XVII J. A. Swieca School - Curitiba (March, 2023)

Nonlinear Optics

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3rd. lecture

Random Lasers

Introduction – short history + comments on light propagation in scattering media + examples

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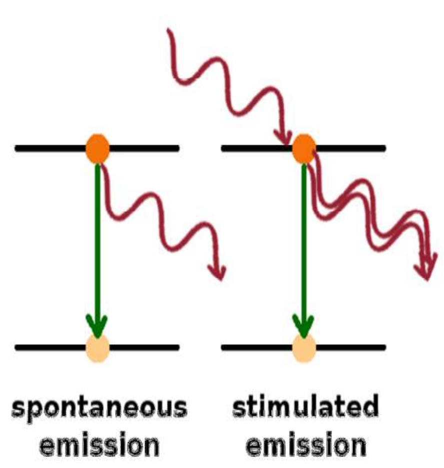
Examples and recent advances

- Stokes and anti-Stokes Random Lasers
- Multicolor emission from RLs
- Universal Photonic Phase-Transitions

Random Lasers

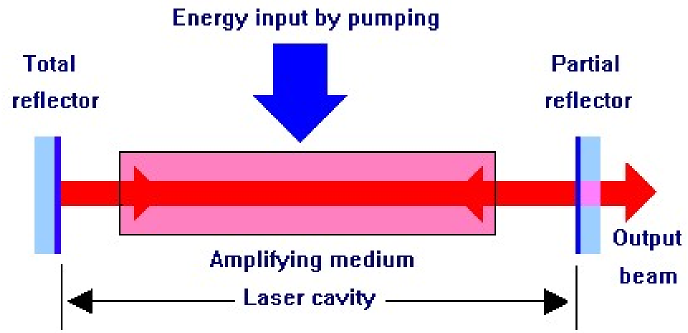
- Disordered Photonics (disordered structures that strongly scatter light)
- Laser Physics
- Nonlinear Wave-mixing and Multiphoton absorption
- Glassy behavior of light (Spin Glass - Replica Symmetry Breaking theory)
- Paramagnetic-to-ferromagnetic photonic phase-transition (spontaneous mode-locking)

Conventional lasers



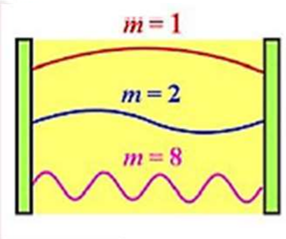
1916 Einstein

Essential components

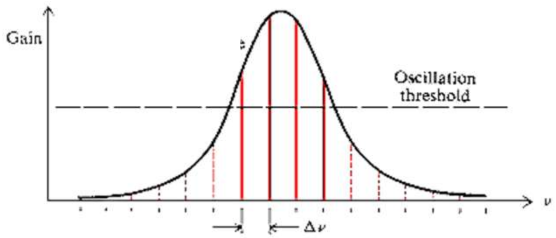


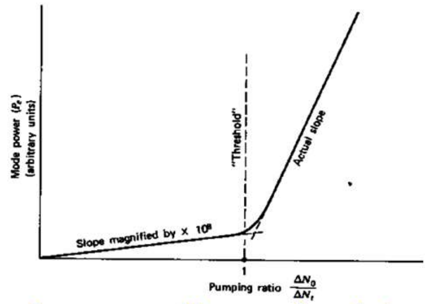
1960 Maiman (Rubi laser)

Resonant modes



Gain curve





Laser threshold

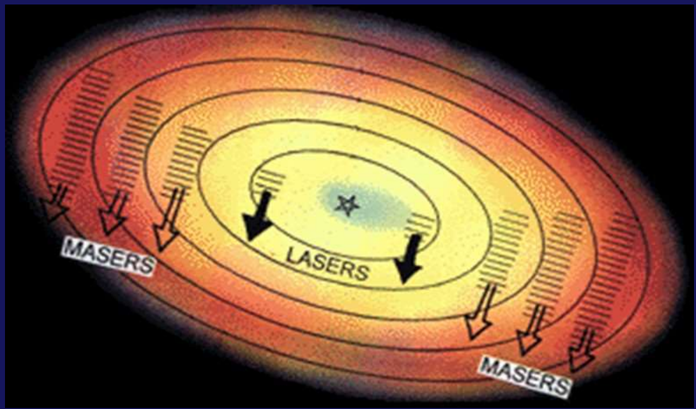
Gain > losses

Townes, Basov, Prokhorov – Physics Nobel Prize - 1964

lasers in Nature

CO_2 lasers - from Mars and Venus

NIR Laser from η - Carinae (star MWC 349A)
(most intense star in the Milky Way)



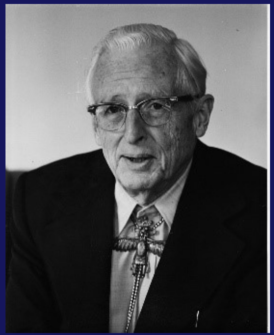
Intensity interferometry

Australia Univ.

Far-infrared hydrogen laser in the peculiar star MWC 349A *Science* 272 (1996) 1459

S. Johansson, V. S. Letokhov, Astrophysical lasers operating in optical FeII lines in stellar ejecta of Eta Carinae. Ast. & Astrophys. J. 428 (2004) 497

Fe II lines: 961.7 and 991.3 nm



D. H. Menzel
(1901-1976)

A study of line intensities in stellar spectra
1924 – PhD thesis (Princeton U.)

1937 - Ap. J. 85, 330 – Stimulated emission from *gaseous nebulae*

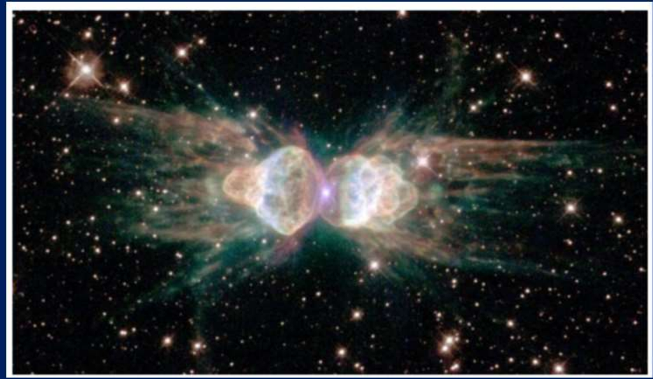
“The physical significance of such a result is that energy is emitted rather than absorbed ... as if the atmosphere had a negative opacity.”

D. H. Menzel
Nat. Bur. Stds. Spec. Publ. 332, 134-137 (1970)
Laser action in non-LTE atmospheres

Formiga espacial dispara lasers em direção à Terra

Por **ZAP** - 23 maio, 2018 23/maio/2018

Report from the Herschel Observatory – European Space Agency: laser emission from the Ant Nebula



Herschel Planetary Nebula Survey (HerPlaNS): hydrogen recombination laser lines in Mz 3

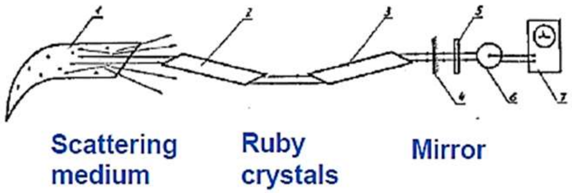
Isabel Aleman ✉, Katrina Exter, Toshiya Ueta, Samuel Walton, A G G M Tielens, Albert Zijlstra, Rodolfo Montez, Jr, Zulema Abraham, Masaaki Otsuka, Pedro P B Beaklini Peter A M van Hoof, Eva Villaver, Marcelo L Leal-Ferreira, Edgar Mendoza, Jacques D R Lépine

Monthly Notices of the Royal Astronomical Society, Volume 477, Issue 4, 11 July 2018, Pages 4499–4510, https://doi.org/10.1093/mnras/sty966

Published: 16 May 2018 **Article history ▾**

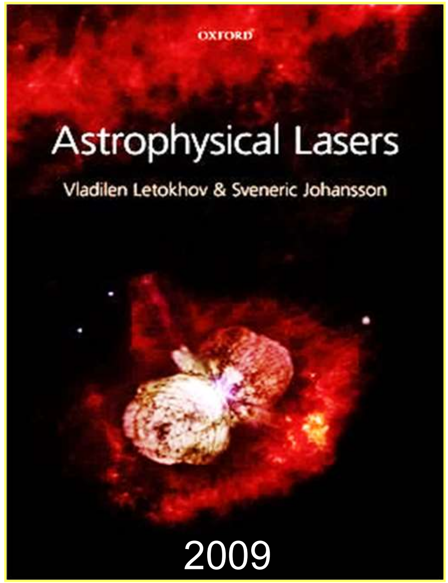
Random Lasers are lasers without mirrors

Ambartsumyan, Basov, Kryukov, Letokhov,
A laser with nonresonant feedback
IEEE J. Quantum Electron. 2 (1966) 442-446



V. S. Letokhov
(1939–2009)

Letokhov, Proposal of scattering with "negative absorption"to describe emissions from astrophysical molecular clouds
Sov. Phys. JETP 5 (1967) 212-215

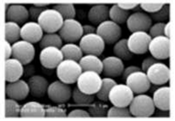


S. Johansson and V. S. Letokhov
Astrophysical lasers and nonlinear optical effects in space. New Astronomy Reviews 51 (2007) 443-523

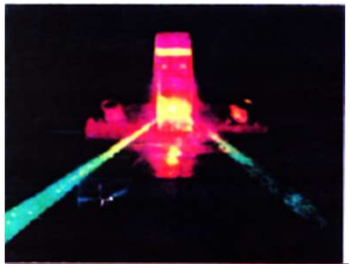
First efficient Random Laser

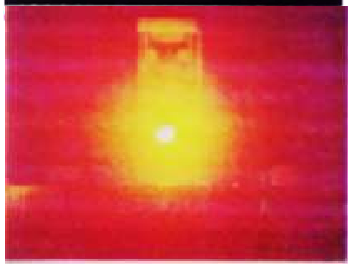
Rhodamine - Excitation: @ 532 nm, ps

+



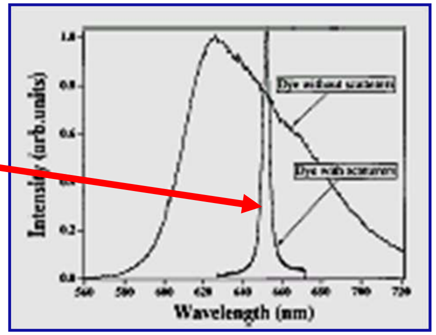
NPs TiO_2 (250 nm)





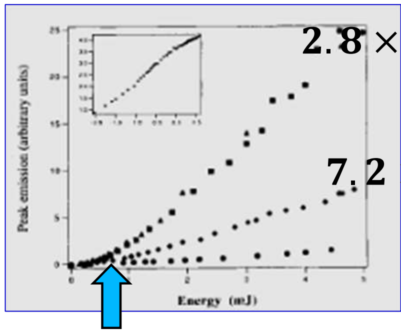
Lawandy, Balachandran, Gomes, Sauvain
Laser action in strong scattering media
Nature 368 (1994) 436

Intensity
÷ 100



Rh: 2 x 10^{-3} M
10^{11} particles / cm^3
Mean free path:
120 μm @ 532 nm
140 μm @ 650 nm

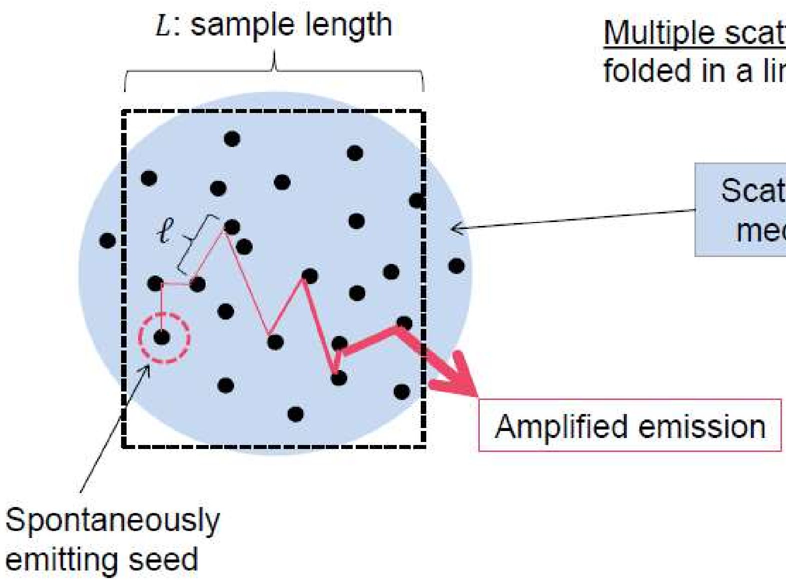
Photons follow random paths due to reflections by TiO_2 NPs



$2.8 \times 10^{10} cm^{-3}$

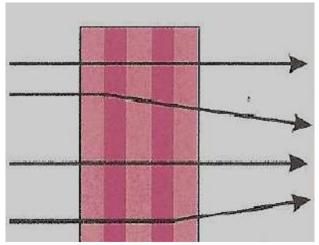
$7.2 \times 10^{9} cm^{-3}$

multiple light scattering is essential



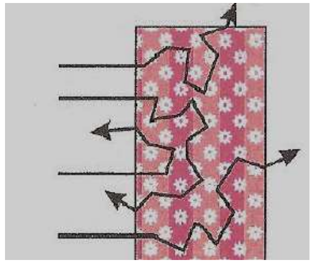
ℓ is the mean free path

Multiple scattering: light paths are folded in a limited pumped volume



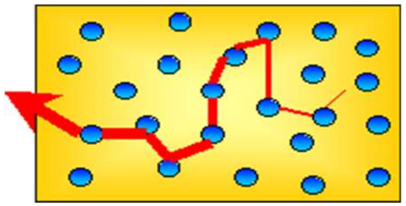
$l \gg L$

- $\ell \gg L$ → linear propagation
- $\ell \ll L$ → diffusion
- $\ell \to 0$ → Strong scattering: **Anderson localization** of light

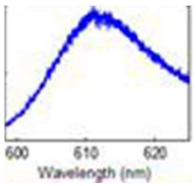


$l \ll L$

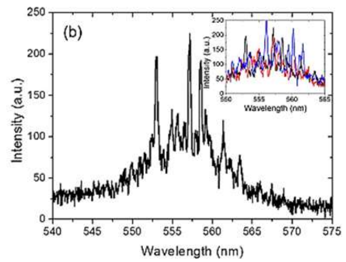
"Incoherent" feedback



Amplified spontaneous emission



"Coherent" feedback

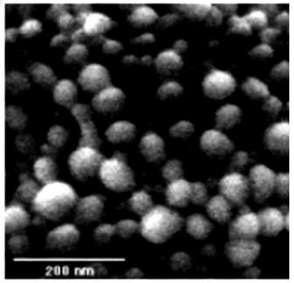


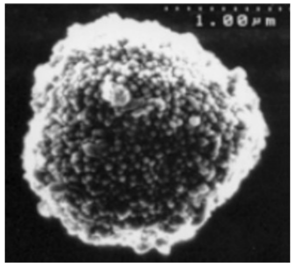
spikes

"Optical cavities" $n\frac{\lambda}{2} = d$

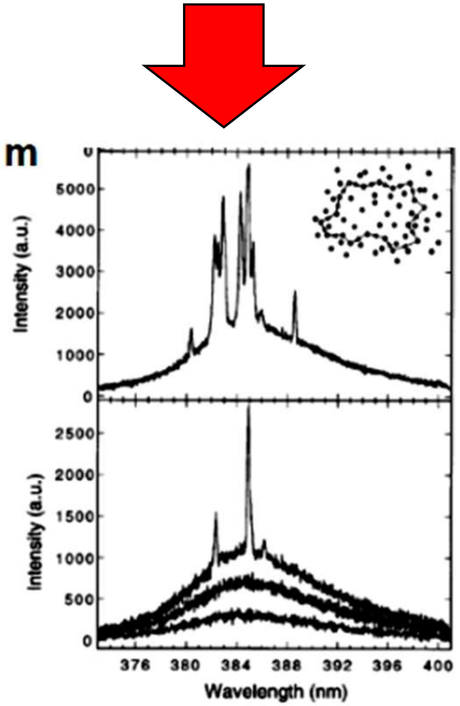
ZnO crystalline powders

Average diameter of particles: ≈100 nm





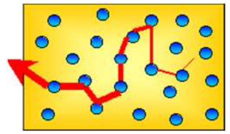
Hui Cao et al.
APL 73 (1998) 3656
PRL 82 (1999) 2278



<u>Feedback</u>

spikes ↔ coherent

ASE ⟷ incoherent



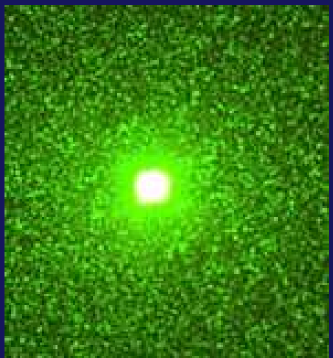
photon-statistics measurements

Poisson distribution well-above threshold

Excitation: 80 ps @ 532 nm
Emission at 380 nm

Conventional laser

- Narrow linewidth
- Long coherence time
- Large spatial coherence
- Directionality
- Modes determined by the cavity



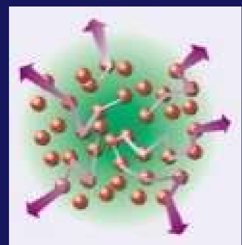
speckle

Beam profile

Random laser

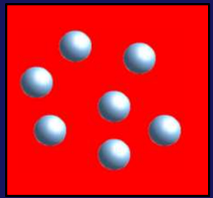
- Large linewidth
- Short coherence time
- Small spatial coherence
- No directionality
- Modes determined by multiple scattering

controlled speckle



"photon bomb"

Random Lasers

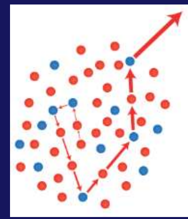


Scatteres inside the gain medium

Rhodamine with TiO_2 NPs

Scatteres form gain medium

Semiconductor quantum-dots



Scatteres+Gain particles

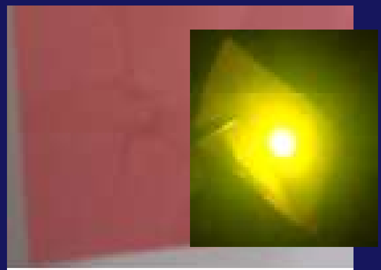
Nanocrystals with RE ions +Ag NPs

Our experiments at Recife

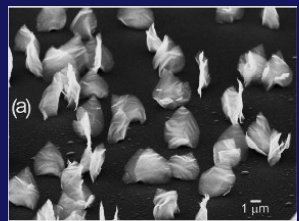
Colloids

Powders

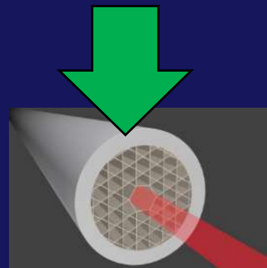
Membranes



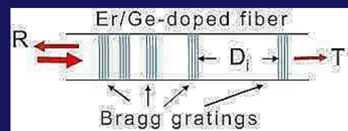
"Chips"



Optical fibers

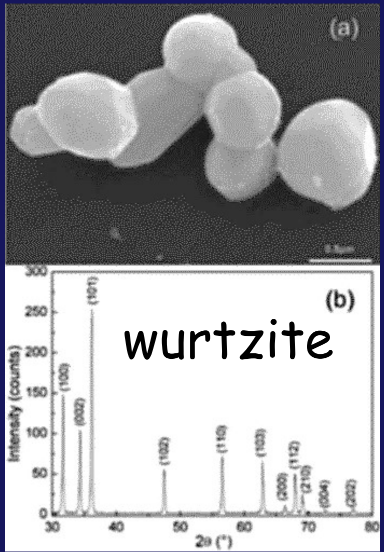


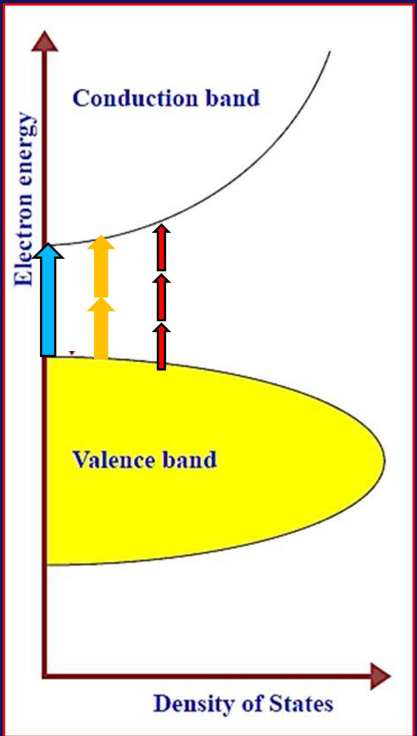
Random Bragg grating



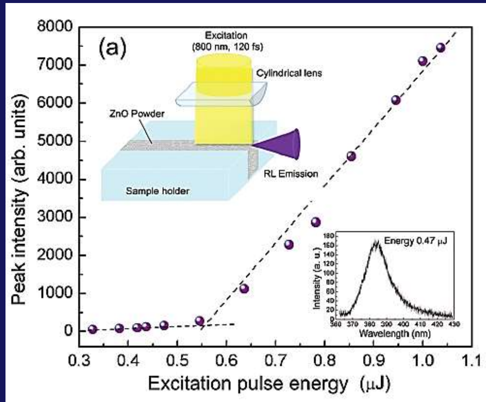
Dominguez, Gomes, Macedo, de Araújo, Gomes,
Multiphoton excited coherent random laser emission in ZnO powders Nanoscale 7 (2015) 317

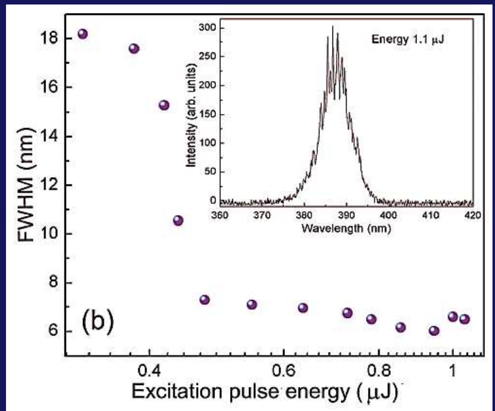
RL @388 nm





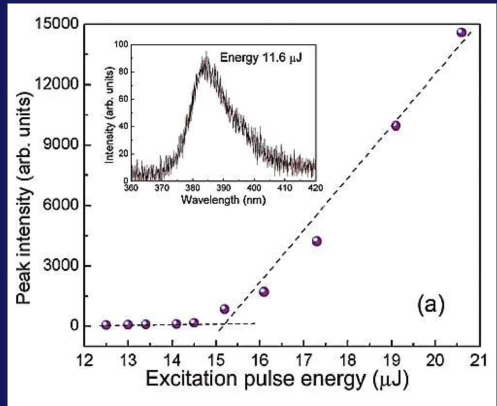
Pump: 354 nm

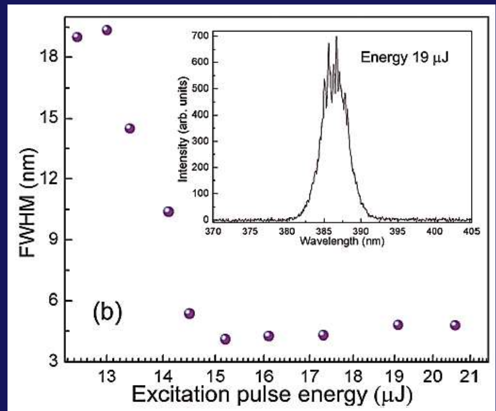




1-PE

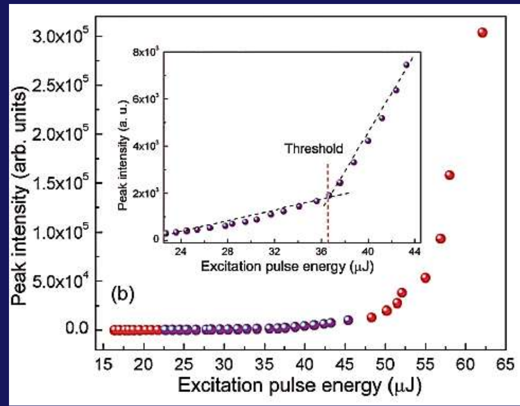
Pump: 710 nm

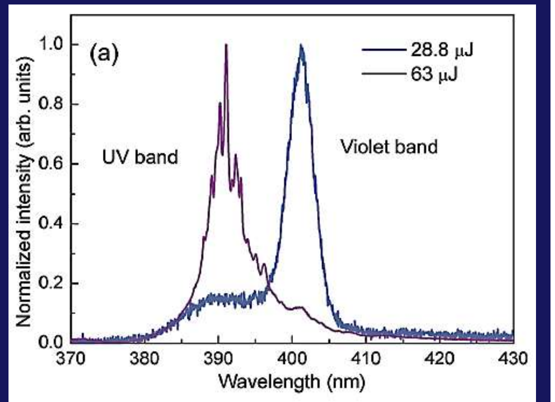




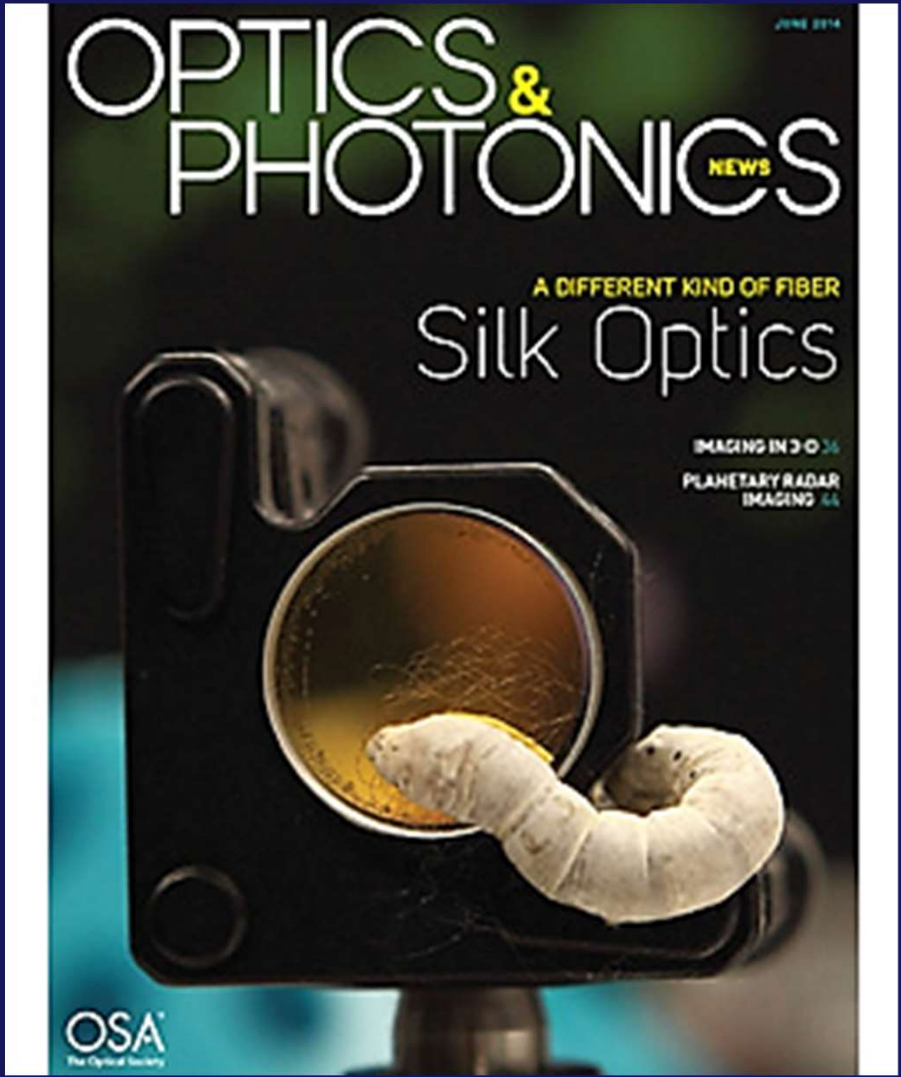
2-PE

Pump: 802 nm





3-PE

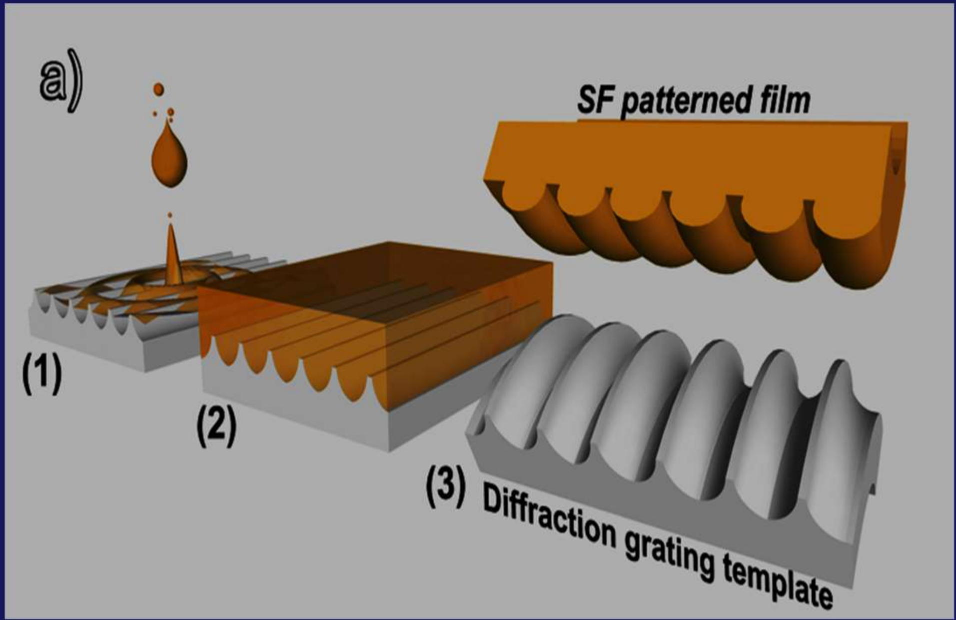


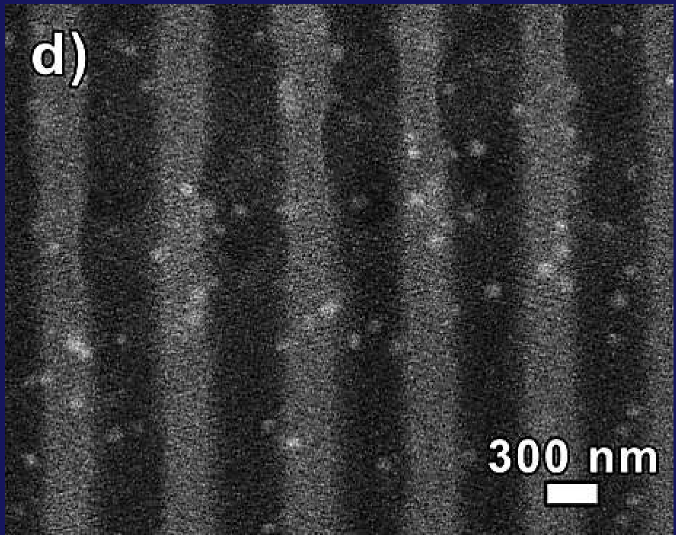
Fibroin is a silk protein found in natural spider cobweb silk fibers and silkworm cocoons filaments that represent the strongest and toughest natural fibers known

A different kind of Fiber Optics

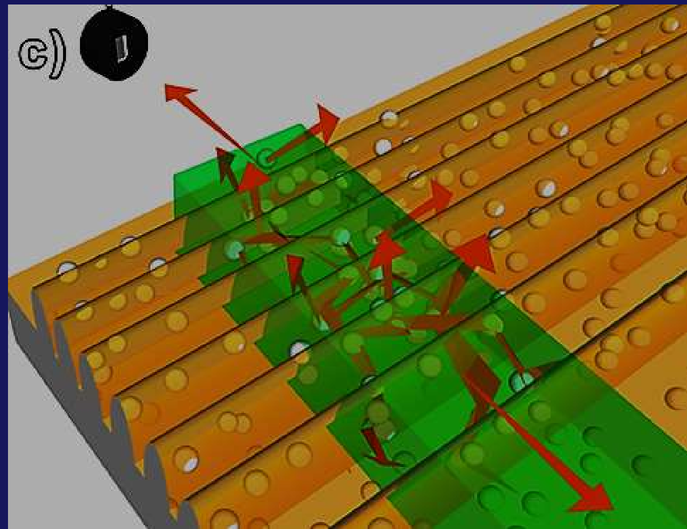
Silk-based devices are optically versatile and friendly to biological systems

Silk fibroin
DFB - Random laser





Silica NPs
average diameter ≈123 nm
or
Ag NPs
average diameter ≈10 nm



Rh 6G: 4×10^{-4} mol/L

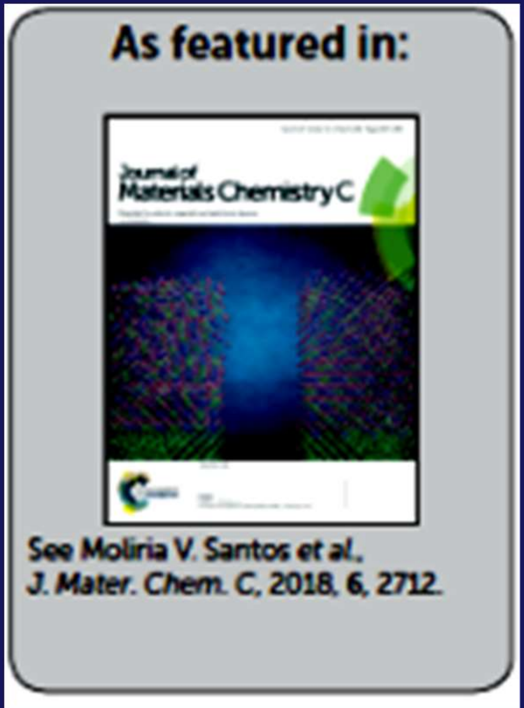
films: 0.112 ± 0.01 mm thick

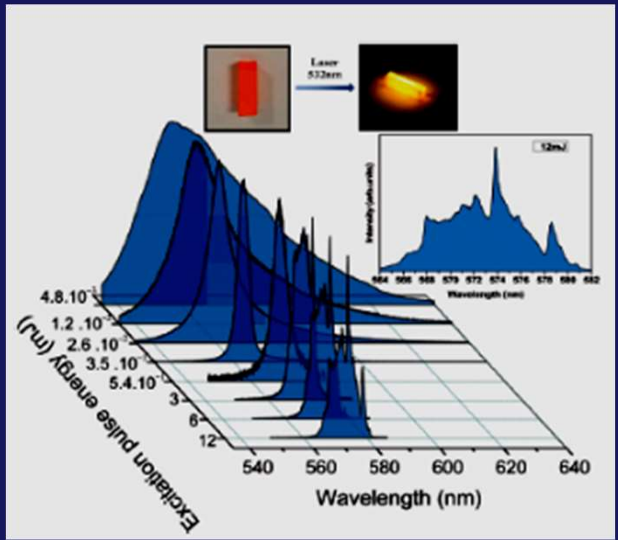
da Silva et al., J. Mater. Chem. C 1 (2013) 7181

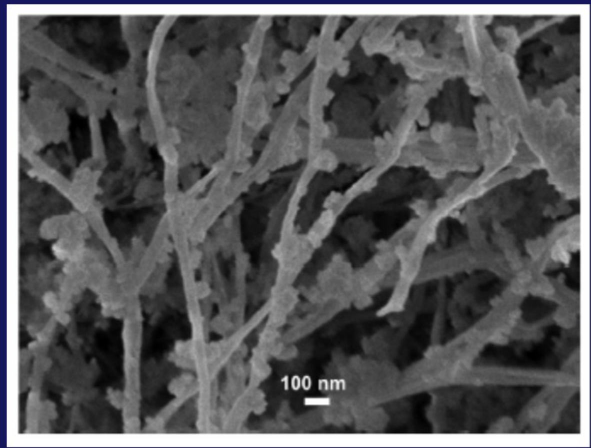
Silk fibroin as a biotemplate for hierarchical porous sílica monoliths for Random Lasers applications

Santos et al. J. Mater. Chem. C 6 (2018) 2712

de Araújo et al.
Photoluminescence and nonlinear optical phenomena in plasmonic random media- a review of recent works
J. Lumin. 169 (2016) 492

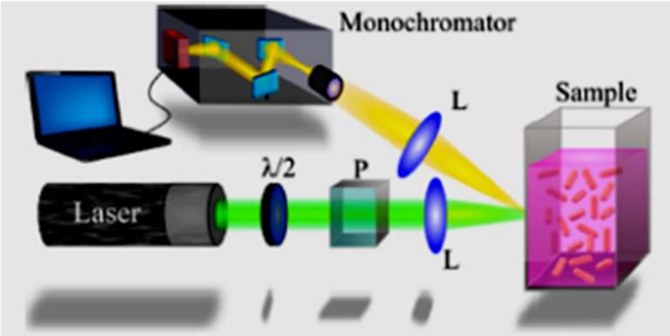




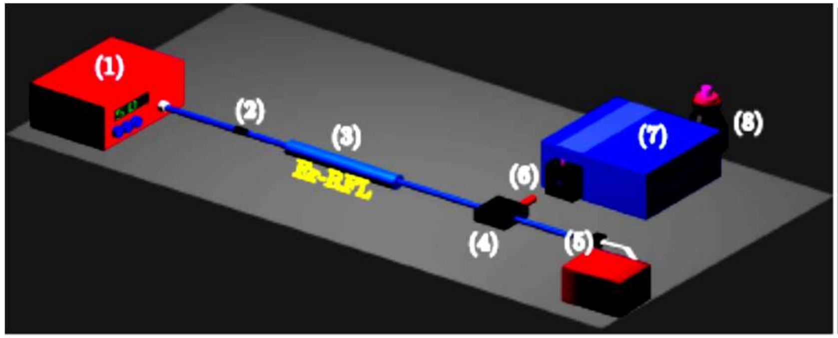


Various experimental schemes - Recife

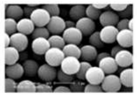
UFPE

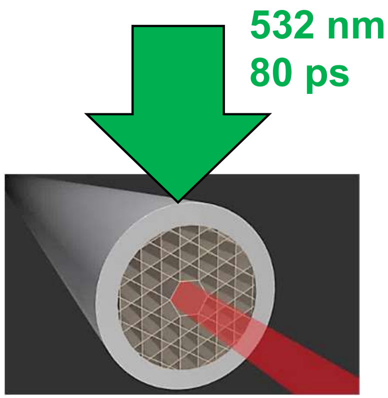


Oliveira et al.
J. Phys. Chem. C 124 (2020) 10705



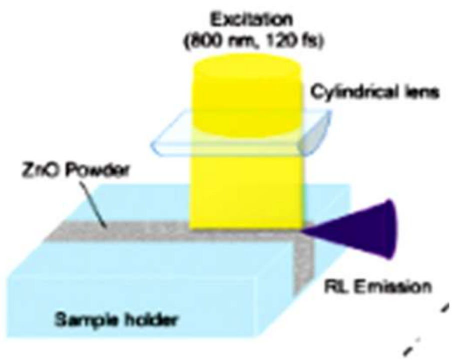
Lima et al. JOSA B 34 (2017) 293



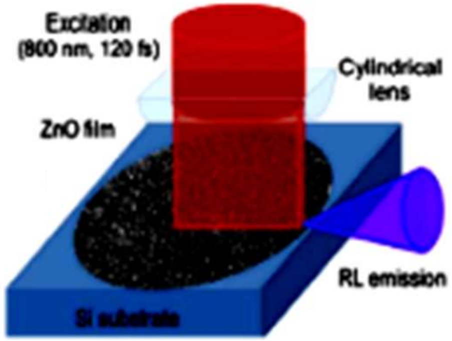


Rh 6G +TiO_2

de Matos et al.
Phys. Rev. Lett. 99 (2007) 153903

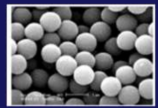


Dominguez et al.
Nanoscale 7 (2015) 317

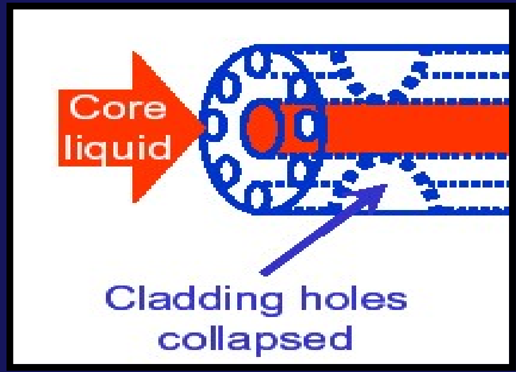


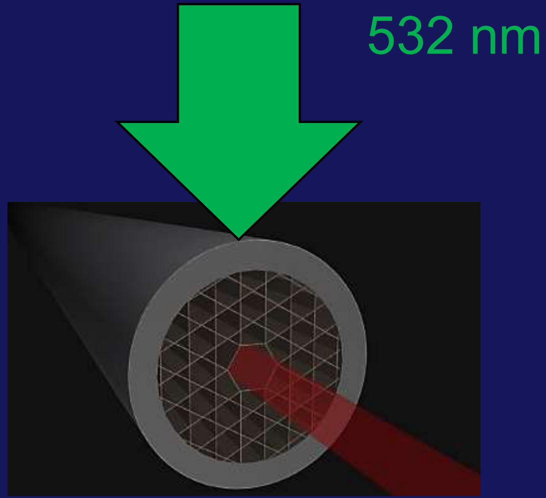
Dominguez et al.
JOSA B 31 (2014) 1975

First Random Fiber Laser



Rh 6G + TiO_2





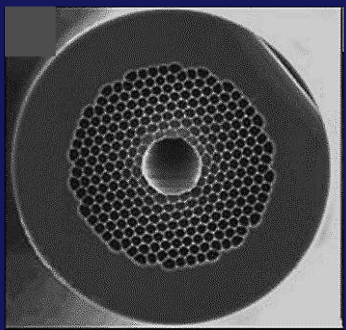
<u>Feedback</u>

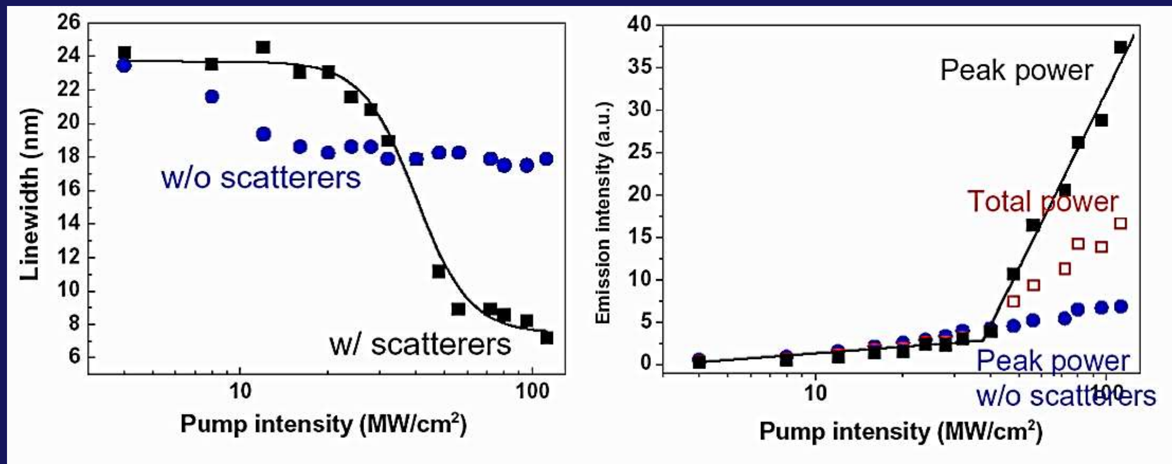
Transverse: total internal reflection

Axial : multiple scattering

Hollow fiber

10 μm – 3 μm



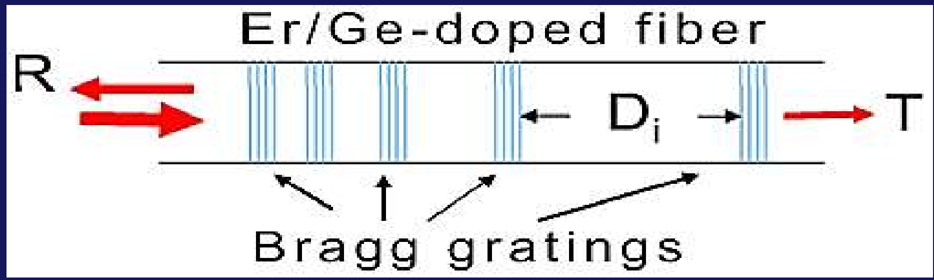


de Matos, Menezes, Silva, Gámez, Gomes, de Araújo

Phys. Rev. Lett. 99 (2007) 153903

Lizarraga et al. Opt. Express 17 (2009) 395

Gagné and Kashyap, Opt. Express 17 (2009) 19067



10-30 cm long fiber

Turitsyn et al. Nature Photon. 4 (2010) 231

Elastic scattering due to inhomogenities of the refractive index of the optical fibers 70 km long fiber

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Review papers on Random Fiber Lasers

Turitsyn et al., Phys. Reports 542 (2014) 133

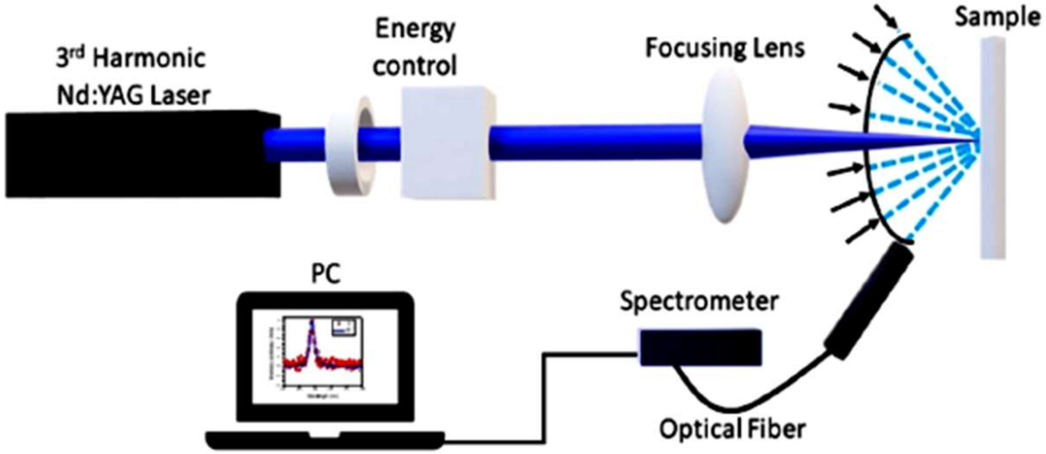
Churkin et al, Adv. Opt. Photon. 7 (2015) 516

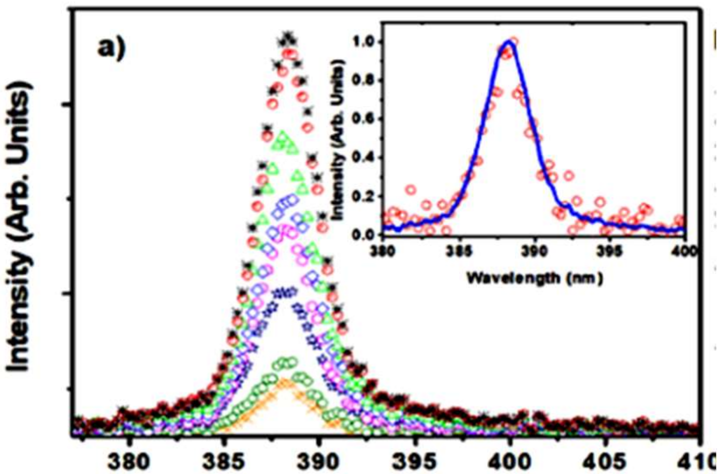
Xu et al., Sci. Reports 6 (2016) 35213

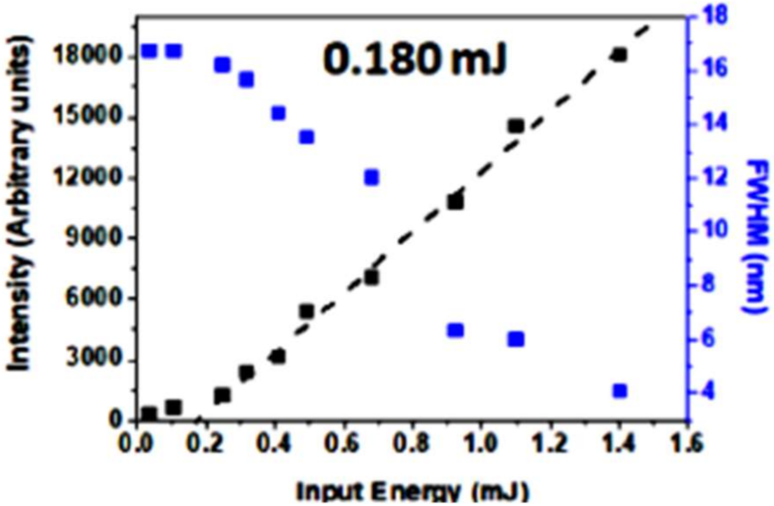
Xu et al., Opt. Express 25 (2017) 5609

UV random laser emission from flexible ZnO-Ag-enriched electrospun cellulose acetate fiber matrix

Silva-Neto et al. Sci. Reports 9 (2019)11765







Nonlinear Optics

Nicolaas Bloembergen
(1920-2017)

1981 Physics Nobel Prize

Optical field
↓
Polarization
↓
NL susceptibilities

...

Review Vol. 59, No. 13 / 1 May 2020 / *Applied Optics* D155

applied optics

Nonlinear effects and photonic phase transitions in Nd^{3+}-doped nanocrystal-based random lasers

André L. Moura,[1,*] Sandra J. Carreño,[2] Pablo I. R. Pincheira,[3] Lauro J. Q. Maia,[4] Vladimir Jerez,[5] Ernesto P. Raposo,[6] Anderson S. L. Gomes,[7] and Cid B. de Araújo[7]

$\chi^{(2)}$ 2nd. order nonlinearity

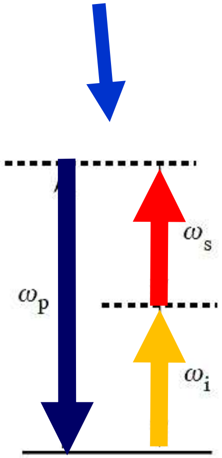
Three Wave- Mixing

$$P^{(2)} = \varepsilon_0 \chi^{(2)} (E_1 \cos \omega_1 t + E_2 \cos \omega_2 t)^2 =$$

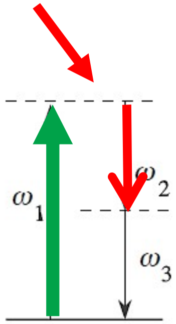
$$\underbrace{P_0^{(2)}}_{\text{Optical retification}} + \underbrace{P_{2\omega_1}^{(2)} + P_{2\omega_2}^{(2)}}_{\text{SHG}} + \underbrace{P_{\omega_1+\omega_2}^{(2)}}_{\text{SFG}} + \underbrace{P_{\omega_1-\omega_2}^{(2)}}_{\text{DFG}}$$

SHG

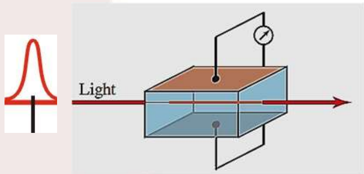
SFG



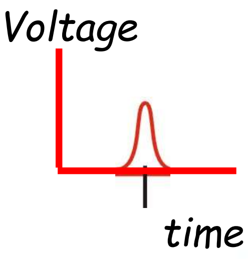
DFG



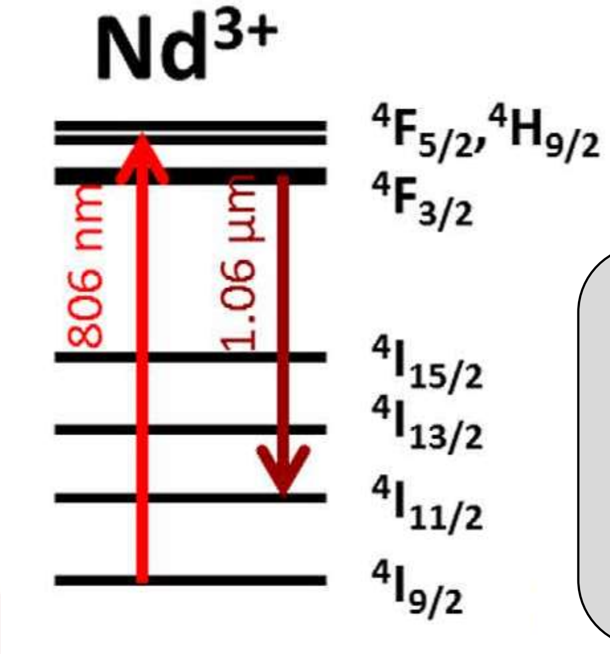
Optical
retification

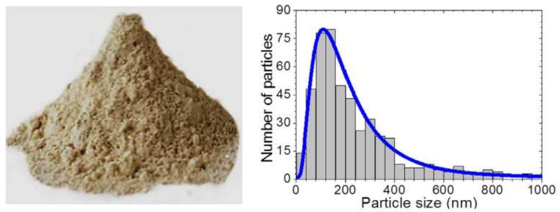


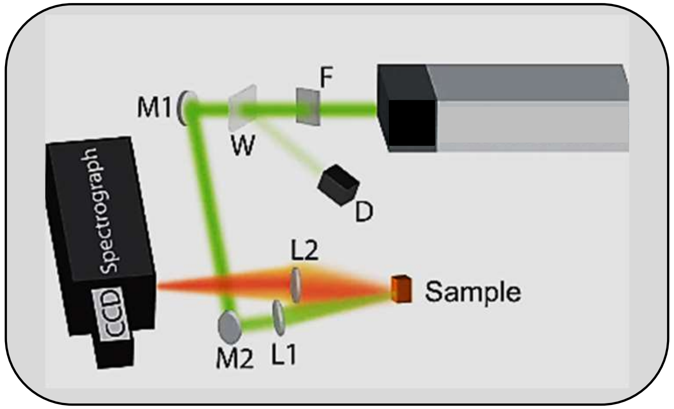
Light pulse

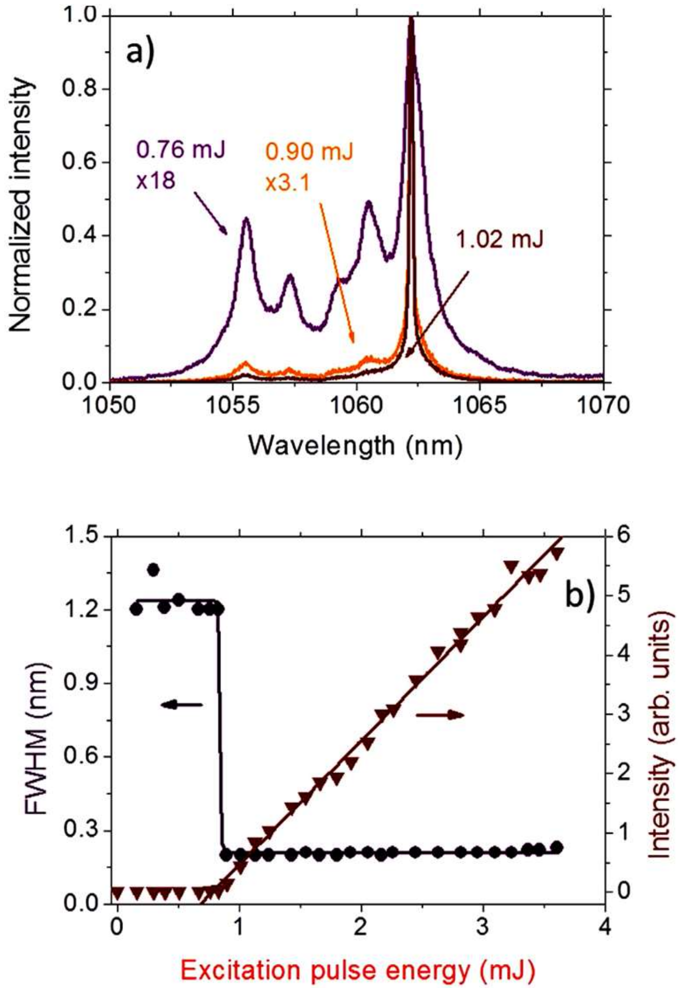


Experiments with Nd^{3+}: $YAl_3(BO_3)_4$ nanocrystals





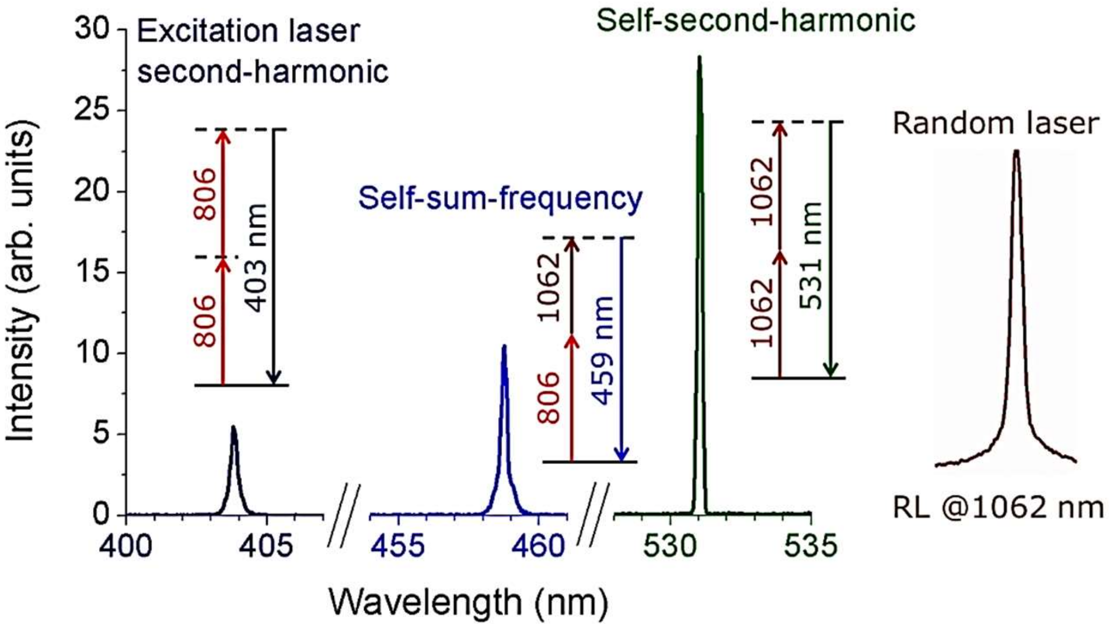




- Stimulated emission
- Multiple scattering
- Second harmonic generation
- Sum of frequencies

$Nd_{0.04}Y_{0.96}Al_3(BO_3)_4$ nanocrystals

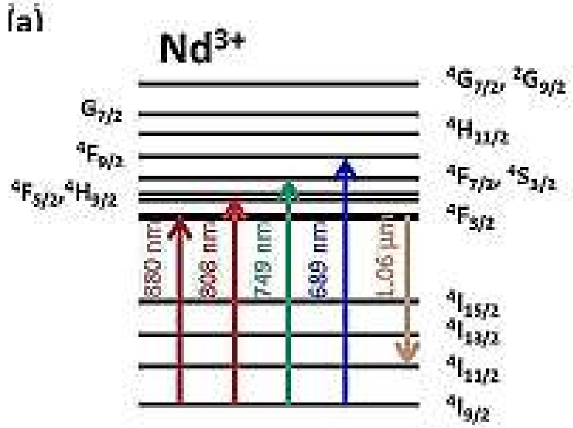
Large $\chi^{(2)}$ ➡ Self frequency conversion

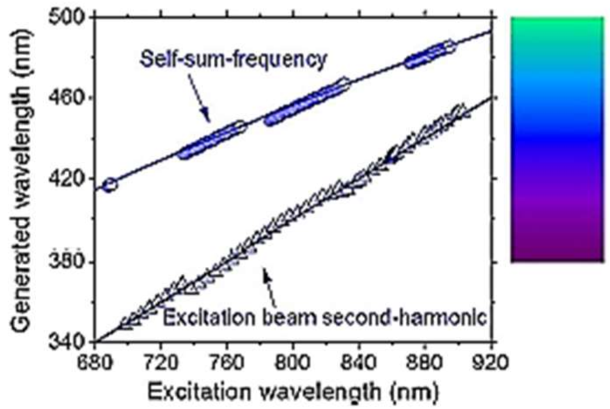


Moura et al.
Sci. Reports 5 (2015) 13816;
Carreño et al.
Opt. Mater. 59 (2016) 262

Tunable emission in the blue and UV

$Nd_{0.10}Y_{0.90}Al_3(BO_3)_4$

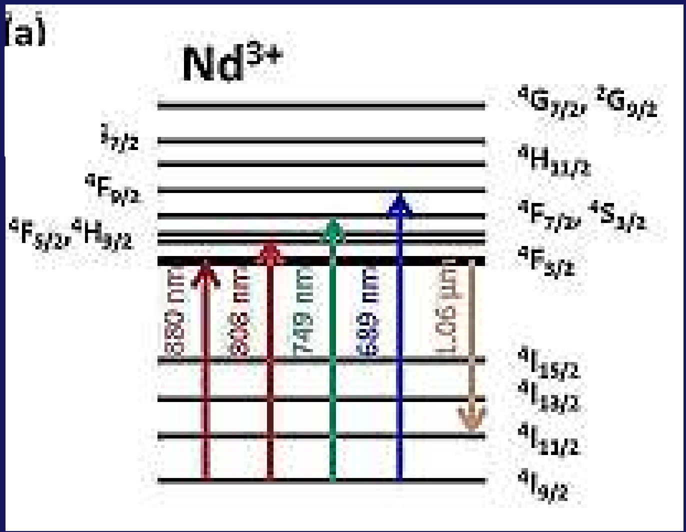


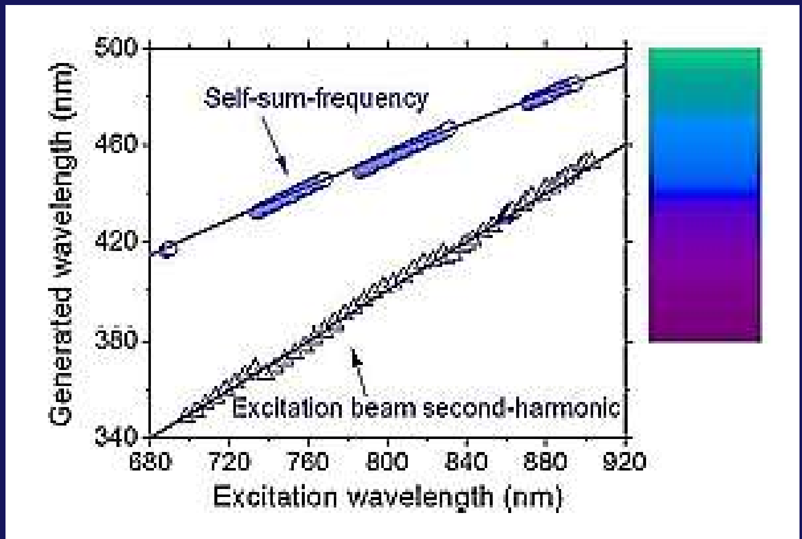


Moura et al.
Sci. Reports 6 (2016) 27107
Moura et al.
Appl. Opt. 59 (2020) D155

Tunable emission in the blue and UV

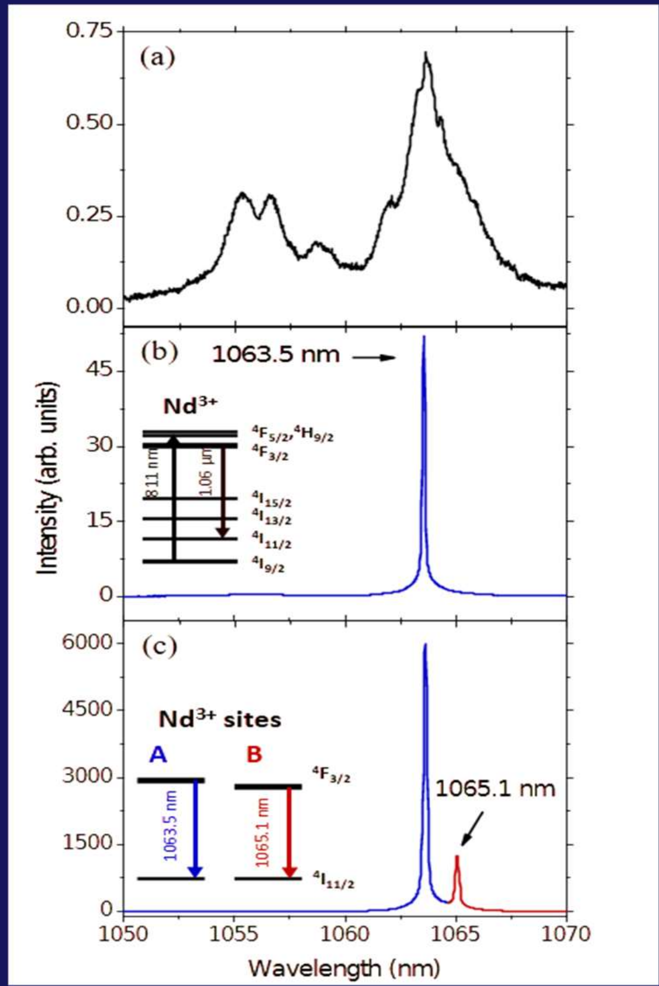
$Nd_{0.10}Y_{0.90}Al_3(BO_3)_4$ nanocrystals

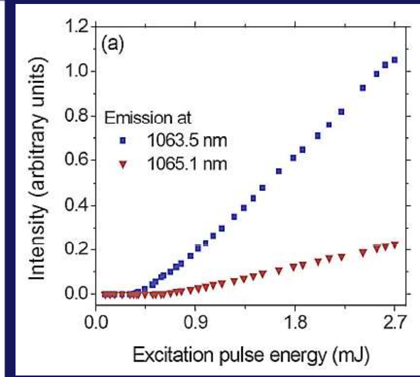


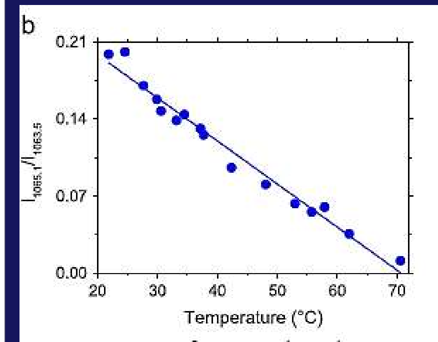


Moura et al. Sci. Reports 6 (2016) 27107

Two-color $NdAl_3(BO_3)_4$ RL application as optical thermometer







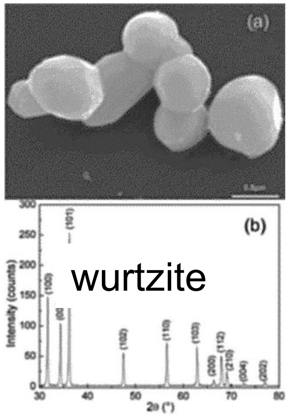
$$R = \frac{I_{1065.1}}{I_{1063.5}}$$

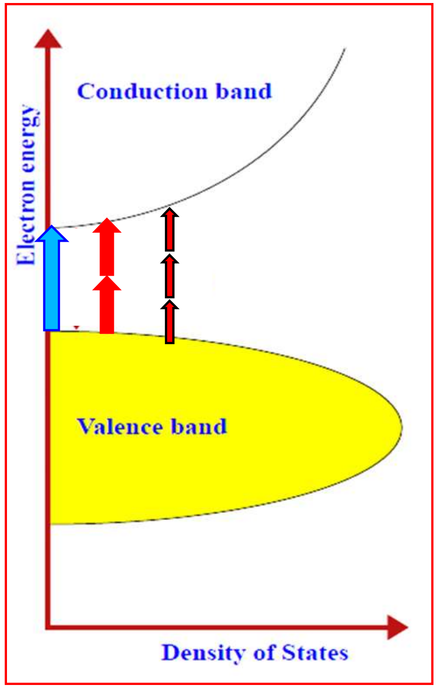
$$S = \frac{1}{R_0}\frac{dR}{dT} = 0.020°C^{-1}$$

Moura et al. J. Lumin. 181 (2017) 44

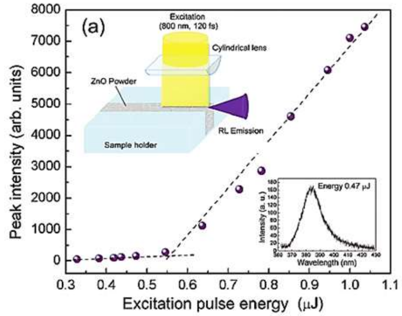
Dominguez, Gomes, Macedo, de Araújo, Gomes,
Multiphoton excited coherent random laser emission in ZnO powders. Nanoscale 7 (2015) 317

RL @388 nm

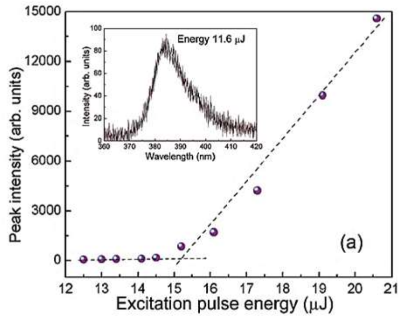




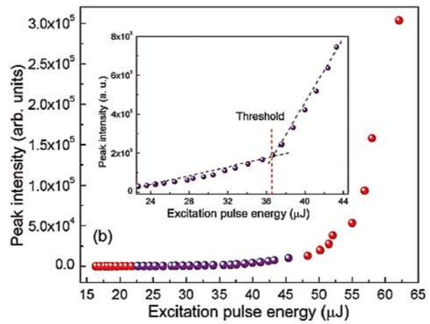
Excitação: 354 nm

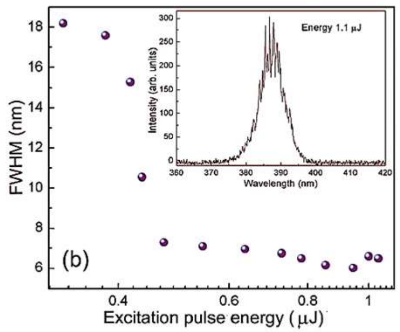


710 nm

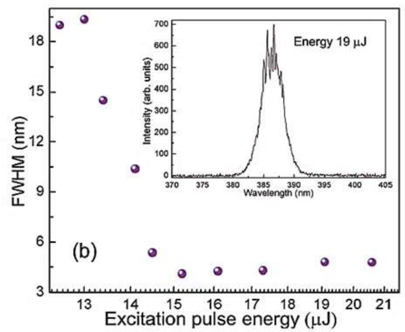


802 nm

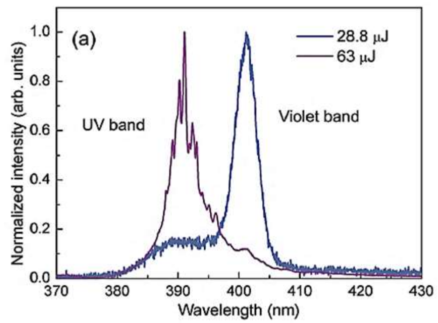




1-PE



2-PE



3-PE

Excitação: 100 fs (laser + OPA)

High-order nonlinearities

THE JOURNAL OF PHYSICAL CHEMISTRY C

pubs.acs.org/JPCC Article

Influence of the Fifth-Order Nonlinearity of Gold Nanorods on the Performance of Random Lasers

Nathália Talita C. Oliveira, Manoel L. Silva-Neto, Albert S. Reyna,* and Cid B. de Araújo

Cite This: J. Phys. Chem. C 2020, 124, 10705−10709 Read Online

PHYSICAL REVIEW A 102, 063515 (2020)

Influence of fifth-order nonlinearities on the statistical fluctuations in emission intensities in a photonic open-cavity complex system

Iván R. R. González[1], Sandra J. Carreño[2], Ernesto P. Raposo[1,3], Antônio M. S. Macêdo[1], Melissa Maldonado[4], Leonardo de S. Menezes[4], Anderson S. L. Gomes[4], and Cid B. de Araújo[4]

NL susceptibilities enable interactions among the optical modes

Glassy light and Replica Symmetry Breaking

VAngelani, Conti, Ruocco, Zamponi

Glass behavior of light

Phys. Rev. Lett. 96 (2006) 065702

Antenucci et al. General phase diagram of multimodal ordered and disordered lasers in closed and open cavities
Phys. Rev. Lett. 114 (2015) 043901

Analogy with magnetic systems
- Spin Glass -

Spin-glass theory is one of the leading paradigms of complex physics and describes condensed matter, neural networks and biological systems, ultracold atoms, random photonics and many other research fields.

According to this theory, identical systems under identical conditions may reach different states

This effect is known as
replica symmetry breaking

Why to look for such behavior in RLs?

Parisi theory was reported long ago and applied by many researchers

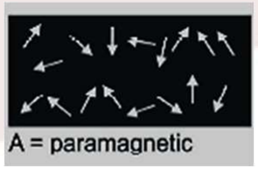
G. Parisi, PRL 43 (1979) 1754; PRL 50 (1983) 1946.
Mezard and Parisi J. Phys. I 1 (1991) 809
G. Parisi Google – 76.027 citations; h=114

BOOK: Spin glass theory and beyond: An introduction to the Replica Method and its Applications - World Sci. Publ. (Citations: 5170 citations)

It has been applied to explain the spin-glass behavior but no direct experimental proof was given for RSB validation in the past.

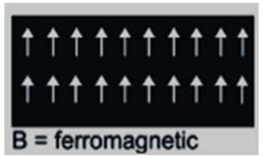
The experiments with RLs provided the first direct evidence supporting the RSB theory.

Spin Glass and Replica Symmetry Breaking



NO magnetization

$$\mathbf{H} = -\sum_{ij} J_{ij} S_i S_j$$



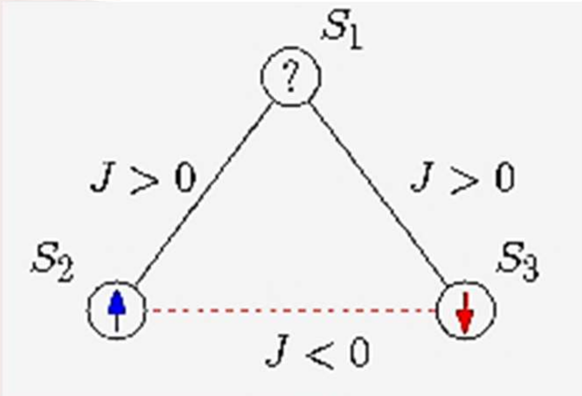
Below T_C spins are parallel

$J_{ij} > 0$

Below T_N spins are anti-parallel

$J_{ij} < 0$

depends on the overlap of wave functions



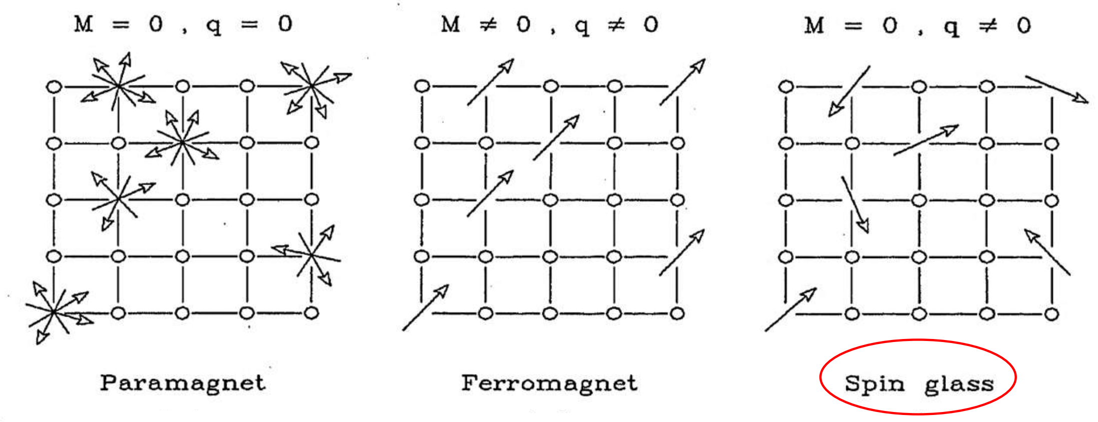
Frustration and disorder

$J_{ij} israndomlydistributed$

$$\mathbf{P}(J_{ij}) \propto \mathbf{exp}\left(-J_{ij}^2/2\,\sigma_s^2\right)$$

Frustration leads to a multiplicity of ground states of the spin system

Below a critical temperature: spins are "frozen"

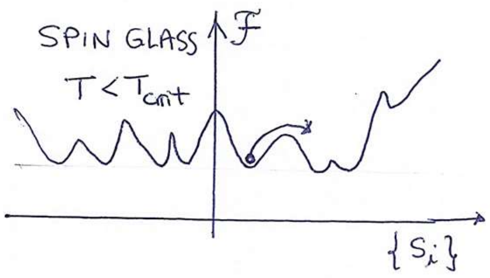


One possible ground state

Many other states are possible

Spin glass:
large number of configurations with minimum energy

Free energy



Replica symmetry breaking (RSB) is one fundamental concept of spin-glass theory: identical copies of the randomily interacting system that manifest completely different dynamics

Large number of locally stable equilibria

G. Parisi, 1979 - Replica Symmetry Breaking “theory”

Replica symmetry scheme

Clusters flip simultaneously to get from one ground state to another
"REPLICAS"

Order parameter

$$q_{\alpha\beta} = \frac{1}{N}\sum_{i}^{N}\left[\left\langle S_i^{\alpha} S_i^{\beta}\right\rangle\right]$$

Spins correlations in distinct replicas

Different values of $q_{\alpha\beta}$ ⇒ $P(q_{\alpha\beta})$

Distribution of replicas

Analogies

Spin glass		Random_Lasers
- spins	⟺	- Modes of the field
- temperature		- inverse of intensity

Each laser pulse creates a REPLICA

Mode coupling via NL susceptibility

Ghofranilha et al. Experimental evidence of replica symmetry breaking in random lasers.
Nature Commun. 6 (2015) 6058

Italian group

How to analise the intensity fluctuations?

$$\bar{I}(\omega) = \sum_{\gamma=1}^{N_S} I_\gamma$$

$\gamma = 1,2,\ldots,N_S$ replicas

$$\Delta_\gamma(\omega) = I_\gamma(\omega) - \bar{I}(\omega)$$

Order parameter

$$q_{\alpha\beta} = \frac{\sum_k \Delta_\alpha(k)\Delta_\beta(k)}{\sqrt{\Delta_\alpha^2(k)}\sqrt{\Delta_\beta^2(k)}}$$

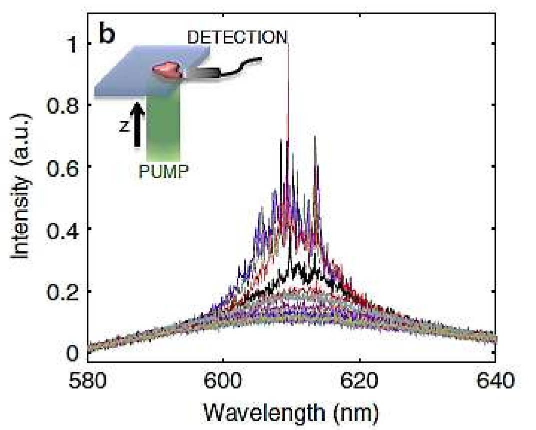
Mode coupling via the NL susceptibility

2D Random Laser

Italian group

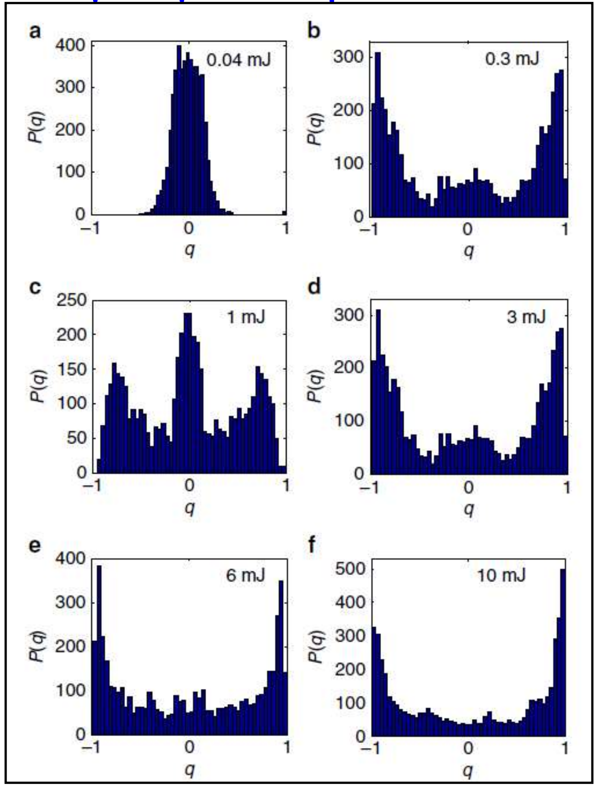
Procedure

Organic film



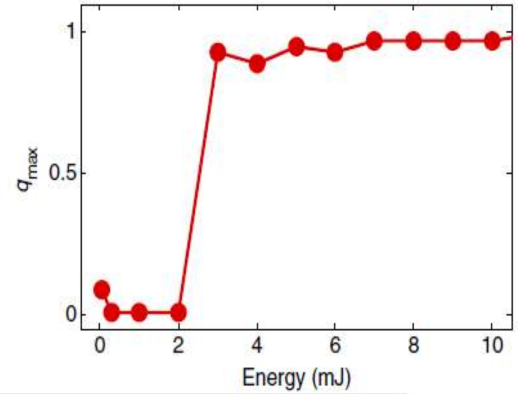
$$\bar{I}(\omega) = \sum_{\gamma=1}^{N_S} I_\gamma$$

Thienyl-S,S-dioxide quinquethiophene



$P(q_{\alpha\beta})$

$$\Delta_\gamma(\omega) = I_\gamma(\omega) - \bar{I}(\omega)$$



$$q_{\alpha\beta} = \frac{\sum_k \Delta_\alpha(k)\Delta_\beta(k)}{\sqrt{\Delta_\alpha^2(k)}\sqrt{\Delta_\beta^2(k)}}$$

order parameter

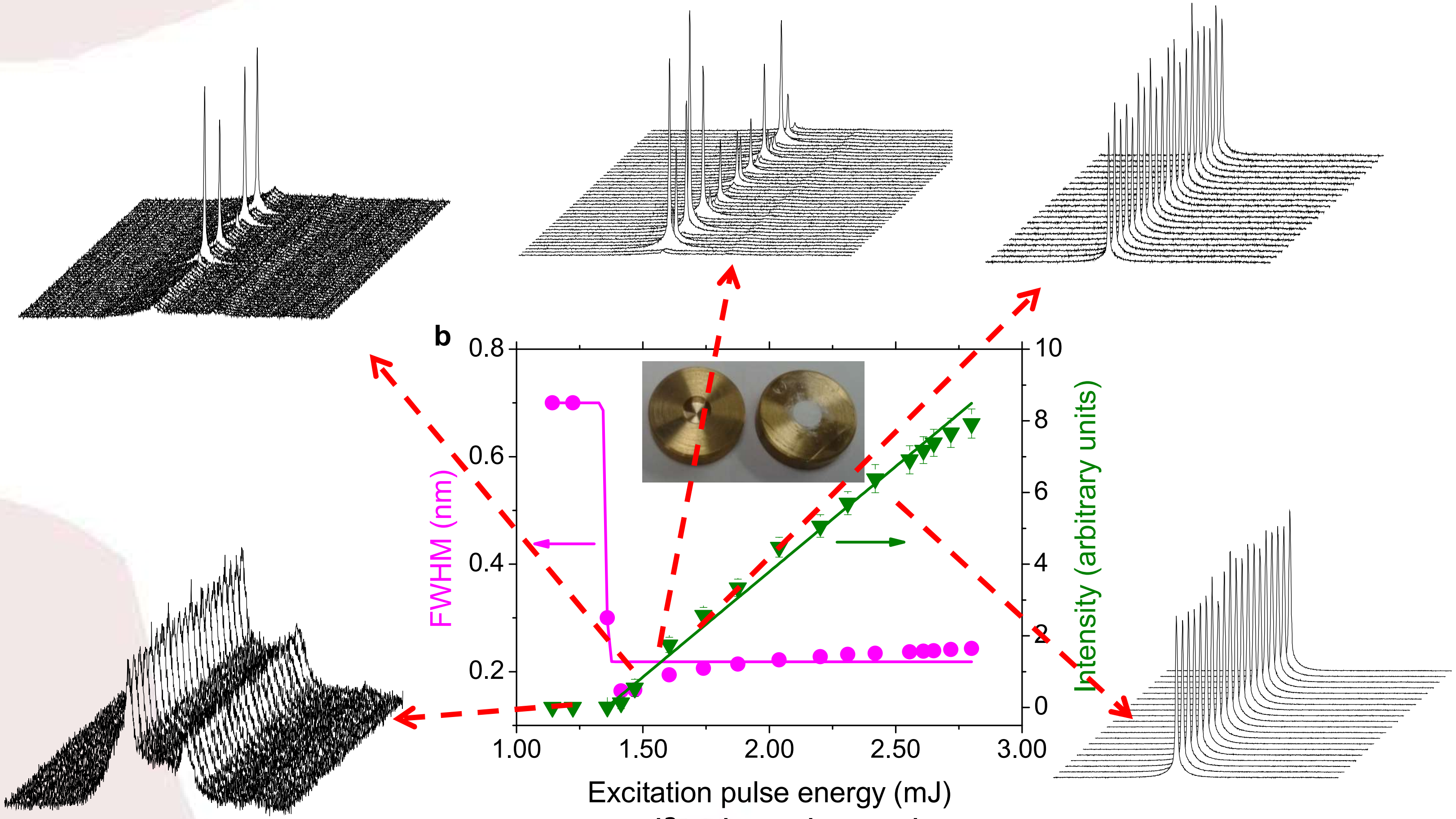
$q_{\gamma\beta}$

3D Nd^{3+} Random Laser

Recife group

Nanocrystals: Nd: YBO_3 4 mol %

Excitation: 800 nm, 5 ns



Nd^{3+} doped powder

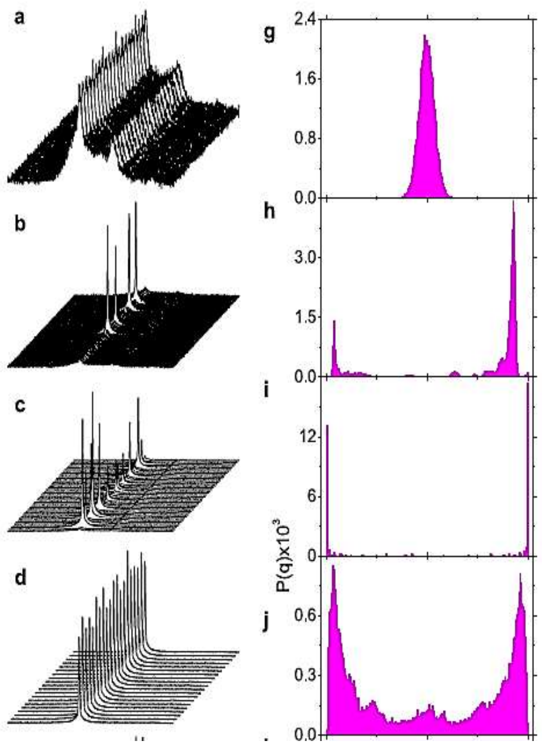
3D Nd^{3+} Random laser – Recife group

Nanocrystals: Nd^{3+} doped YBO_3

Replicas probabilities

$$P(q_{\alpha\beta})$$

Gomes, Raposo, Moura, Fewo, Pincheira, Jerez, Maia, de Araújo
Sci. Reports 6 (2016) 27987



P/P_{th}

0.88

1.00

1.03

1.18

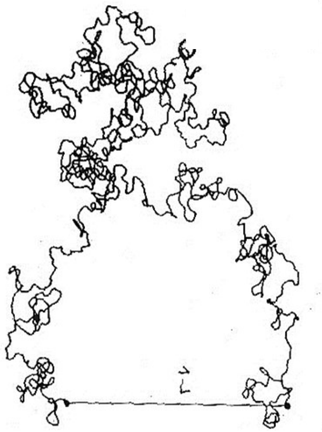
Pincheira et al.
3D coloidal Rh+TiO_2 RL
Opt. Lett. 41 (2016) 3459

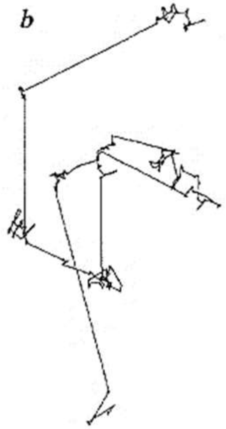
Emission @1.06

Statistics of intensity fluctuations

UFPE

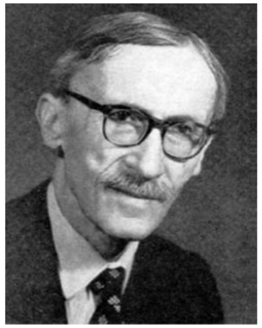
Gaussian random walk





Lévy random walk

Lévy flights



Paul P. Lévy

(1886-1971)

Lévy distribution: continuum probability distribution for one random continuum variable

NATURE · VOL 381 · 30 MAY 1996

Lévy flight search patterns of wandering albatrosses

G. M. Viswanathan*, V. Afanasyev†, S. V. Buldyrev*, E. J. Murphy†, P. A. Prince† & H. E. Stanley*

nature Vol 449|25 October 2007|doi:10.1038/nature06199

LETTERS 2007

Revisiting Lévy flight search patterns of wandering albatrosses, bumblebees and deer

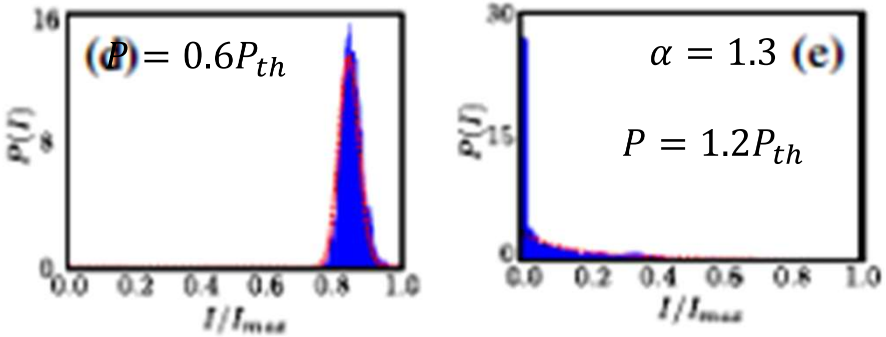
Andrew M. Edwards[1]†, Richard A. Phillips[1], Nicholas W. Watkins[1], Mervyn P. Freeman[1], Eugene J. Murphy[1], Vsevolod Afanasyev[1], Sergey V. Buldyrev[2,3], M. G. E. da Luz[4], E. P. Raposo[5], H. Eugene Stanley[2] & Gandhimohan M. Viswanathan[6]

In random lasers: statistics of the measured values of intensity for each frequency of the RL spectrum

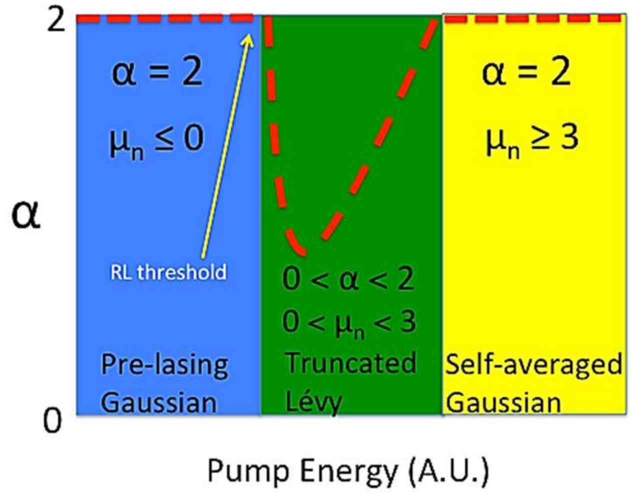
Uppu et al. Phys. Rev. A 90 (2014) 025801

Recife group

Analytical solution:Raposo+Gomes, Phys. Rev. A 91 (2015) 043827



Lima et al. JOSA B 34 (2017) 293



$$P(I_i) = \frac{A}{I_i^{1+\alpha}}$$

$$\alpha = \mu - 1$$

Lévy exponent alpha act as a universal identifier of the laser threshold.

for each excitation power

Well-above threshold ➡ $\acute{\chi}^{(5)}$ Izrailev distribution

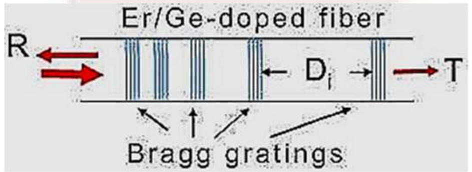
González et al. Phys. Rev. A 102 (2020) 063515

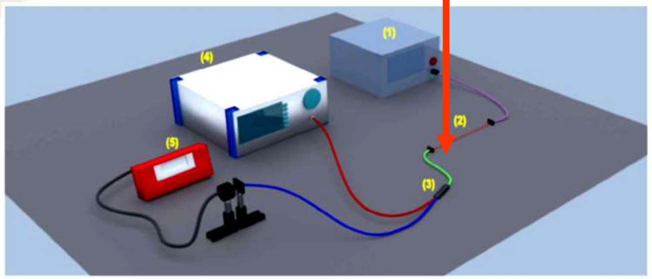
CW 1D Er^{3+} RFL

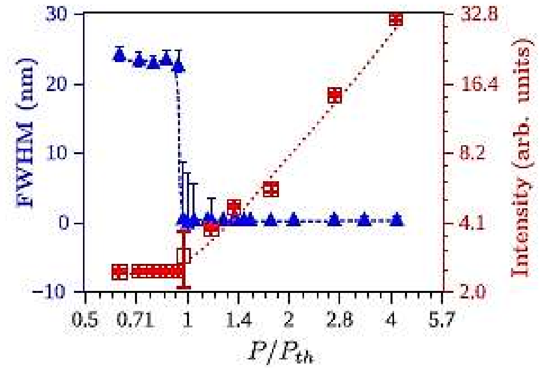
Recife group

UFPE

30 cm long

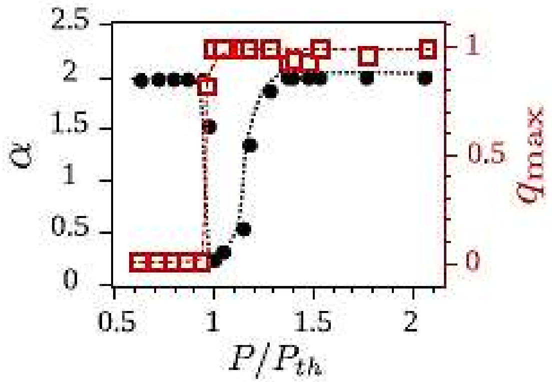






$P_{th} = 16.30 \pm 0.05mW$

Lévy's exponent



Parisi's parameter

Gomes et al. Sci. Reports 6 (2016) 27987
de Araújo et al. Appl. Sci. 7 (2017) 644
Lima et al. JOSA B 34 (2017) 293

RSB
Photonic spin-glass

PRL 114, 043901 (2015) PHYSICAL REVIEW LETTERS week ending 30 JANUARY 2015

Photonic phase-transition with RSB

General Phase Diagram of Multimodal Ordered and Disordered Lasers in Closed and Open Cavities

F. Antenucci,[1,2] C. Conti,[1,3] A. Crisanti,[1,3] and L. Leuzzi[2,1,*]
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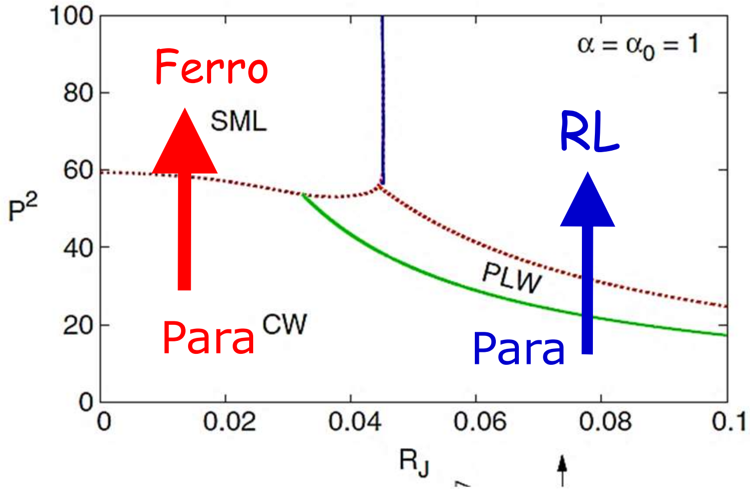
$R_J: disorder degree$

$\alpha_0: nonlinearity degree$

Recife group



Paramagnetic to spin glass transition

SML: spontaneous mode-locking (without saturable absorber inside the cavity)

PRL 119, 163902 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

Replica Symmetry Breaking in the Photonic Ferromagneticlike Spontaneous Mode-Locking Phase of a Multimode Nd:YAG Laser

André L. Moura,[1,2] Pablo I. R. Pincheira,[1] Albert S. Reyna,[1] Ernesto P. Raposo,[3,*] Anderson S. L. Gomes,[1] and Cid B. de Araújo[1]

Report of the Nobel Committee 2021

The Nobel Prize in Physics 2021

"For groundbreaking contributions
to our understanding of complex physical systems"

Klaus Hasselmann 1/4

Syukuro Manabe 1/4

Giorgio Parisi 1/2

Citation for Giorgio Parisi by the Nobel Committee:

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

Replica Symmetry Breaking Theory

RLs experiments

first direct evidence favorable to the RSB theory

KUNGL. VETENSKAPS-AKADEMIEN

THE ROYAL SWEDISH ACADEMY OF SCIENCES

05/10/2021

5 OCTOBER 2021

Scientific Background on the Nobel Prize in Physics 2021

"FOR GROUNDBREAKING CONTRIBUTIONS TO OUR UNDERSTANDING OF COMPLEX PHYSICAL SYSTEMS"

The Nobel Committee for Physics

V. THE VASTNESS OF THE LANDSCAPE OF DISORDER

A. Replicas, Spin Glasses and Frustration.

The term "spin glass" was coined in the early 1970's to describe disordered magnetic systems that appeared to have a phase transition to a state in which each magnetic atom was stably aligned, but with the essential proviso that the alignment direction varies randomly between atoms. Imagine a triangle with magnets placed

densifying colloidal glass [37]. Importantly, experimental evidence of replica symmetry breaking has been provided in systems using random lasers [30, 33, 99, 108], in plane cavity lasers without disorder but with frustration between interacting lasing modes without added disorder [7, 74] and in nonlinear optical propagation through photorefractive disordered waveguides [90]. Finally, the

connection between spin-glasses and turbulence [34], particularly nonlinear wave interactions, which link the early work of Hasselmann [40, 41] to that of Parisi and to the role of disorder and fluctuations in complex systems in general.

Report of the Nobel Prize Committee 2021

https://www.nobelprize.org/prizes/physics/2021/press-release/

50 anos

www.nature.com/scientificreports

SCIENTIFIC REPORTS

OPEN

Observation of Lévy distribution and replica symmetry breaking in random lasers from a single set of measurements

Received: 02 March 2016
Accepted: 26 May 2016
Published: 13 June 2016

Anderson S. L. Gomes[1], Ernesto P. Raposo[2], André L. Moura[1,3], Serge I. Fewo[4], Pablo I. R. Pincheira[1], Vladimir Jerez[5], Lauro J. Q. Maia[6] & Cid B. de Araújo[1]

Random lasers have been recently exploited as a photonic platform for studies of complex systems. This cross-disciplinary approach opened up new important avenues for the understanding of random-laser behavior, including Lévy-type distributions of strong intensity fluctuations and phase transitions to a photonic spin-glass phase. In this work, we employ the Nd:YBO random
from a single set of measurements, the physical origin of the complex corres
Lévy fluctuation regime and the replica-symmetry-breaking transition to the
unexpected finding is also reported: the trend to suppress the spin-glass beh
pulse energies. The present description from first principles of this correspon
possibilities to characterize other random lasers, such as random fiber lasers,
lasers, which include plasmonic-based, photonic-crystal and bio-derived nan
nature of the emission provided by random lasers can also impact on their pr
for speckle-free laser imaging, which nowadays represents one of the most p
random lasers, with expected progress even in cancer research.

www.nature.com/sci

SCIENTIFIC REP

OPEN

Coexistence of turbulence-like glassy behaviours in a photoni system

d: 26 July 2018

Iván R. R. González[1], Ernesto P. Raposo[1], Antônio M. S. Macêdo[1], Leonardo de

PRL 119, 163902 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

Replica Symmetry Breaking in the Photonic Ferromagneticlike Spontaneous Mode-Locking Phase of a Multimode Nd:YAG Laser

André L. Moura,[1,2] Pablo I. R. Pincheira,[1] Albert S. Reyna,[1] Ernesto P. Raposo,[3,*] Anderson S. L. Gomes,[1] and Cid B. de Araújo[1]

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(Received 20 November 2016; revised manuscript received 12 July 2017; published 20 October 2017)

We demonstrate the replica symmetry breaking (RSB) phenomenon in the spontaneous mode-locking regime of a multimode Q-switched Nd:YAG laser. The underlying mechanism is quite distinct from that of the RSB recently observed in random lasers. Here, there is no random medium and the phase is not glassy with incoherently oscillating modes as in random lasers. Instead, in each pulse a specific subset of longitudinal modes are activated in a nondeterministic way, whose coherent oscillation dominates and

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Characterization of RLs:

- bandwidth narrowing,
- increasing in the slope efficiency (output versus input),
- time shortening of the upper level of the RL transition,
- intensity and spectral fluctuations (Lévy and Parisi parameters),
- statistics of photons (Bose-Einstein and Poisson distributions).

Random Lasers are "complex nonlinear systems"

excelent platforms to study

Laser physics, Non Linear Optics,

Statistical physics, Non Linear Dynamics, Atomic Physics, ...

Photonic phase-transitions, turbulence, extremes events, ...

Why the interest in Spin Glass?

Concepts that arose in the study of spin glasses have led to applications in areas as diverse as:

computer science

neural networks

prebiotic evolution

protein conformational dynamics

protein folding and a variety of others

Other contributions from our labs at RECIFE

de Araújo et al. Lévy Statistics and the Glassy Behavior of Light in Random Fiber Lasers – Invited Review
Appl. Sciences 7 (2017) 644 (1-18)

Lima et al. Extreme-value statistics of intensities in a cw-pumped random fiber laser
Phys. Rev. A 96 (2017) 013834 (1-8)

Gonzales et al. Turbulance hierarchy in a random fibre laser. Nature Commun. 8 (2017) 15731

Characterization of RLs:

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excelent platforms to study

Laser physics, Non Linear Optics,

Statistical physics, Non Linear Dynamics, Atomic Physics, ...

Photonic phase-transitions, turbulence, extremes events, ...

Random Lasers are “nonlinear complex systems“

<u>they are excellent platforms to study</u>:

Laser Physics,

Nonlinear Optics, Quantum Optics,

Statistical Physics, Solid State Physics,

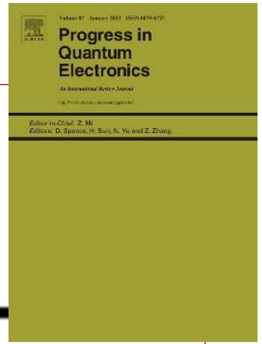
Nonlinear dynamics, Atomic Physics, ...

Plenty of fundamental work to be done ...

Many possible applications ...

Invited

78 (July 2021) 100343



Contents lists available at ScienceDirect

Progress in Quantum Electronics

journal homepage: www.elsevier.com/locate/pqe

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Review

Recent advances and applications of random lasers and random fiber lasers

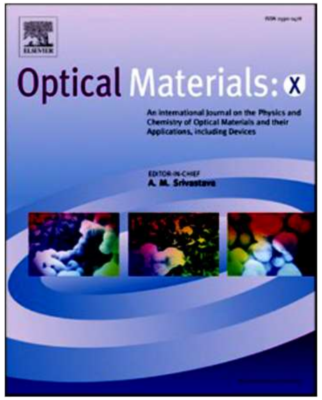
Anderson S.L. Gomes [a,*], André L. Moura [b,c], Cid B. de Araújo [a], Ernesto P. Raposo [d]

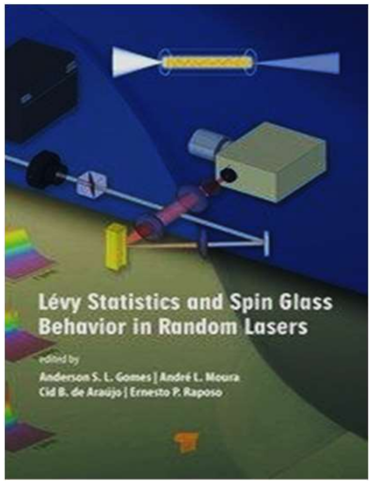
69 pages

443 references

Optical Materials: X 16 (2022) 100203

(INVITED)Optical Materials for Flexible and Stretchable Random Lasers A. S.L. Gomes, D. Valente, H. P. de Oliveira, S. J. L. Ribeiro, C. B. de Araújo 21 pages , 153 references





Book: Lévy Statistics and Spin Glass Behavior in Random Lasers

Eds: A. S. L. Gomes, A. L. Moura, C. B. de Araújo, E. P. Raposo

ISBN 9781003336181
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Taylor & Francis Group/J.Stanford Publishing

Nonlinear phenomena in metal - dielectric nanocomposites

Albert S. Reyna (PD)

Nathália T. Oliveira (D)

Manoel L. Silva (D)

NL spectroscopy of materials

Jessica Q. Bautista (PD)

Rudson Ferreira (D)

Maxwell Nogueira (D)

Felipe Elan (D)

Andrea F. da Silva (D)

Random Lasers

Renato B. da Silva (PD)

Andre Moura (PD) ➡ UFAl

Collaboration with other laboratories

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- Lucio Acioli
- Edilson Falcão Filho
- Anderson Amaral
- Ernesto Raposo
- Anderson Gomes
- Leonardo Menezes
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UNESP-Araraquara
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Jake Fontana

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