The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964-2014

2583-14

Workshop on Coherent Phenomena in Disordered Optical Systems

26 - 30 May 2014

Random Laser - Physics & Application

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Random Laser - Physics & Application

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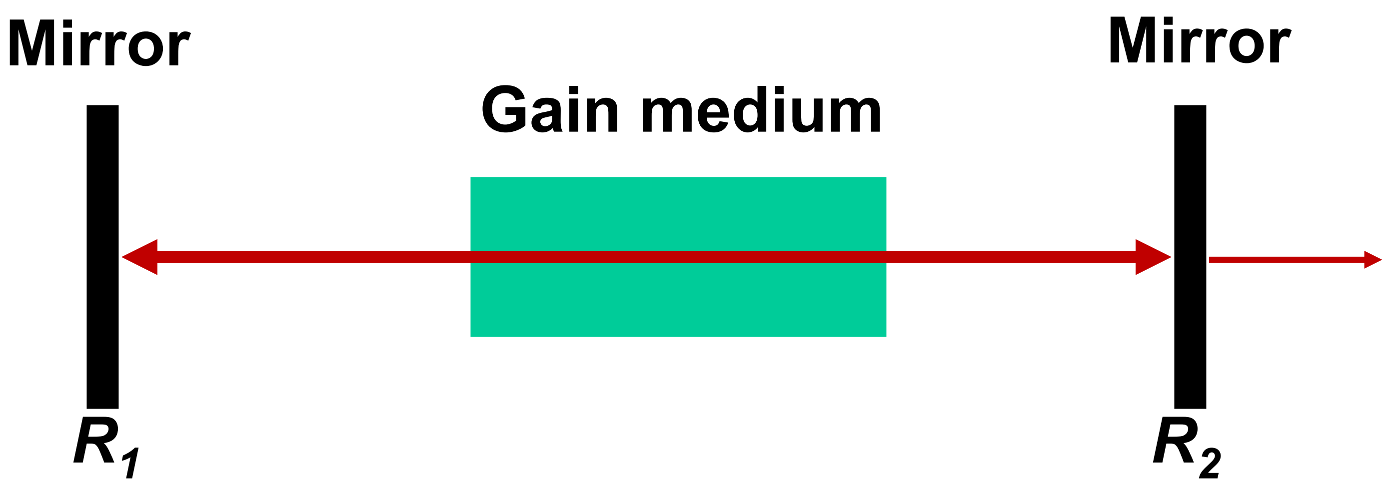
Michael Choma
Doug Stone
Michael Rooks

Laser

Essential components for a laser

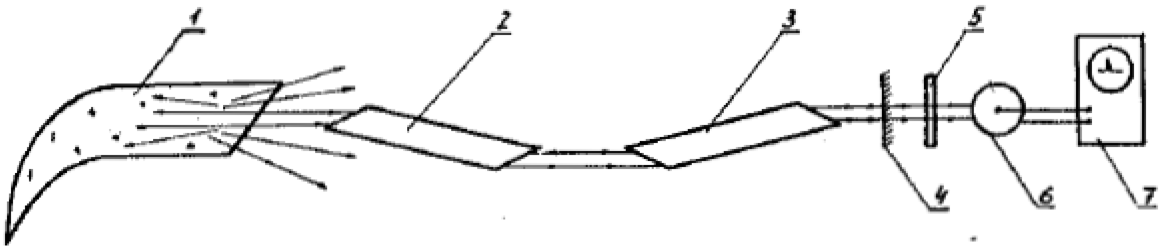
- **Gain medium** — **Light amplification**
- **Cavity** — **Coherent feedback**



Threshold $R_1 R_2 e^{2gL_g} = 1$

Resonance $2kL_c = 2\pi m$

Laser with Scattering Reflector



Scattering medium

Ruby crystals

Mirror

Nicolay Basov

Non-Resonant Feedback

Lasing Threshold $R_1 R_2 e^{2gL_g} = 1$

Vladilen Letokhov

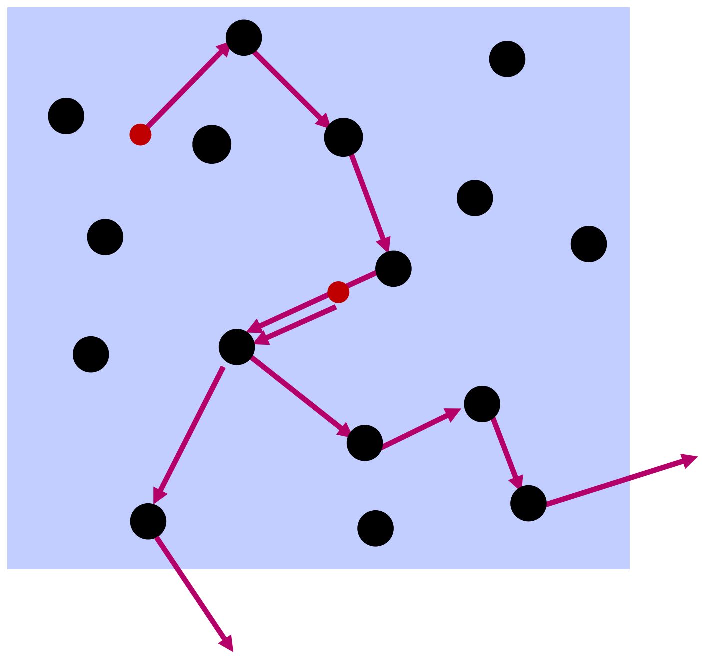
Ambartsumyan, Basov, Kryukov, and Letokhov, *IEEE J. Quantum Electron. 2 442* (1966)

Photonic Bomb

Instability for Amplification of Spontaneous Emission (ASE)

Average path length of photon exceeds amplification length

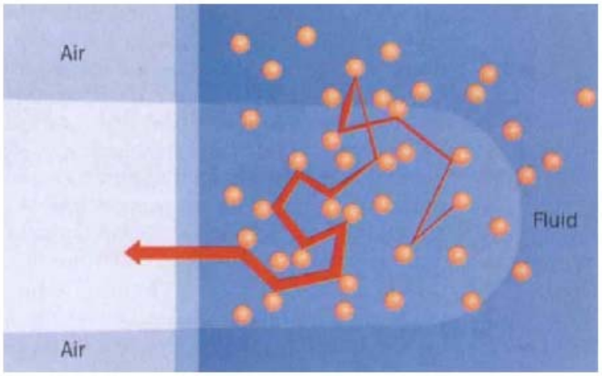
Photon multiplication



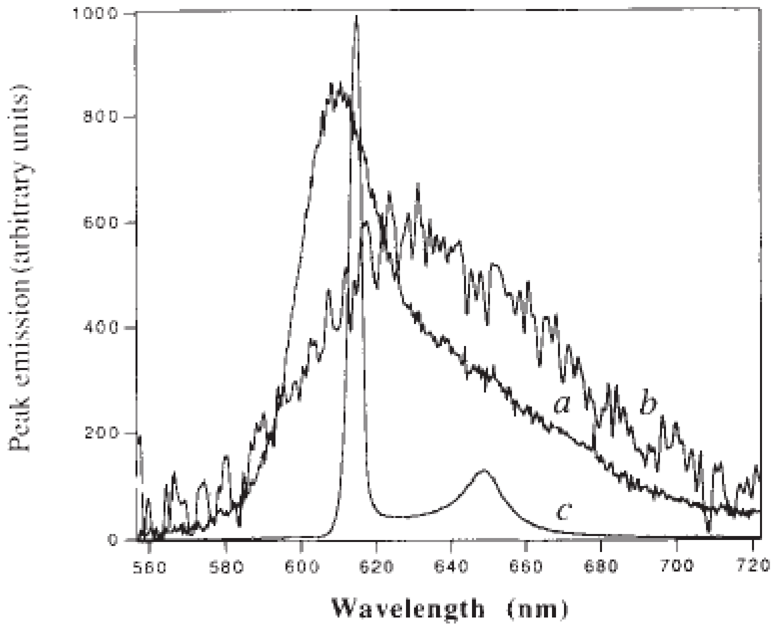
Letokhov, Sov. Phys. JETP **26**, 1109 (1968)

Laser Paint

Dye molecules and scattering particles



Dramatic narrowing of emission spectra



Lawandy, Balachandran, Gomes & Sauvain, Nature **368**, 436 (1994)

Light Diffusion, Absorption, Emission, and Amplification

Pump light and probe light in 4-level atomic media

$$\frac{\partial W_G(\vec{r},t)}{\partial t} = D\nabla^2 W_G(\vec{r},t) - \sigma_{abs} v[N_t - N_1(\vec{r},t)]W_G(\vec{r},t) + \frac{1}{l_G} I_G(\vec{r},t),$$

$$\frac{\partial W_R(\vec{r},t)}{\partial t} = D\nabla^2 W_R(\vec{r},t) + \sigma_{em} v N_1(\vec{r},t) W_R(\vec{r},t) + \frac{1}{l_R} I_R(\vec{r},t),$$

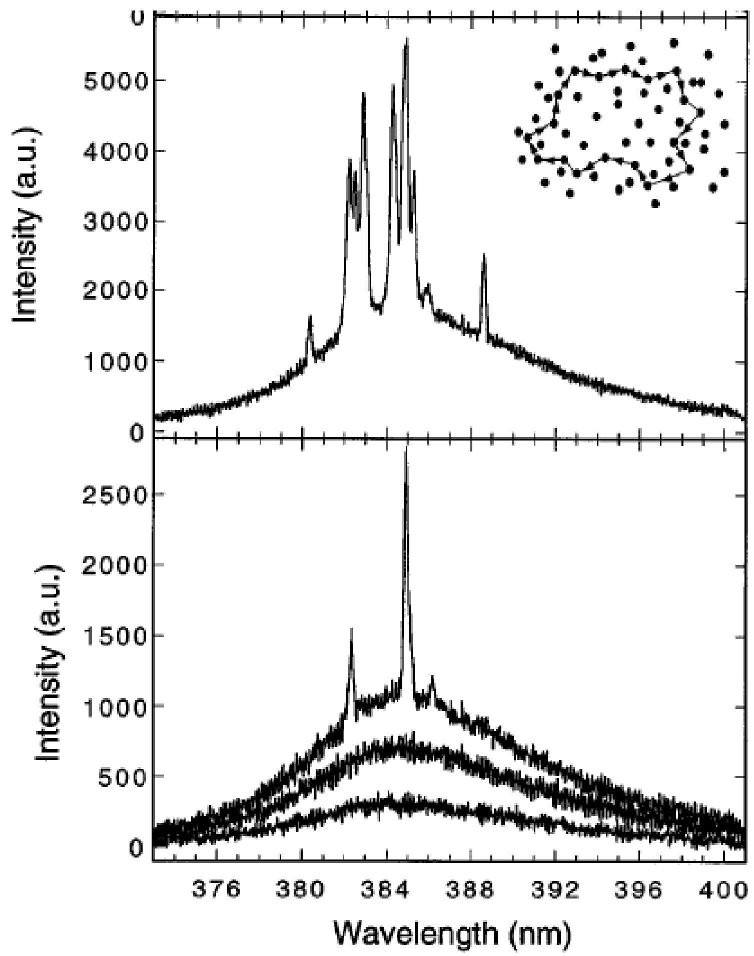
$$\frac{\partial W_A(\vec{r},t)}{\partial t} = D\nabla^2 W_A(\vec{r},t) + \sigma_{em} v N_1(\vec{r},t) W_A(\vec{r},t) + \frac{1}{\tau_e} N_1(\vec{r},t),$$

$$\frac{\partial N_1(\vec{r},t)}{\partial t} = \sigma_{abs} v[N_t - N_1(\vec{r},t)]W_G(\vec{r},t) - \sigma_{em} v N_1(\vec{r},t)[W_R(\vec{r},t) + W_A(\vec{r},t)] - \frac{1}{\tau_e} N_1(\vec{r},t).$$

Wiersma & Lagendijk, Phys. Rev. E **54**, 4256 (1997)

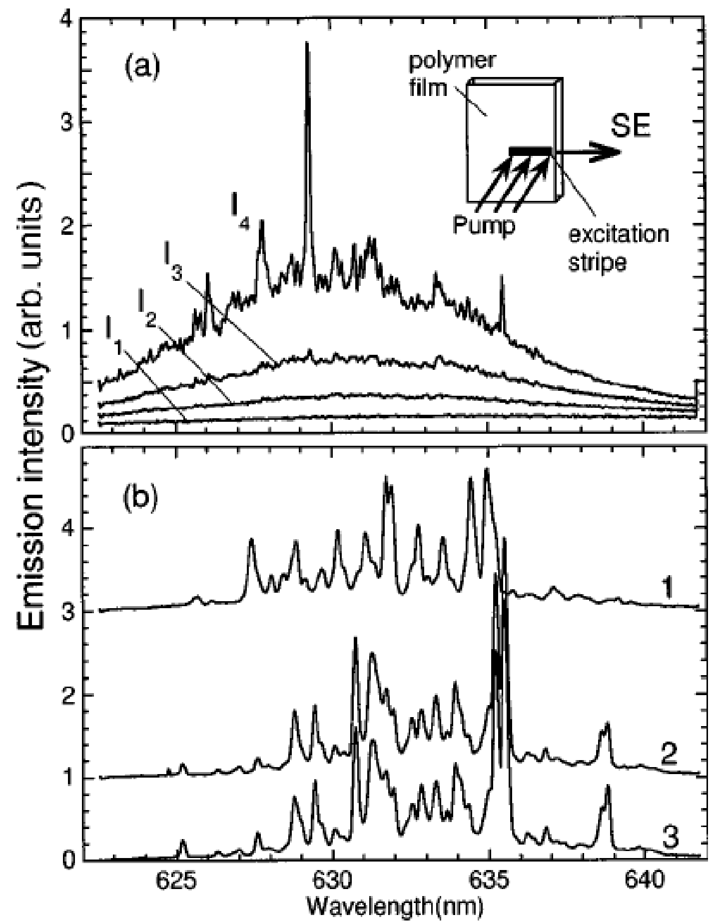
Discrete Lasing Peaks

ZnO powder



HC et al, Phys. Rev. Lett. **82**, 2278 (1999)

DDO-PPV film



Frolov et al, Phys. Rev. B **59**, 5284 (1999)

Electromagnetic Mode

Maxwell's equations

$$\frac{\partial \vec{H}(\vec{r},t)}{\partial t} = -\frac{1}{\mu_0}\nabla \times \vec{E}(\vec{r},t)$$

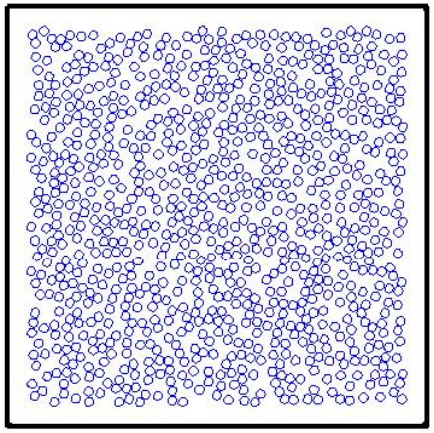
$$\frac{\partial \vec{E}(\vec{r},t)}{\partial t} = \frac{1}{n^2(\vec{r})}\nabla \times \vec{H}(\vec{r},t)$$

Complex refractive index $n = n_r + in_i$

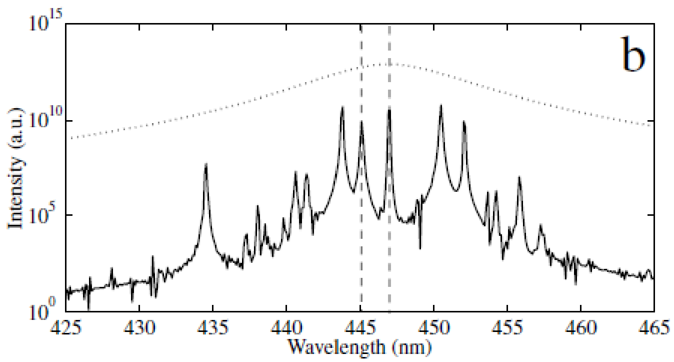
Boundary condition: only outgoing waves

HC et al, Phys. Rev. E, **61**, 1985 (2000)
Jiang & Soukoulis, Phys. Rev. Lett. **85**, 70 (2000)

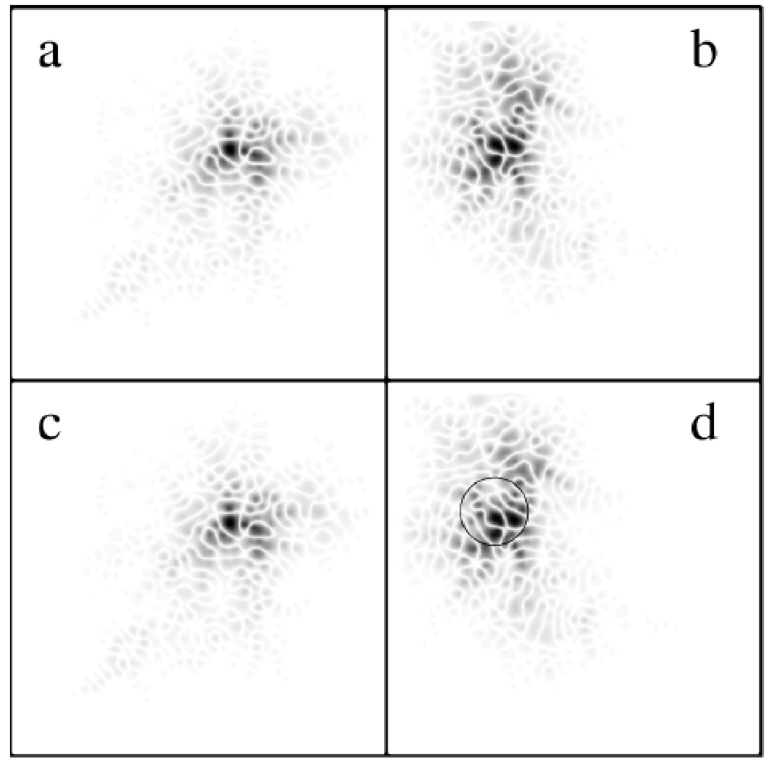
Localized Modes



Spectrum



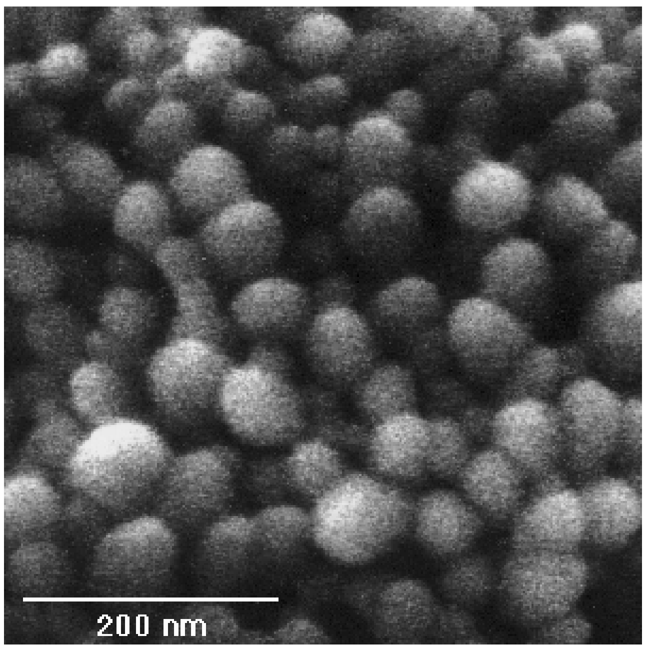
Mode Pattern



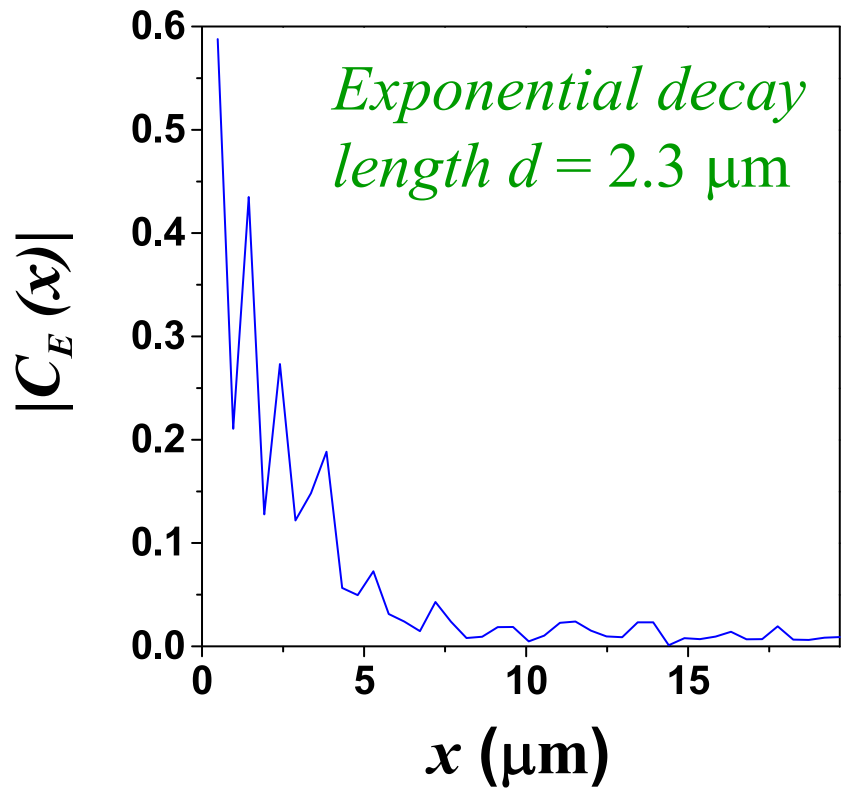
Vanneste & Sebbah, Phys. Rev. Lett. **87**,183903 (2001)

ZnO Powder

Average particle diameter ~ 100 nm



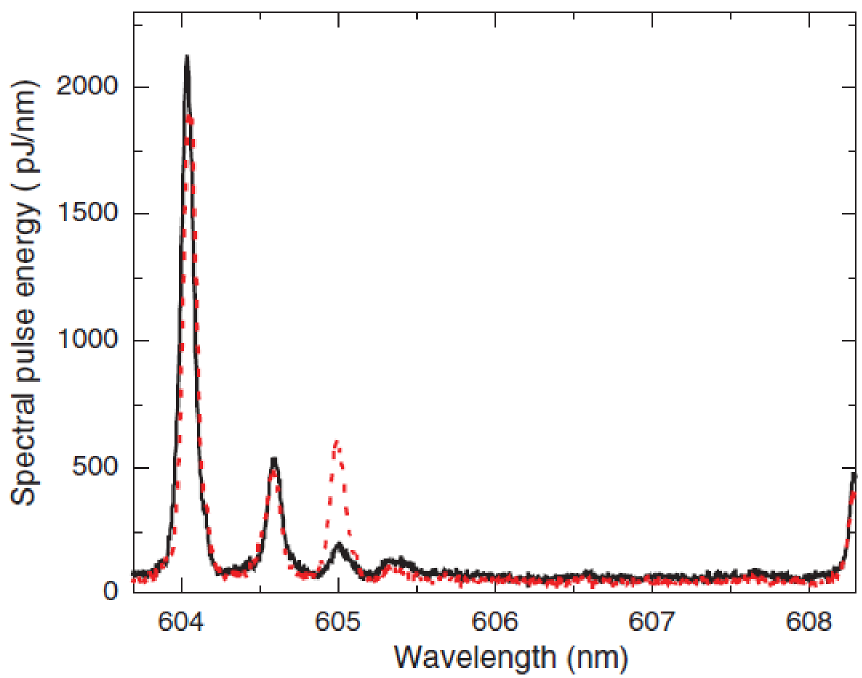
$$C_E(x) \equiv \int E^*(x')\,E(x+x')\,dx'$$

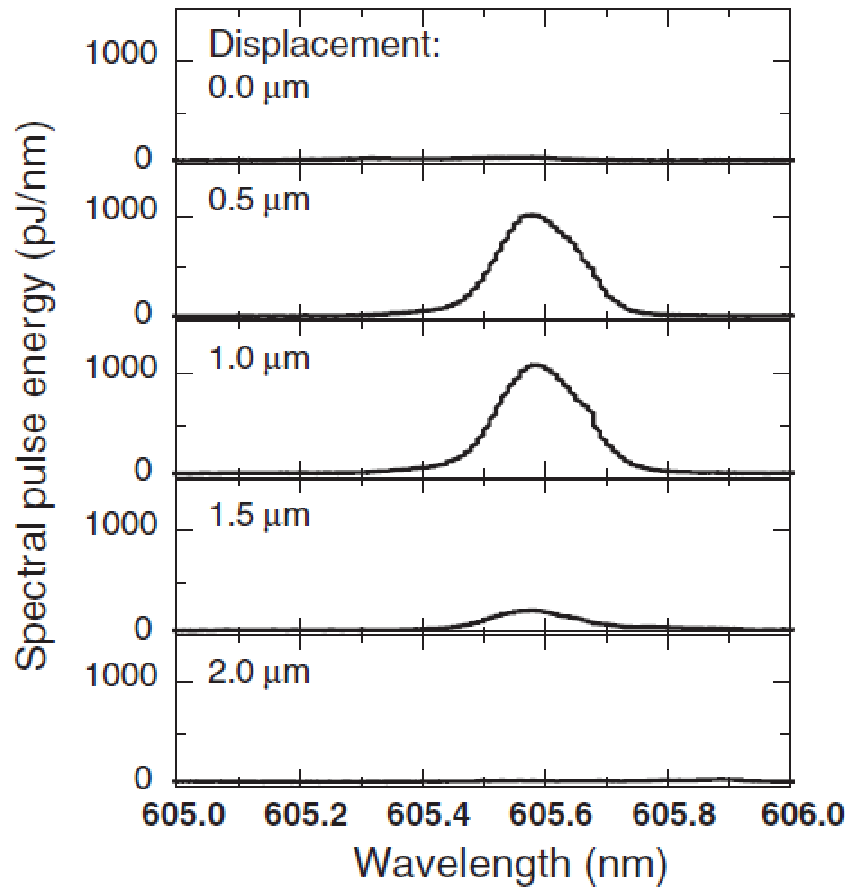


HC et al, Phys. Rev. E **66**, R25601 (2002)

Porous GaP

$$k\,l_t \approx 6$$





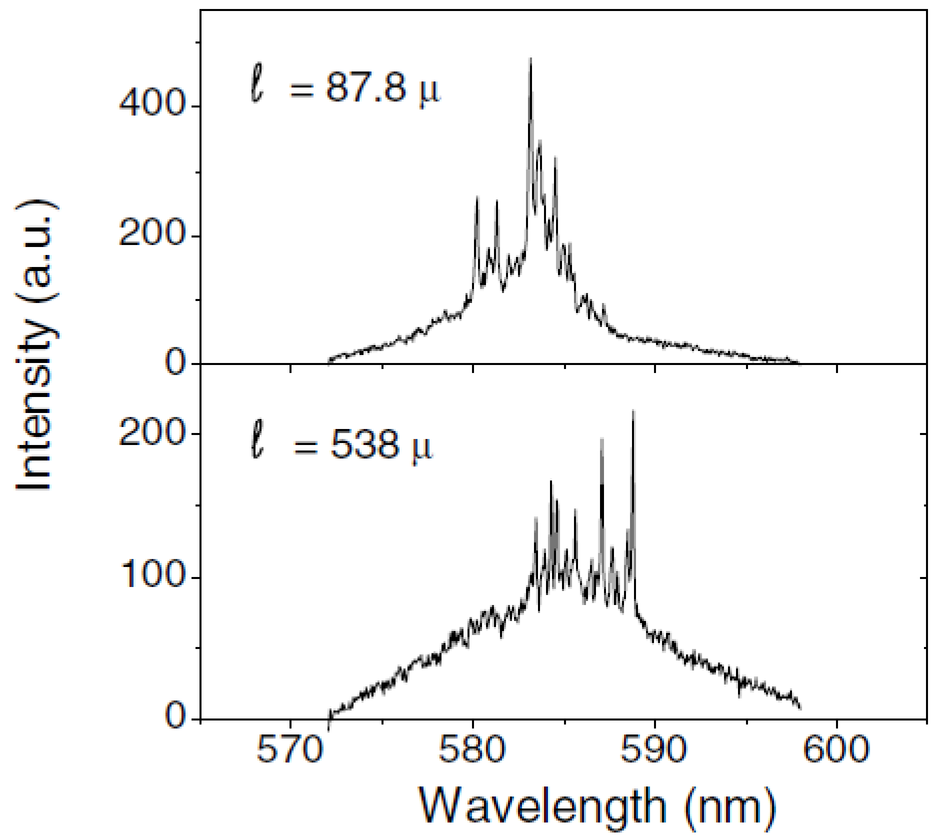
van der Molen et al, Phys. Rev. Lett. **98**, 143901 (2007)

Weak Scattering System

Dye solution with scattering particles

$$k\, l_t >> 1$$

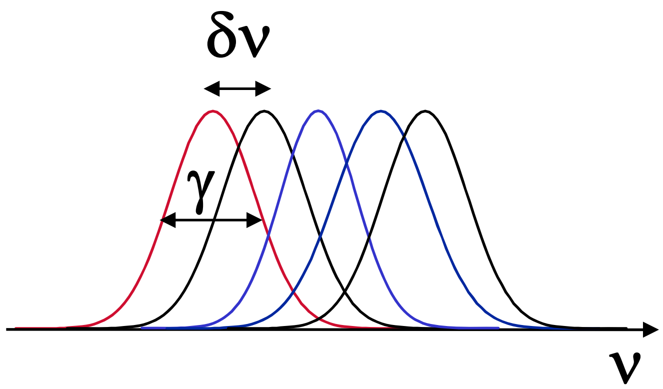
Amplification of spatially extended modes in random laser



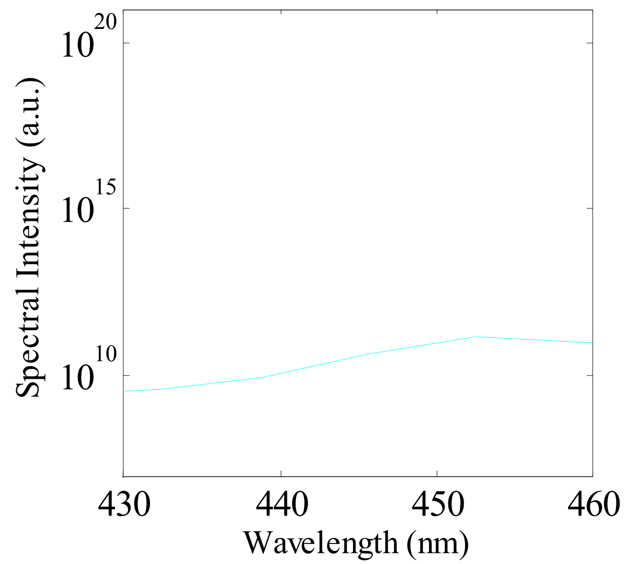
Mujumdar et al, Phys. Rev. Lett. **93**, 053903 (2004)

Overlapping Resonances

Thouless number $N_T = \dfrac{\gamma}{\delta\nu} >> 1$



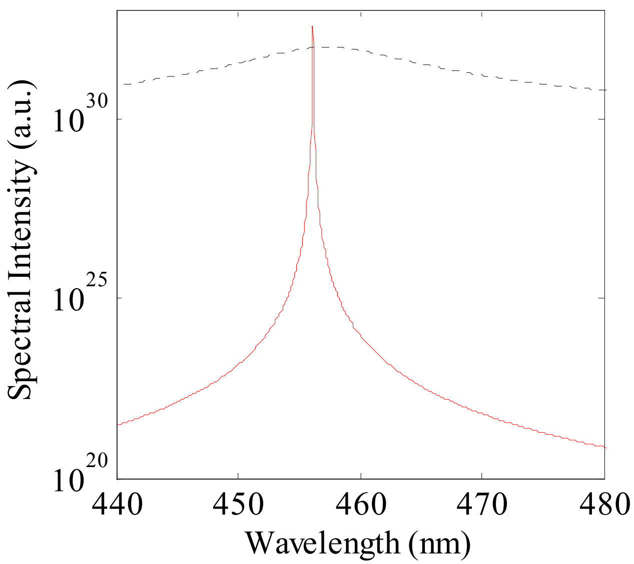
Excitation spectrum of a passive system



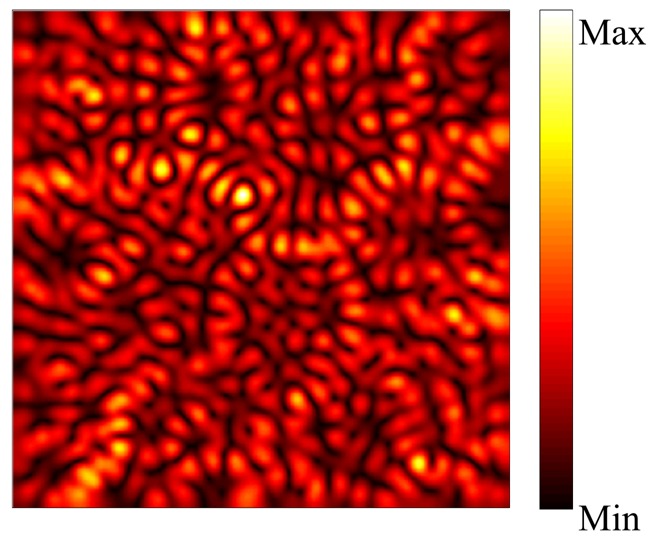
Resonances are strongly overlapped <u>spatially</u> and <u>spectrally</u>.

Coherent Lasing Mode

Lasing spectrum



Lasing Mode Pattern

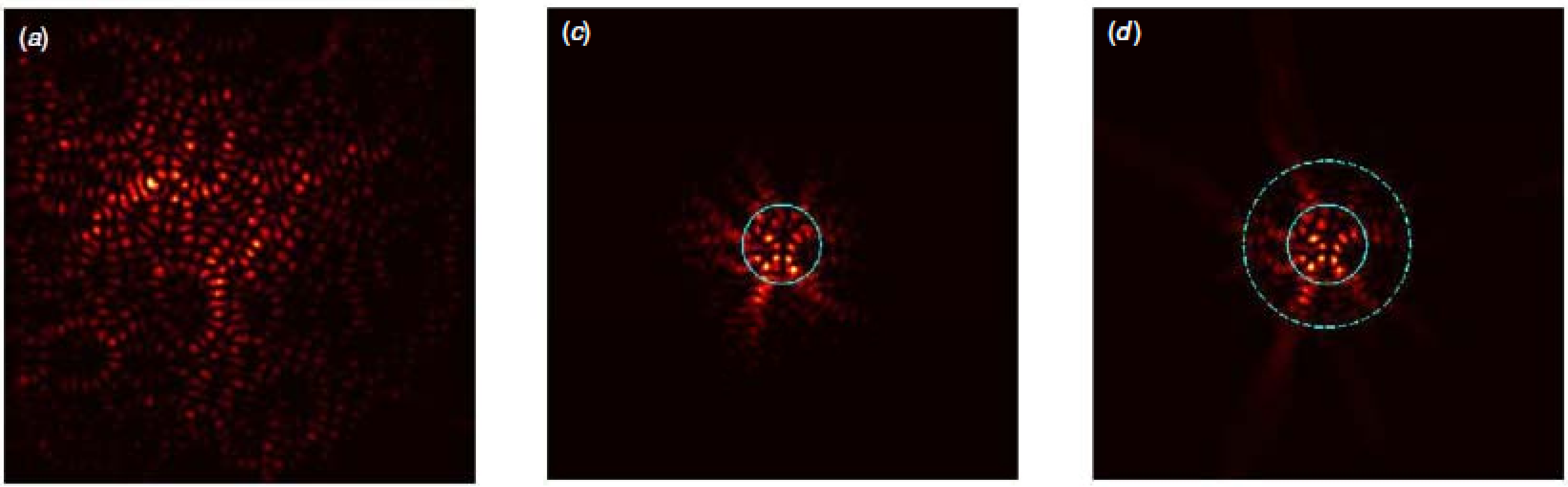


Laser Field Amplitude

Vanneste, Sebbah & HC, Phys. Rev. Lett. **98**,143902 (2007).

Non-Uniform Gain and Absorption

Absorption outside gain region effectively reduces the size of random structure by suppressing feedback from the unpumped region, and creates localized lasing modes.

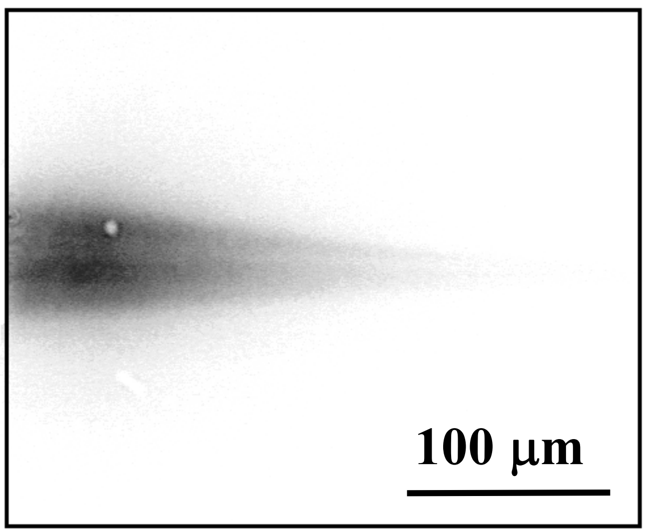


Yamilov et al., Opt. Lett. **30**, 2430 (2005)
Andreasen & HC, Opt. Lett. **30** 2430 (2009)

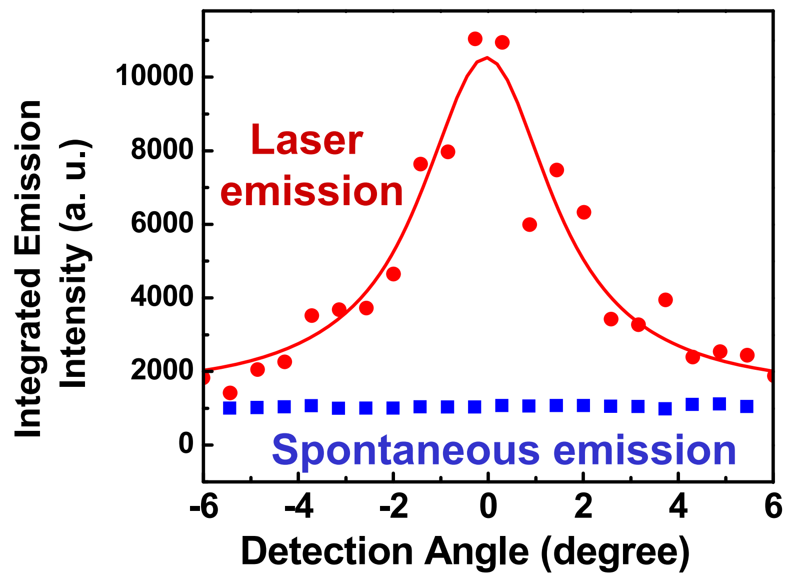
Directional Laser Emission

Local pumping of weakly scattering samples

Cone shaped pump volume



Angular distribution of output intensity



Wu & HC, Phys. Rev. A **74**,053812 (2006)

Mode Interaction

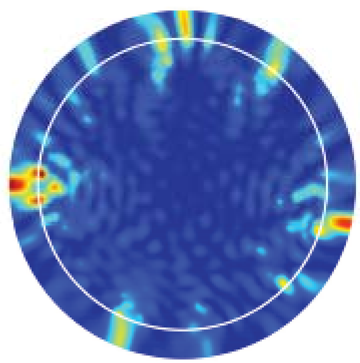
Mode competition for gain

Gain saturation, spatial hole burning

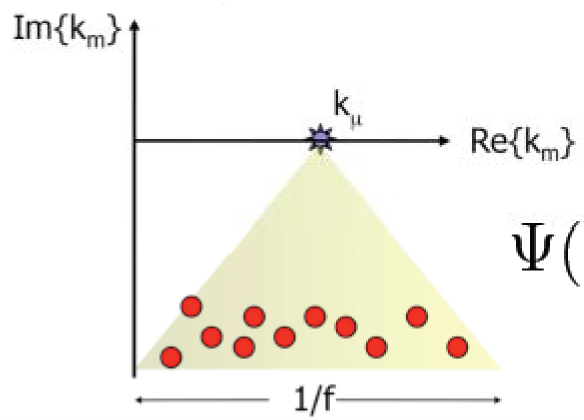
Localized modes, spatially non-overlapping,
$\longrightarrow$ weak interaction

Extended modes, spatial overlapping,
$\longrightarrow$ strong interaction

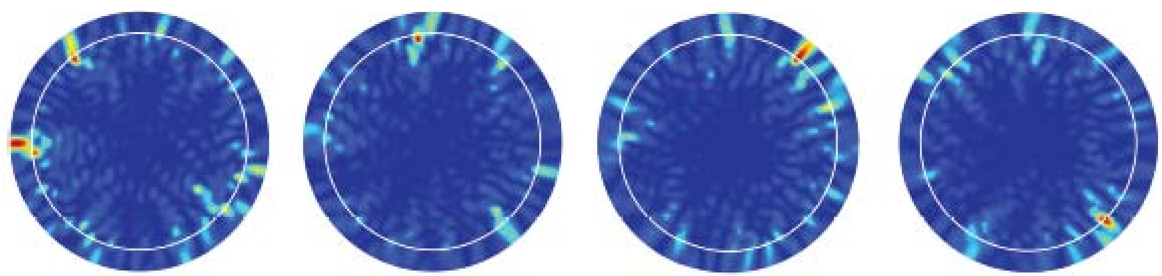
Composite Lasing Modes



Mode 4



$$\Psi(x) = \sum_m c_m \varphi_m(x)$$

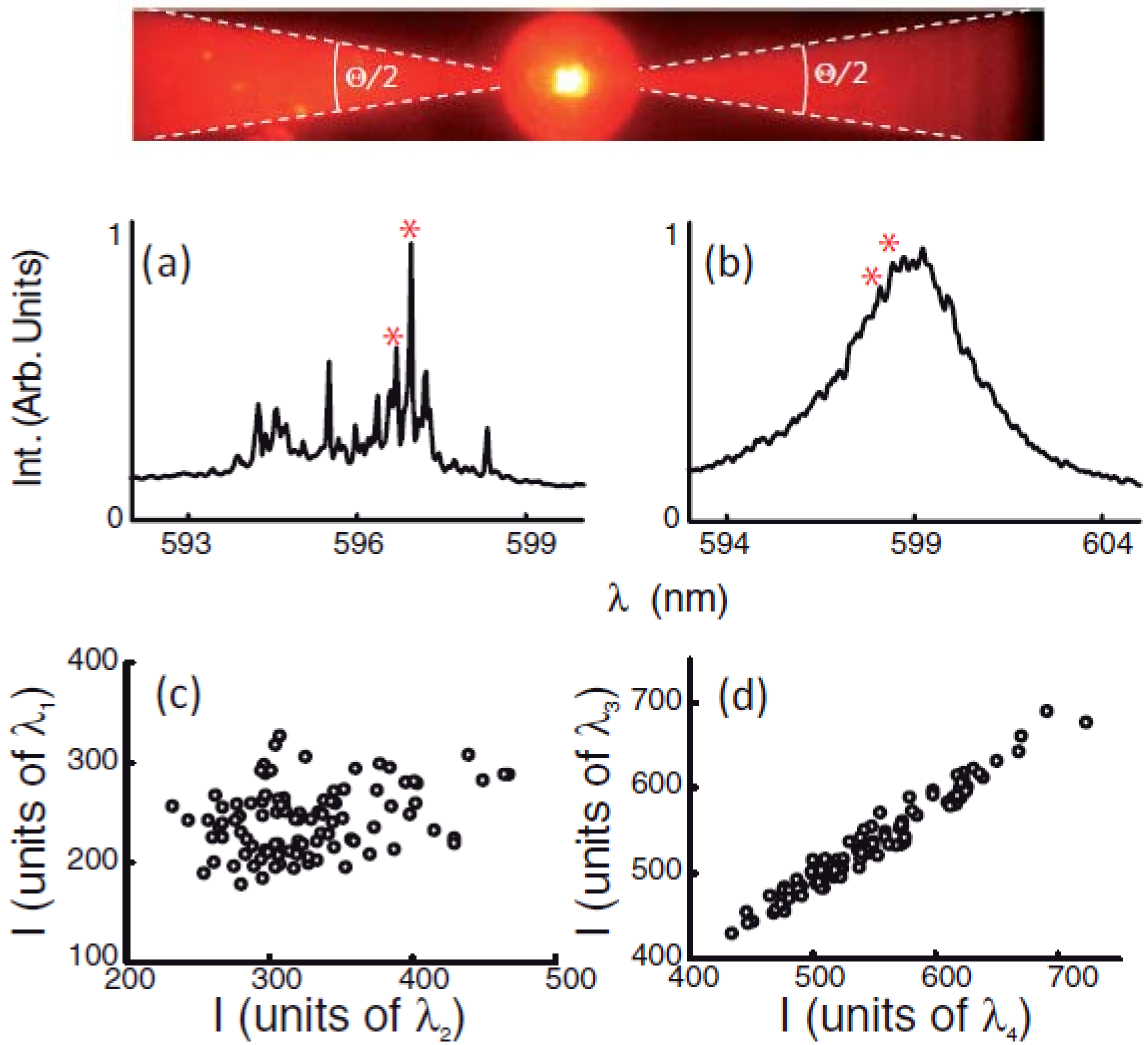


CF3: 26.9%   CF 6: 17.8%   CF 12:8.4%   CF 11: 7.2%

Composite Lasing Modes

*HE Türeci, L. Ge, S. Rotter, AD Stone, Science **643**, 320 (2008)*

Nonlinear Dynamics



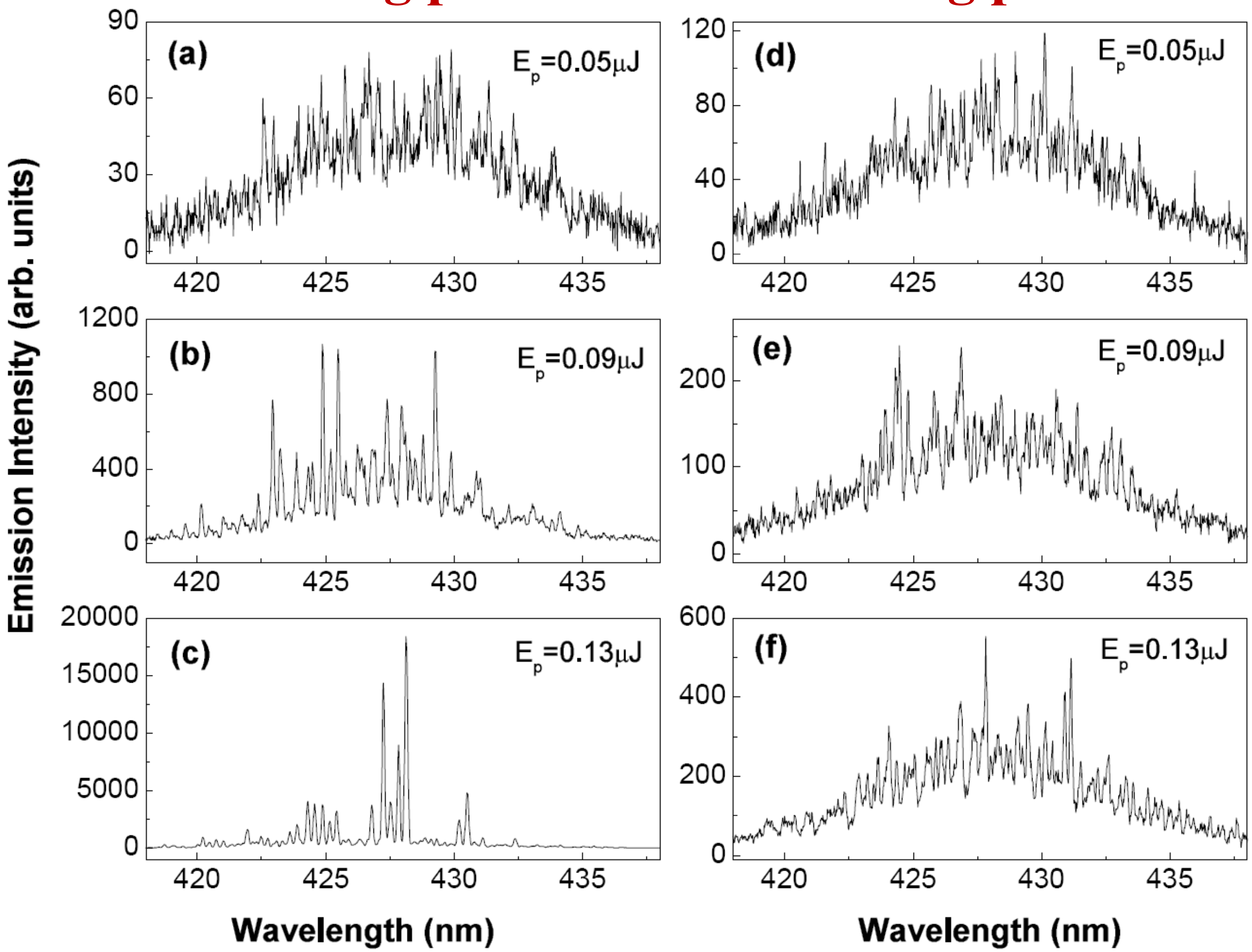
Conti et al, Phys. Rev. Lett. **96**, 065702 (2006); Leonetti, Conti & Lopez, Nat. Photon. **5**, 615 (2011)

Question

What is the statistical properties of random lasing modes?

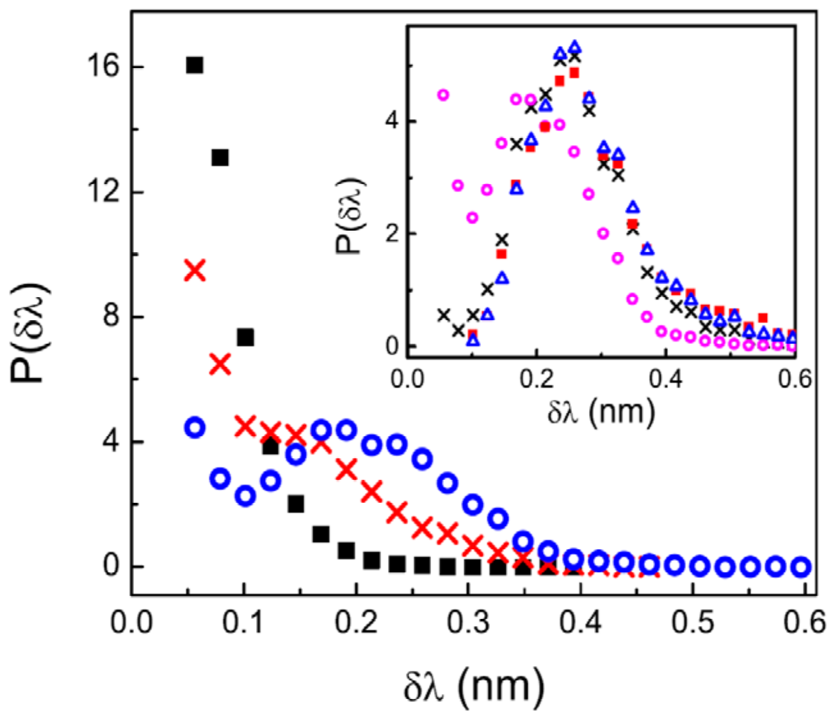
Single-Shot Emission Spectra

Dye solution with scattering particles | **Dye solution without scattering particles**

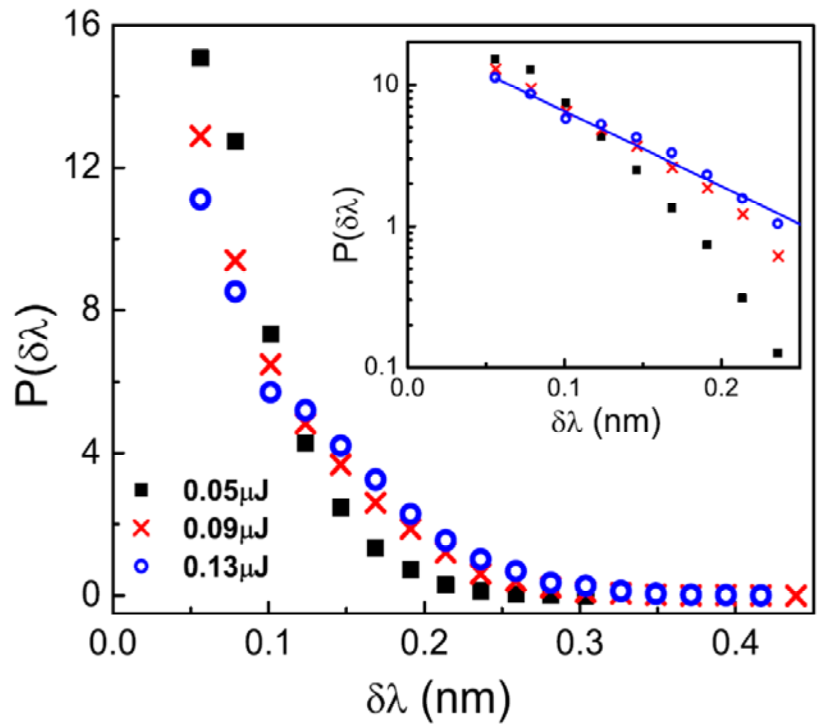


Peak Spacing Statistics

Dye solution with scattering particles



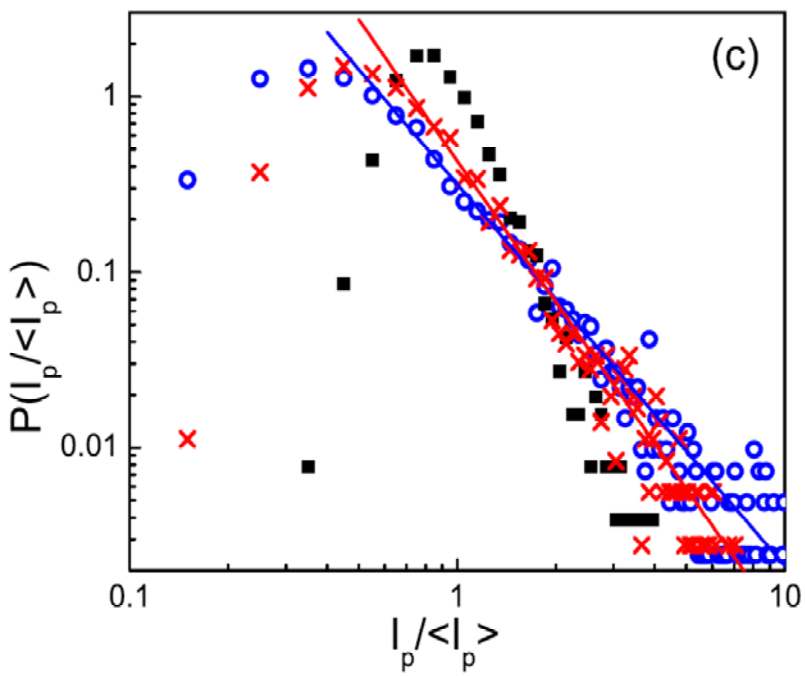
Dye solution without scattering particles



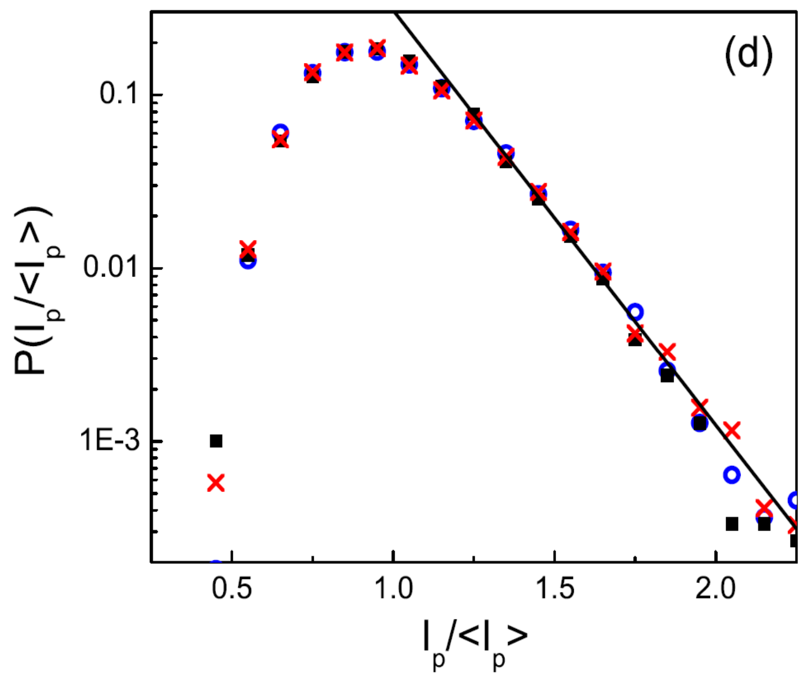
Wu & HC, Opt. Lett. **32**, 3089 (2007)

Peak Height Statistics

Dye solution with scattering particles



Dye solution without scattering particles



$P\left(I/\langle I\rangle\right) \propto \left(I/\langle I\rangle\right)^{\beta}$ $\quad \boldsymbol{\beta}$ **= -2.7, -2.2**

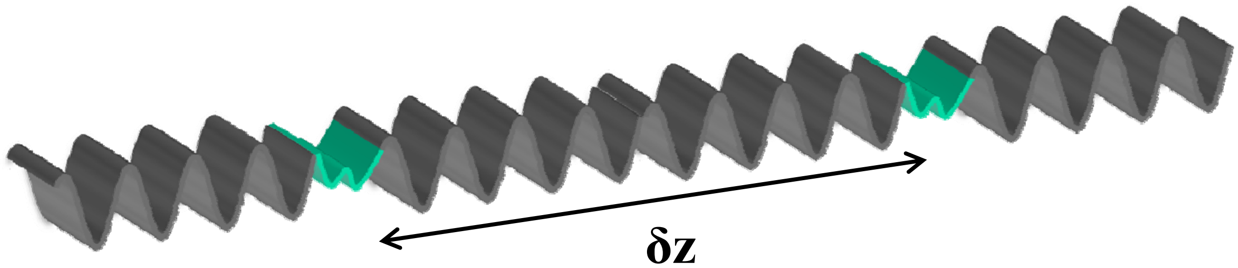
$P\left(I/\langle I\rangle\right) \propto e^{-\alpha I/\langle I\rangle}$ $\quad \boldsymbol{\alpha}$ **= 5.6**

Wu & HC, Phys. Rev. A **77**,013832 (2008)

Question

How coherent is random laser emission?

Temporal Coherence

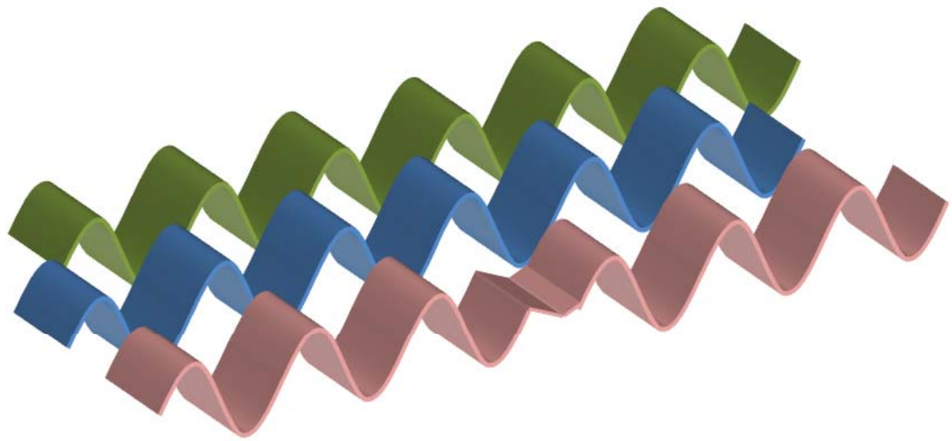


Temporal coherence length is determined by spectral bandwidth of laser emission

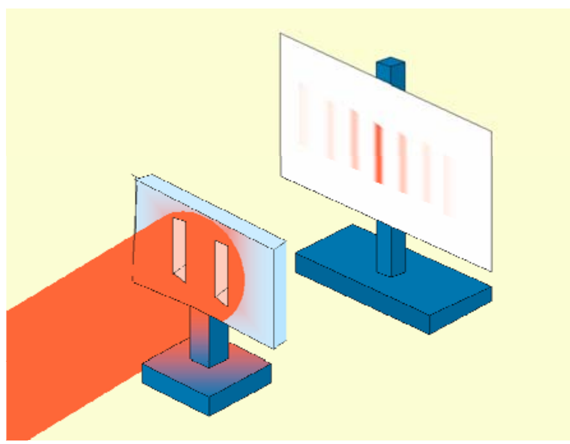
$$\delta z = \frac{2\ln 2\lambda^2}{\pi \cdot \Delta\lambda} = ct_c$$

Noginov et al, Opt. Mater. **12**, 127 (1999);
Papadakis et al, J. Opt. Soc. Am. B **24**, 31 (2010)

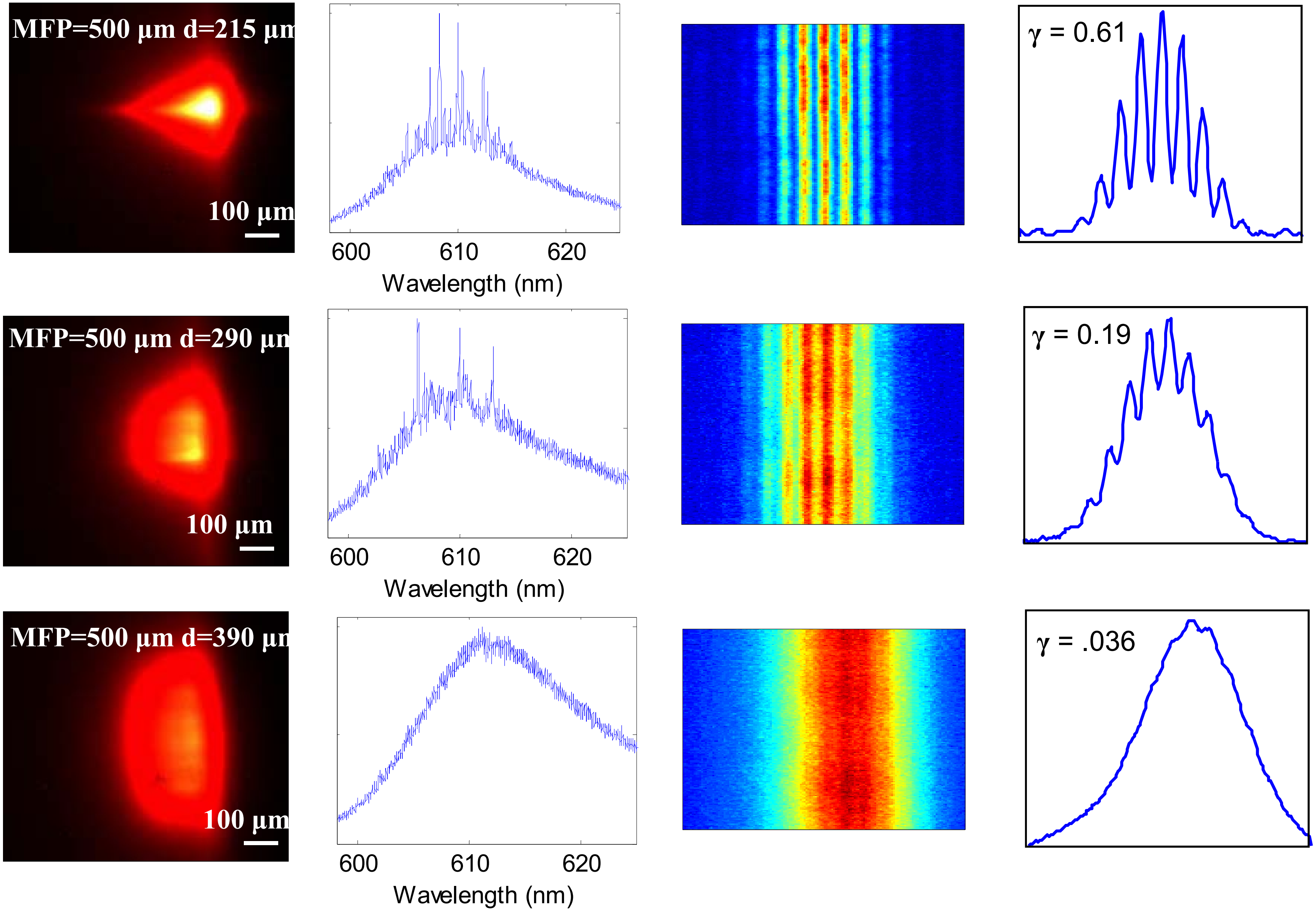
Spatial Coherence



Young's double slit experiment

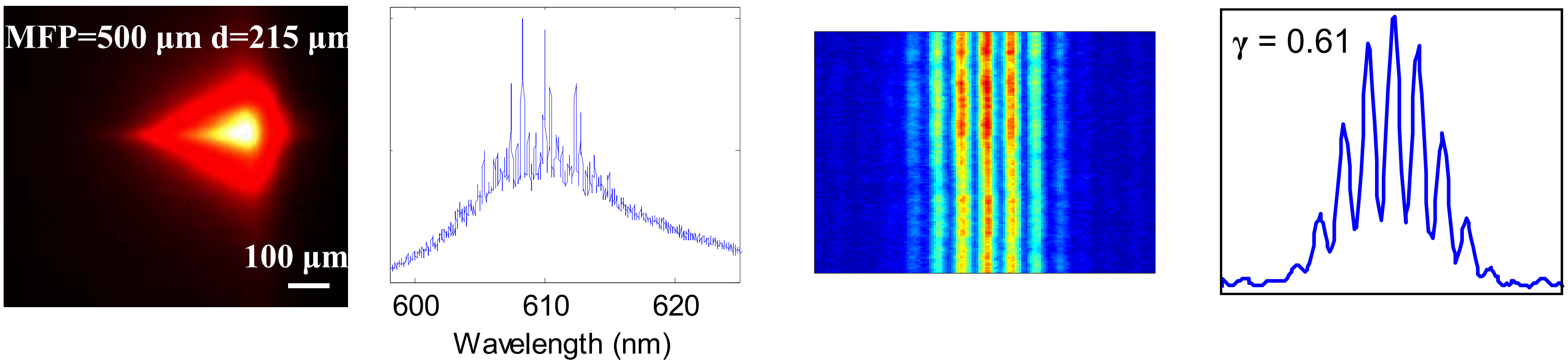


Tailoring Spatial Coherence by Varying Pump Region

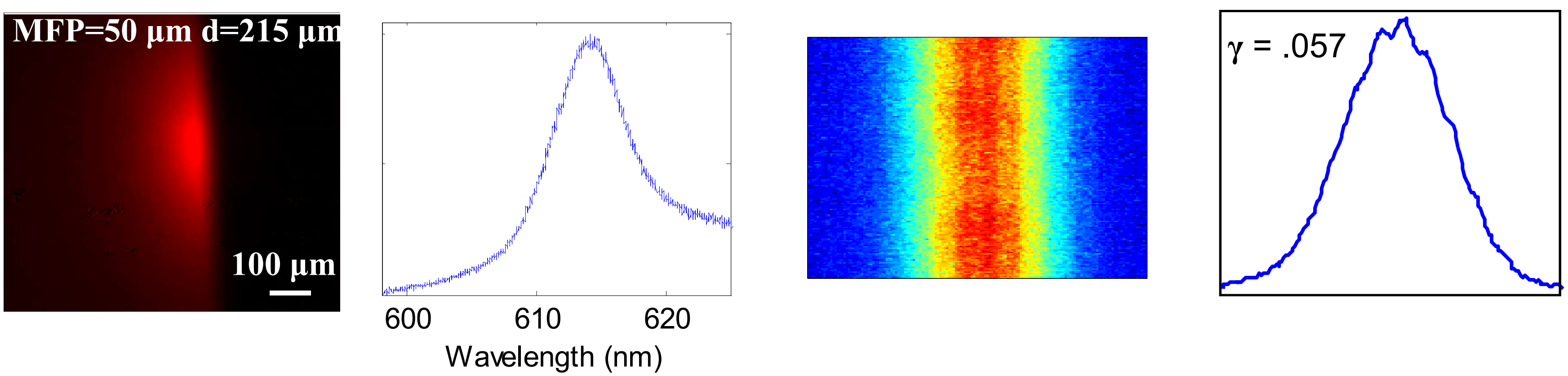


Tailoring Spatial Coherence by Changing Scattering Strength

Weaker scattering



Stronger scattering



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

Second-Order Coherence

Emission intensity or photon number fluctuations

$$G_2 = \frac{\left\langle \left(\Delta I\right)^2 \right\rangle - \left\langle I \right\rangle}{\left\langle I \right\rangle^2}$$

Single-mode coherent light: $G_2 = 1$

Single-mode chaotic light: $G_2 = 2$

Emission Intensity Statistics of Nonresonant Feedback Laser

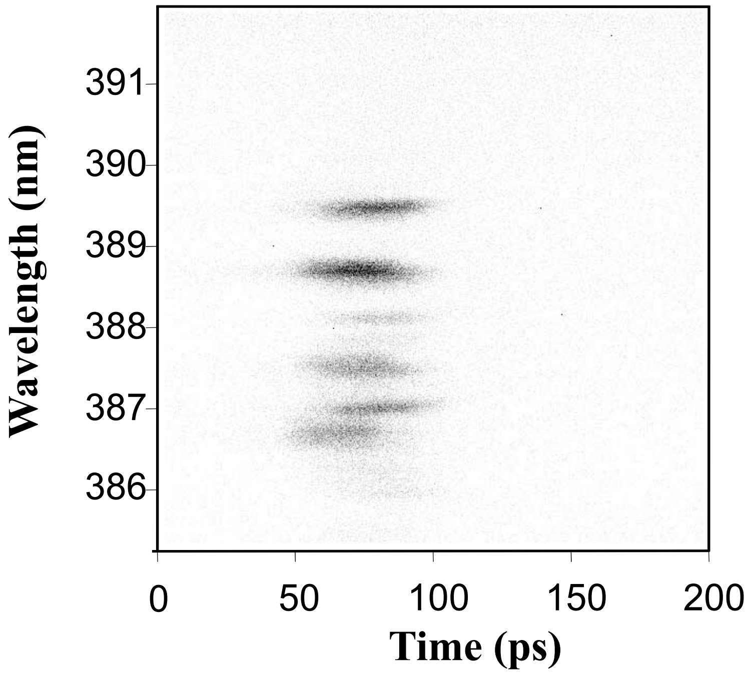
Fluctuation of total emission intensity is suppressed by gain saturation.

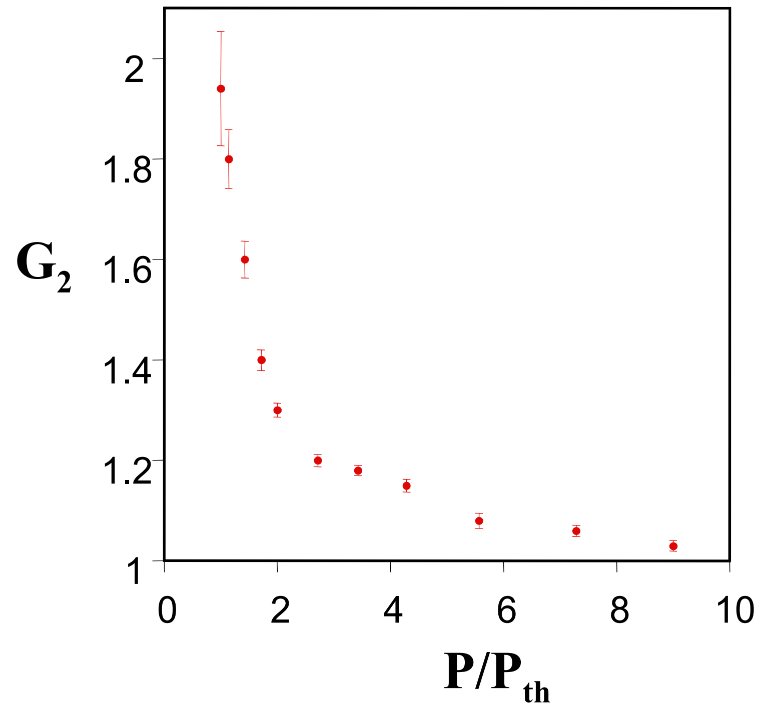
Intensity fluctuation of individual mode remains large due to mode interaction.

$$G_2 = 2$$

Ambartsumyan *et al.* Sov. Phys. JETP **26**, 1109 (1968)

Photon Statistics of Random Laser with Resonant Feedback

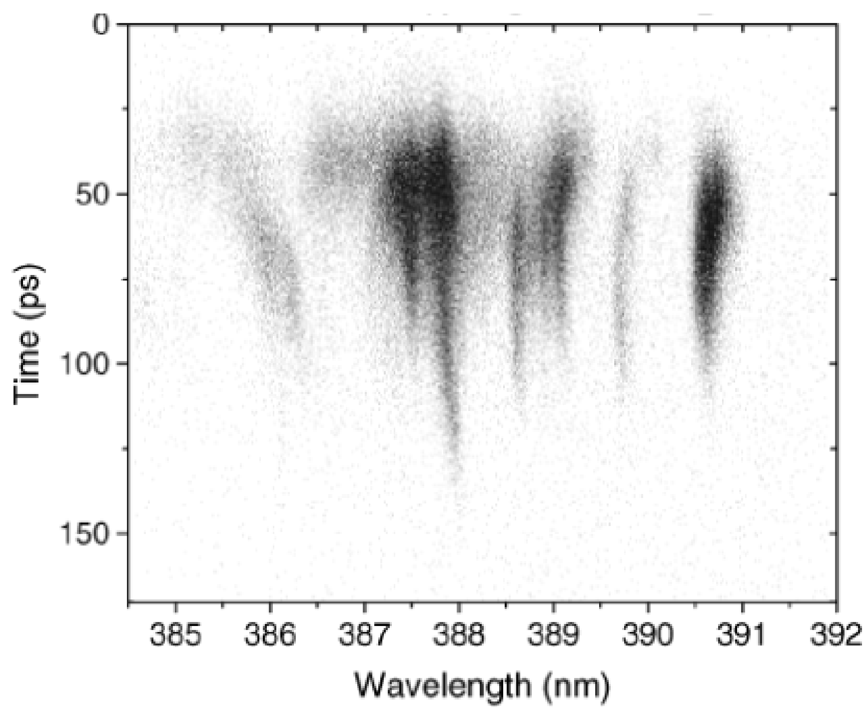




HC *et al*, Phys. Rev. Lett. **86**, 4524 (2001)

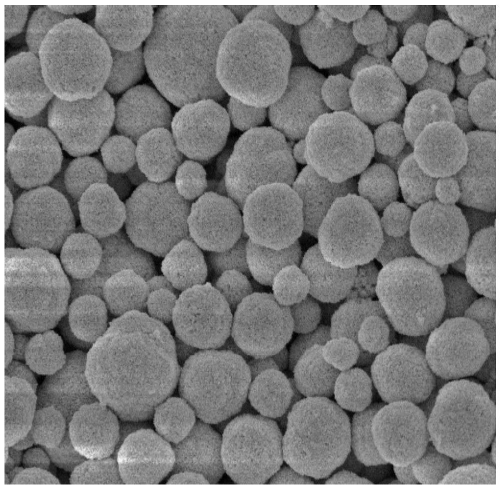
Nonlinear Effect in Random Laser

Strong third-order nonlinearity $n = n_0 + n_2 I$

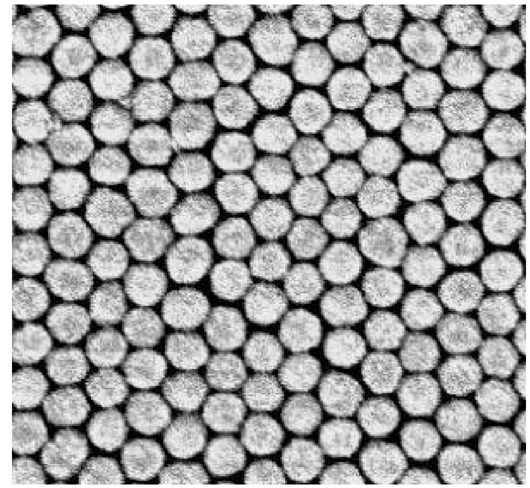


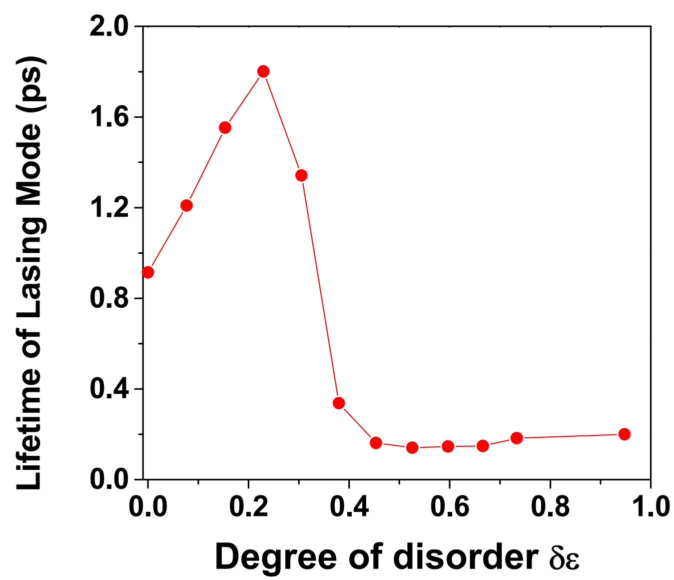
Liu et al, Phys. Rev. Lett. **91**, 063903 (2003); Appl. Phys. Lett. **83**,1092 (2003).

Partially-Ordered Random Laser



?





Optimal degree of disorder

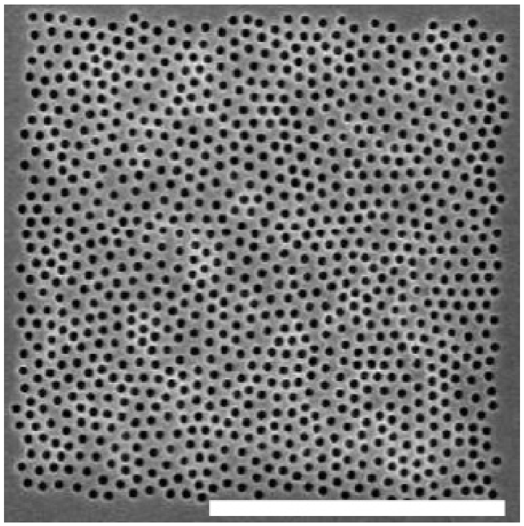
↓

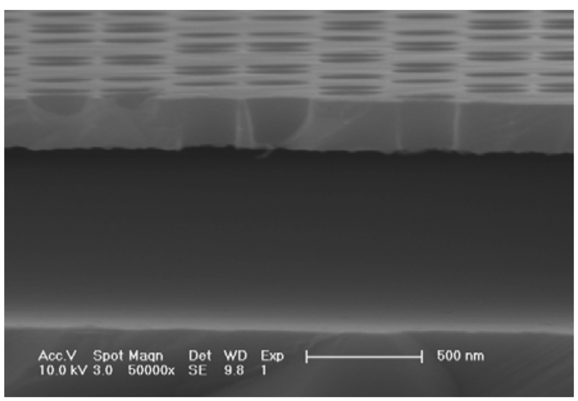
Strongest light confinement

Yamilov & HC*, Phys. Rev. A*, 69, 031803 (2004)

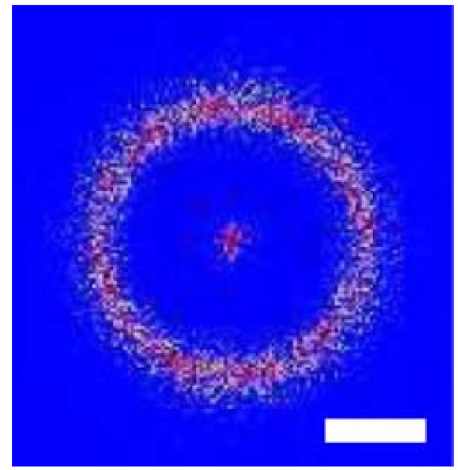
Short-Range Order

GaAs membrane

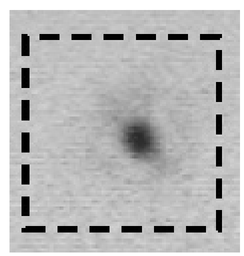




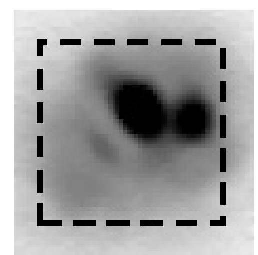
Spatial Fourier spectra



Localized mode



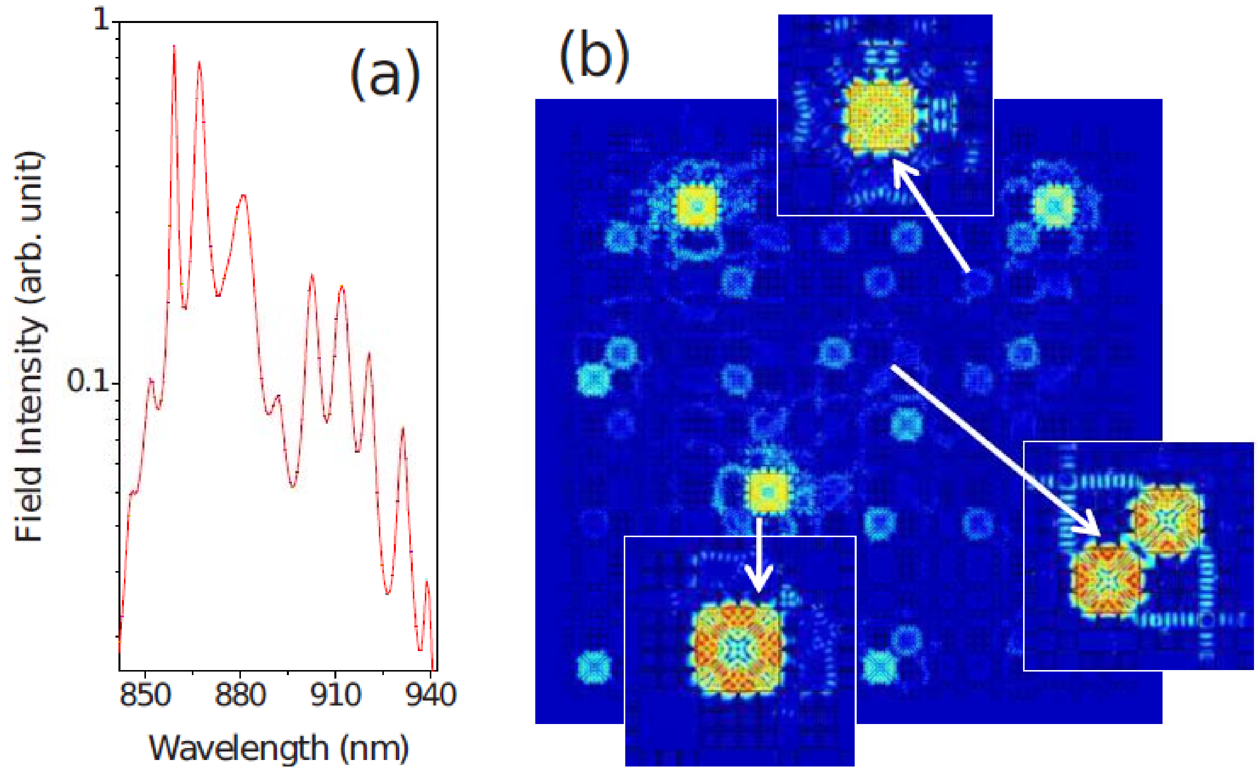
Coupled mode



Noh et al., Phys. Rev. Lett. **106**, 183901 (2011)

Deterministic Aperiodic Structure

The Rudin-Shapiro structure creates localized modes with well-defined frequencies and positions



Yang et al., Appl. Phys. Lett. **97**, 223101 (2010)

Light Transport in Amplifying Random Media

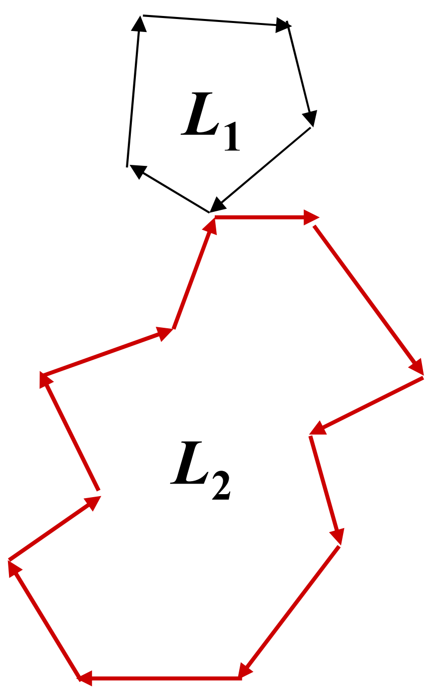
In a diffusive system *below* lasing threshold

<u>Effect of coherent amplification on transport</u>:

- **Enhances long-range correlation**
- **Increases fluctuation of transmission & reflection**
- **Pushes a diffusive system towards localization**

Yamilov, HC *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).

Amplification Enhances Interference Effect



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

In the absence of gain

$L_1 < L_2$ $|E_1| > |E_2|$

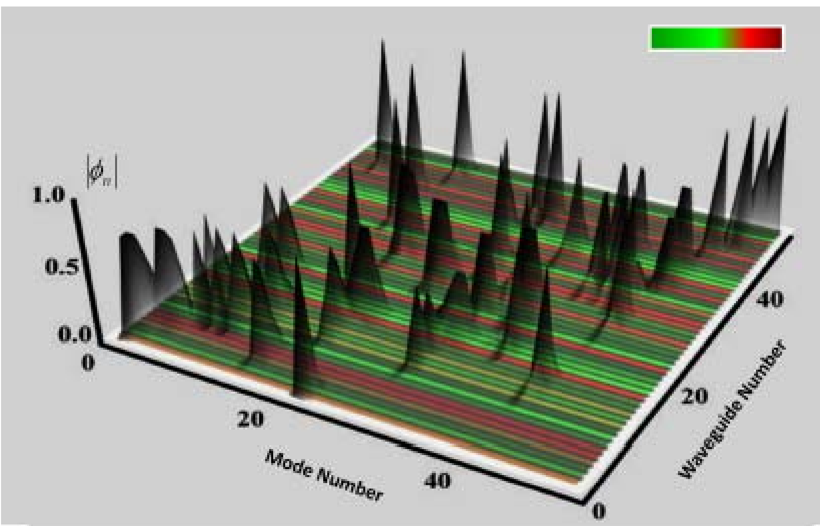
Weak interference

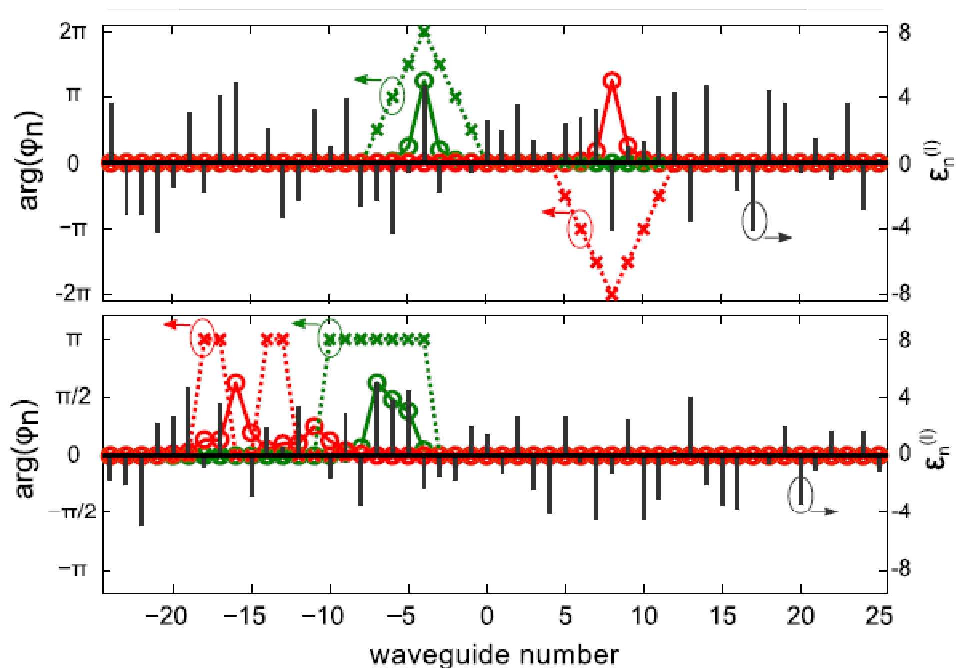
In the presence of gain

Longer path, more amplification

$|E_1| \sim |E_2|$ **Stronger interference**

Light Localization Induced by Random Imaginary Permittivity





Basiri, Bromberg, Yamilov, Cao, Kottos, arXiv 1403.2120

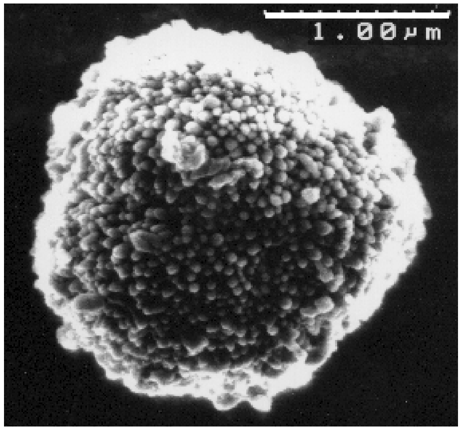
Physics

Random lasers are complex, open, nonlinear chaotic systems.

Mesoscopic transport, laser physics, nonlinear optics, quantum optics, statistical physics, quantum chaos, nonlinear dynamics, atomic physics …

Application

Microlaser

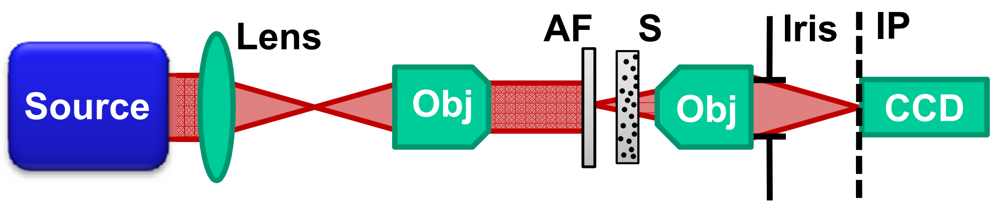


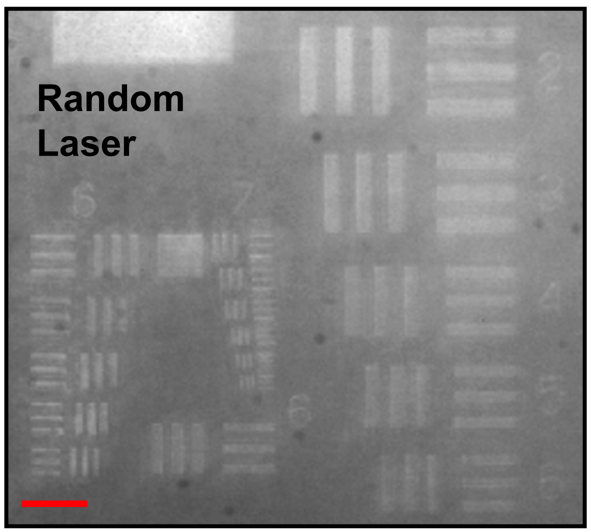
X-ray laser, γ-ray laser

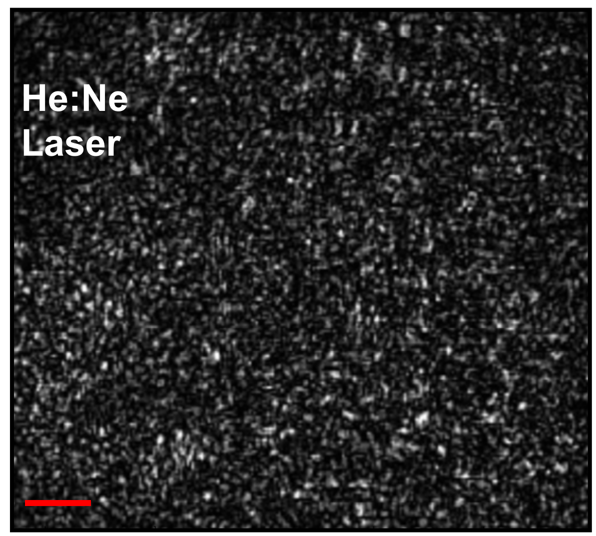
Galaxy maser, stellar laser

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

Speckle-free Laser Imaging

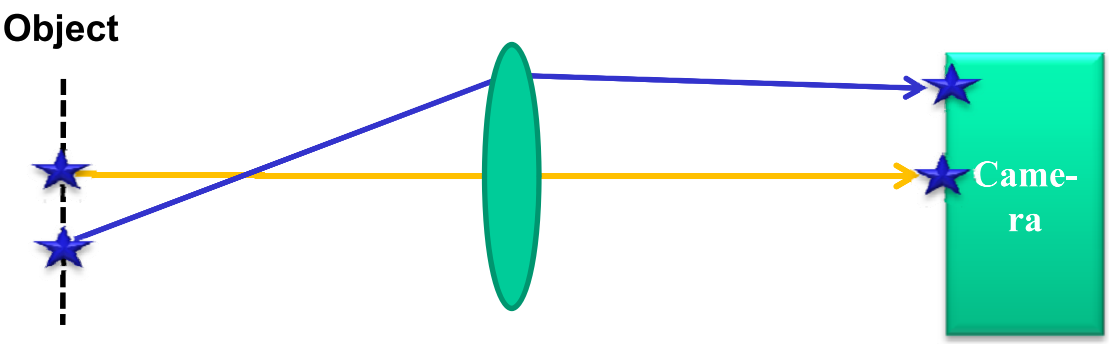


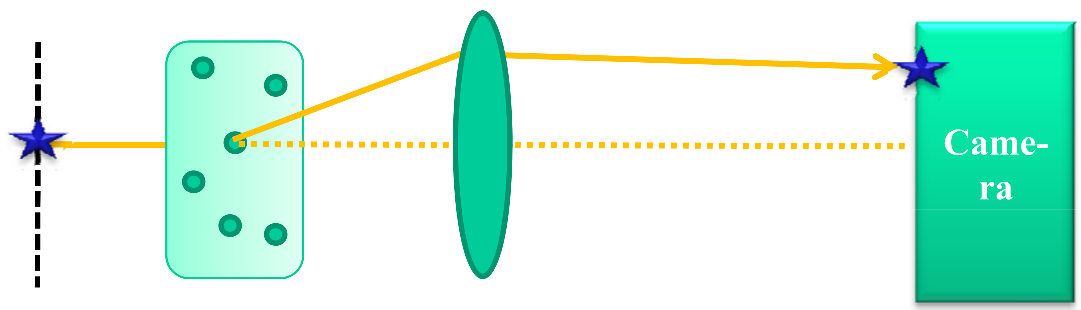




Redding, Choma & HC, Nature Photonics **6,** 355 (2012)

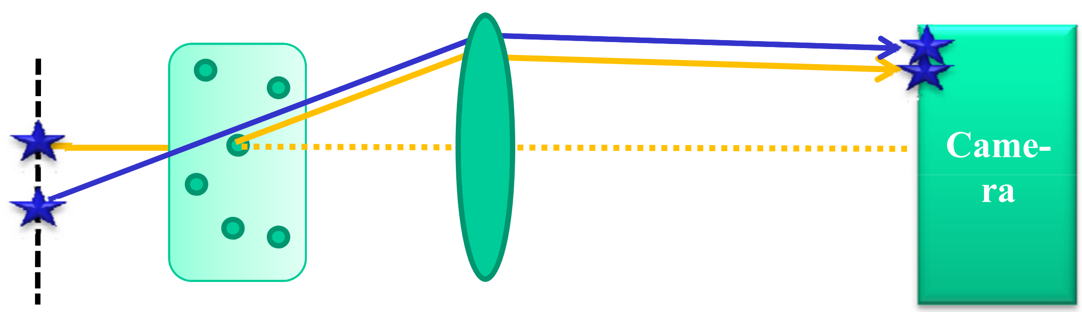
Spatial cross talk





Coherent illumination

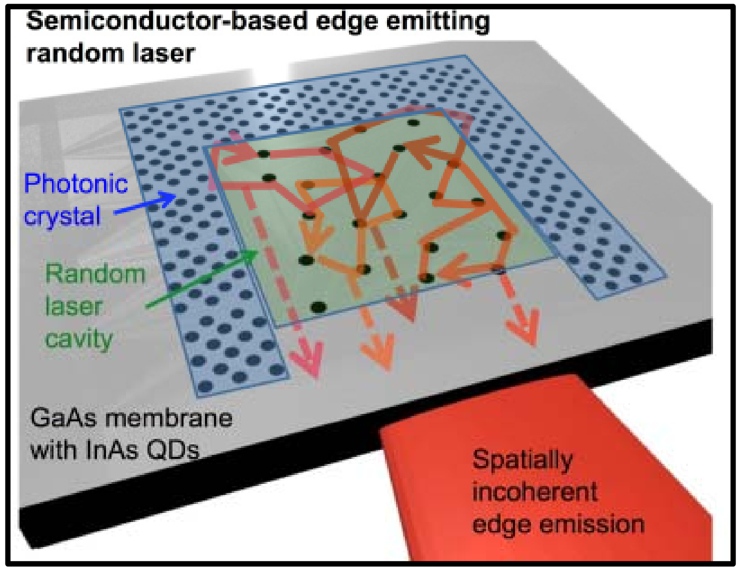
$$I = |E|^2 = |E_1 + E_2|^2$$
$$= |E_1|^2 + |E_2|^2 + 2E_1E_2\cos(\theta)$$



Incoherent illumination

$$I = I_1 + I_2$$

On-chip Electrically-Pumped Semiconductor Random laser



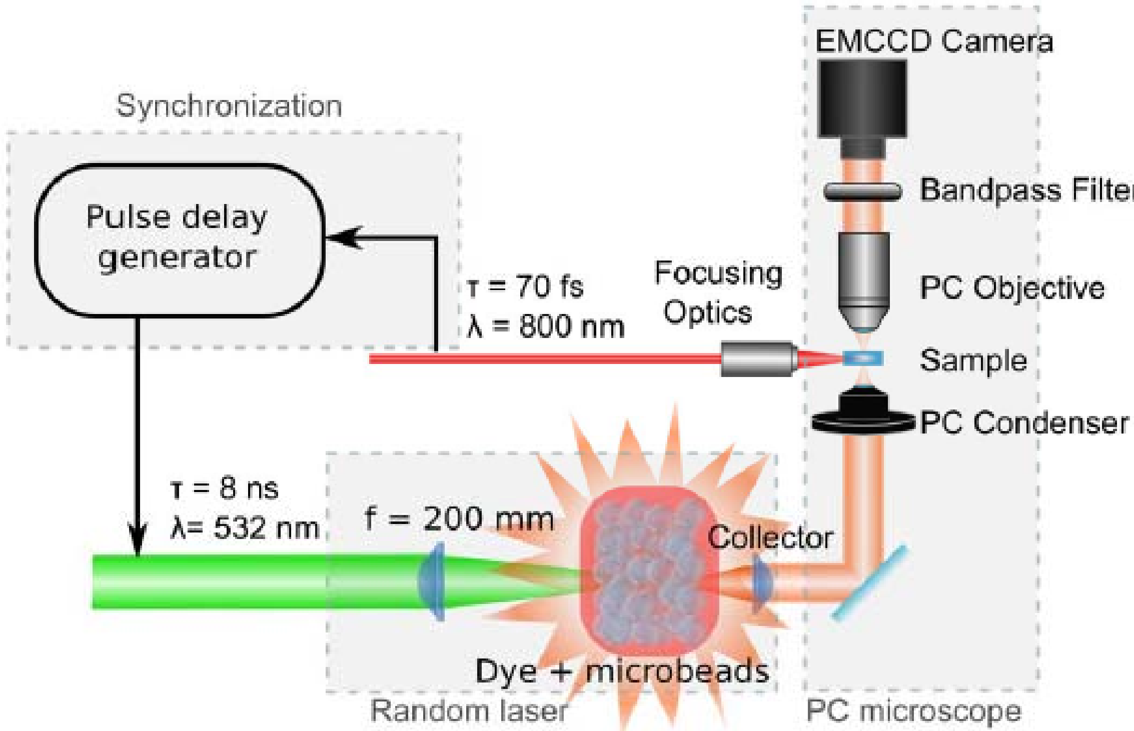
Development of a New Light Source for Massive Parallel Confocal Microscopy and Optical Coherence Tomography

NIH National Institutes of Health
Turning Discovery Into Health

Time-resolved microscopy with random lasers

Alexandre Mermillod-Blondin,* Heiko Mentzel, and Arkadi Rosenfeld

Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie, Max-Born-Straße, D-12489 Berlin, Germany



Ideal Illumination Source