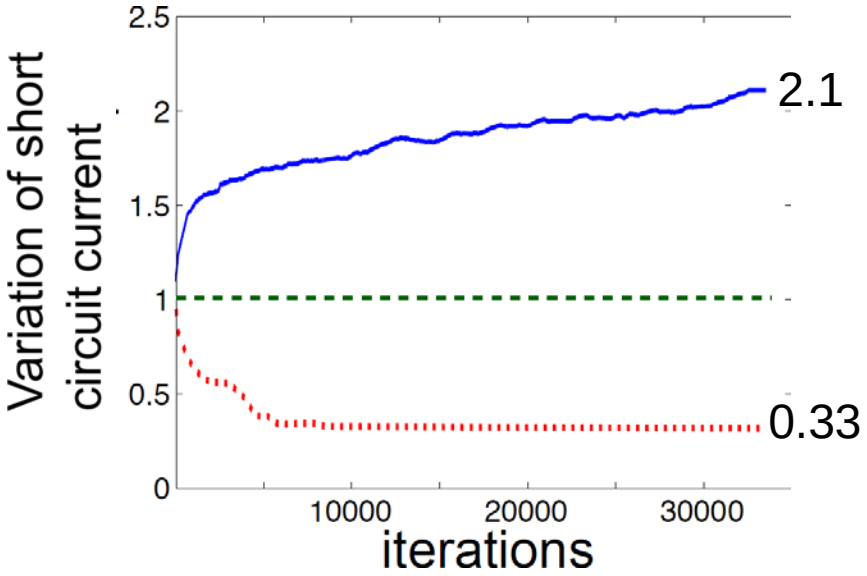
**Dye-sensitized solar cell**



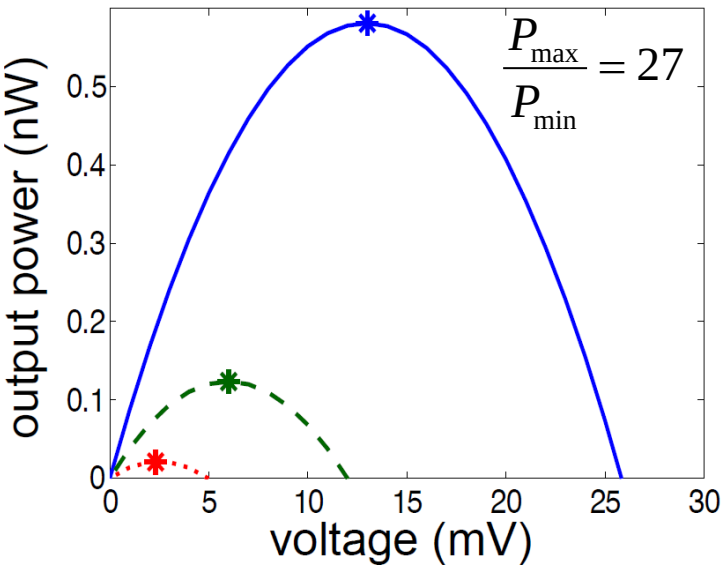

Liew et al, *ACS Photon.* 3, 449 (2016)

# Coherent Control of Optical Absorption

**Light-induced current**




**Light-induced electric power**




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

# Summary

- **Coherent control of light propagation and absorption in a strong-scattering medium by shaping incident wavefront of a laser beam**

- **Manipulate wave interference effects to break incoherent diffusion limit and achieve diverse transport behavior**

# Distinction between Electron Transport and Photon Transport

**Stimulated emission of photons adds a new dimension to mesoscopic physics**

**Combination of scattering and amplification leads to lasing action**

HC, Optics & Photonics News **16**, 24 (2005)

Wiersma, Nat. Phys. **4**, 359 (2008)

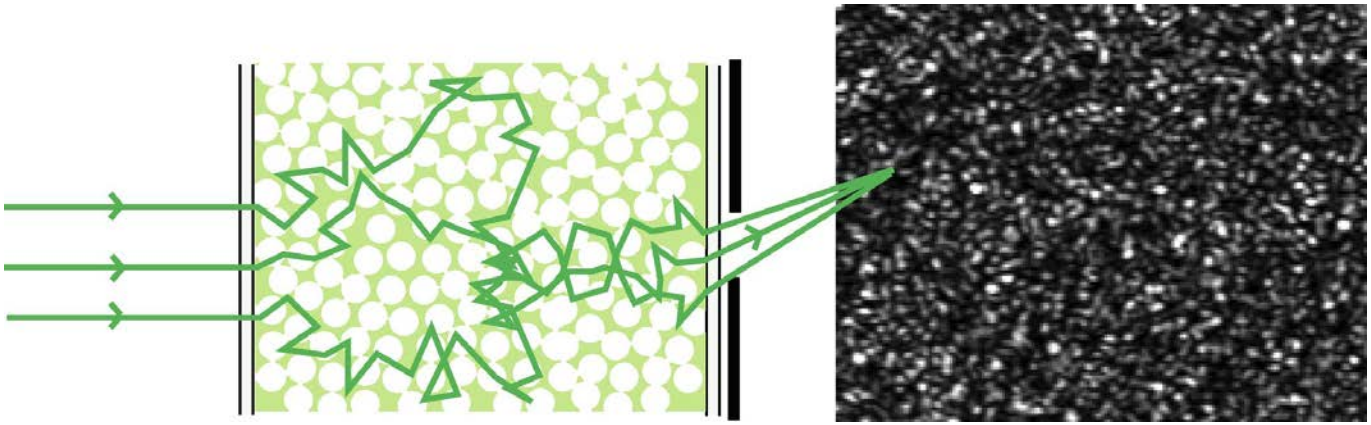
# Laser Illumination

**Advantages**

- Brightness
- Directionality
- Power consumption
- Spectral control

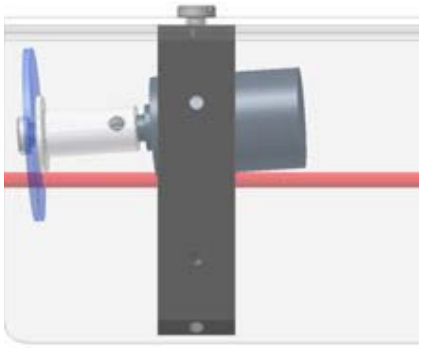
**Applications**

- Full-field Imaging
- Laser projectors
- Photolithography
- Holography



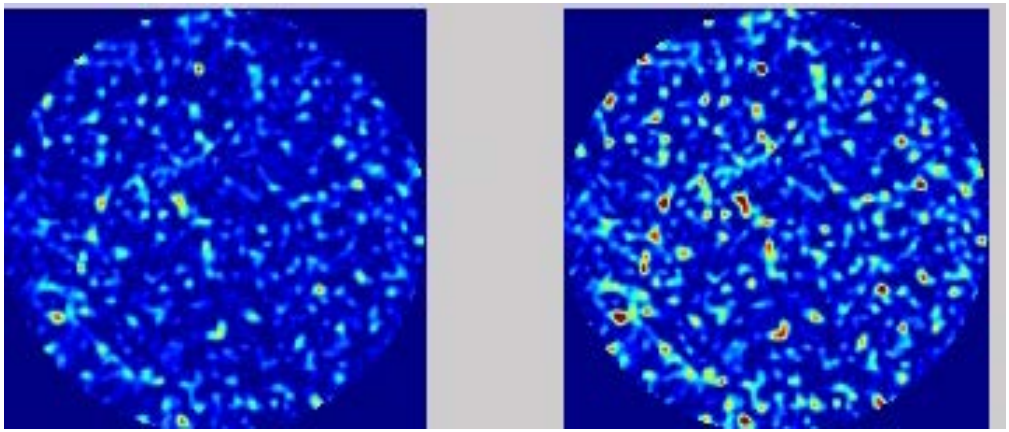
# Removing Speckle

**Rotating diffuser**

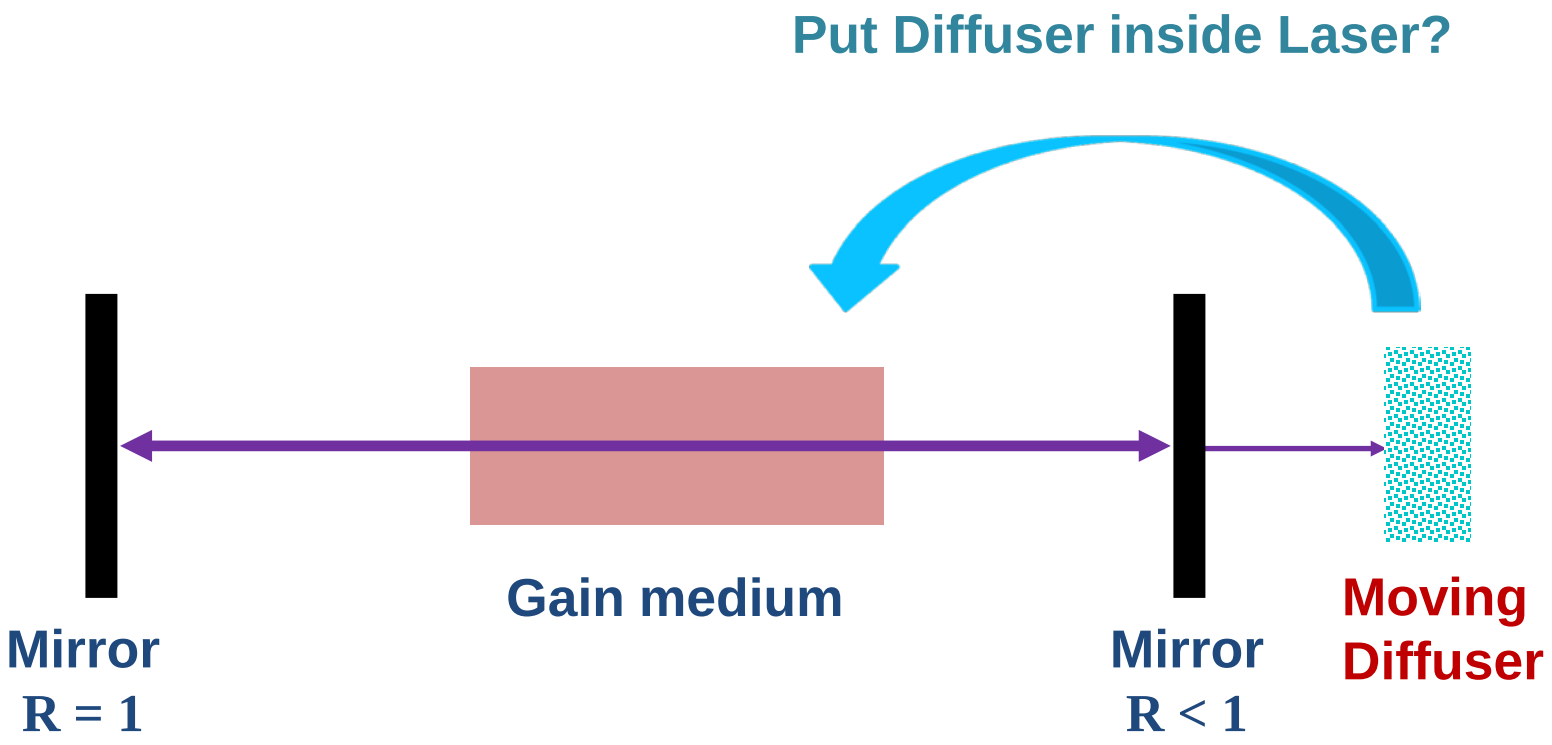


**Speckle contrast**

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

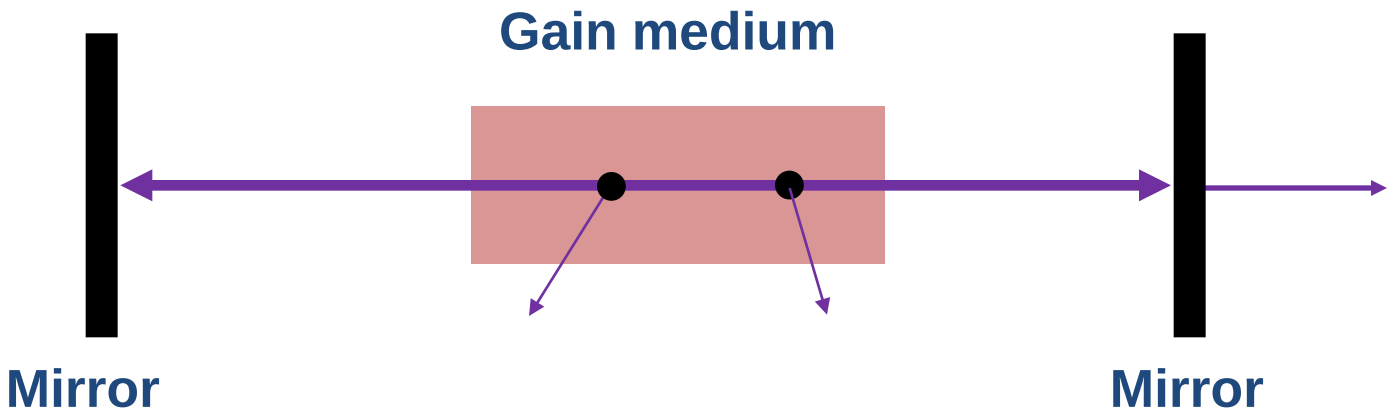


# Laser


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

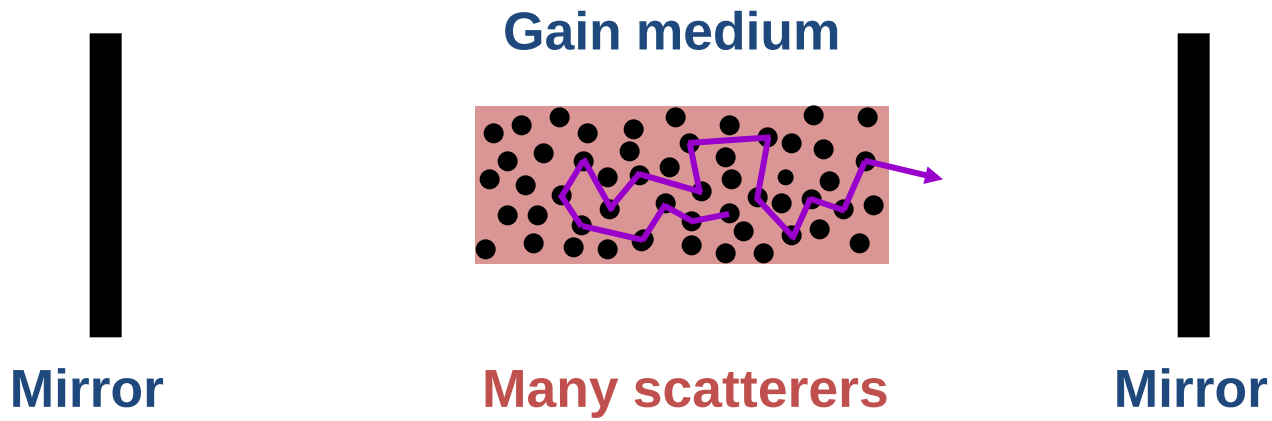
# Weak Scattering

**Weak scattering of light inside the laser cavity causes additional loss, increasing lasing threshold**



# Strong Scattering

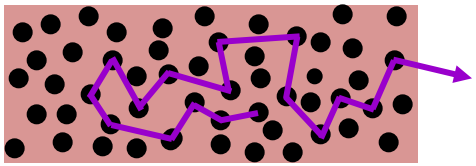
**Multiple scattering increases path length of light inside gain medium, enhancing amplification**



# Mirrorless Laser

**Light is trapped inside gain medium without mirrors**

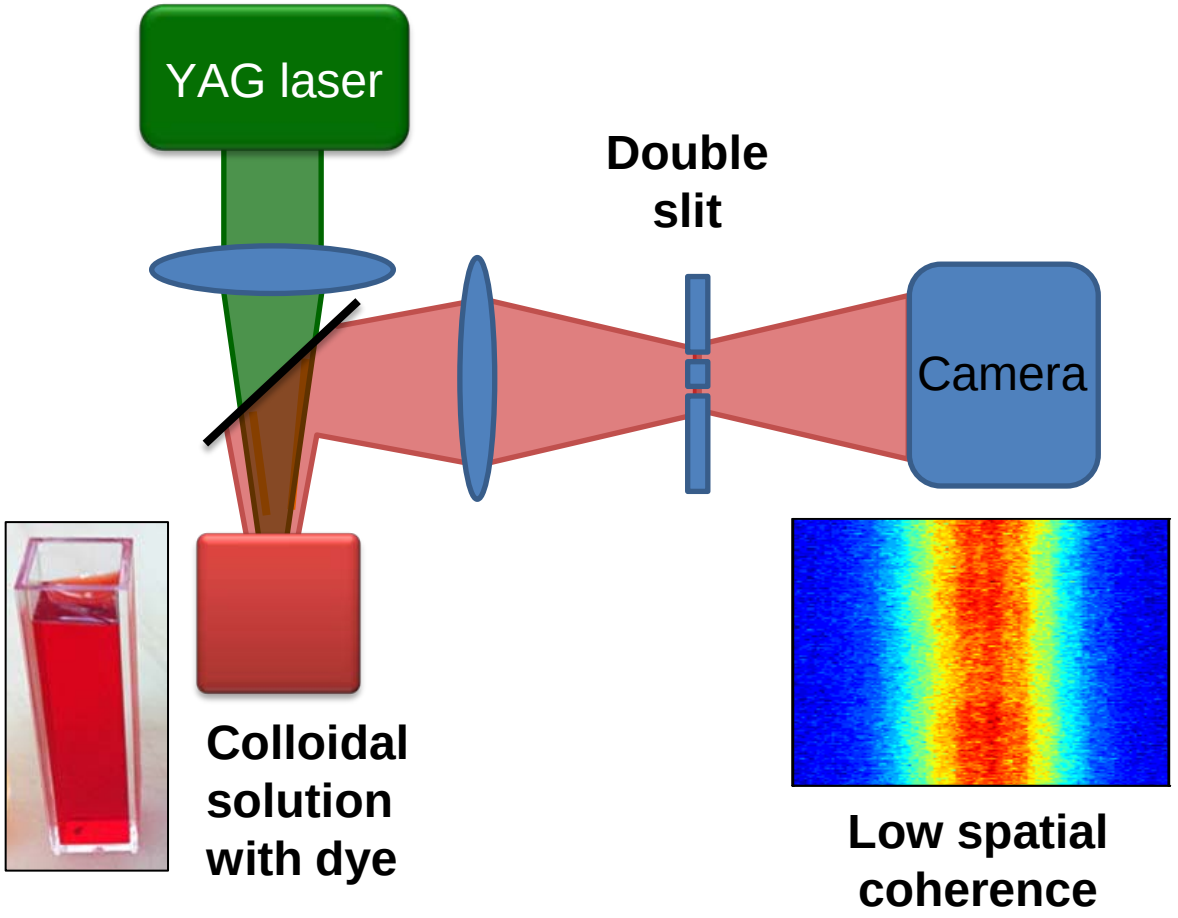
**Gain medium**



**Multiple scattering**

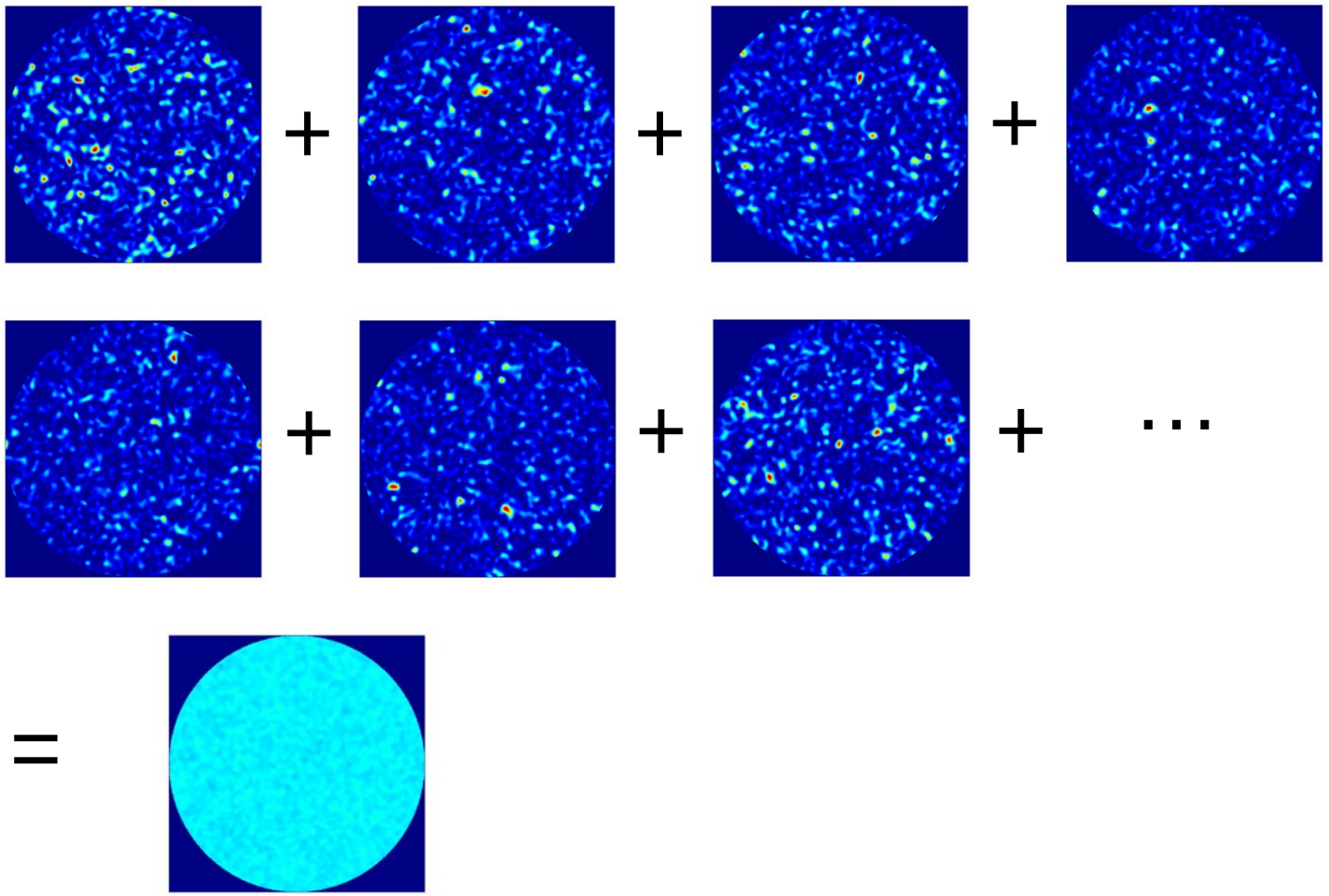
HC, Progress in Optics 45, 317 (2003)

# Low Spatial Coherence

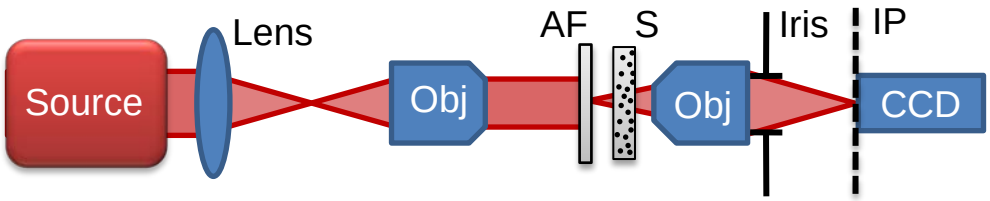


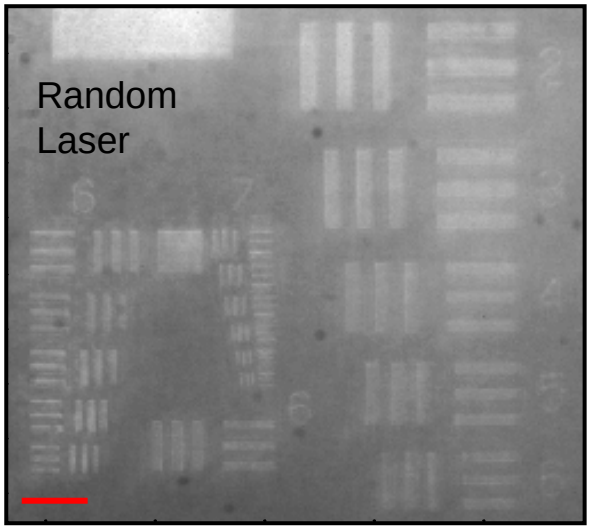

Redding, Choma & HC, *Opt. Lett.* 36, 3404 (2011)

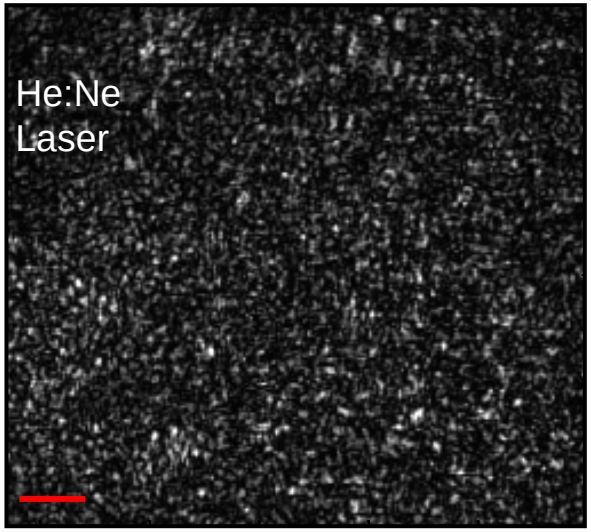
# Many Independent Random Lasing Modes



# Speckle-free Full-Field Imaging




*Nature Photon*. 6, 355 (2012)

4112 OPTICS LETTERS / Vol. 38, No. 20 / October 15, 2013

# Time-resolved microscopy with random lasers

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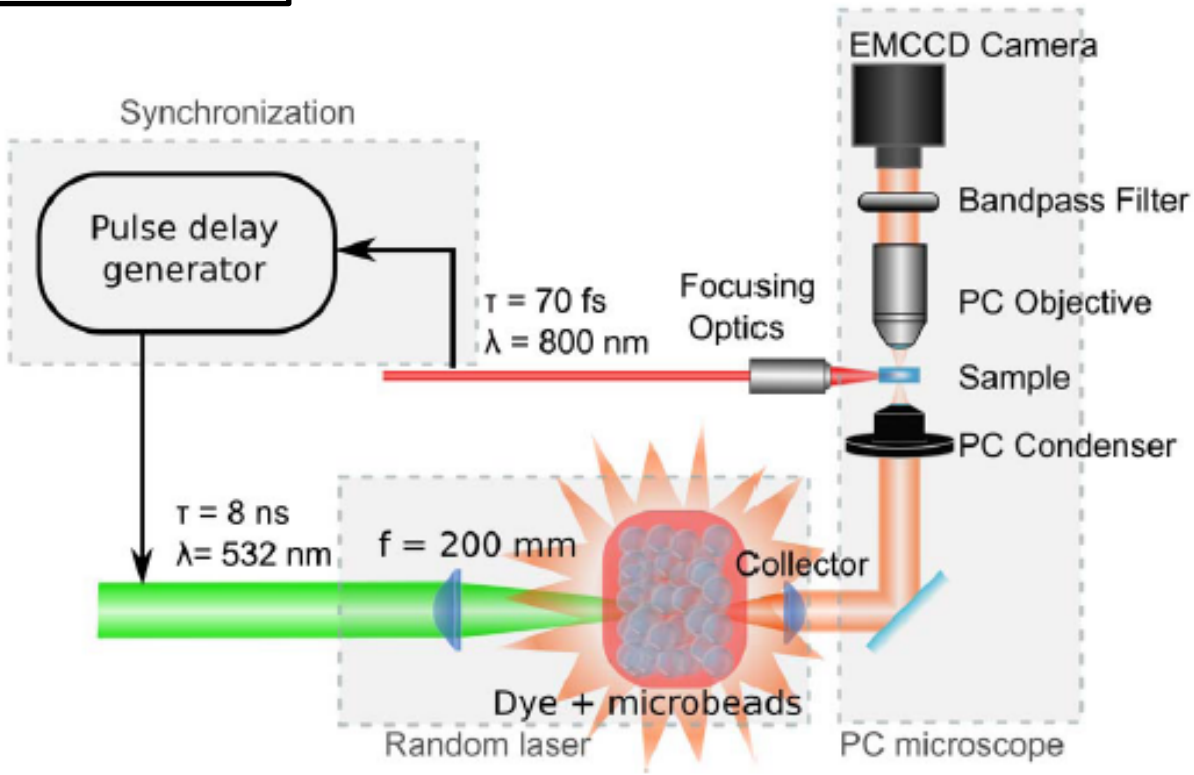
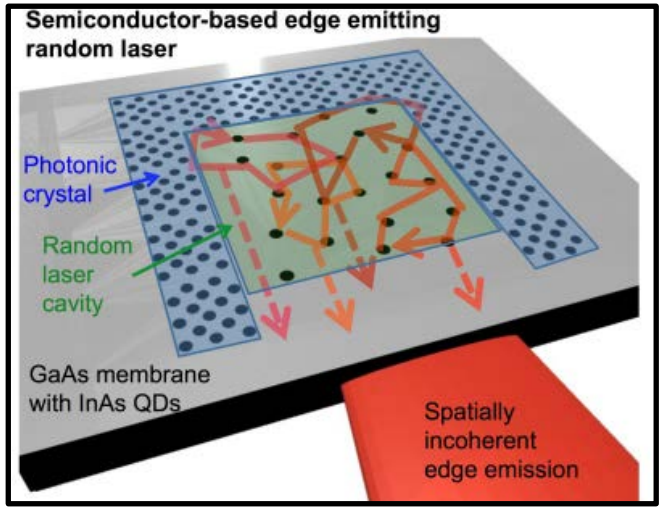
**Corresponding author: mermillod@mbi-berlin.de*

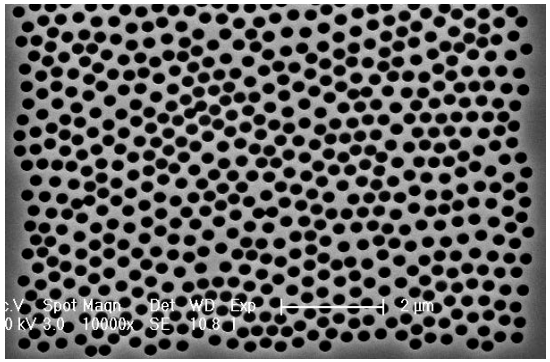
**10 ns Speckle-Free Images**

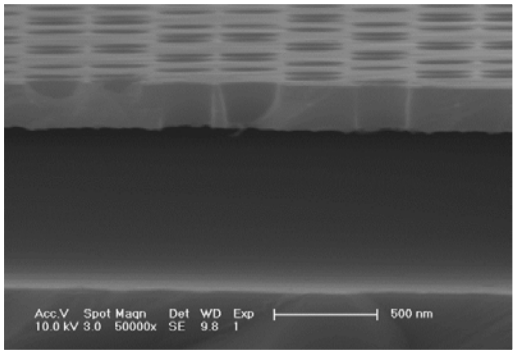


# Practical Random Laser

Compact, electrically pumped, low-cost, long lifetime...



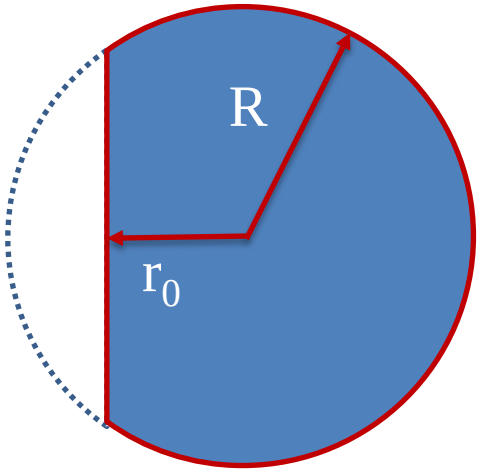



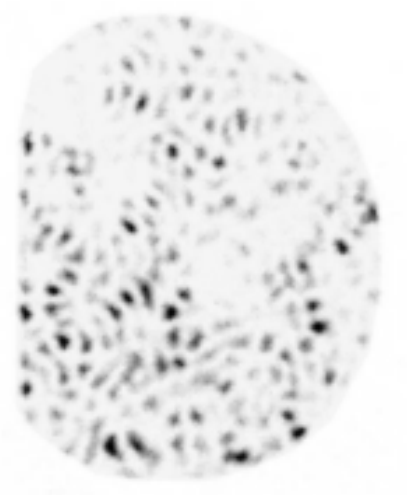


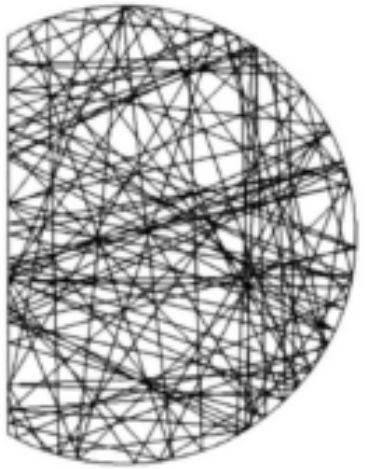

Noh, Rooks, Liew, Solomon, HC, *Phys. Rev. Lett.* **106**, 183901 (2011)

# Low Spatial Coherence Laser

- **Many modes of similar Q factor**
- **Minimal gain competition**
- **Speckled emission pattern**



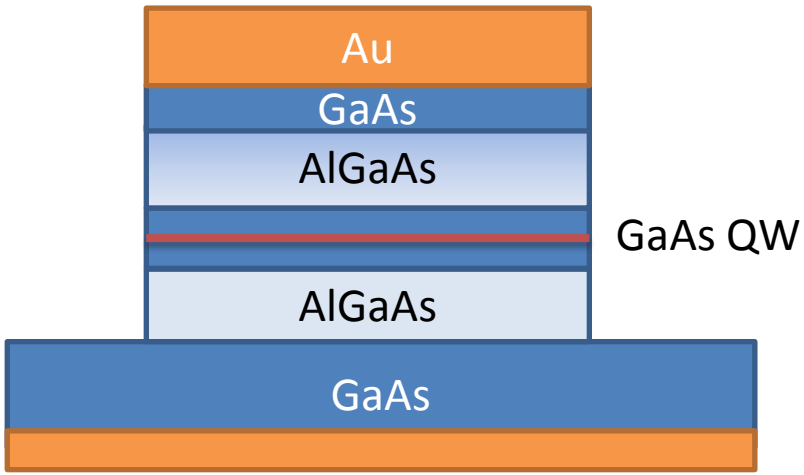





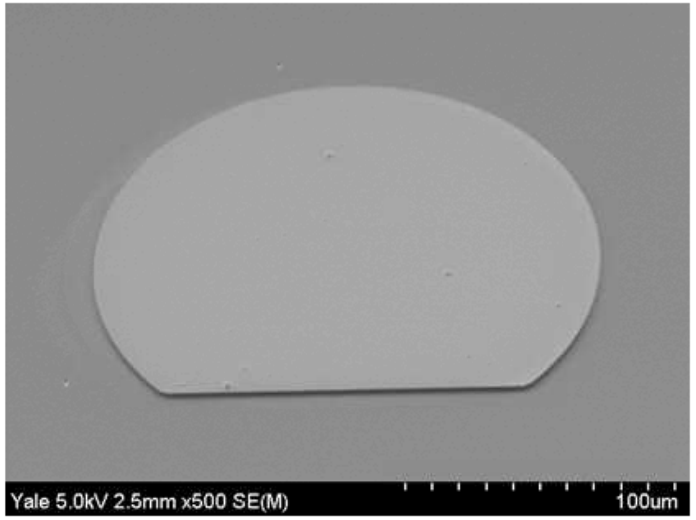
HC & Wiersig, *Rev. Mod. Phys.* 87, 61 (2015)

# D-shaped Semiconductor Microcavity

**Commercial epi wafer**



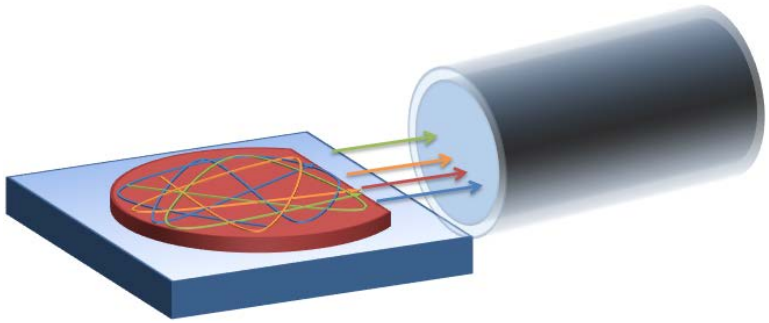

**Photolithography**
**Wet etching**

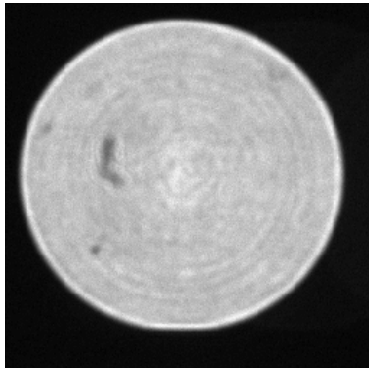



Redding et al, *PNAS* 112, 1304 (2015)

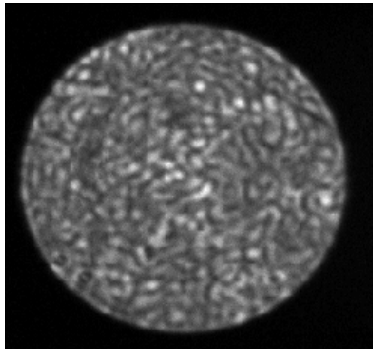
# Speckle-Free Laser

- **Electrical current injection**
- **Room temperature lasing**



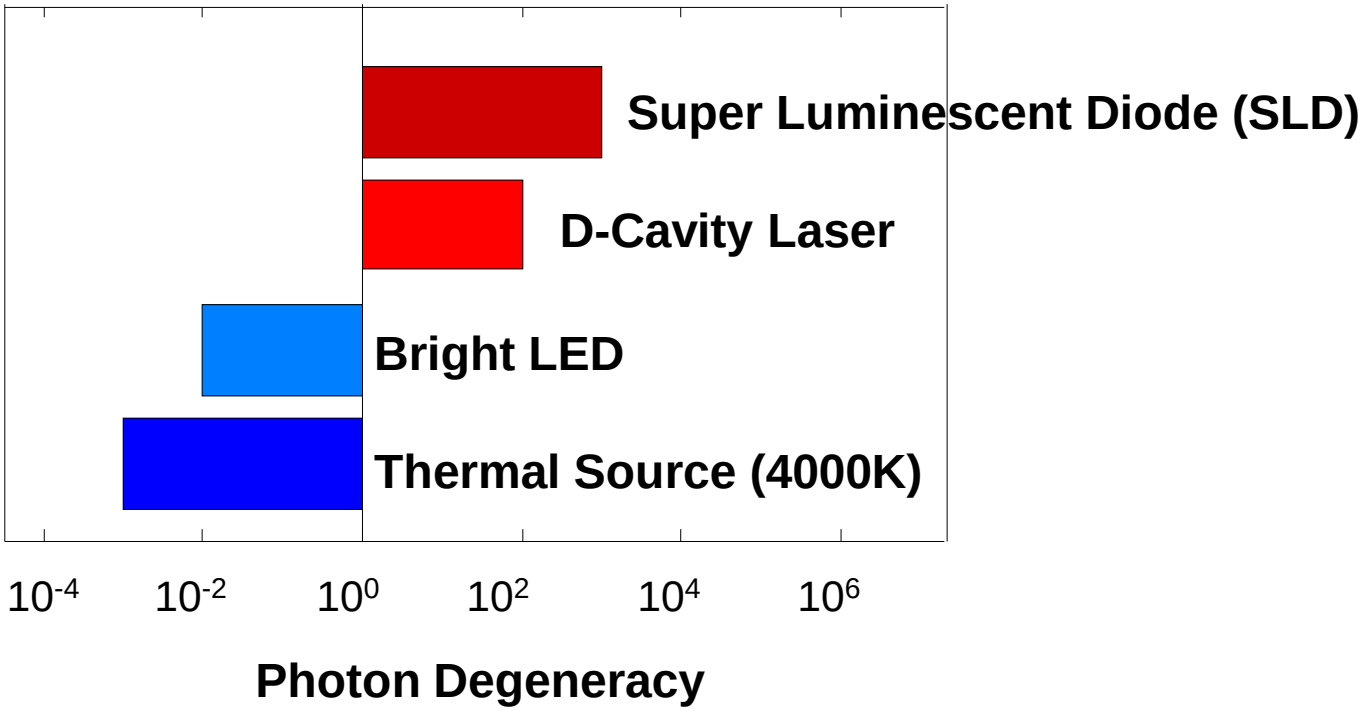


**Circular microdisk laser**



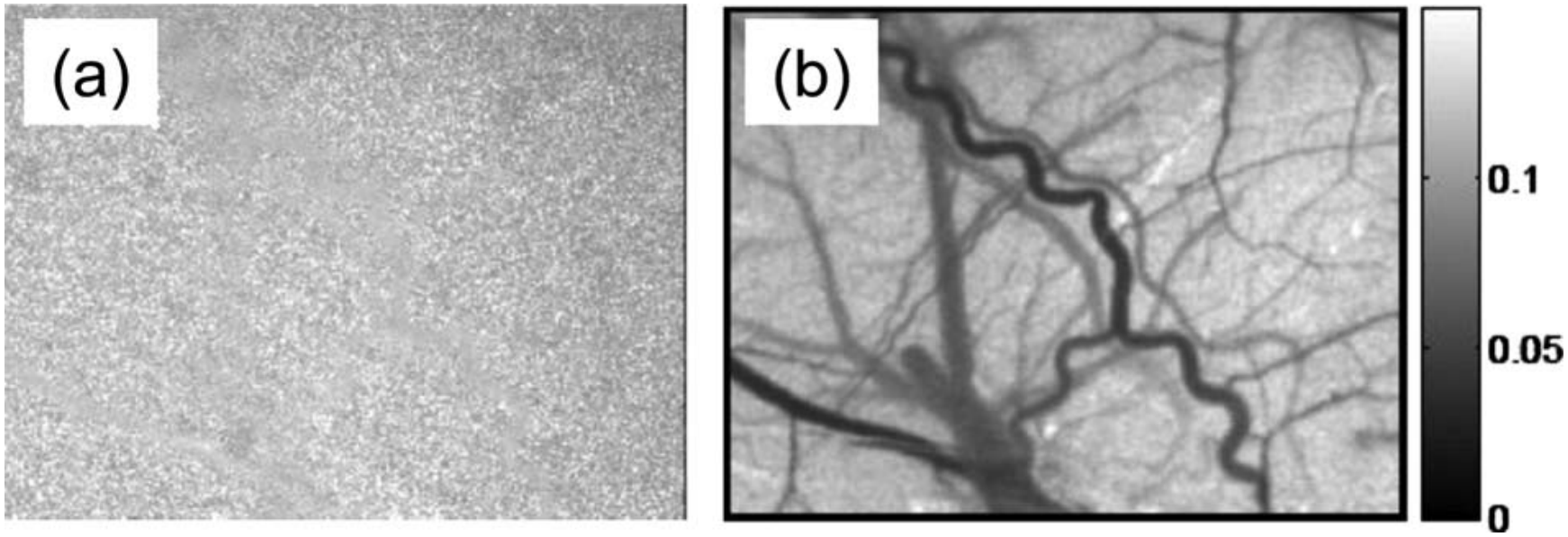
Redding et al, *PNAS* 112, 1304 (2015)

# Source Brightness Comparison




Redding et al, *PNAS* 112, 1304 (2015)

# Laser Speckle Contrast Imaging




D. A. Boas and A. K. Dunn, J. Biomed. Opt. 15, 011109 (2010).

# Bimodality Imaging

Switch spatial coherence of a laser

low spatial coherence -> structural image

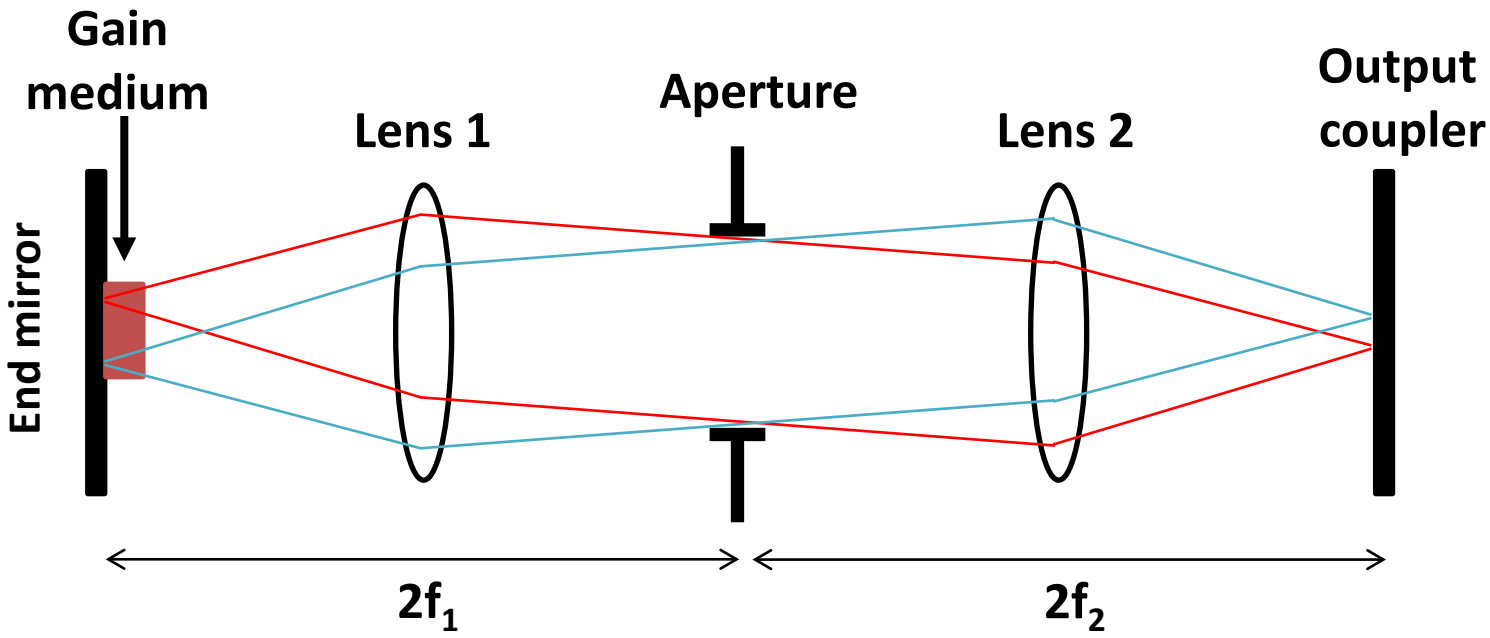
high spatial coherence -> dynamic process

Challenges

constant emission power

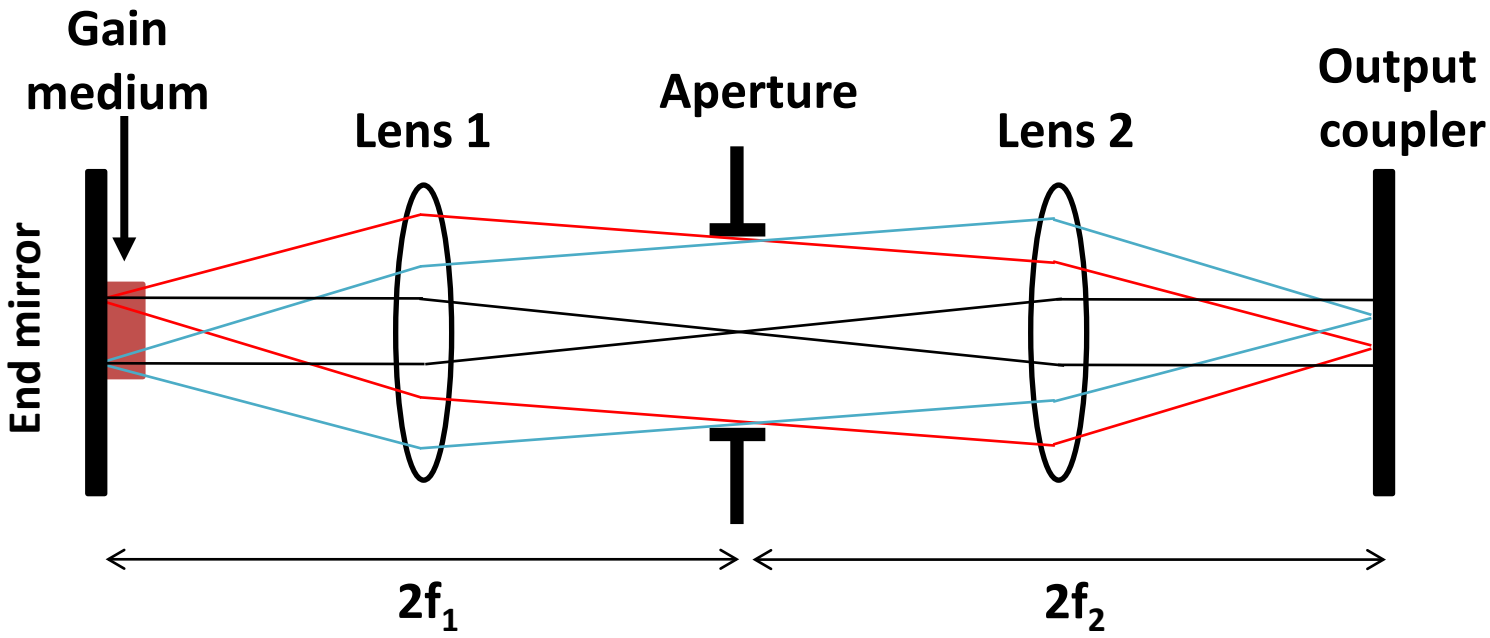
same output direction

# Degenerate Laser Cavity



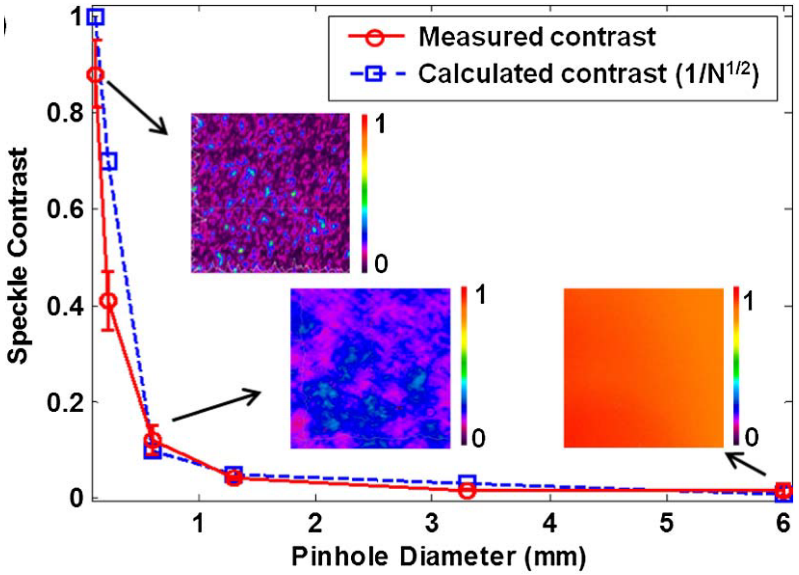

**Multiple transverse modes lasing, low spatial coherence**

# Single Mode Lasing

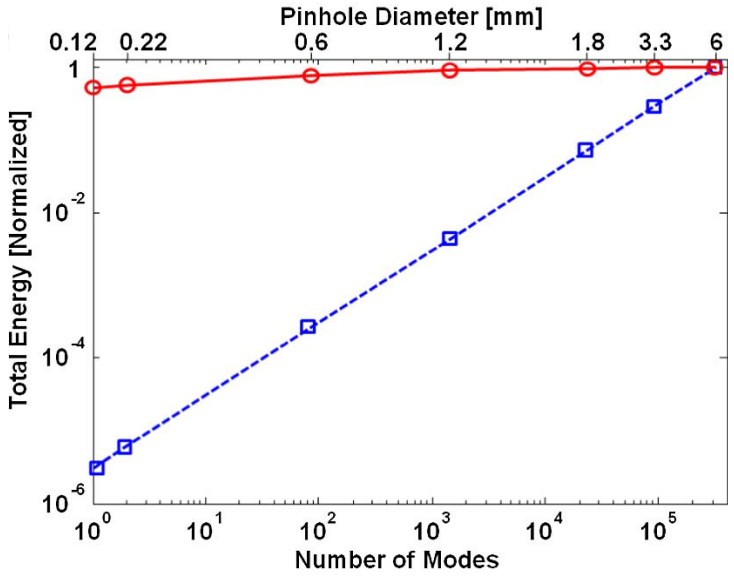



**Single mode lasing, high spatial coherence**

# Solid State Degenerate Laser




**1 mode lasing** ⟺ **320,000 modes**

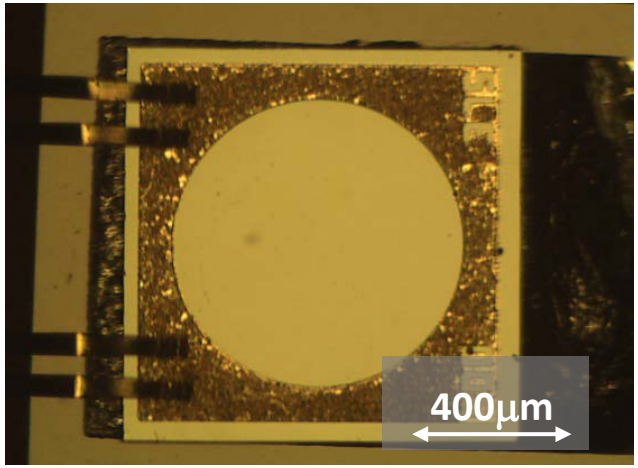


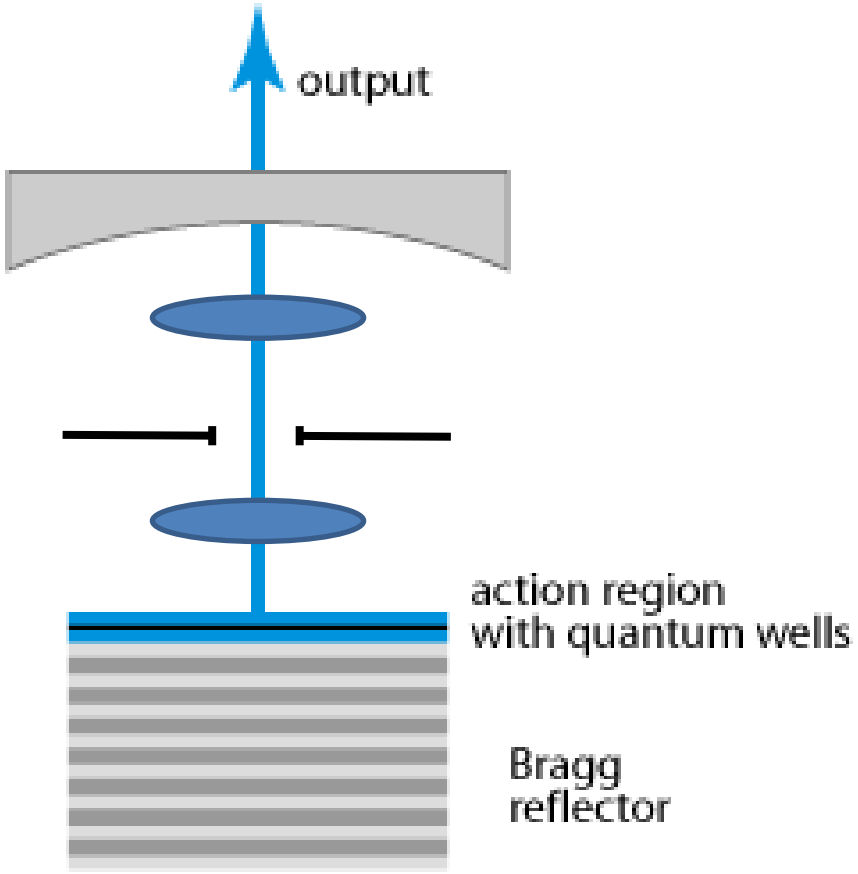

**Less than 50% change in total output power**

Nixon et al, Opt. Lett. 38, 3858 (2013)

# Degenerate VECSEL

## Broad-area VECSEL



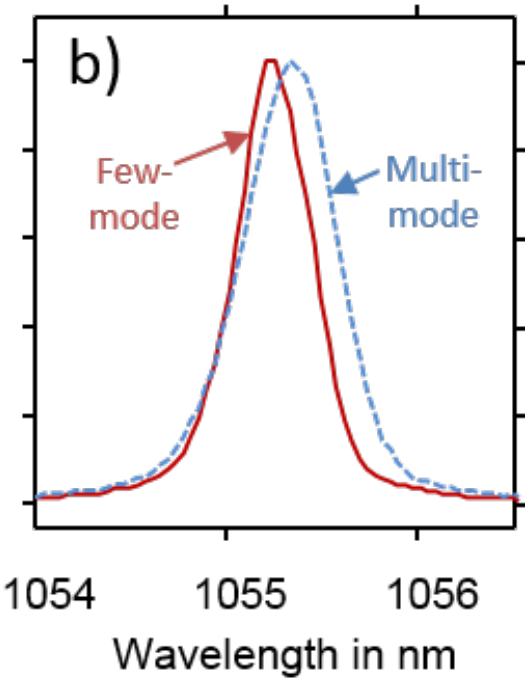

**Electrical pumping**

**High power**

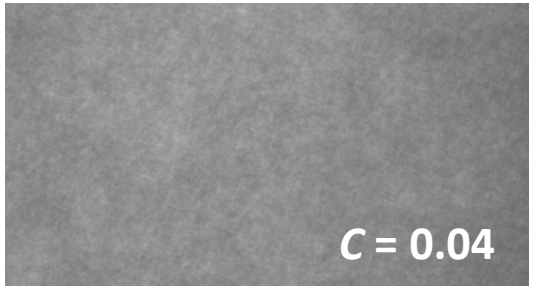
Knitter et al, *Optica* 3, 403 (2016)

# Degenerate VECSEL

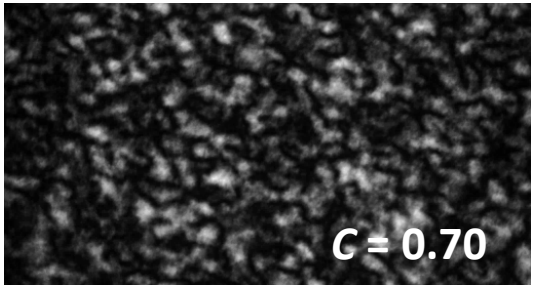
**Lasing spectrum**




**Multi-mode**

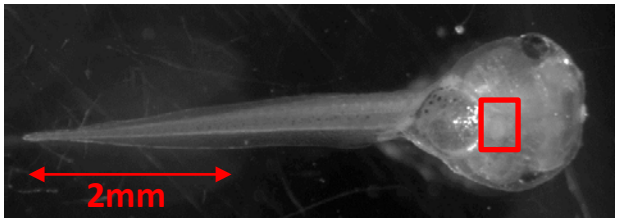


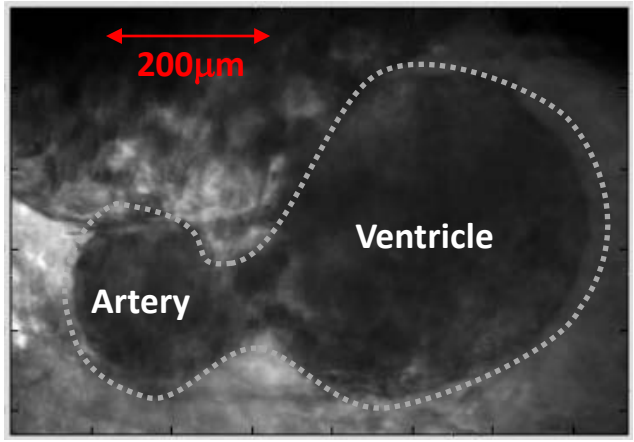

**Few-mode**

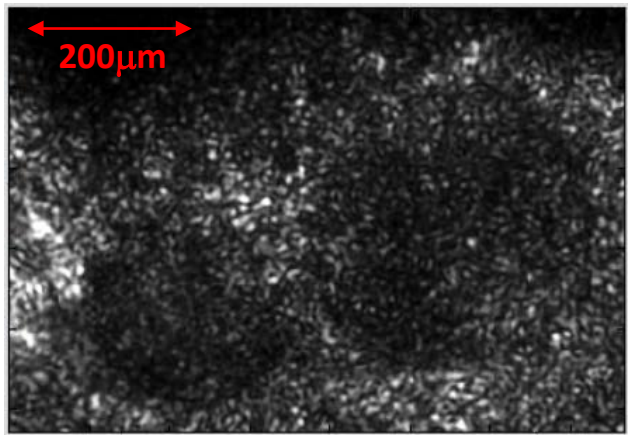



Knitter et al, *Optica* 3, 403 (2016)

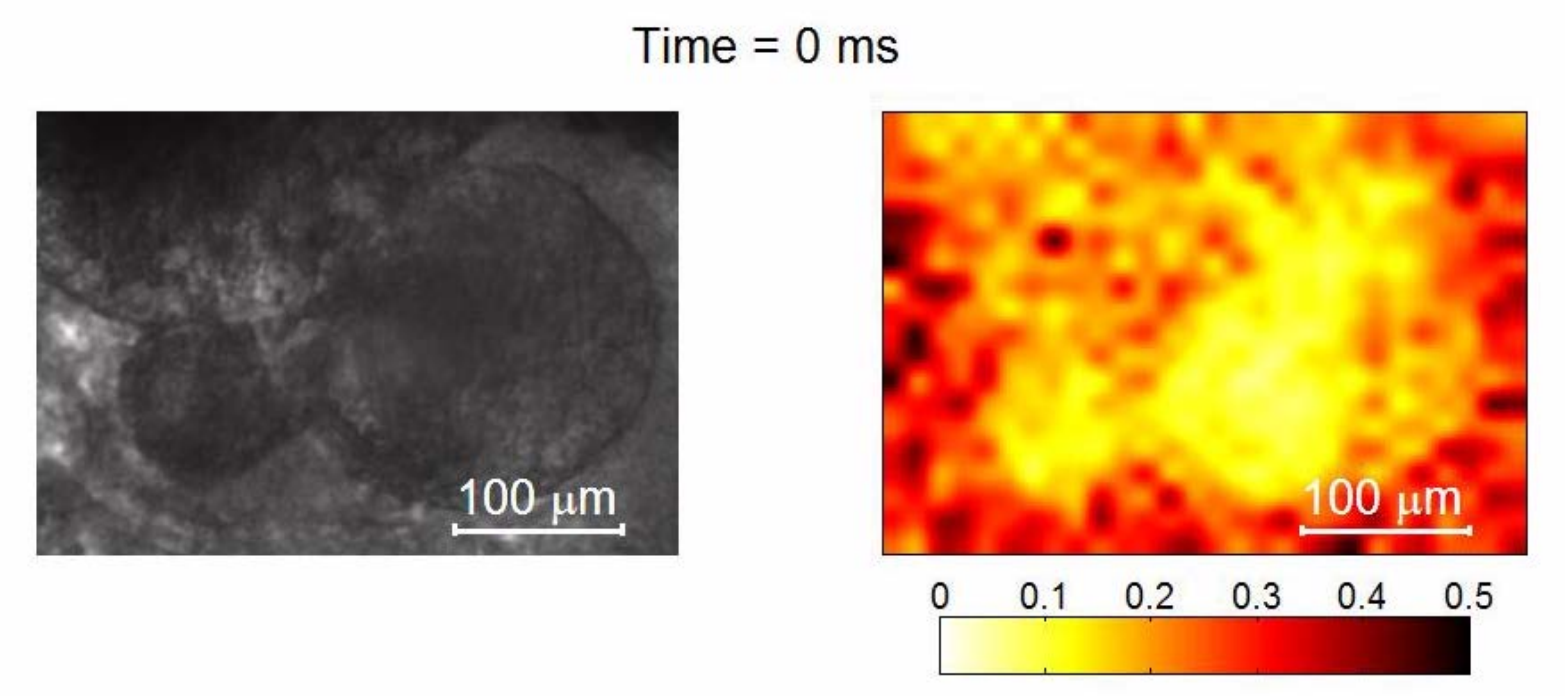
# Imaging Heartbeat of a Living Tadpole

# Imaging Heartbeat of a Living Tadpole




Knitter et al, *Optica* 3, 403 (2016)

# Summary

- **Reduce spatial coherence of laser for speckle-free imaging**
- **Switch spatial coherence of laser for bimodality imaging**

# Acknowledgement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