Lasers and Random Lasers

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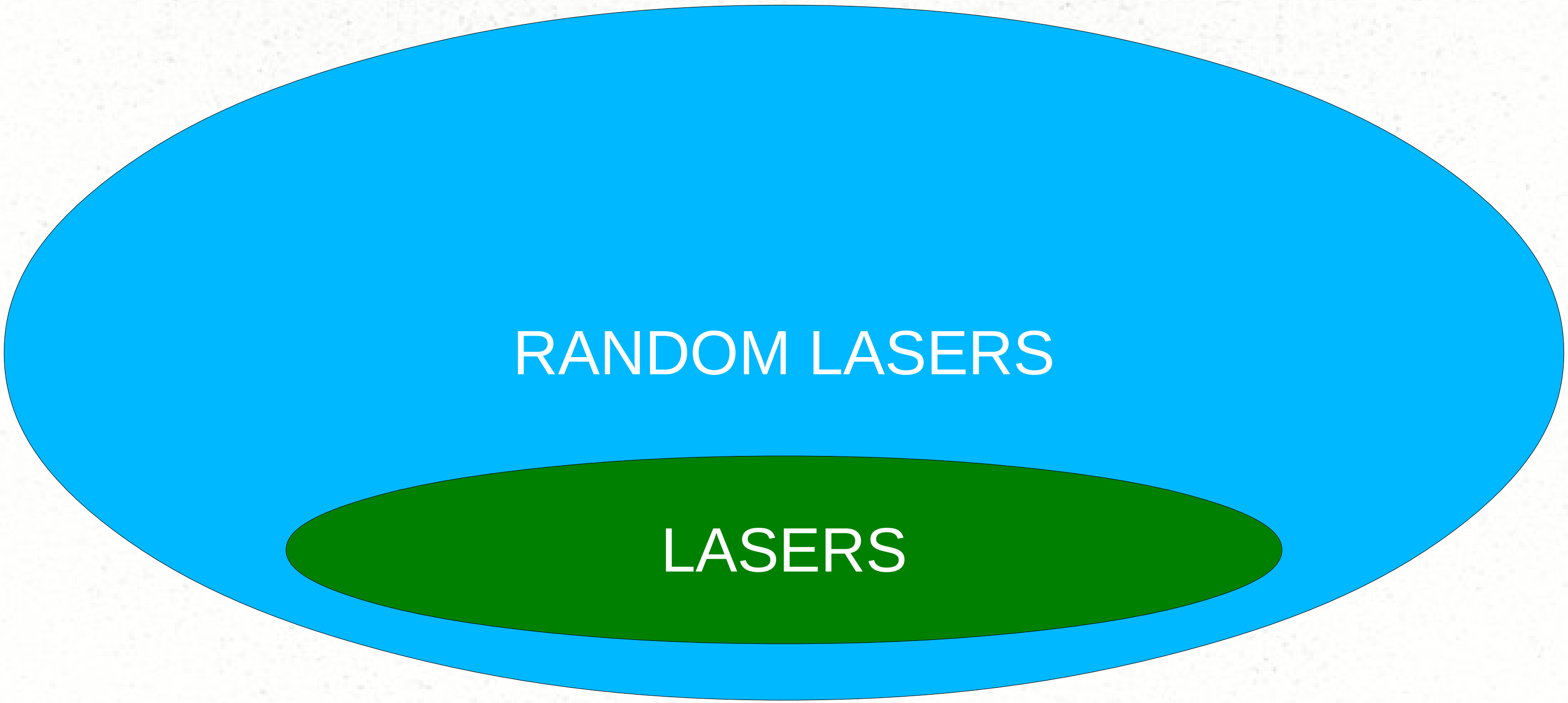
Rome, Italy

Overview

- Lasers and Random Lasers
- Shaken Granular Lasers: gravity affected random lasers
- Paper-based Random Lasers: geometry affected random lasers
- Control of Random Lasers

Lasers and Random Lasers



Make an example of a laser

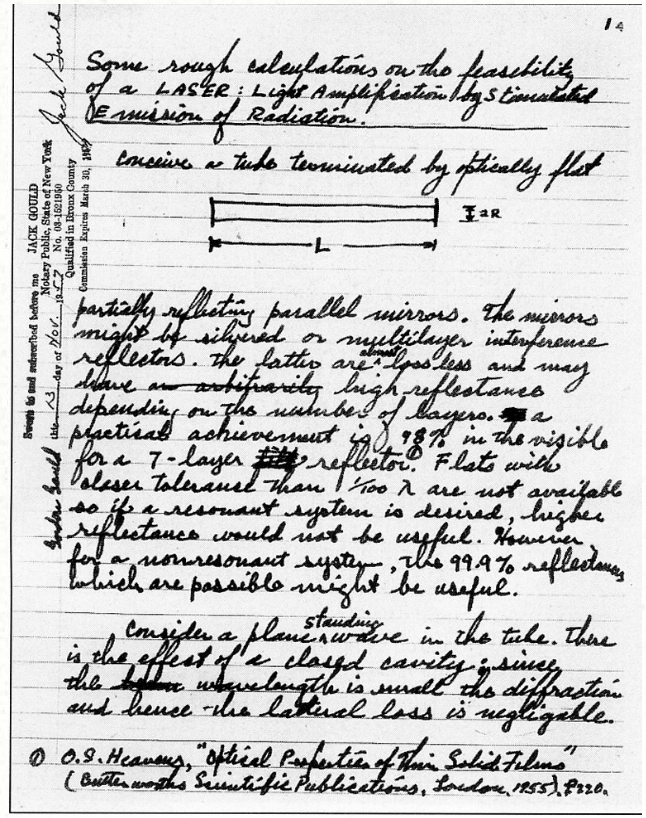
- LASER

  Light amplification by stimulated emission of radiation

- YES... but how?

- Gould, Prokhorov, Schawlow, Townes

  Invented the open cavity design (1957)



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Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat

partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost lossless and may have an arbitrarily high reflectance depending on the number of layers. a practical achievement is 98% in the visible for a 7-layer reflector.① Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectances which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity; since the wavelength is small the diffraction and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955) P.220.

Sworn to and subscribed before me this 13 day of Nov. 1957

JACK GOULD
Notary Public, State of New York
No. 03-1621950
Qualified in Bronx County
Commission Expires March 30, 1959

Jack Gould

Gordon Gould

Gordon Gould 1957

(source:wikipedia)

The way a standard laser works

- In two mirrors the electromagnetic field is a standing wave
- The amplitude of the wave is amplified by gain
- Gain is due to population inversion by stimulated emission
- In simple terms

$$\mathcal{E} = A(t)\cos[\omega_n t + \phi(t)]\sin\left[\frac{\pi n z}{L}\right]$$

$$\mathcal{E} = \Re[a(t)e^{-i\omega t}]\sin\left[\frac{\pi n z}{L}\right]$$

$$\frac{da}{dt} = -\alpha a + g[a]a$$

The Schwalow and Townes law

$$\omega|A|^2$$

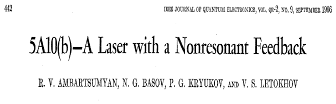
$$\frac{da}{dt} = -\alpha a + g[A]a + \imath\eta(t)$$

$$\frac{da}{dt} = -\alpha a + \frac{g_0}{1+\gamma|A|^2}a + \imath\eta(t)$$

The Langevin equation predicts the linewidth
of a single mode lasers decreases with energy

VS Letokhov (1966), Dubna (URSS)

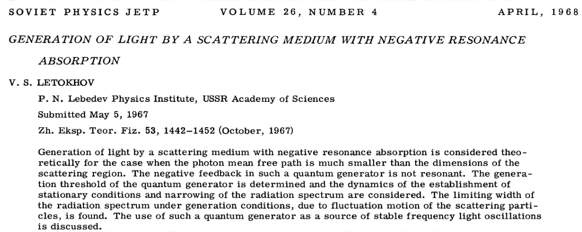
- Alternatives to the Gould design?
- We need a mechanism to trap photons in a spatial region
- "Another type of laser with positive feedback is possible"
- … simple … use a bomb!



442 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-2, NO. 9, SEPTEMBER 1966

5A10(b)–A Laser with a Nonresonant Feedback

R. V. AMBARTSUMYAN, N. G. BASOV, P. G. KRYUKOV, AND V. S. LETOKHOV



SOVIET PHYSICS JETP VOLUME 26, NUMBER 4 APRIL, 1968

GENERATION OF LIGHT BY A SCATTERING MEDIUM WITH NEGATIVE RESONANCE ABSORPTION

V. S. LETOKHOV

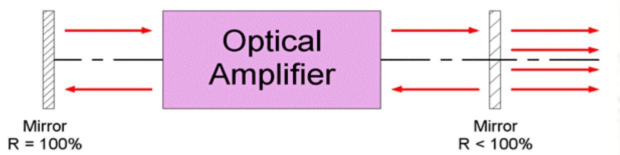
P. N. Lebedev Physics Institute, USSR Academy of Sciences

Submitted May 5, 1967

Zh. Eksp. Teor. Fiz. 53, 1442–1452 (October, 1967)

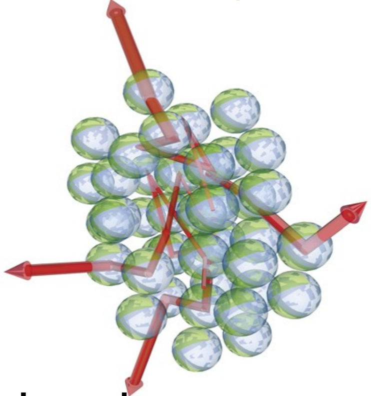
Generation of light by a scattering medium with negative resonance absorption is considered theoretically for the case when the photon mean free path is much smaller than the dimensions of the scattering region. The negative feedback in such a quantum generator is not resonant. The generation threshold of the quantum generator is determined and the dynamics of the establishment of stationary conditions and narrowing of the radiation spectrum are considered. The limiting width of the radiation spectrum under generation conditions, due to fluctuation motion of the scattering particles, is found. The use of such a quantum generator as a source of stable frequency light oscillations is discussed.

Gould design



Ordered resonators (two mirrors)

Letokhov design



"Stochastic resonator"

A bomb, nuclear Vs photonic

- Chain reaction in nuclear fission
  - Neutrons diffuse and their number amplifies
  - More neutrons sustain the reaction
- Diffusion and amplification are needed

- To have diffusion of photons

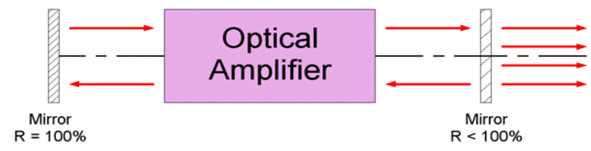
  you use a multiple scattering medium
- So photons are put

  in a diffusing medium with gain

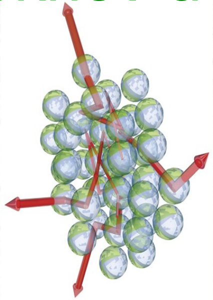
Comparison

- "Standard laser"
    - Directional
    - Spatially and temporal coherent
    - Efficient
    - Fixed and sensible design
- "Random laser"
    - Omni-directional
    - Variable degree of coherence
    - In-efficient
    - Everything can lase and can be "trained" to lase

"Gould design"



"Letokhov design"



Define the Laser and the Random Laser

- A standard laser is
  - LASER in a ordered resonator (Gould)
- A random laser is
  - LASER in a disordered resonator (Letokhov)

Ambartsumyam, Basov, Kryukov, Lethokov (ABKL) experiment, 1966

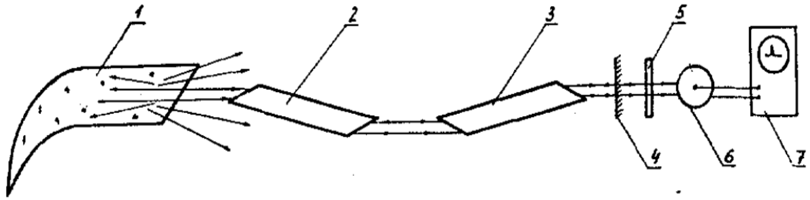


Fig. 1. Experimental arrangement—laser with a resonant feedback due to scattering.

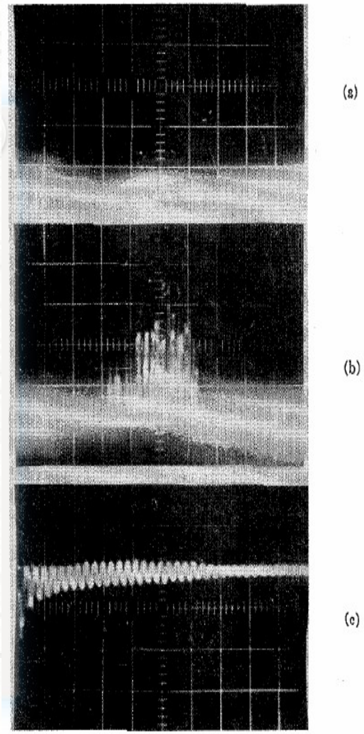


Fig. 2. Oscillograms of the laser emission. (a) Pumping below the threshold, (b) Pumping above the threshold, surface scatterer, (c) Pumping above the threshold, volume scatterer. Scanning: (a), (b)—200 microseconds per frame; (c)—10 microseconds per frame.

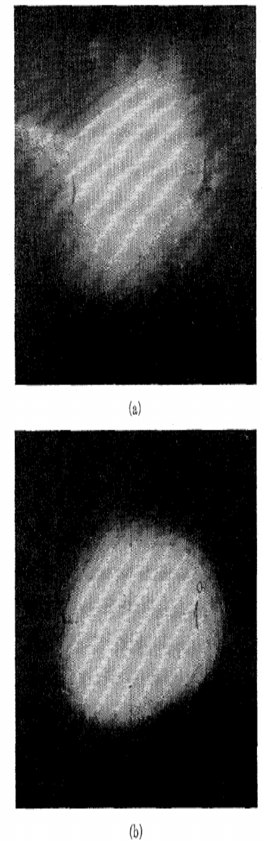
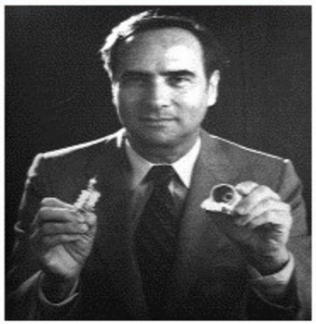


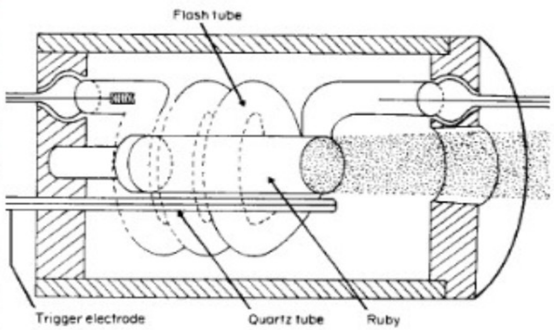
Fig. 5. Intensity distribution of laser emission on a screen. (a) Feedback due to scattering. (b) Resonant feedback.

JQE 2, 442 (1966)

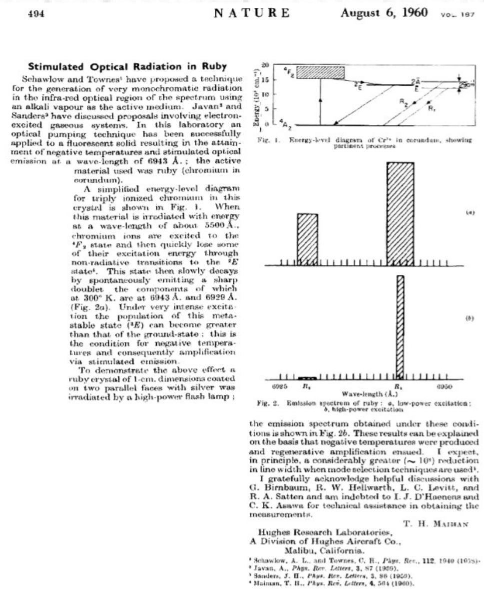
Lasers and Random Lasers birth (the same day and year?!)

- Theodore Meiman (summer 1959) US Patent 3,353,115





Maiman, 1960 ....
This man ignored the ridicule of his peers and easiliy succeeded in producing history's first visible light laser from this simple photographic coiled flashlamp and his ruby crystalline rod.



494 NATURE August 6, 1960 Vol. 187

Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2a). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp; the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10^8) reduction in line width when mode selection techniques are used[1].

Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

Fig. 2. Emission spectrum of ruby: a, low-power excitation; b, high-power excitation

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

T. H. Maiman

Hughes Research Laboratories,
A Division of Hughes Aircraft Co.,
Malibu, California.

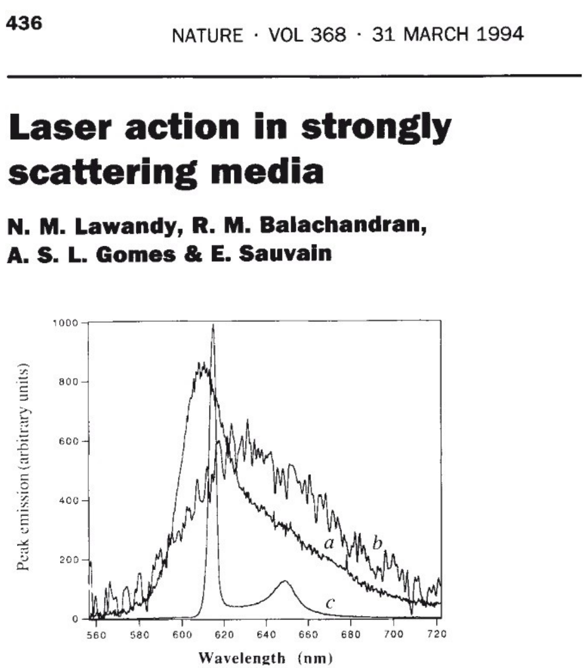
[1] Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1958).
[2] Javan, A., *Phys. Rev. Letters*, **3**, 87 (1959).
[3] Sanders, J. H., *Phys. Rev. Letters*, **3**, 86 (1959).
[4] Maiman, T. H., *Phys. Rev. Letters*, **4**, 564 (1960).

http://www.worldlinkbiomedical.com/laser_history.htm

- According to Orazio Svelto, the first laser was criticized because the spatial coherence properties were limited
- This was probably due to bad-quality (disorder...) of the mirror
- Was an almost-mirrorless laser ---- i.e. a random laser!

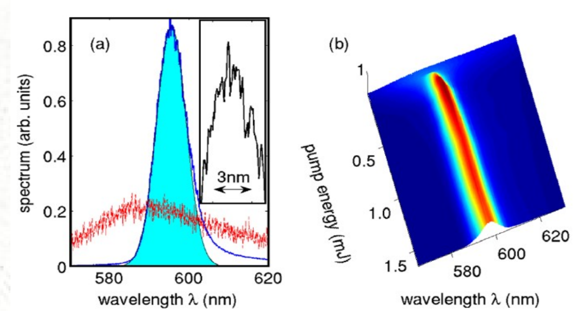
The experiment of Lawandy et al

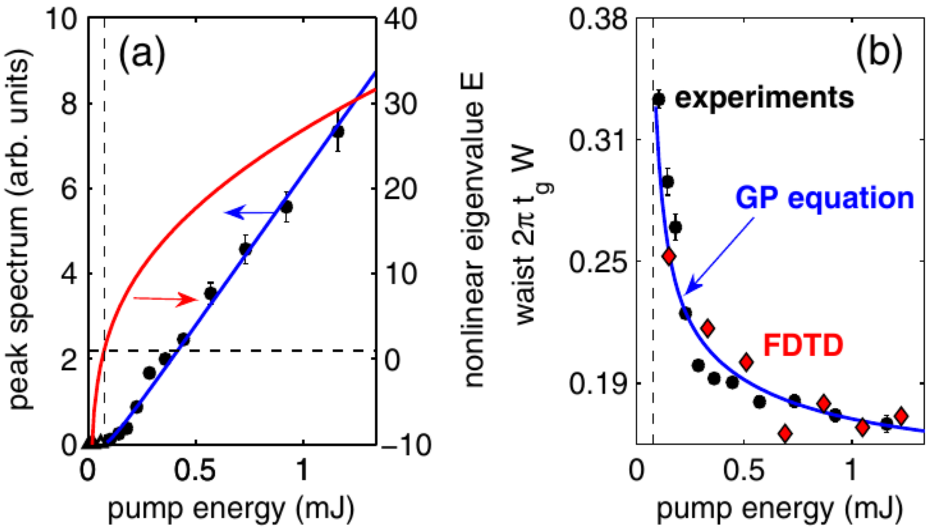
- Nature 1994


436 NATURE · VOL 368 · 31 MARCH 1994

Laser action in strongly scattering media

N. M. Lawandy, R. M. Balachandran, A. S. L. Gomes & E. Sauvain





Very similar to the Schawlow-Townes law

PRL 101, 143901 (2008)

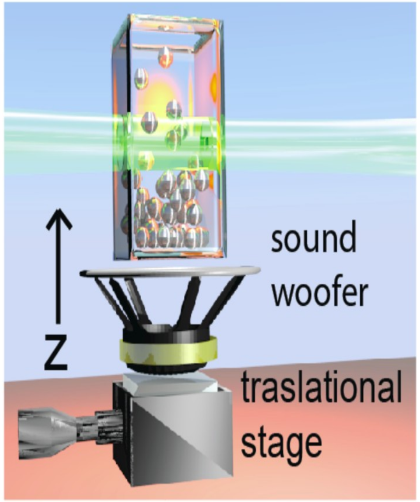
Applications of Random Lasers

- Sources
  - Multidirectional coherent source
  - Flexible devices
- Biophysics:
  - Early cancer detection and related
  - Selective irradation and spectral analysis
  - Transport through disorder (tissue)
  - Microfluidic Random Lasers
  - Compatible with optofludic
  - Biodegradable etc
- Imaging:
  - Tailorable Spatial and Coherent properties
  - Transport through disorder (opaque media)
  - Ultra-focused sources
- Telecom:
  - Cryptography
  - Novel kind of amplifiers

SHAKEN GRANULAR LASERS

(gravity affected)

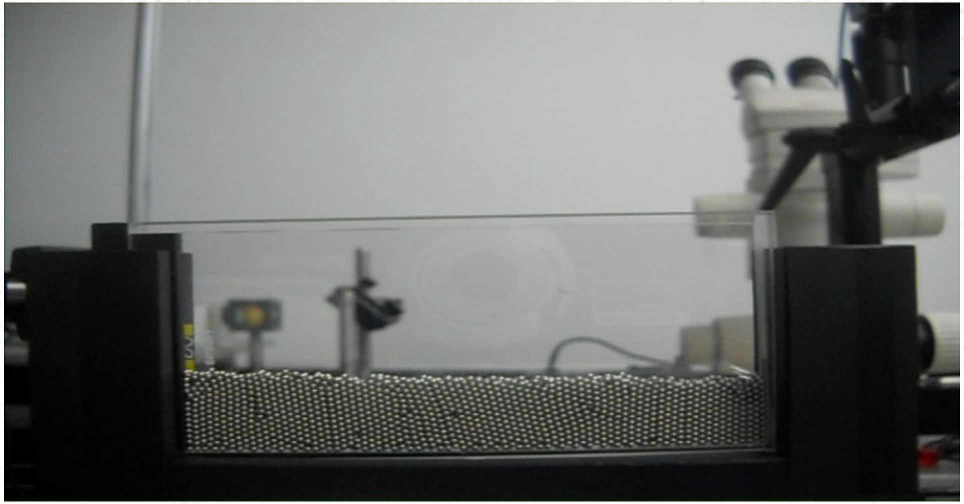
Viola Folli (IPCF-CNR)
Neda Ghofraniha (IPCF-CNR)
Andrea Puglisi (ISC-CNR)
Luca Leuzzi (IPCF-CNR)



Granular matter

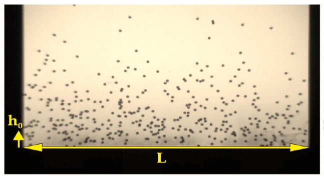
- Solid macroscopic particles loosing energy when interacting (friction)
- “The second-most used material in industry after water”
- Sand, icebergs, asteroids, nuts, rice, coffee...

- Are affected by gravity and by external mechanical driving

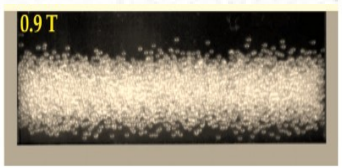


Phase-diagram of vertically shaken granular matter

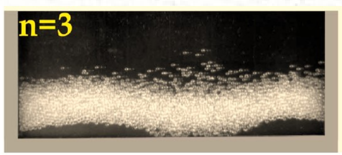
- Various phases



Gas

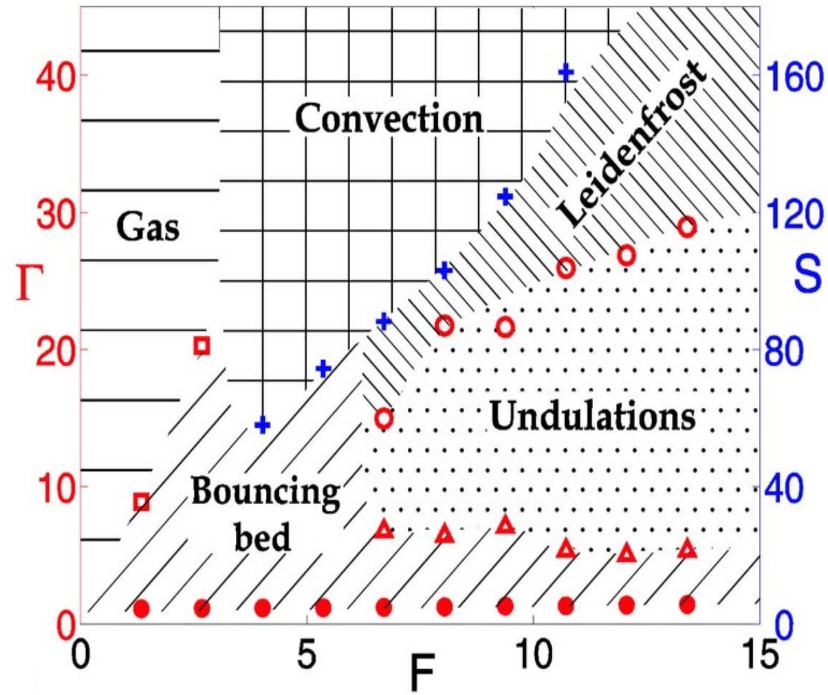


Leidenfrost



Undulations

Shaking



Number of granular layers

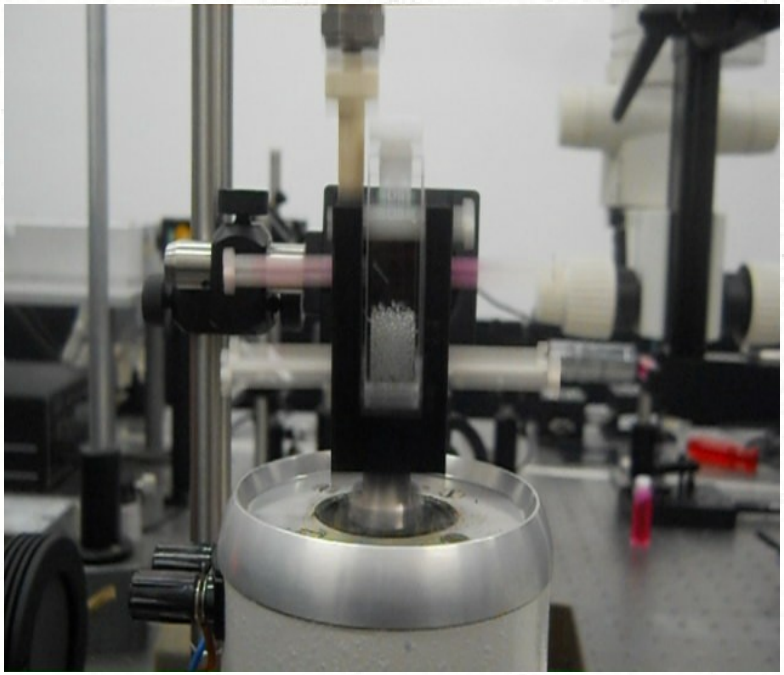
Phase diagram of vertically shaken granular matter

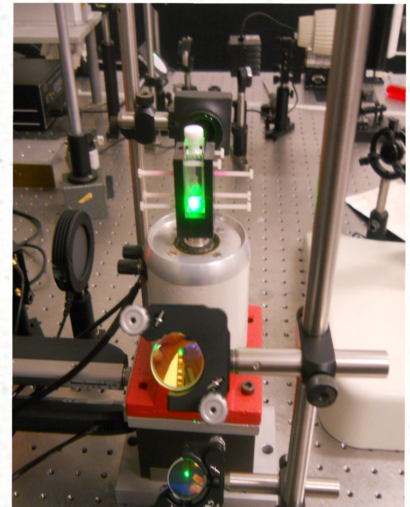
Peter Eshuis, Ko van der Weele, Devaraj van der Meer, Robert Bos, and Detlef Lohse

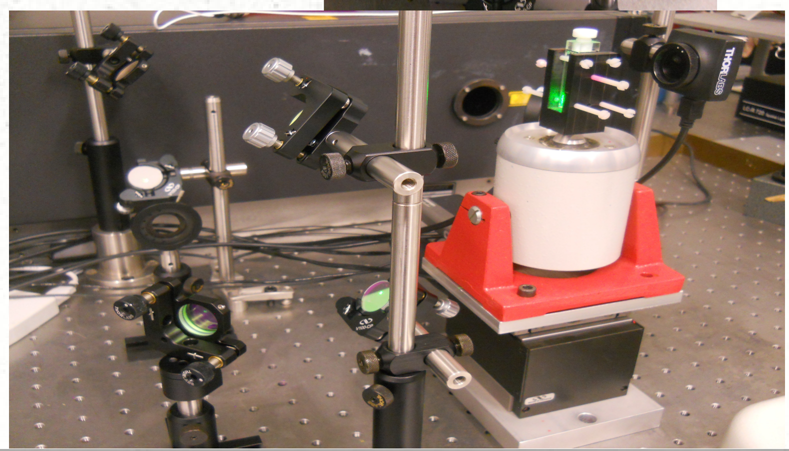
Citation: Physics of Fluids (1994-present) **19**, 123301 (2007); doi: 10.1063/1.2815745

Experimental setup

- Shaking lasers

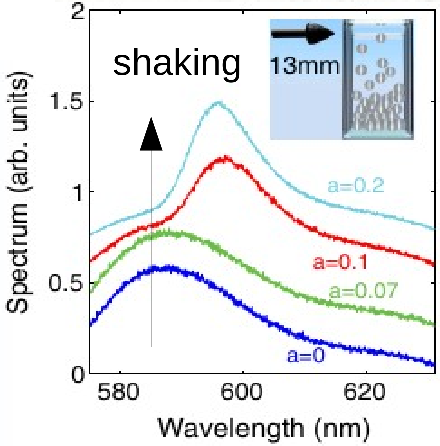


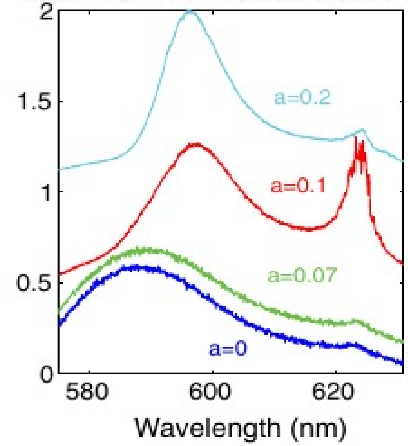


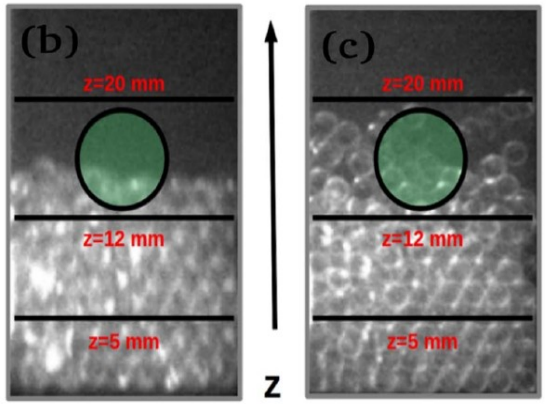


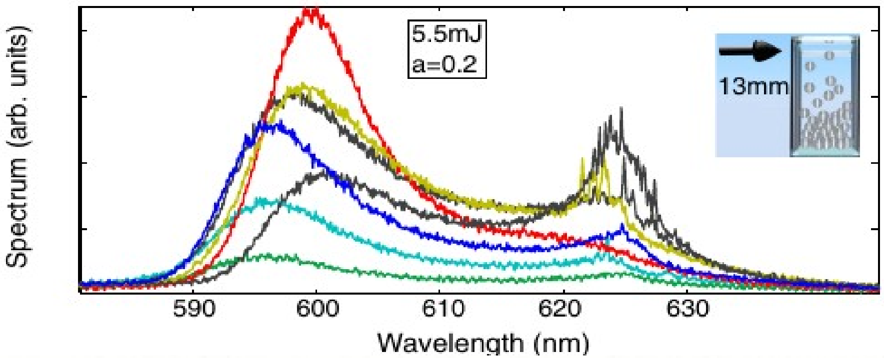
Spectra of granular random lasers

1.6 mJ 3.7 mJ (Pump energy)









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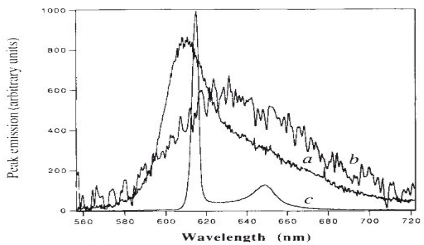
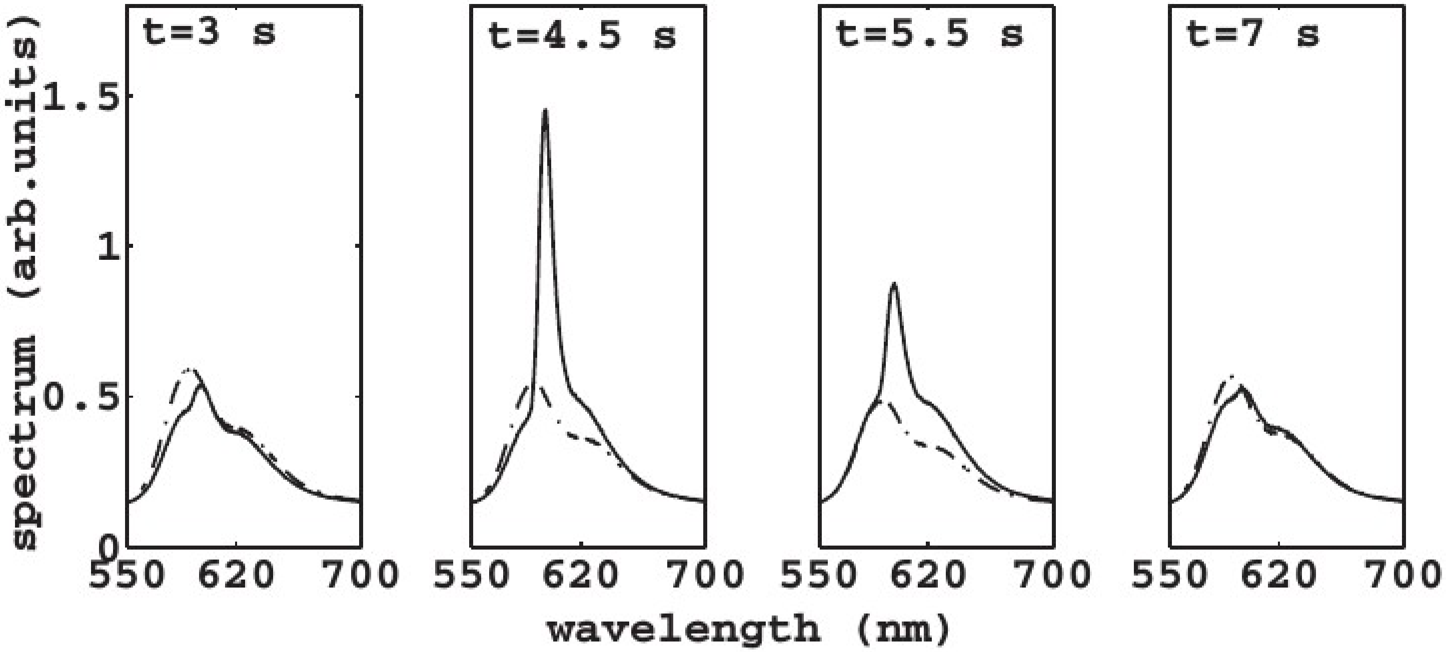


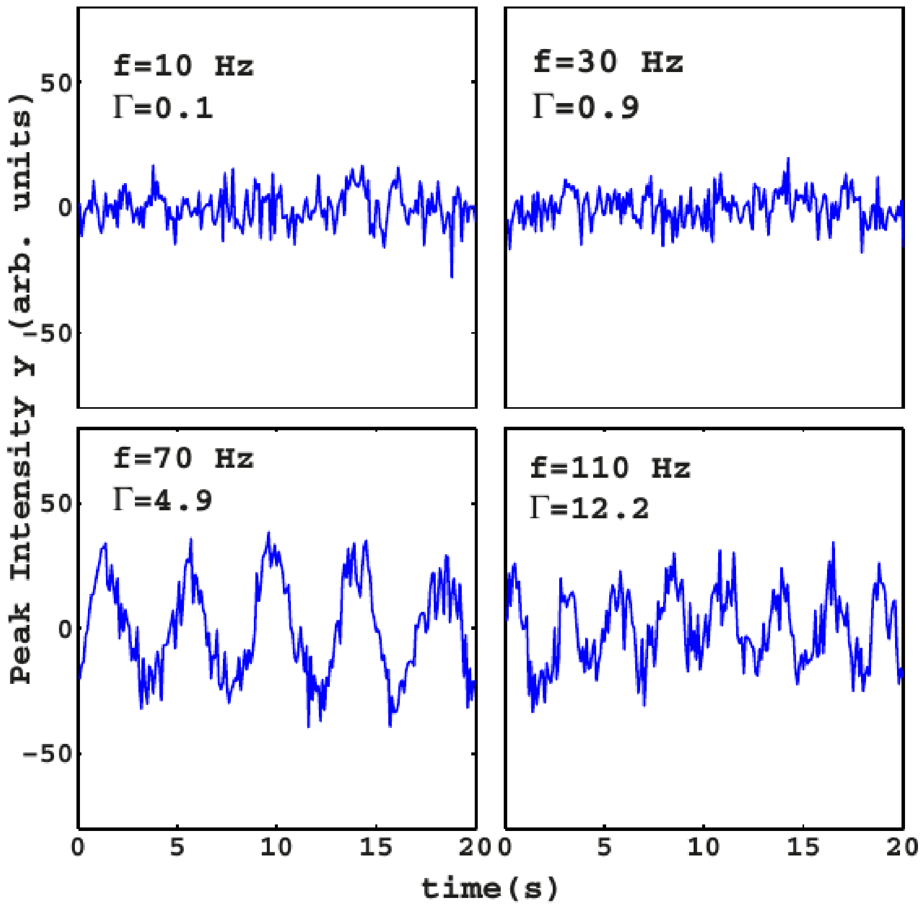
PRL 2012

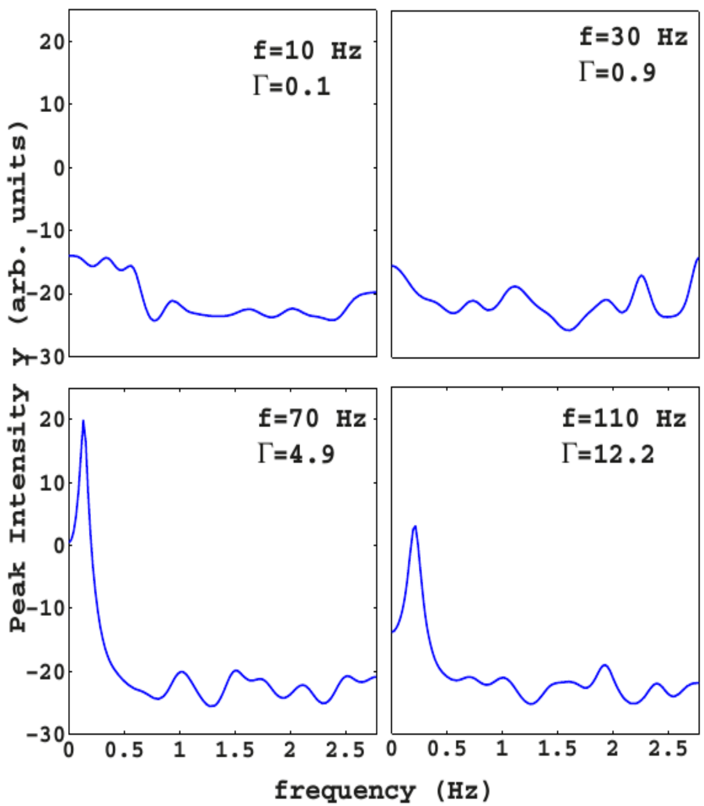
Dynamics of the emission



Scientific Reports 2013

Temporal signals



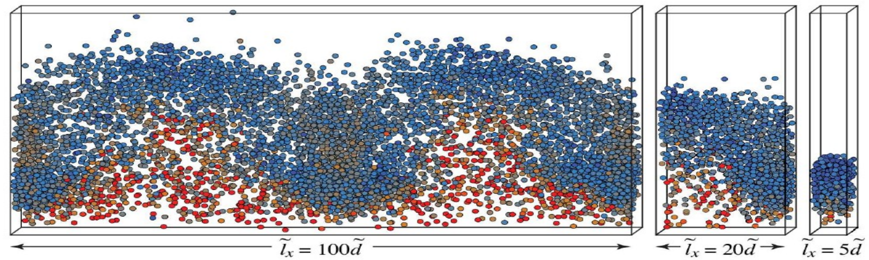


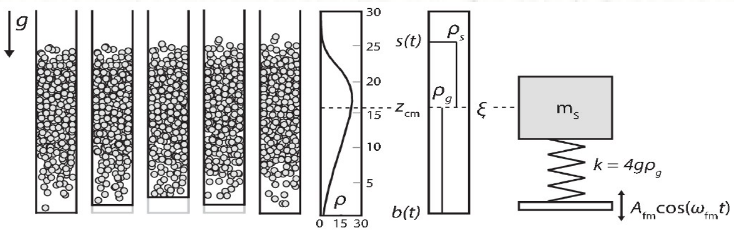
Scientific Reports 2013

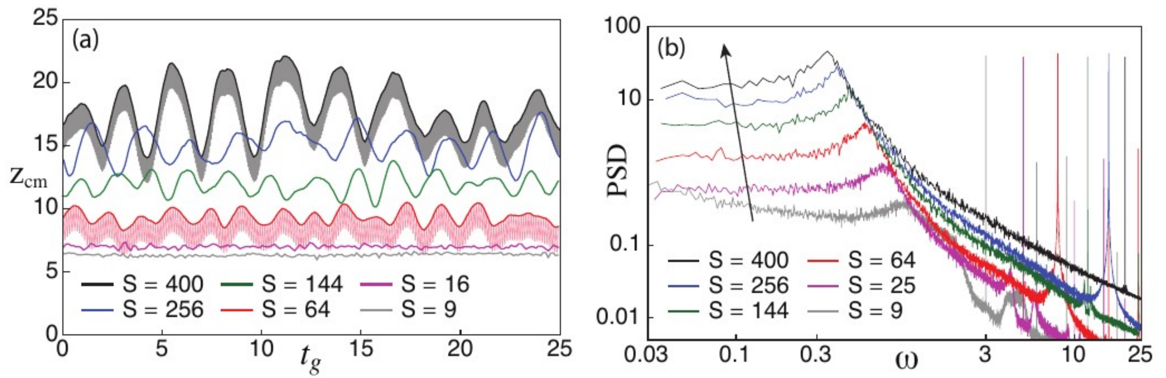
A related theoretical work

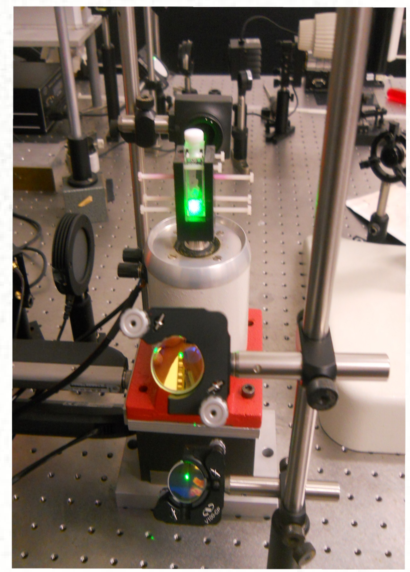
Low-frequency oscillations in narrow vibrated granular systems.

N Rivas, S Luding and A R Thornton
Multi Scale Mechanics (MSM), MESA+, CTW, University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands.







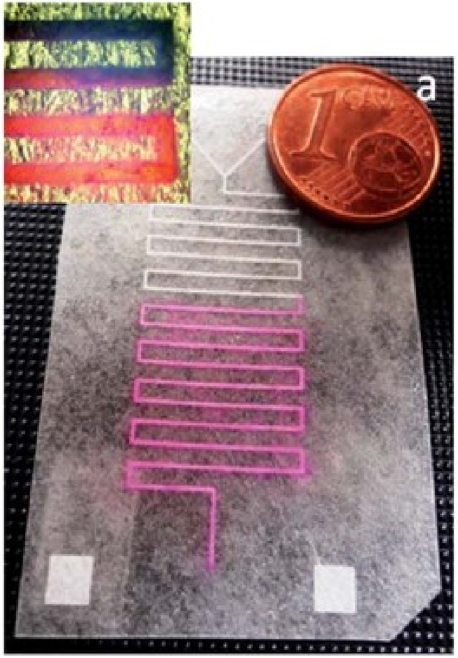


Rivas, Luding, Thoruton, ArXiv:1310.1776 (2013)

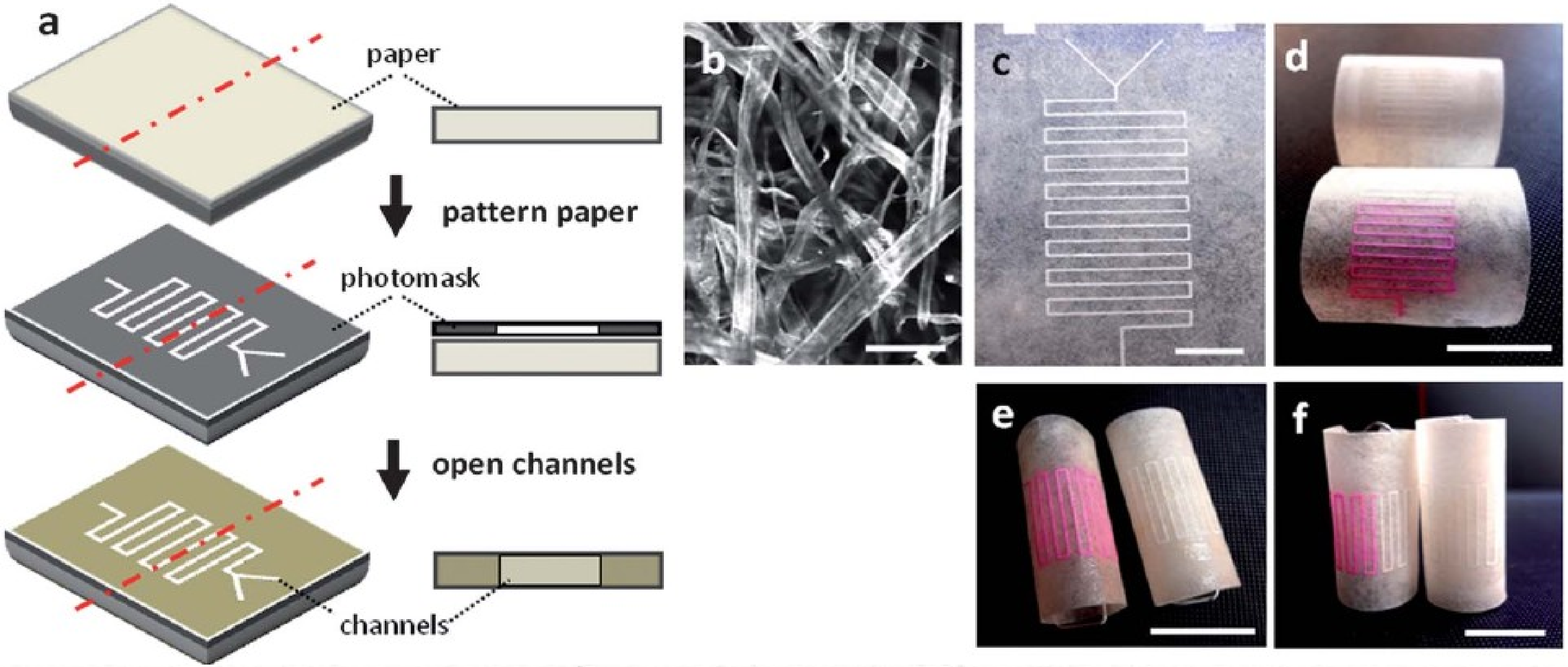
PAPER-BASED RANDOM LASERS

(geometry affected)

Neda Ghofraniha (IPCF-CNR)
Ilenia Viola (Nano-CNR)
Antonella Zacheo (Nano-CNR)
Valentina Arima (Nano-CNR)
Giuseppe Gigli (Univ. Salento)



Flexible Paper

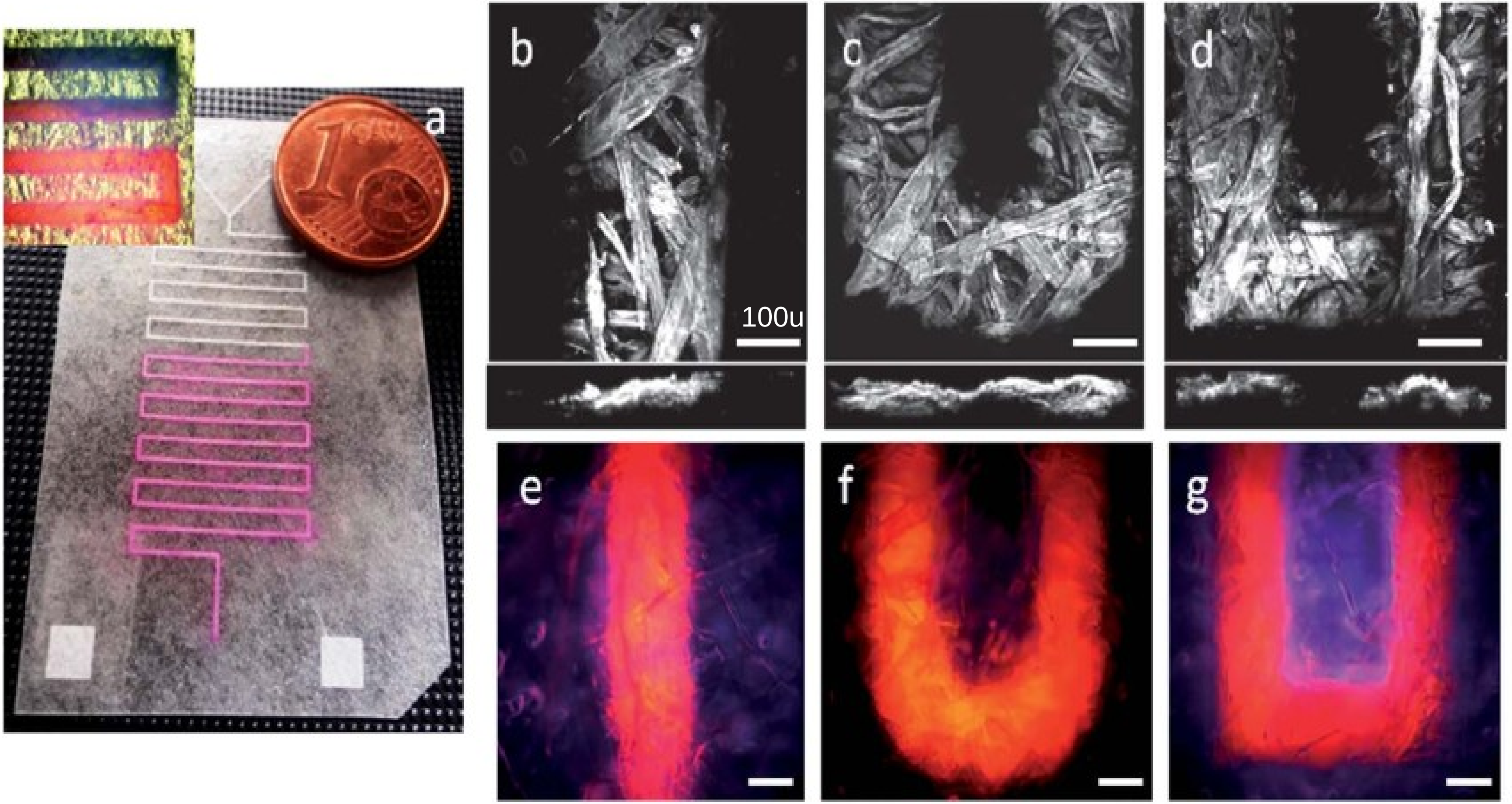


J. Mater. Chem. C 2013; Optics Letters 2013

Technological advantages

- Tendency: replace inorganic materials with organic matter (e.g., silk) in optical and electronic devices
- Paper
    - Bio-compatible and bio-degradable
    - Low cost
    - Flexible
    - Bio-fluidic ready
    - Chemically and mechanically stable
    - Scalable to large area
    - Simple soft-litography compatible

Paper-based random laser



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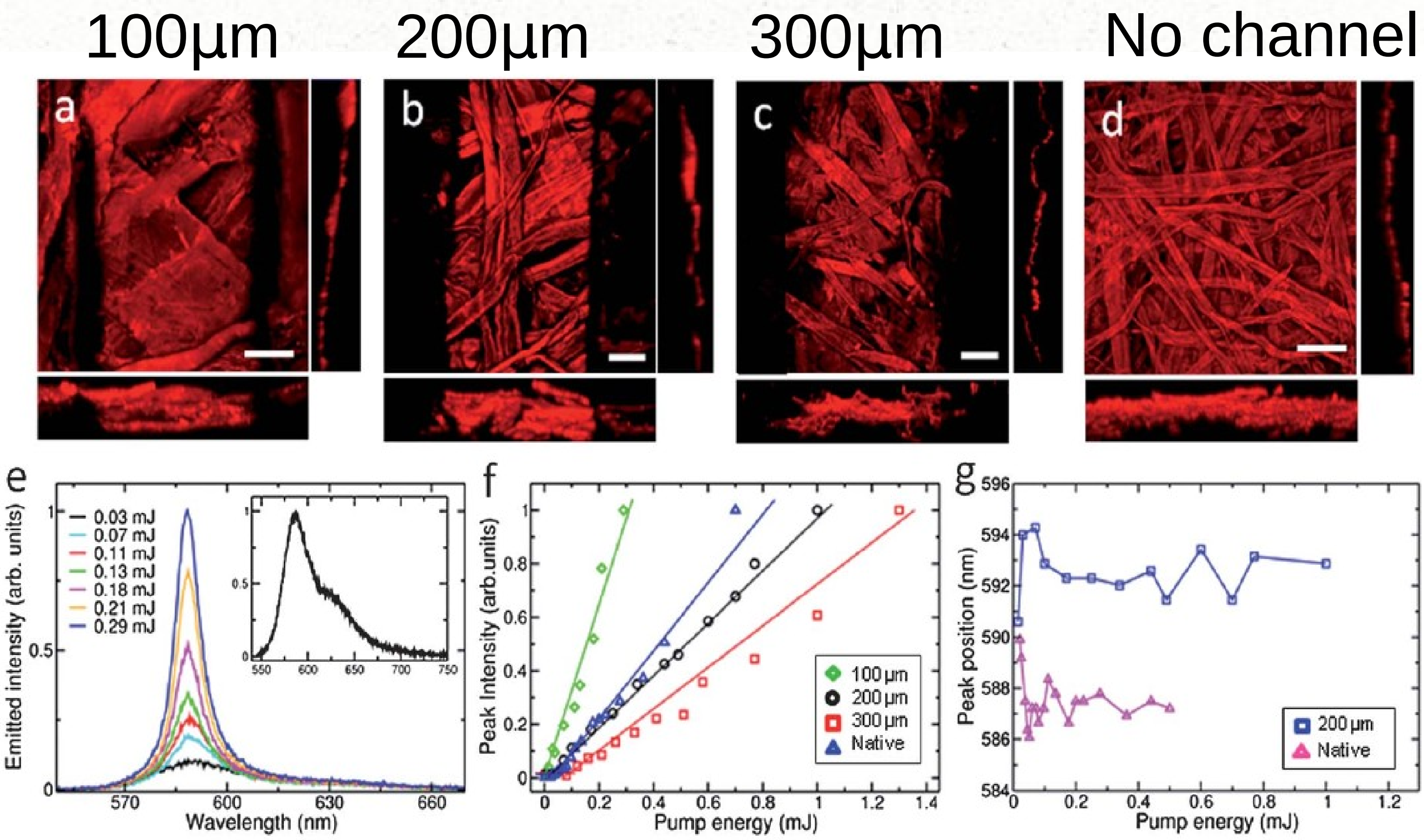
Effect of channel size



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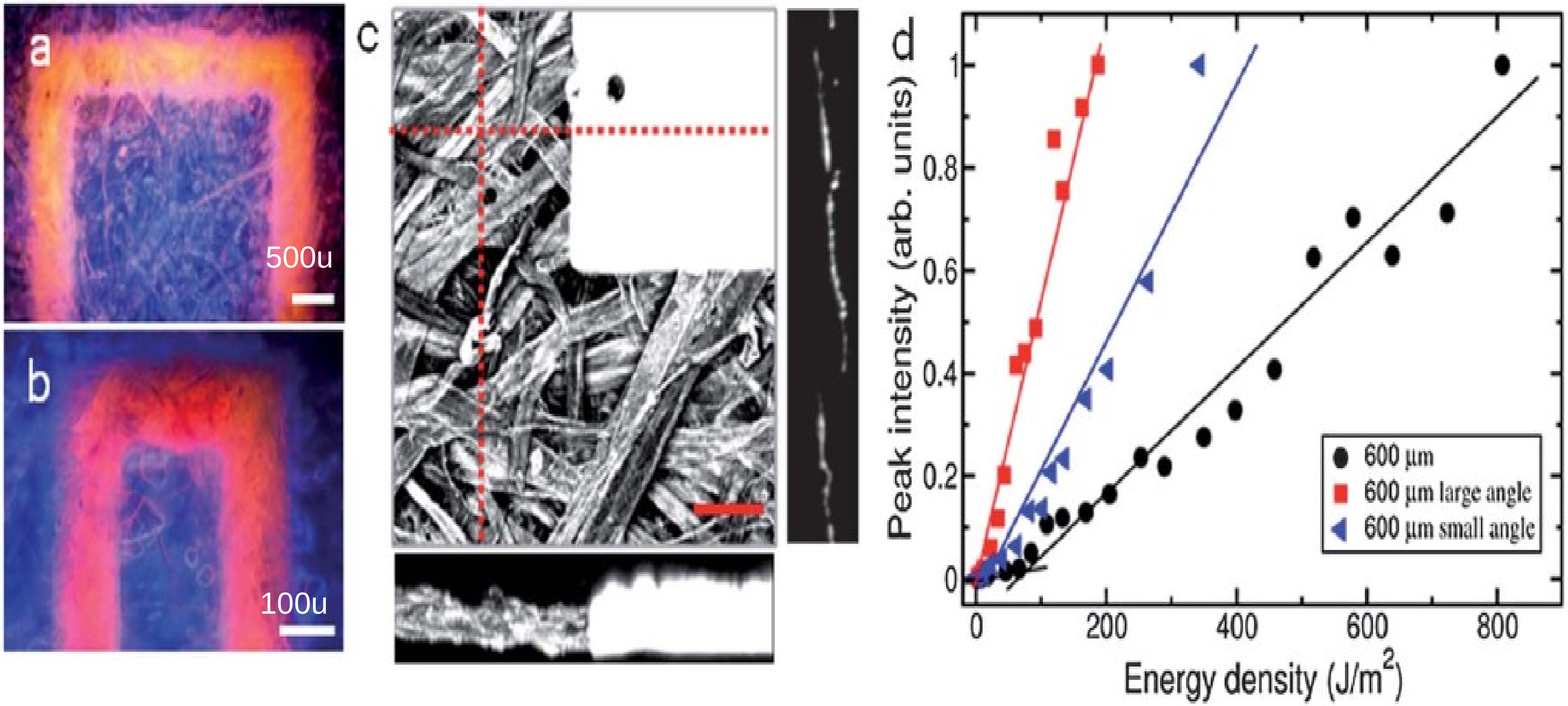
Effect of curvature

We study the effect of a local curvature on the threshold



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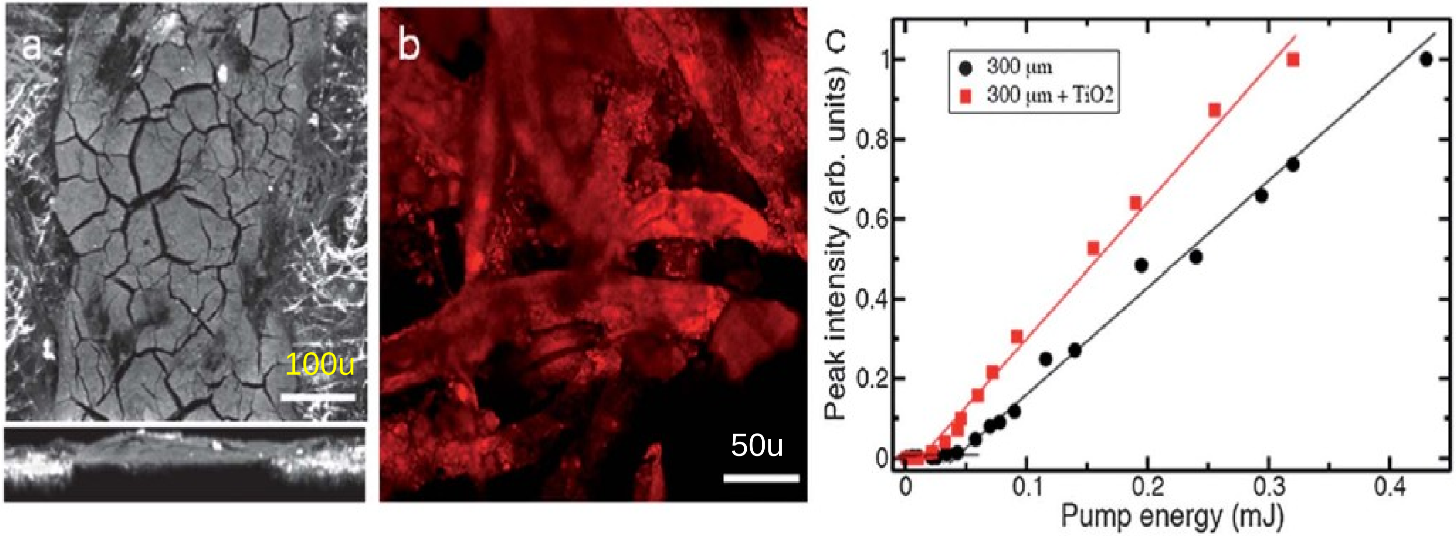
Functionalizing paper (add TiO2)

We add TiO2 particle to increase disorder



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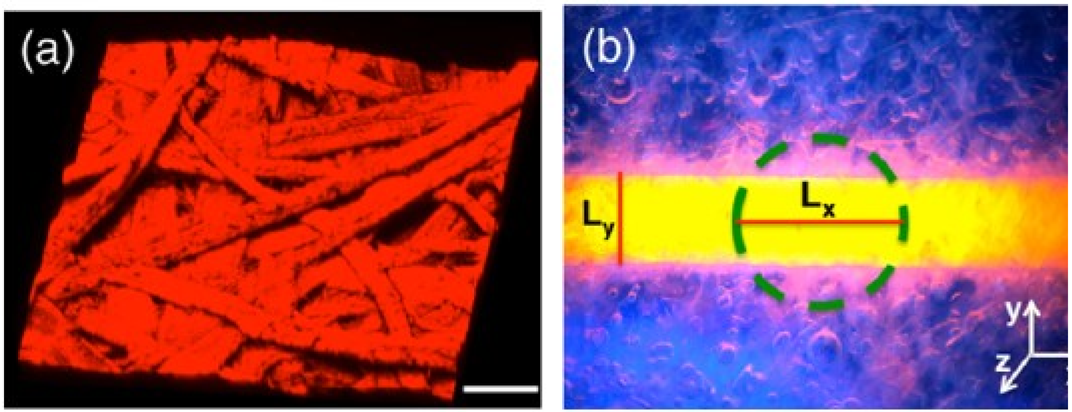
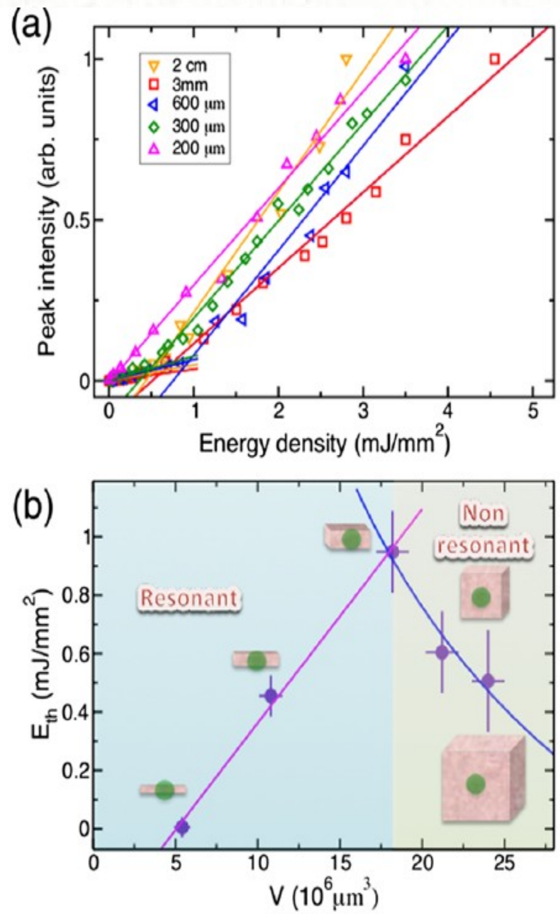
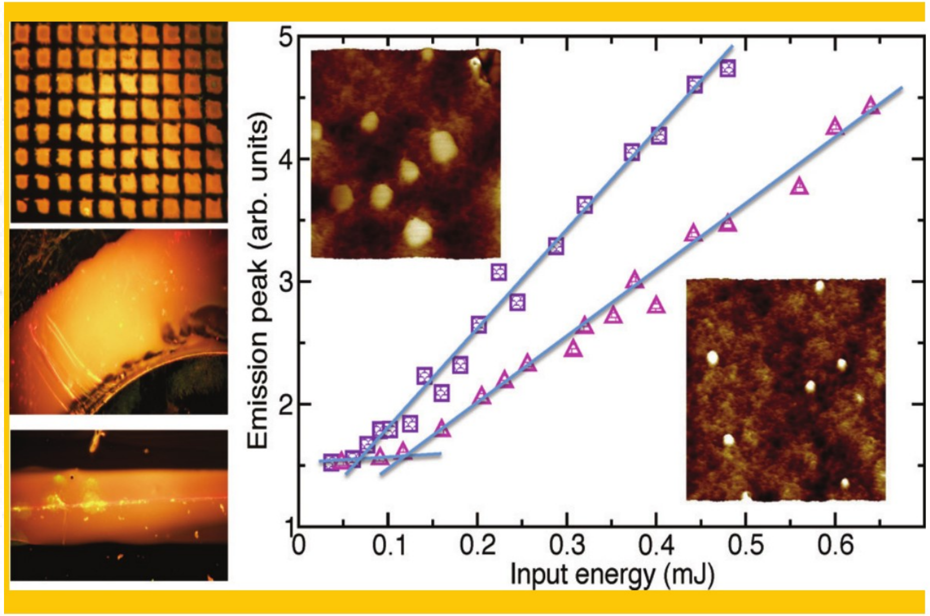
Threshold Vs Geometry





Surface Tension Driven Litography

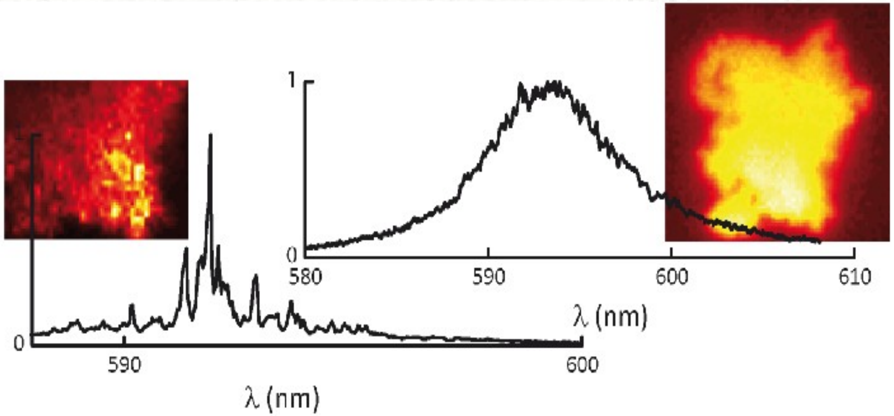
- We also reported on similar results based on a different technology on other kinds of functionalized organic substrates



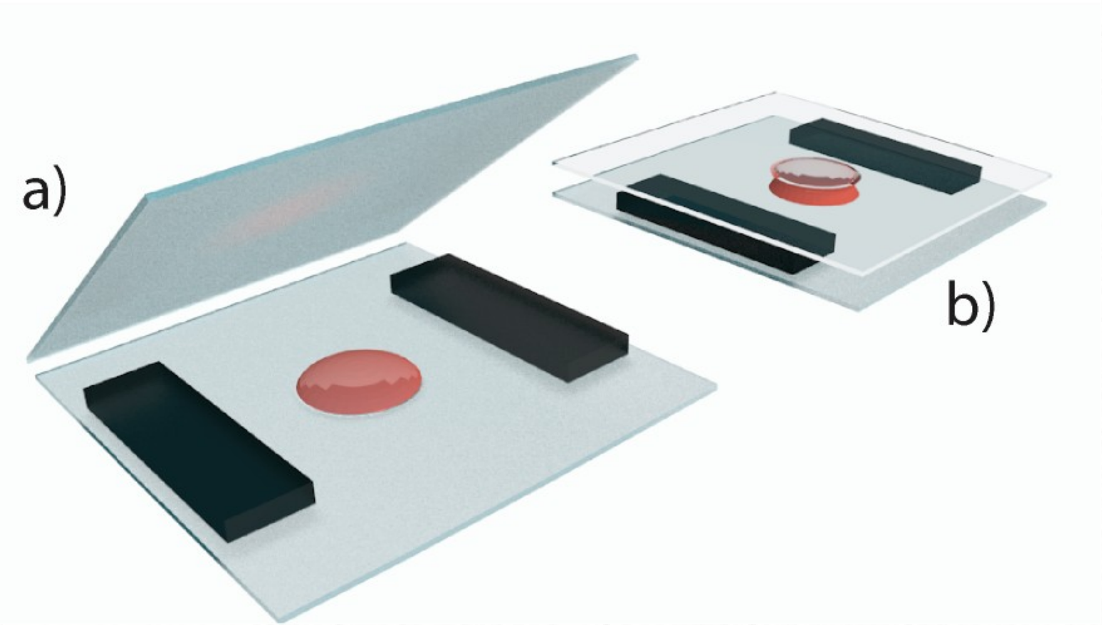
Laser and Photonics Review 7, 432 (2013)

Control of Random Lasers

Marco Leonetti (IPCF-CNR, Rome)
Cefe Lopez (ICMM, Madrid)

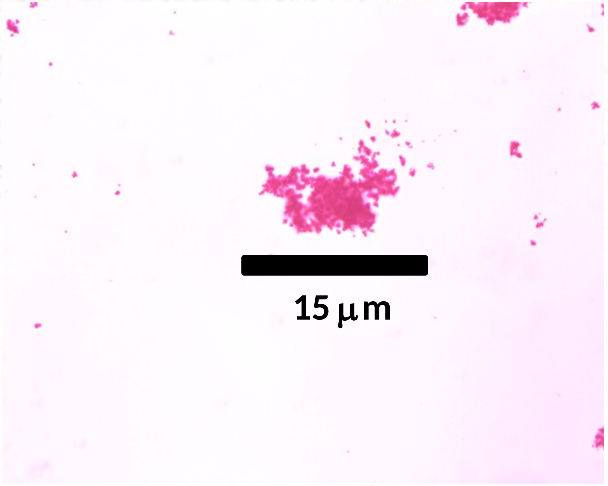


Sample

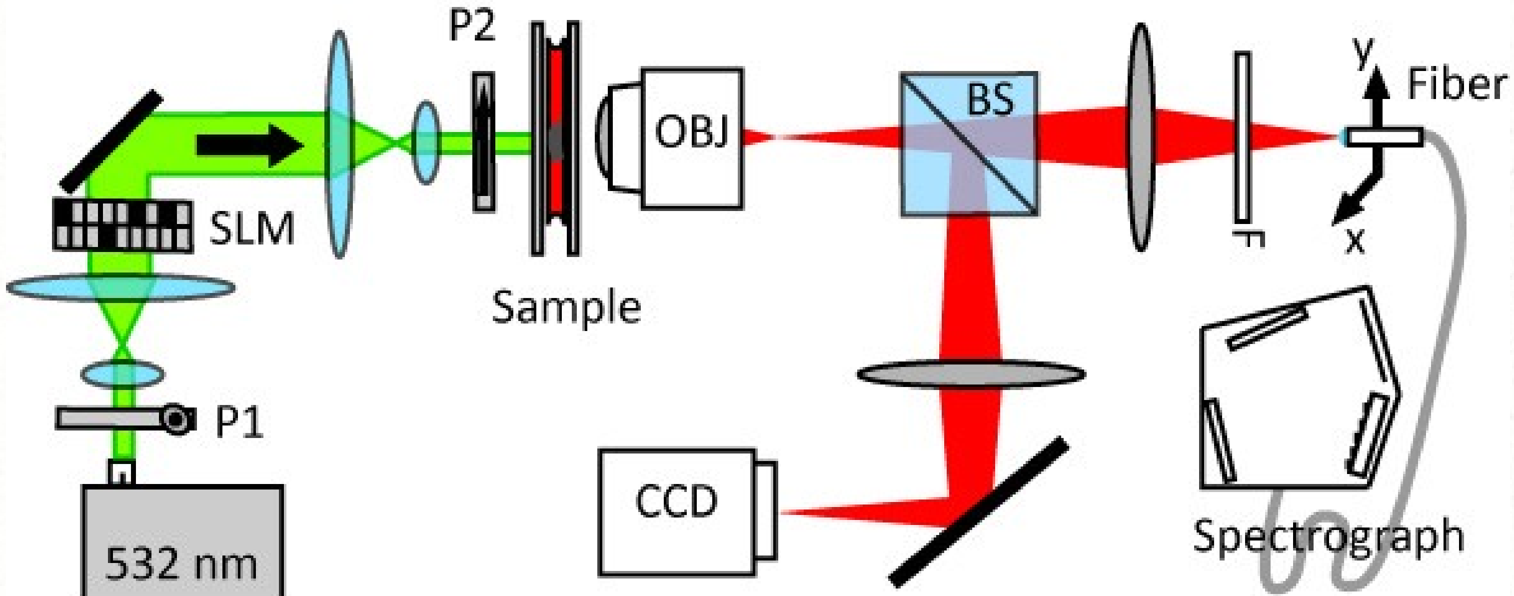


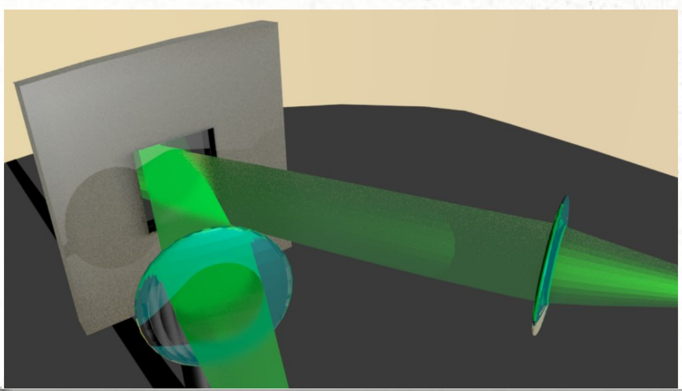
A solution containing :
-diethylene glycol
-Rhodamine
-titanium dioxide nanoparticles (<1 μm)

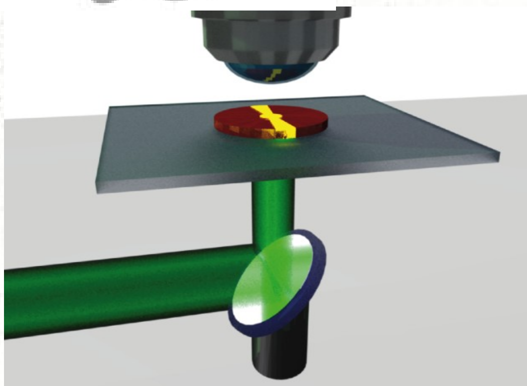
Self assembled cluster of titanium nanoparticles



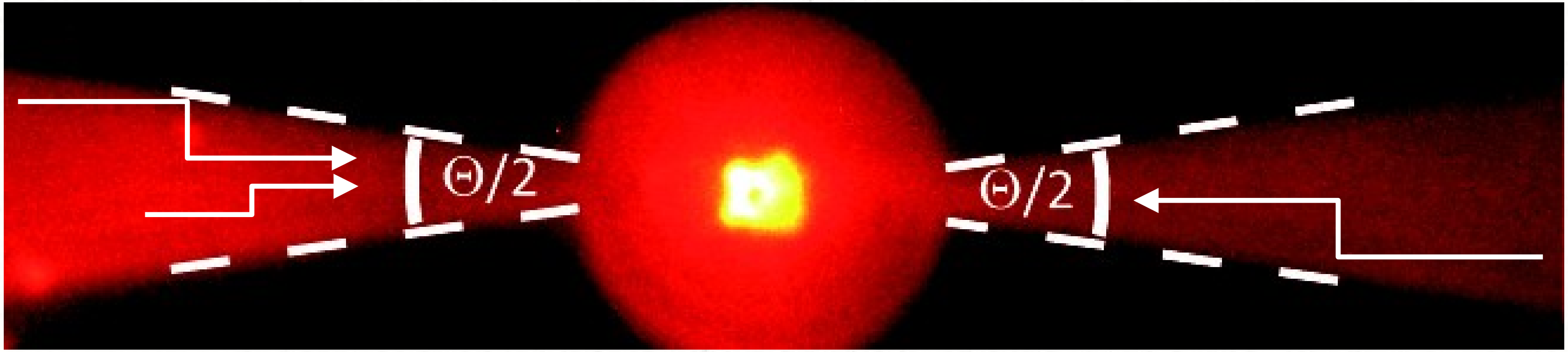
Experimental setup



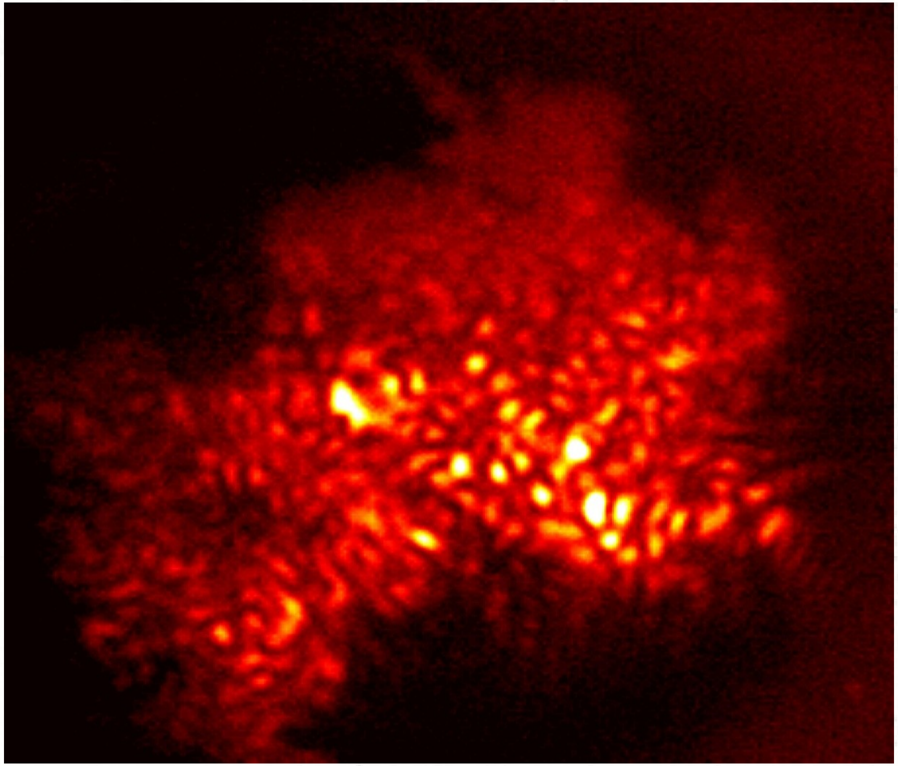


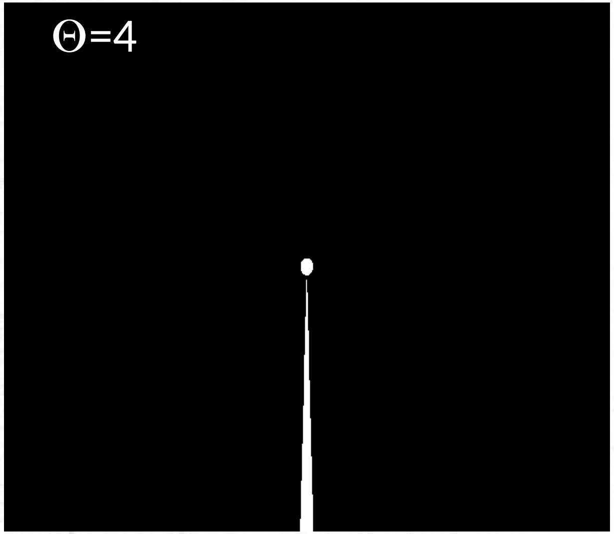


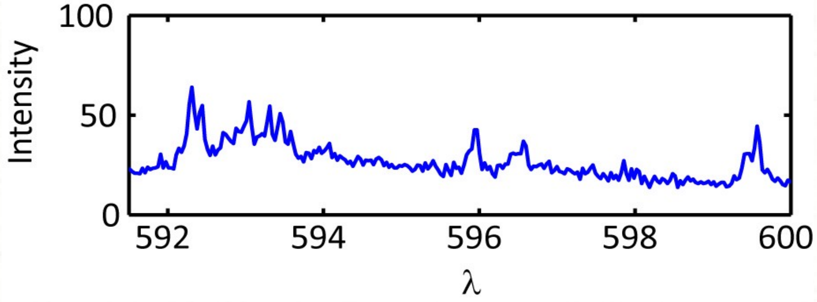
Control strategy (pump shape)



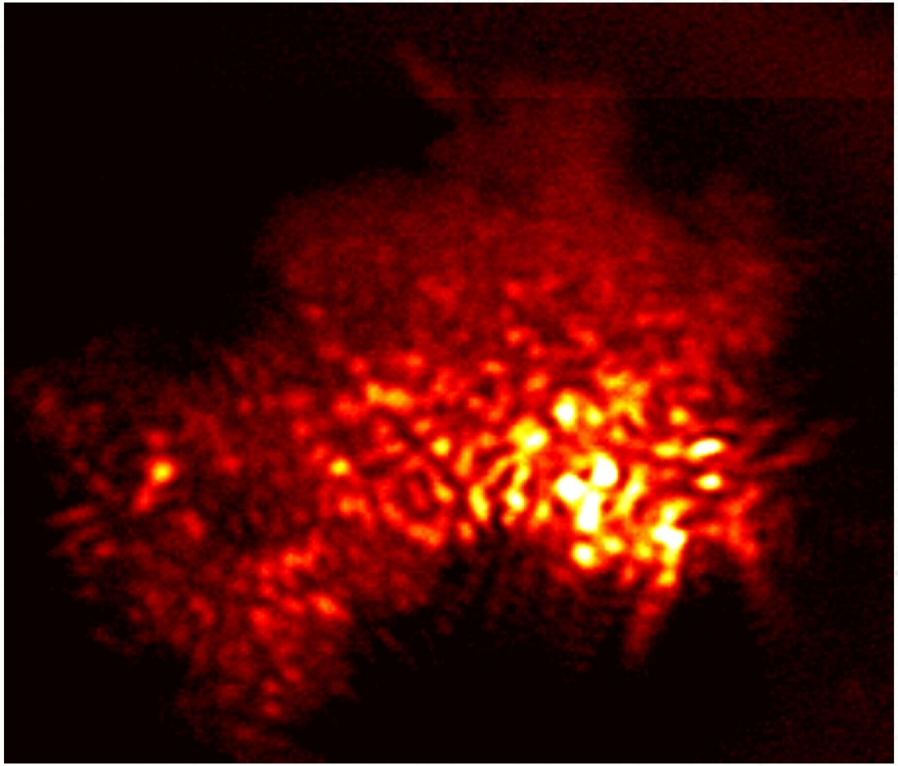
Control of RL (1/4)

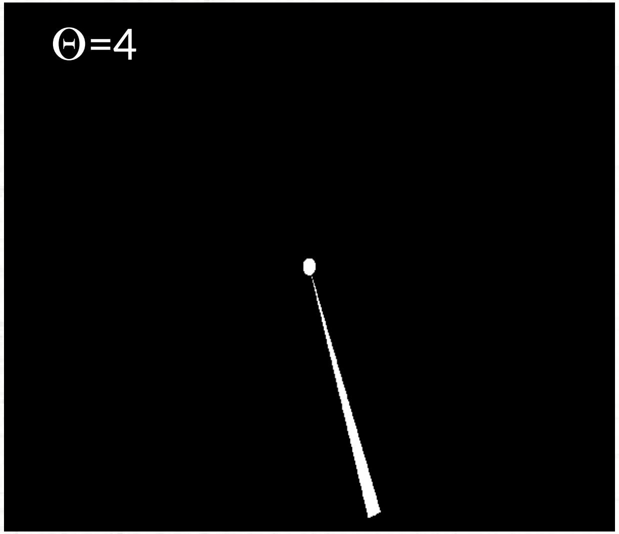


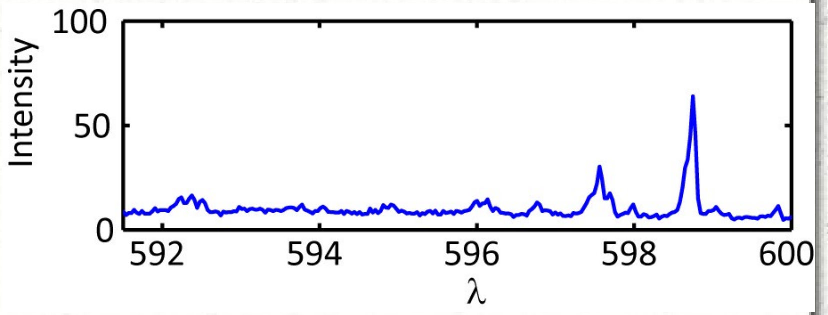




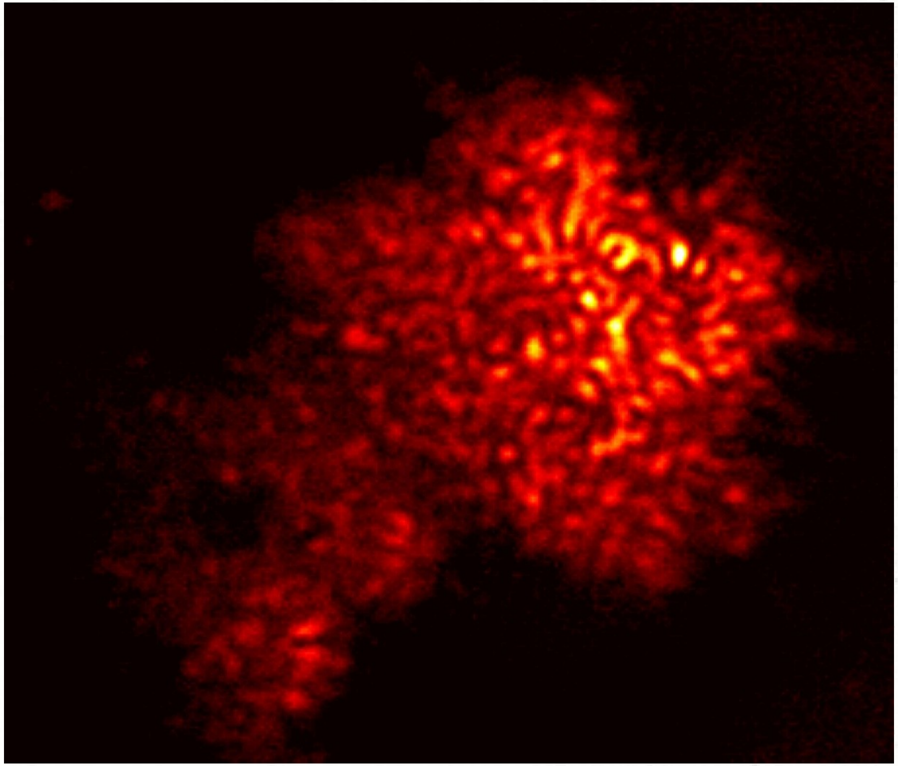
Control of RL (2/4)

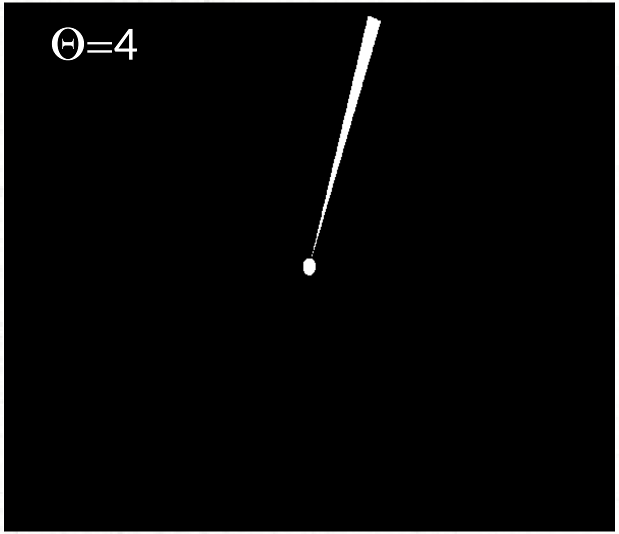


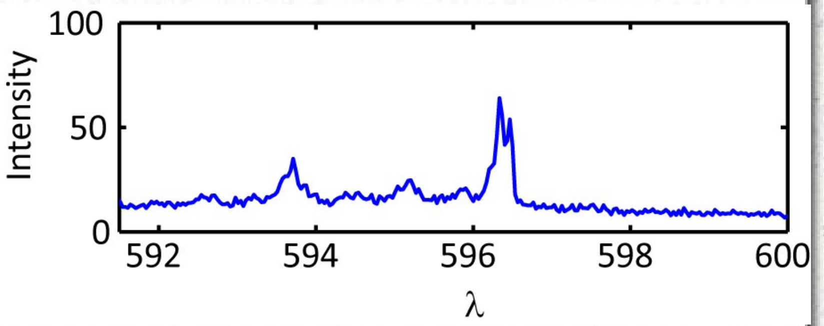




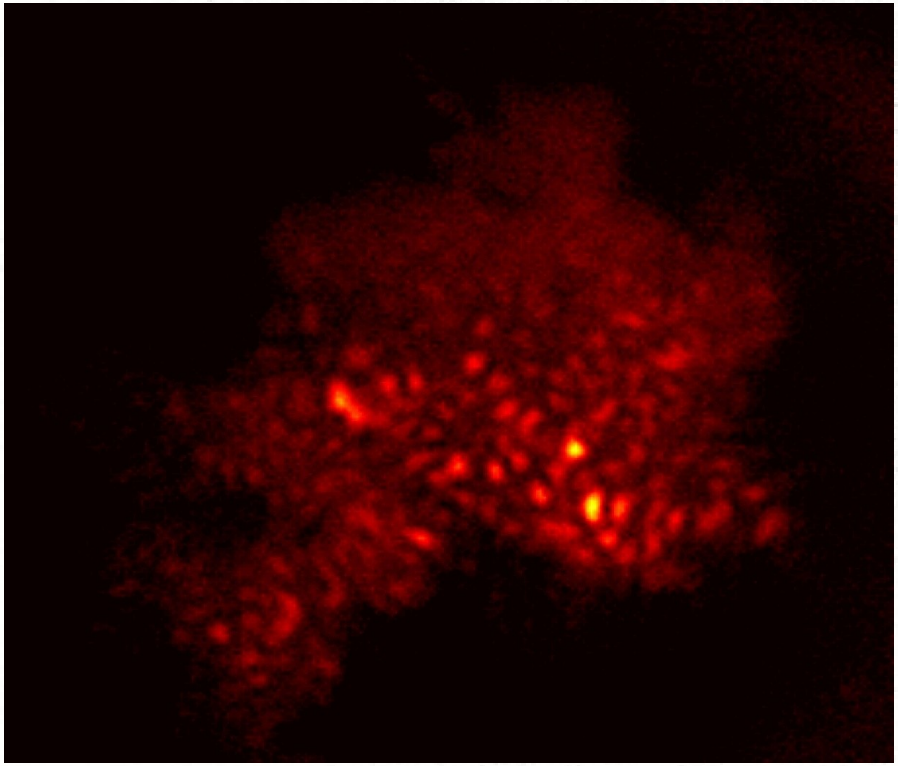
Control of RL (2/3)

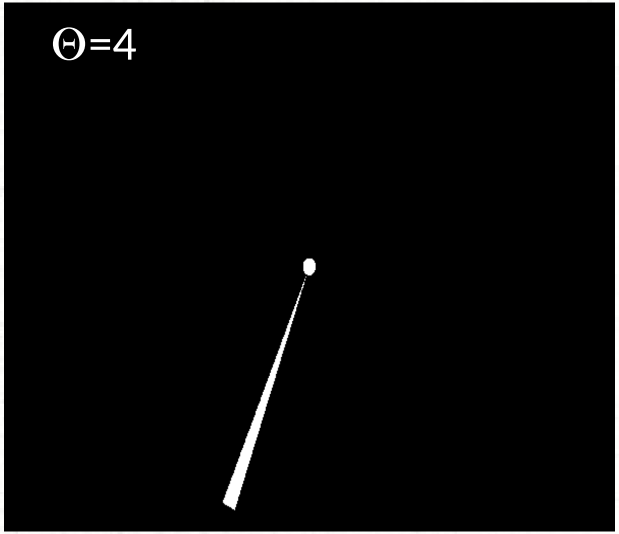


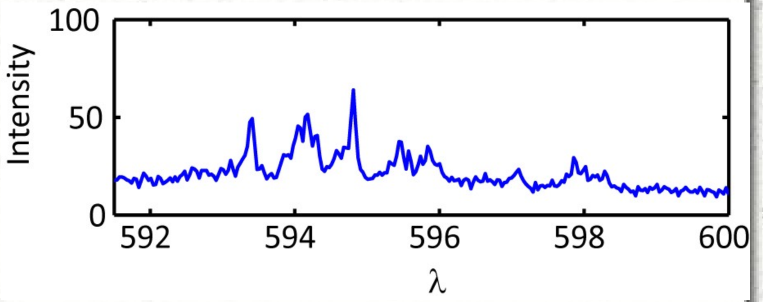




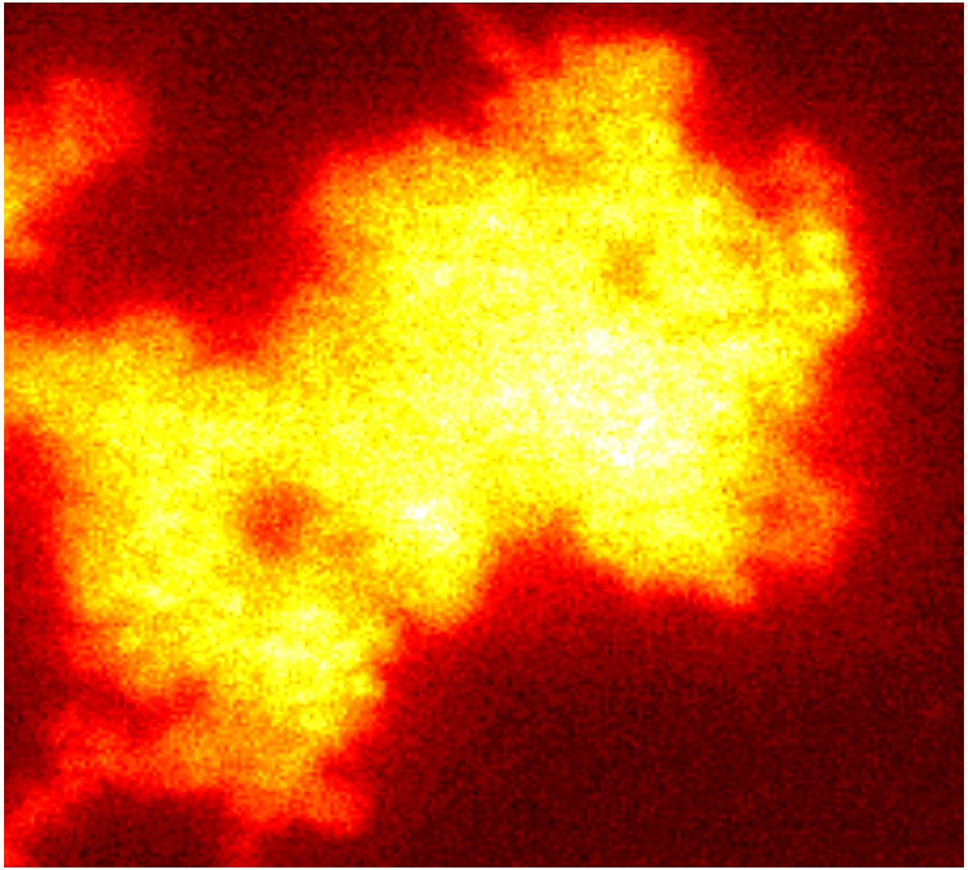
Control of RL (4/4)

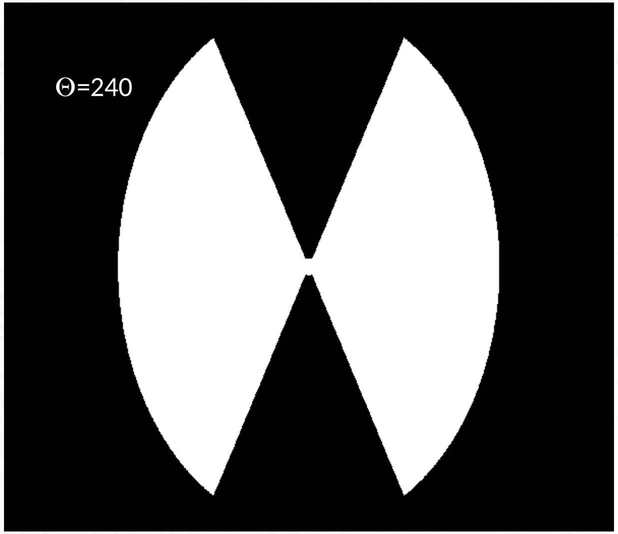


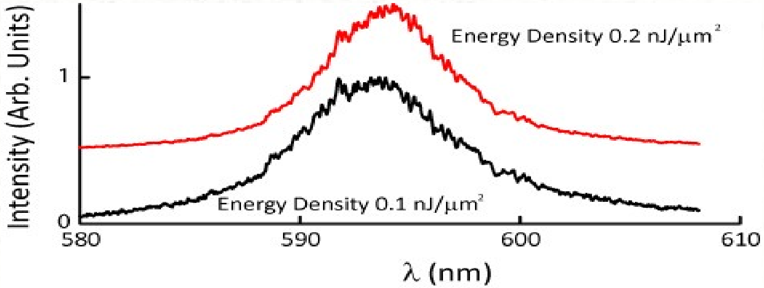




Large scale excitation







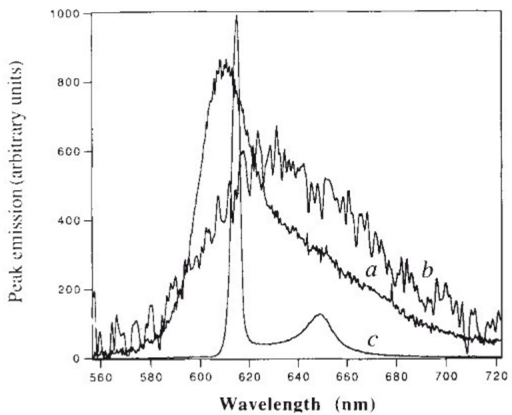
Earlier literature

Diffusive random laser

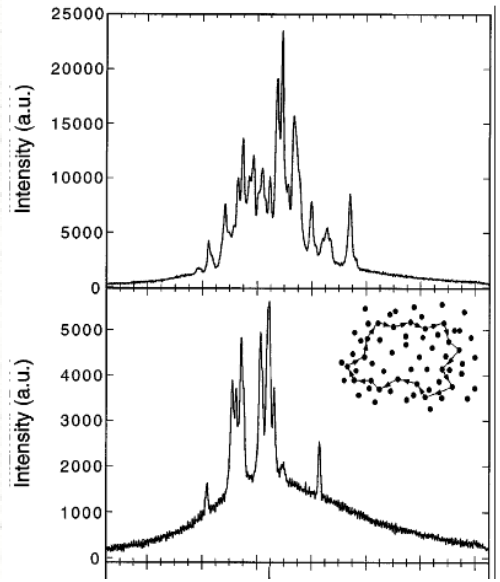
436 NATURE · VOL 368 · 31 MARCH 1994

Laser action in strongly scattering media

N. M. Lawandy, R. M. Balachandran, A. S. L. Gomes & E. Sauvain



Resonant random laser



VOLUME 82, NUMBER 11 PHYSICAL REVIEW LETTERS 15 MARCH 1999

Random Laser Action in Semiconductor Powder

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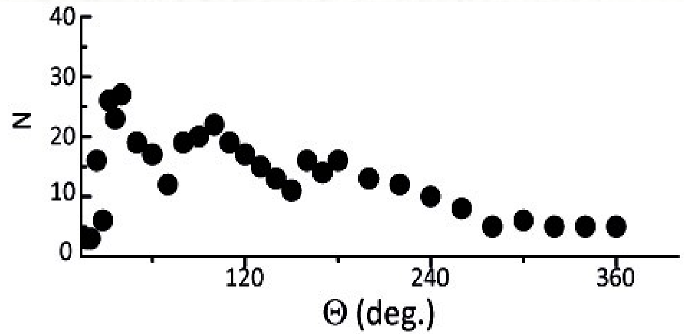
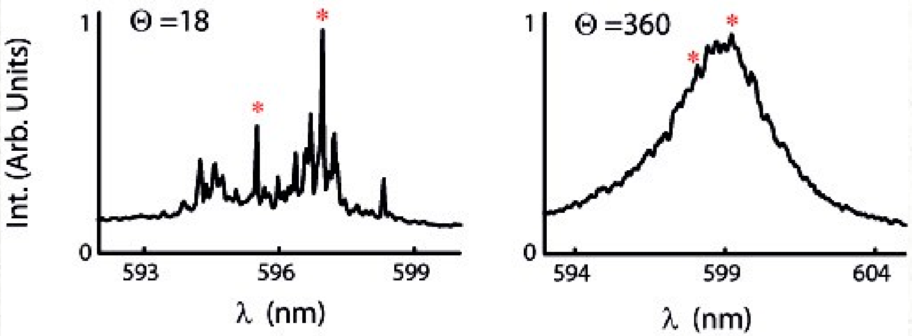
(Received 9 September 1998; revised manuscript received 16 December 1998)

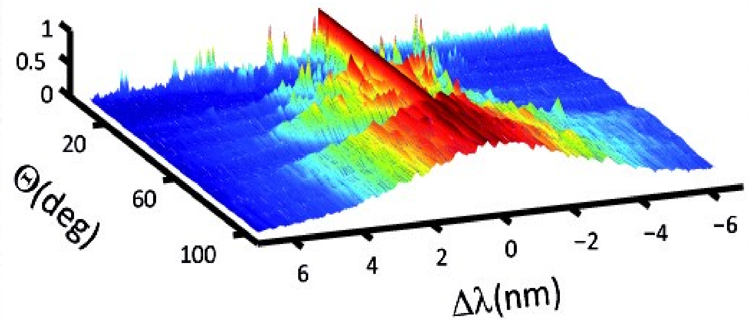
The number of peak changes

Number of activated modes





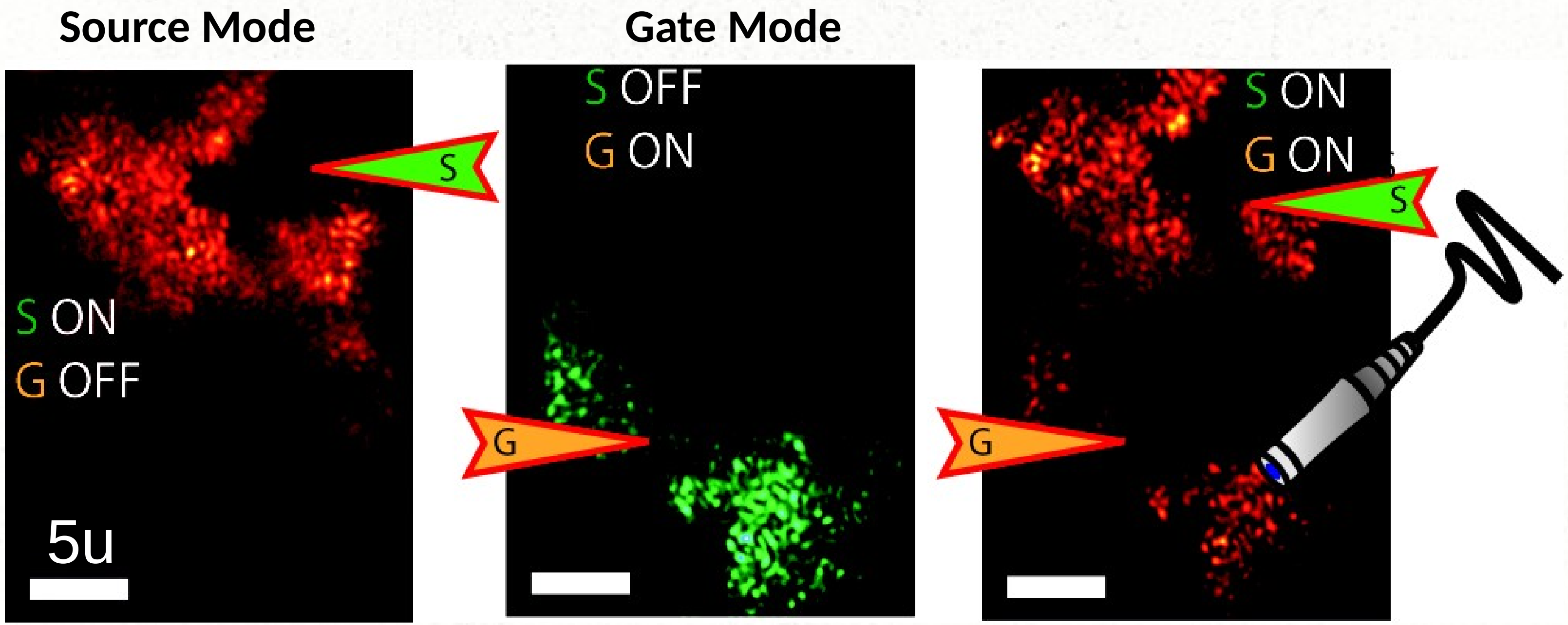
Spectrum Vs Θ



Modes interact!

Nature Photonics 2011; PRA 2012; PRA 2013

Gating and control



Nature Communications 4, 1740 (2013)

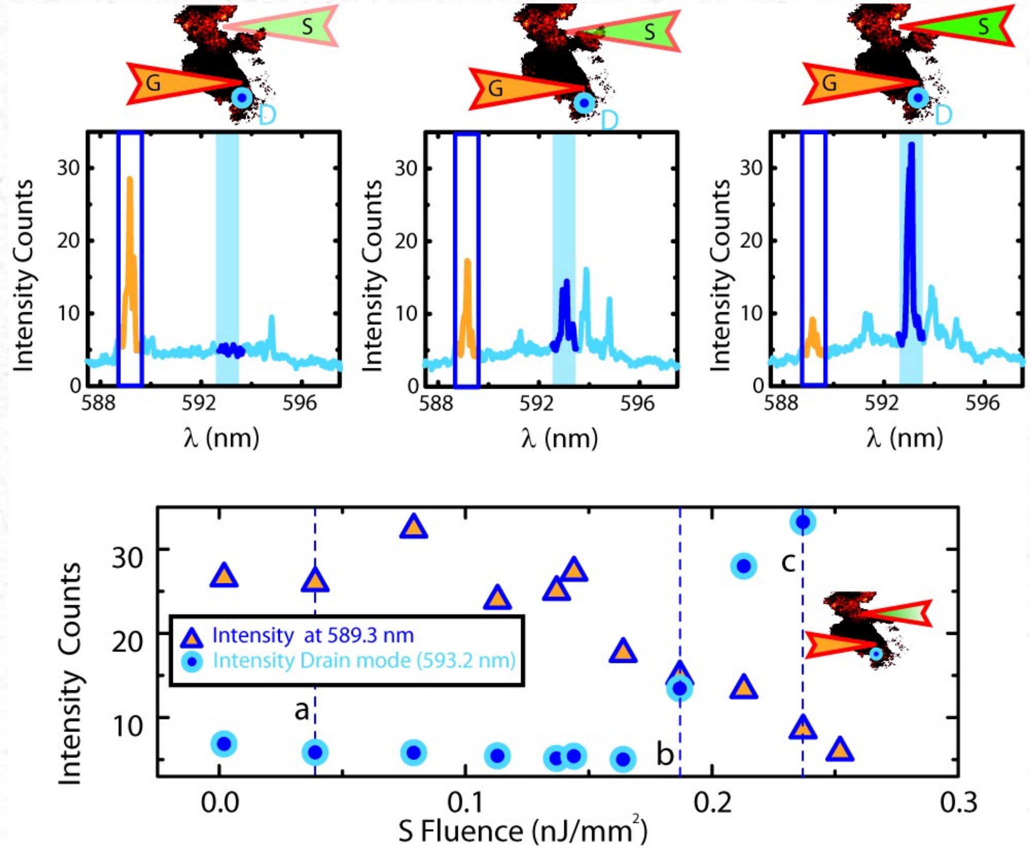
Mode competition and nonlocality

Increasing Source Strength

Spectrum @Gate

Gate Frequency

Source Frequency

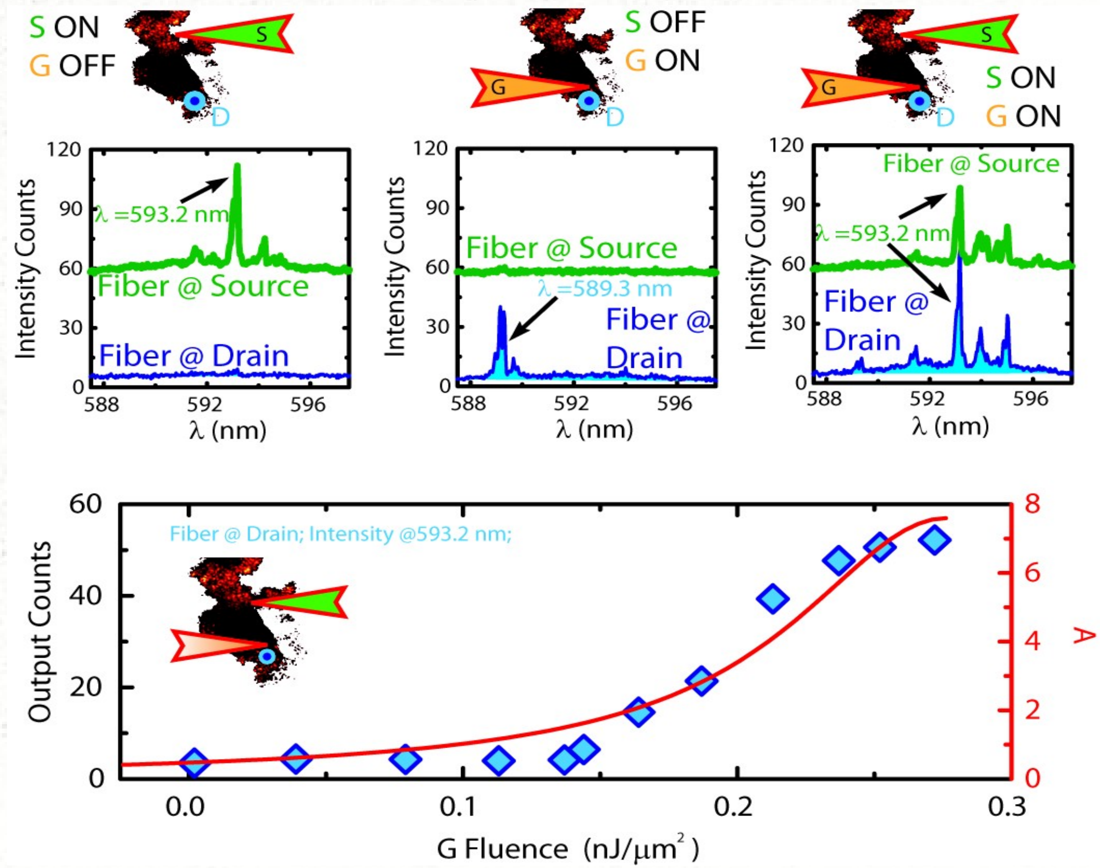


Nature Communications 4, 1740 (2013)

A transistor-like action

Intensity@source

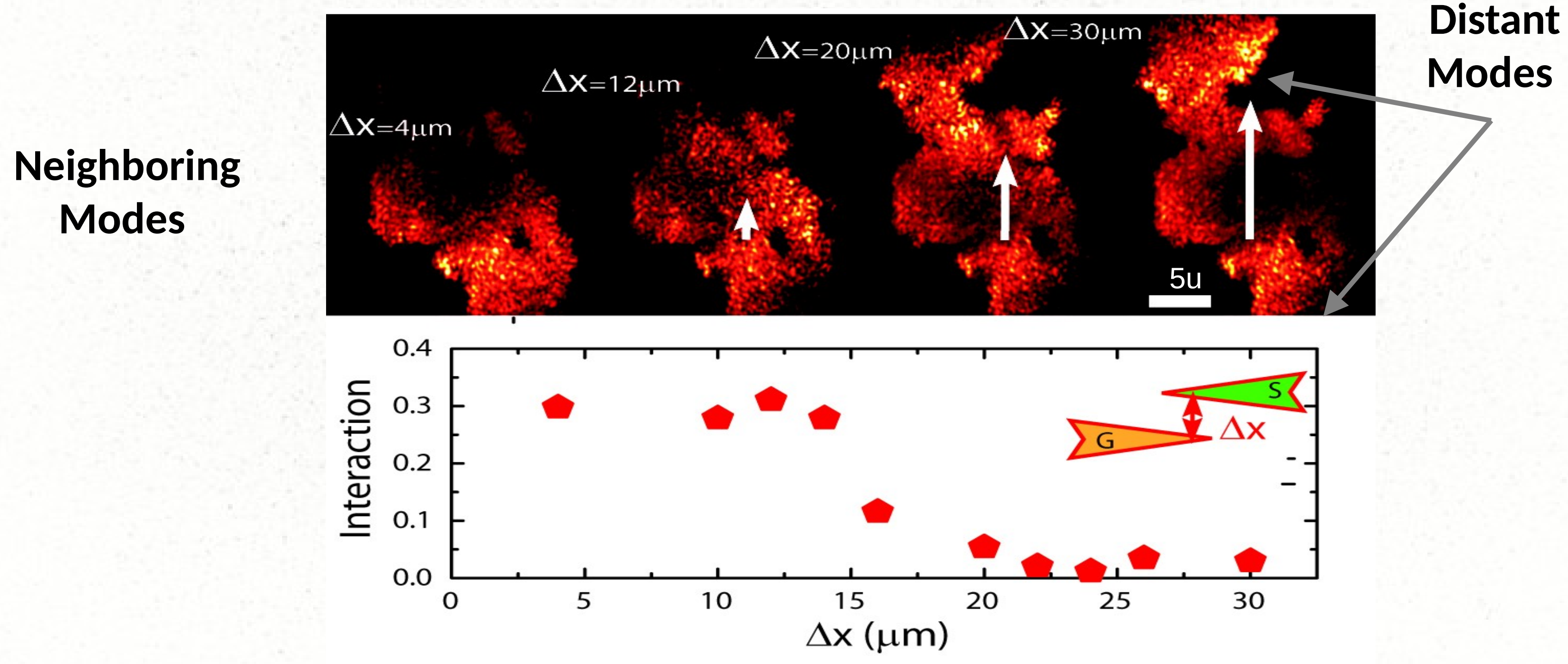
Intensity @Gate



Intensity @ Gate/Drain (source frequency)

Nature Communications 4, 1740 (2013)

Measuring the degree of nonlocality



Nature: Light Science and Applications 2, e88 (2013)

Multi-color localization

Profile of localized modes Vs excitation shape

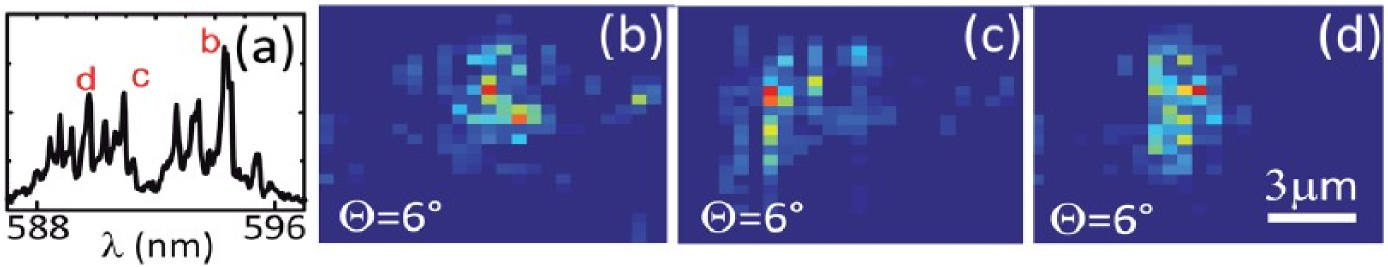


FIG. 3. (a) Spectrum from the cluster C3 obtained by pumping with $\Theta = 6°$; (b)-(d) spatial distribution of intensity for the three modes indicated in (a).

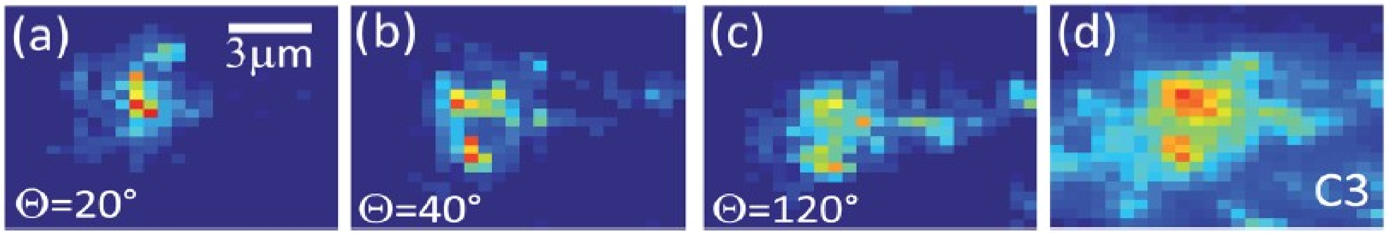
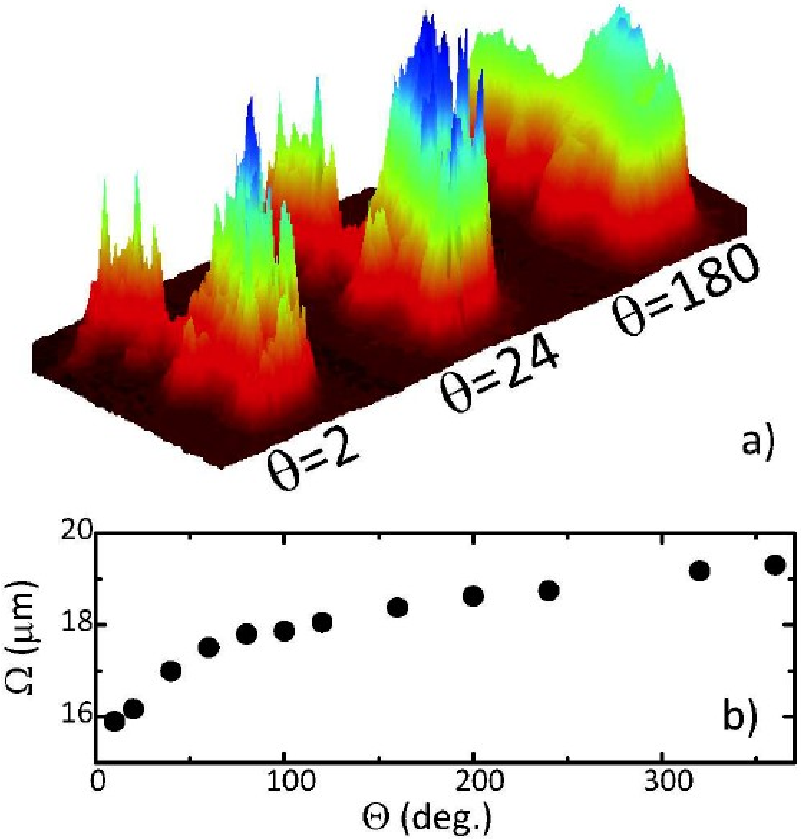


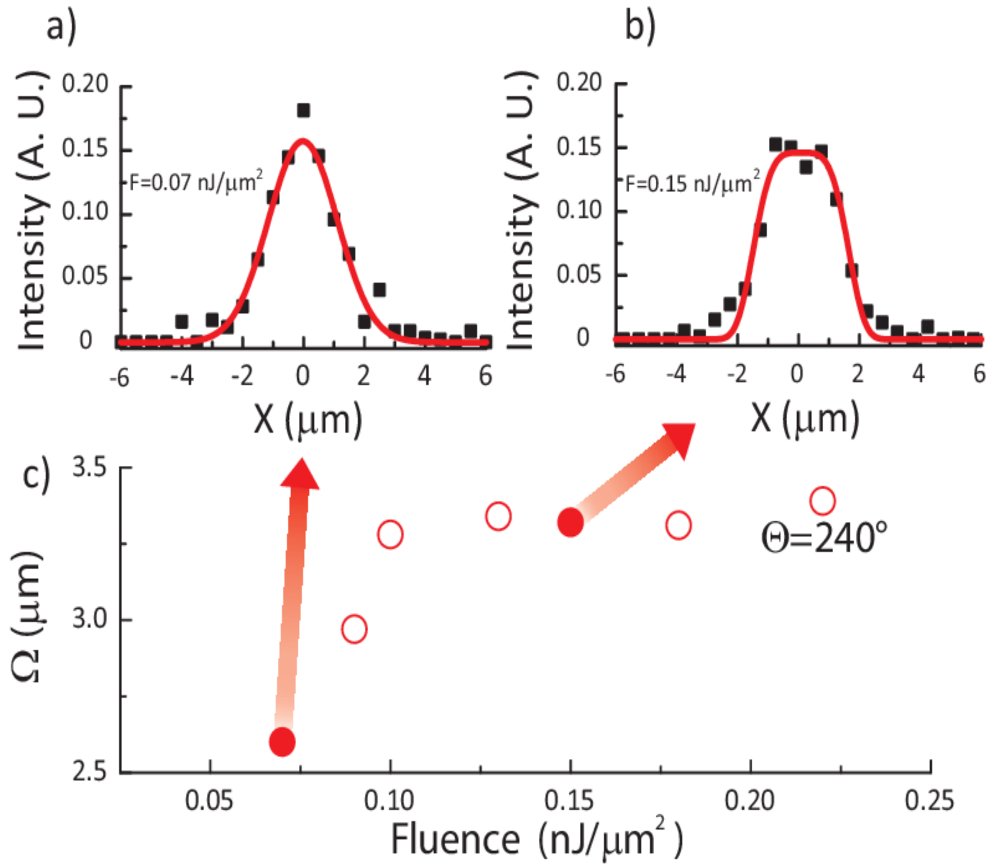
FIG. 4. (a)-(c) Represent the spatial intensity distribution for the most intense mode of cluster C3 when pumped with $\Theta = 20°$, $\Theta = 40°$, and $\Theta = 120°$, respectively, while panel (d) reports the spatial distribution of the intensity (all wavelengths summed) below lasing threshold providing the shape of the cluster.

Leonetti, Marco, Conti, Claudio and Lopez, Cefe (2012),
"Tunable degree of localization in random lasers with controlled interaction",
Applied Physics Letters, 101, 5: 051104.

Energy dependent localization in random lasers

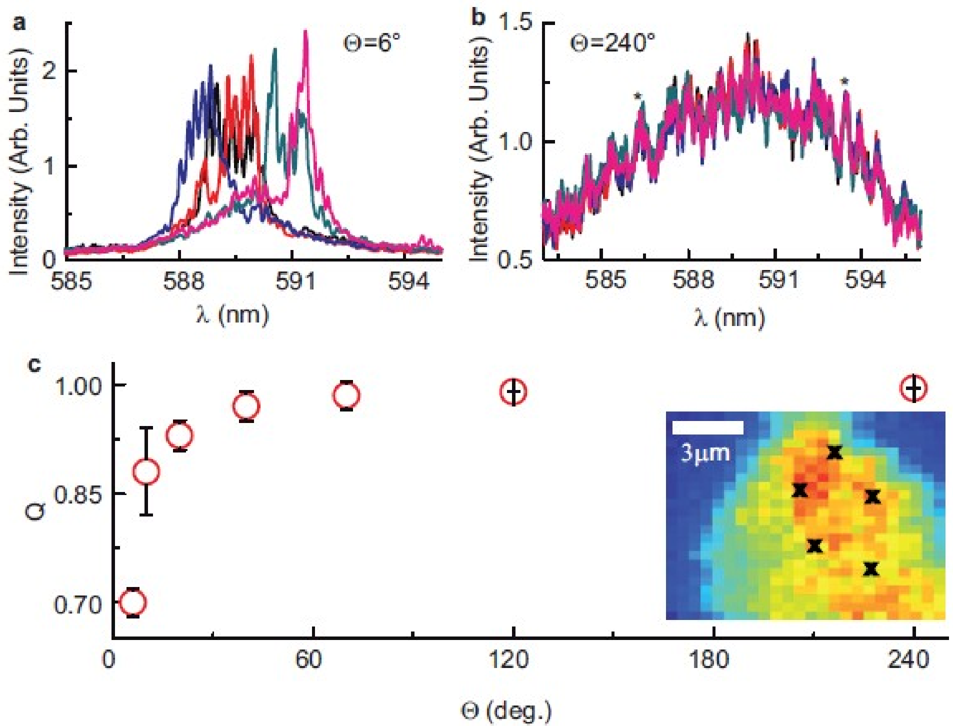
$$P_\lambda(\Theta) \equiv \frac{\int I_\lambda(x,y)^2}{\left(\int I_\lambda(x,y)\right)^2} \qquad \Omega_\lambda(\Theta) = 1/\sqrt{P_\lambda}.$$

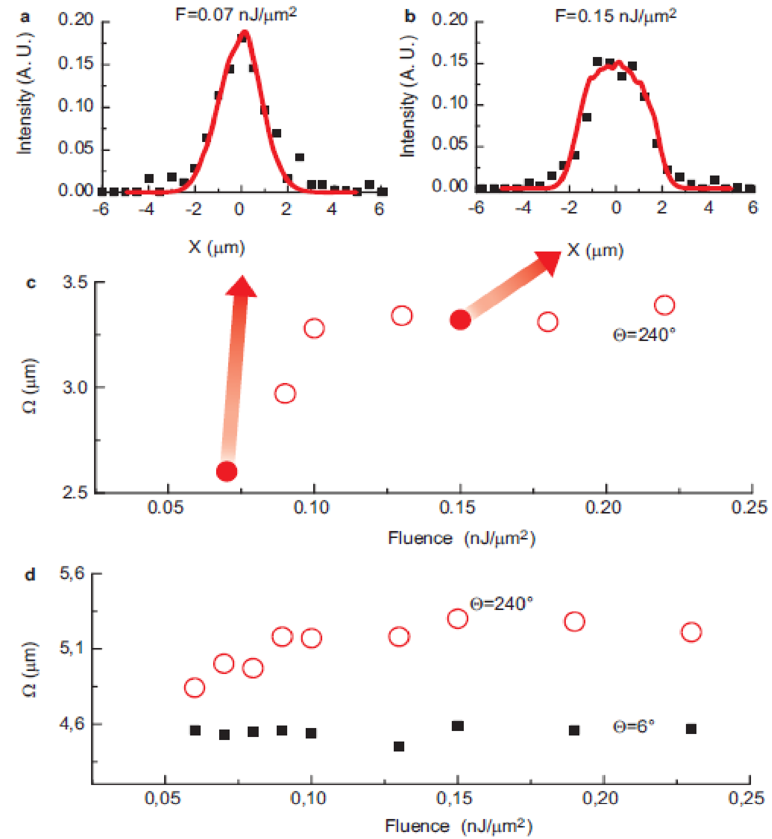




Light: Science and Applications, Leonetti, Conti and Lopez, 2013 to appear

Collective regime





Open

Light: Science & Applications (2013) 2, e88; doi:10.1038/lsa.2013.44

www.nature.com/lsa

ORIGINAL ARTICLE

Non-locality and collective emission in disordered lasing resonators

To appear 30 August 2013