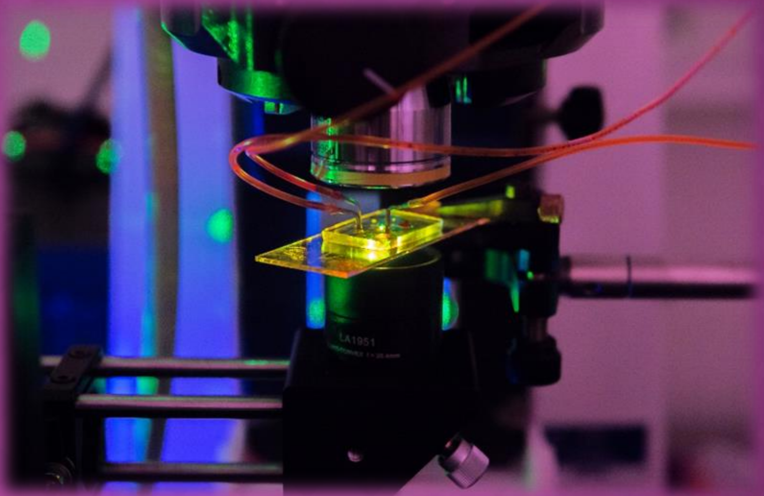
Control of Light in Scattering Media by Gain and Loss

Bhupesh Kumar[1] and Patrick Sebbah[1,2]

[1]Physics Department, Bar Ilan University, Ramat Gan, Israel

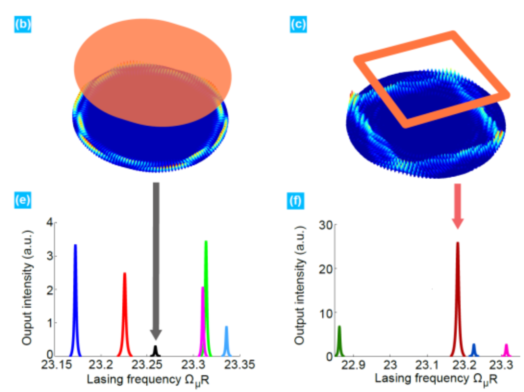
[2]Institut Langevin, ESPCI ParisTech , CNRS, Paris, France



OUTLINE

- Controlling laser emission : Motivations and methods
- Control of Random Lasers in the presence of strong mode overlap
- Imaging localized lasing modes in the strongly scattering regime
- Exceptional points in Random Laser
- Constant Intensity waves

WHY CONTROLLING LASER EMISSION ?

- Mode selection and frequency tuning
- Reducing threshold
- Power output
- Wall-plug efficiency
- Emission directivity
- Managing thermics
- Miniaturization
- 

L.Ge et al, Nat.Photonics (14)

CONTROLLING LASER EMISSION: METHODS

- Designing the gain medium

- Optimizing the optical cavity or the photonic structure

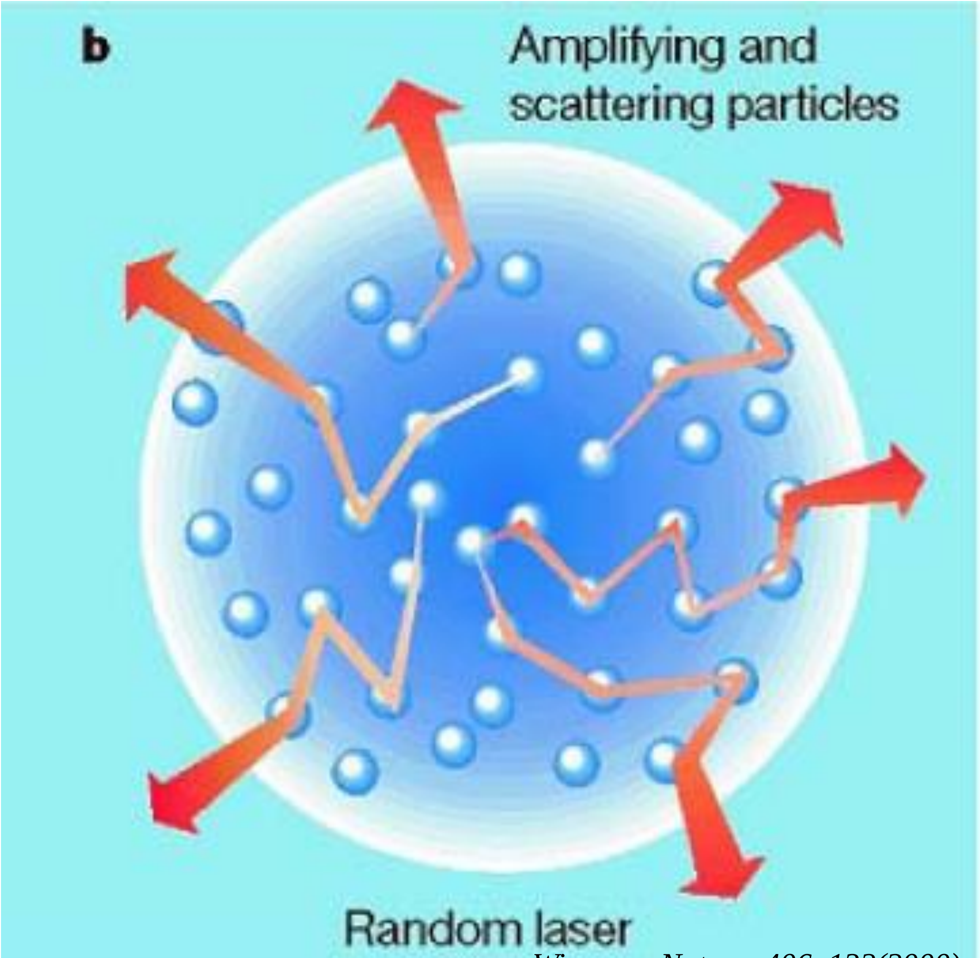
- Tailoring the gain distribution for selective pumping
  - Patterned contacts
  - Spatial modulation of the pump intensity profile

SPATIAL MODULATION OF THE PUMP INTENSITY PROFILE

- To optimize
  - Singlemode operation
  - Directionality
  - Spatial or Temporal focusing behind the medium

- Application to
  - Microdisks and microresonators
  - Asymmetric resonant cavities
  - Random lasers

RANDOM LASERS



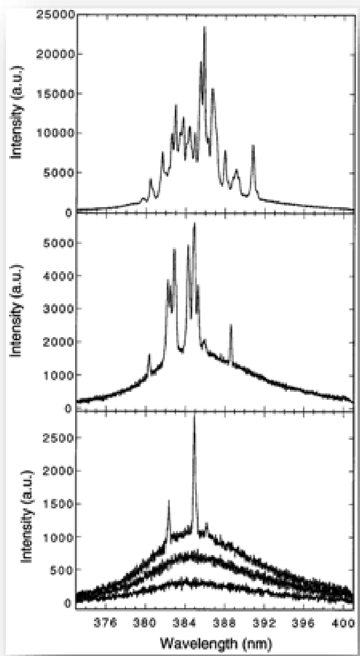
Wiersma, Nature, 406, 132(2000)

Multiple scattering :
➔ dwell time increases
➔ enhanced light amplification

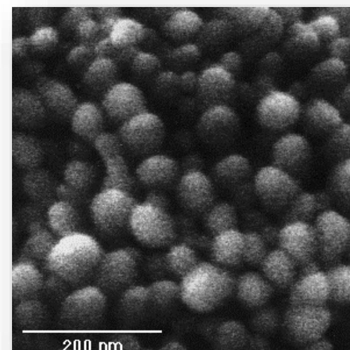
Mirrorless laser

Lethokov, Sov. Phys. JETP 26, 835 (1968).
Review: Wiersma, *Nature Physics*, 4, 359(2008)

RANDOM LASER WITH COHERENT FEEDBACK



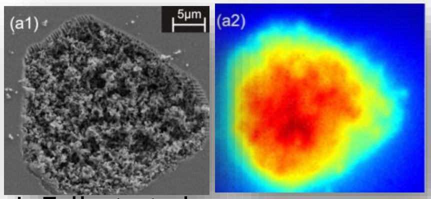
H. Cao, PRL82 (1999)



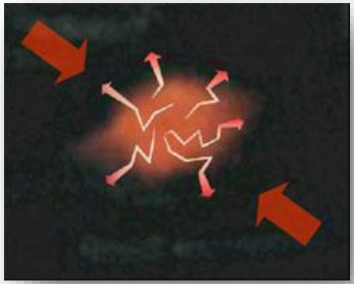
ZnO Powder

Threshold behavior
Sub-nm linewidth

DIFFERENT RANDOM LASERS

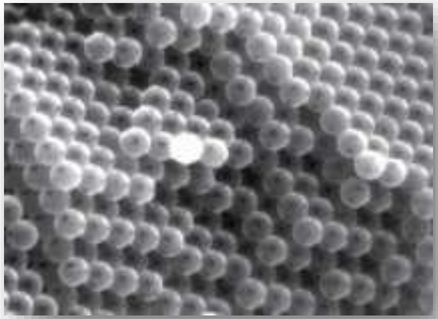


J. Fallert et al.
Nature Photonics, 279 (2009)

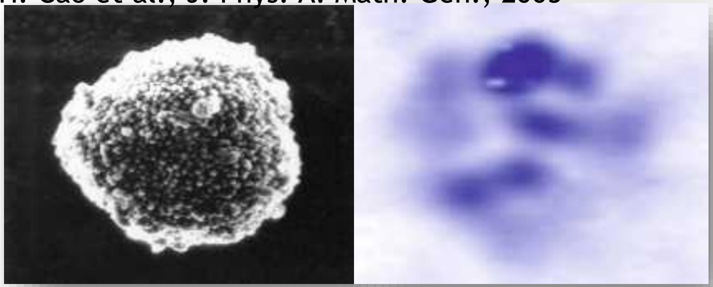


R. Kaiser, Cold atoms

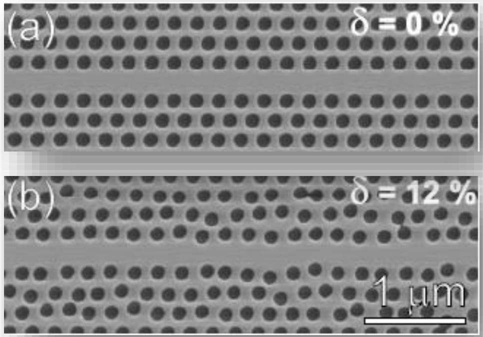
C. López
The Photonic Crystals Group



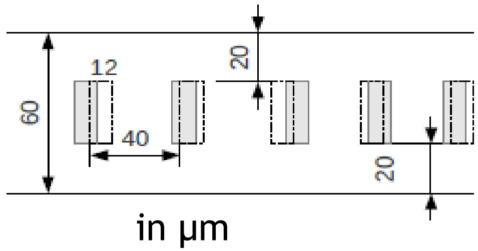
H. Cao et al., J. Phys. A: Math. Gen., 2005

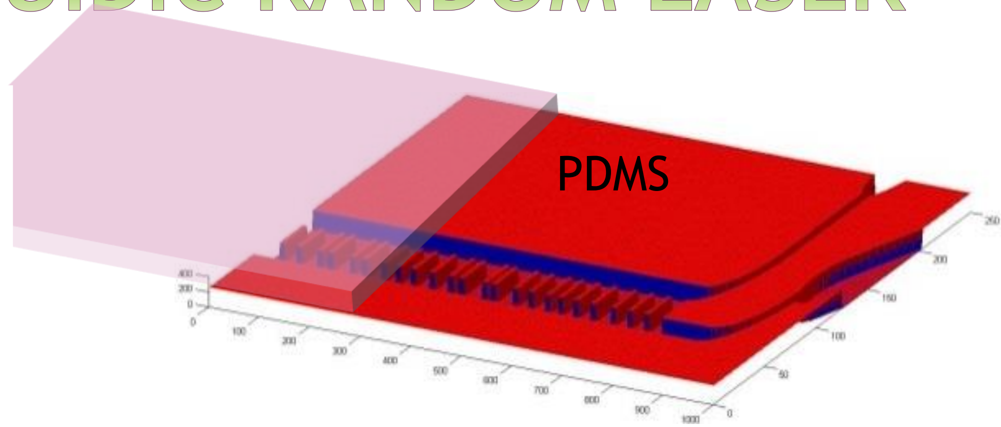


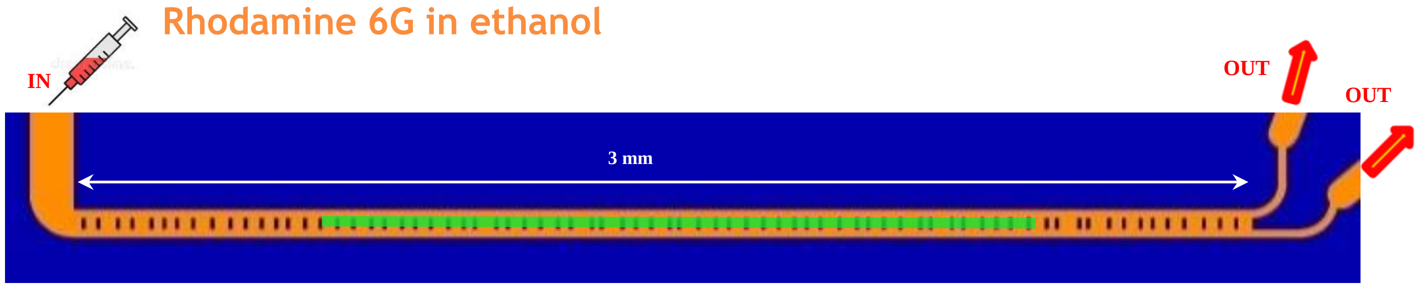
Sapienza et al., Science 327 (2010)



A 1D OPTOFLUIDIC RANDOM LASER







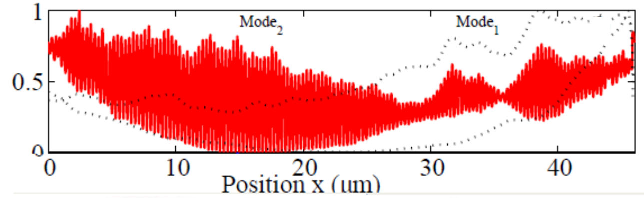
Δn = 0.06

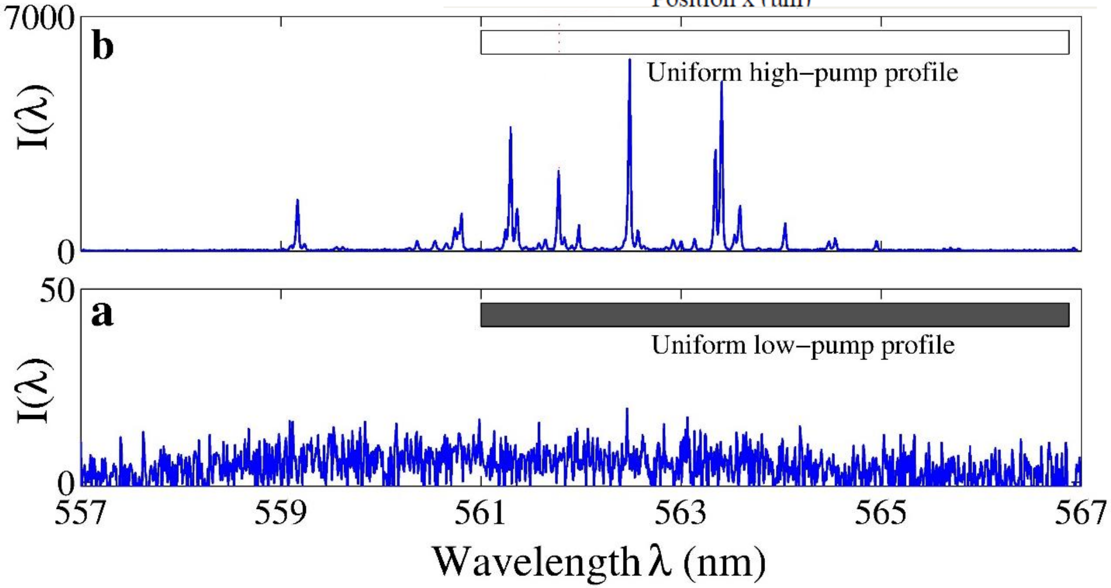
Weak scattering

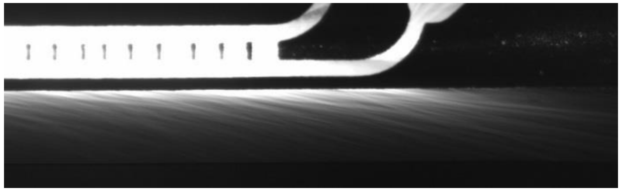
Modes are extended

K. Bhaktha *et al.*,
"An optofluidic random laser", APL **101**, 151101 (2012)

RANDOM LASING

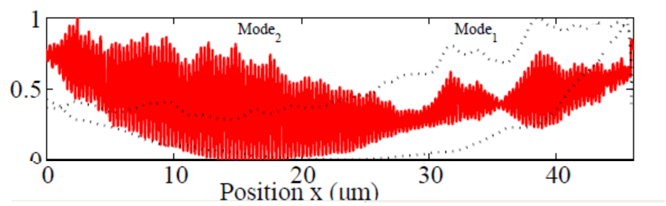






ACTIVE CONTROL OF RANDOM LASERS ?

- *Emission spectrum is unpredictable*
- *extreme sensitivity to disorder perturbation*
- *Low spatial coherence (non-directional emission)*
- *Highly non-hermitian systems: high threshold*
- *Highly nonlinear: spatial hole burning and mode competition*
- *Spatial modal overlap : spatial selectivity a priori not possible*

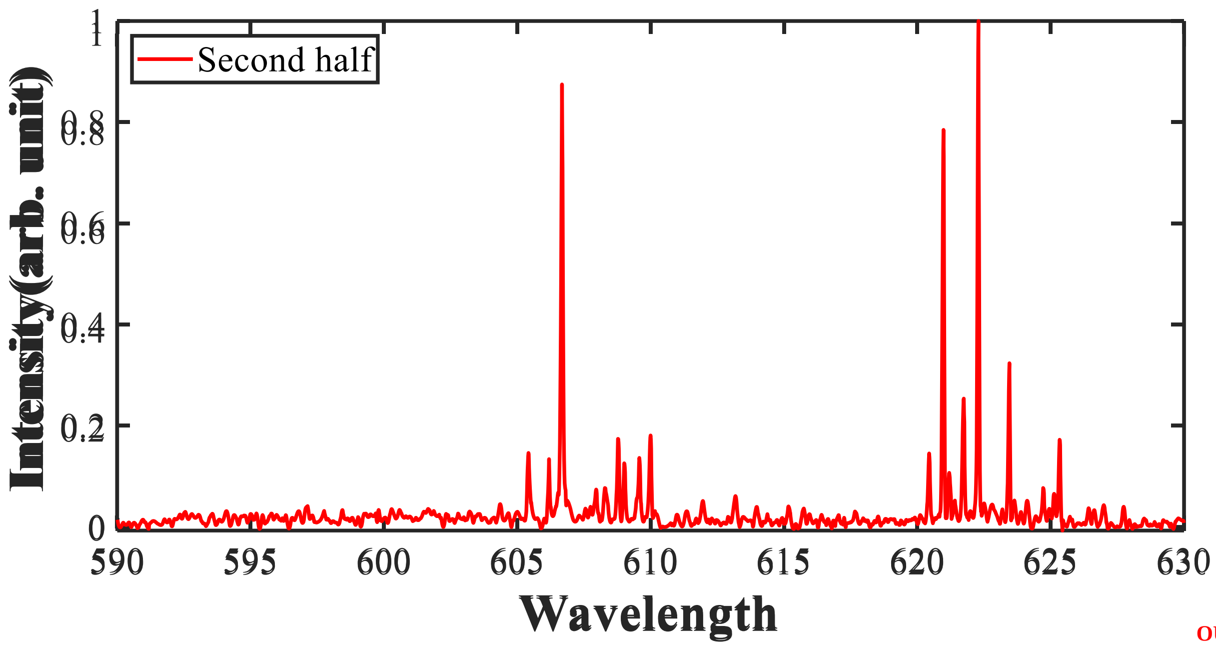


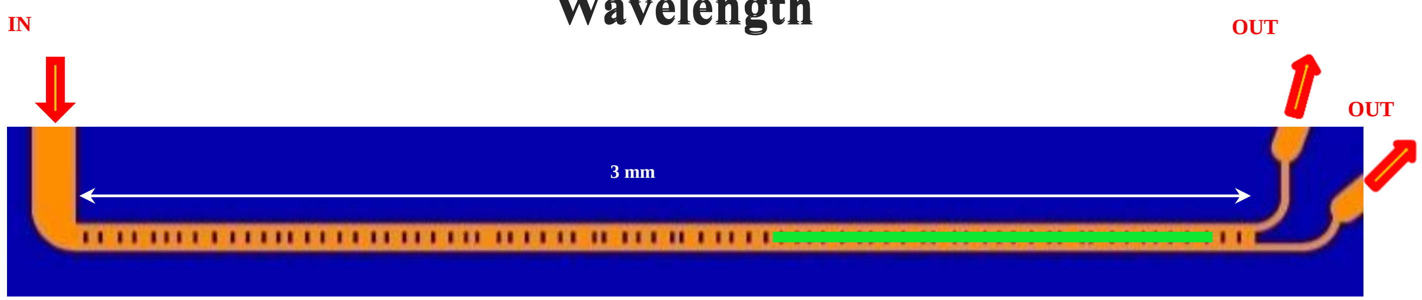
EARLIER APPROACHES

- Manipulation of the underlying random structure
  - **temperature-tunable RL (Wiersma 01, Lawandy02)**
  - **Resonance tuning (Ripoll04, Gottardo08)**
- constraining the range of lasing frequencies
  - Engineering the gain media (Bardoux11)

Can control over random lasing emission be regained in a non invasive way …

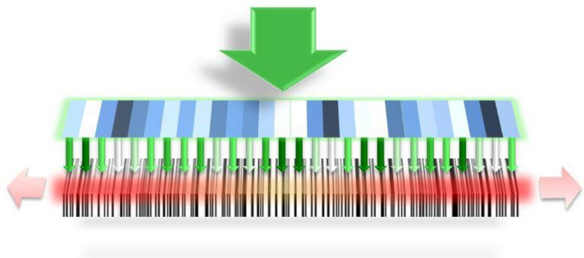
PARTIAL PUMPING





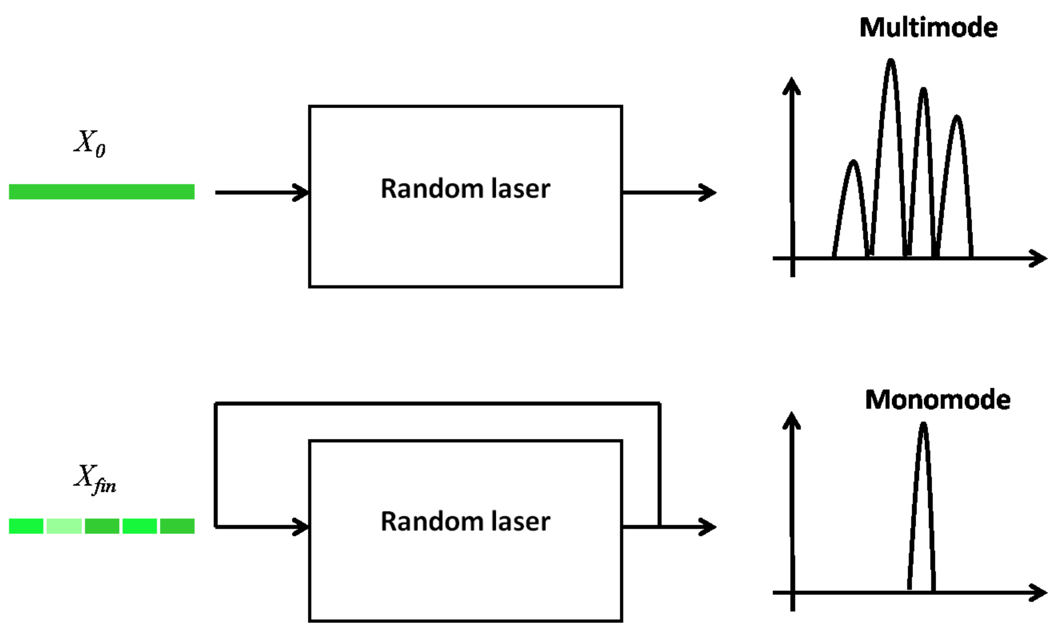
J. Andreasen *et al.*,
"Partially Pumped Random Lasers", Int. J. of Modern Phys. B 28, 1430001 (2014).

METHOD

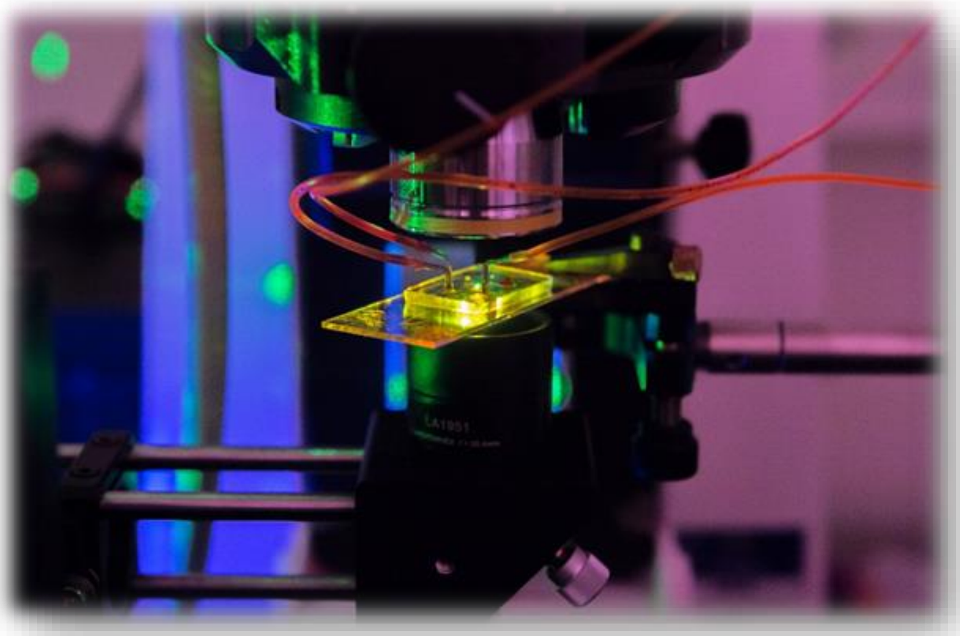


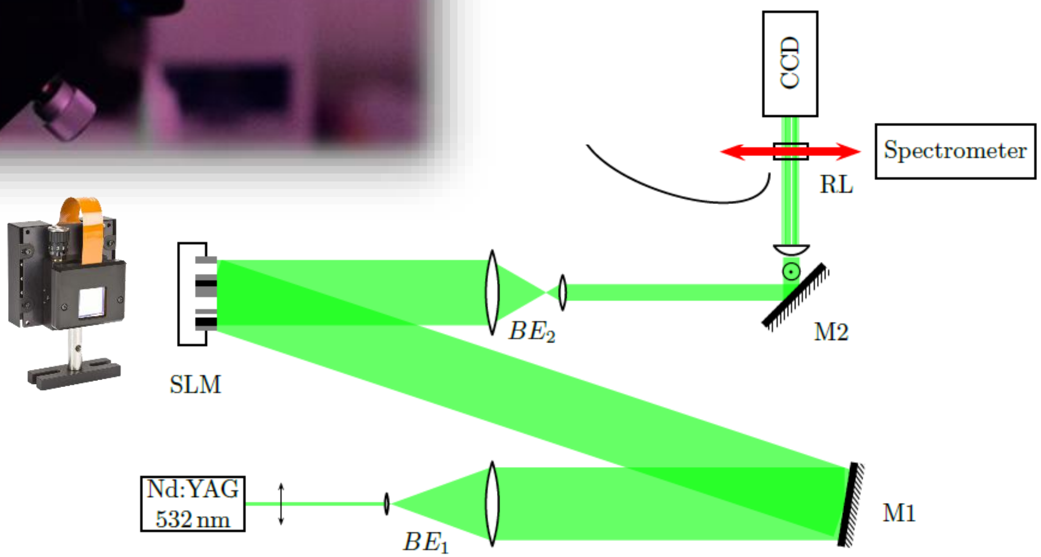
Iterative method without prior knowlegde of the lasing modes

(inspired from spatial shaping methods recently employed for coherent light control)



EXPERIMENTAL SETUP

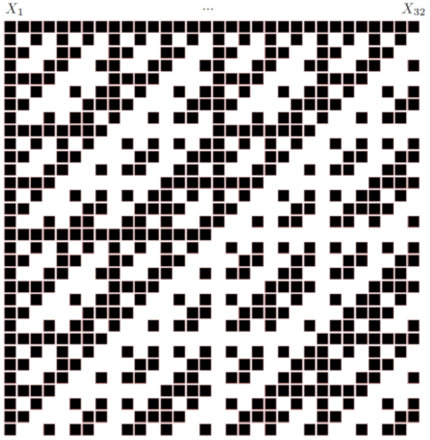




« OPTIMIZATION ALGORITHM

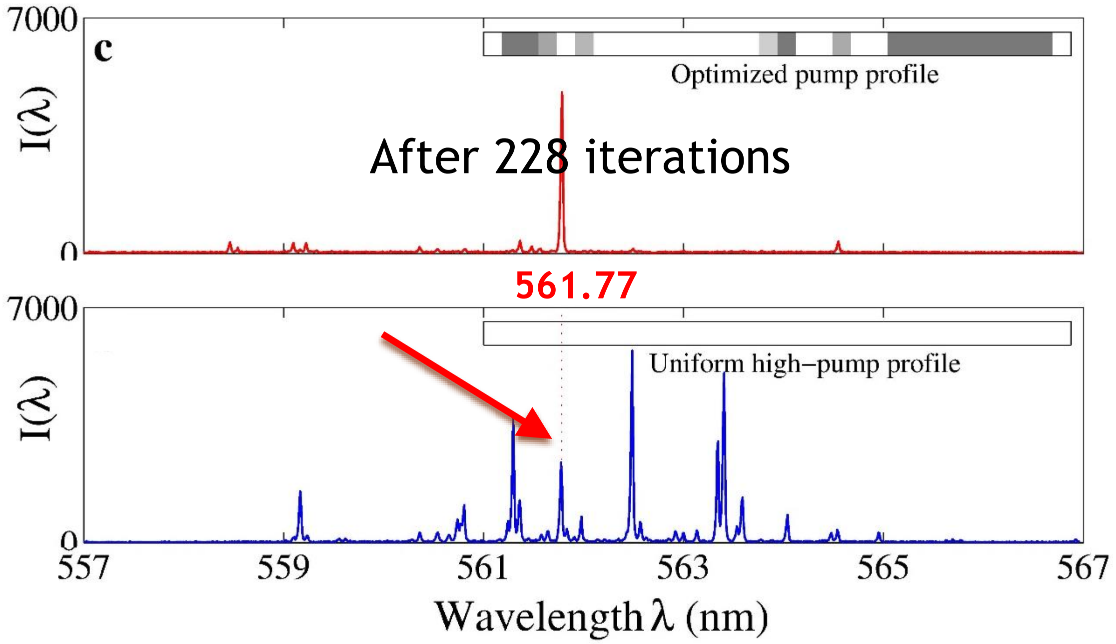
Cost function: $1/R$ where $R(\lambda_0) = I\,(\lambda_0)/I\,(\lambda_1)$

- Simplex method
- 32 pixels
- 32 Hadamard matrices



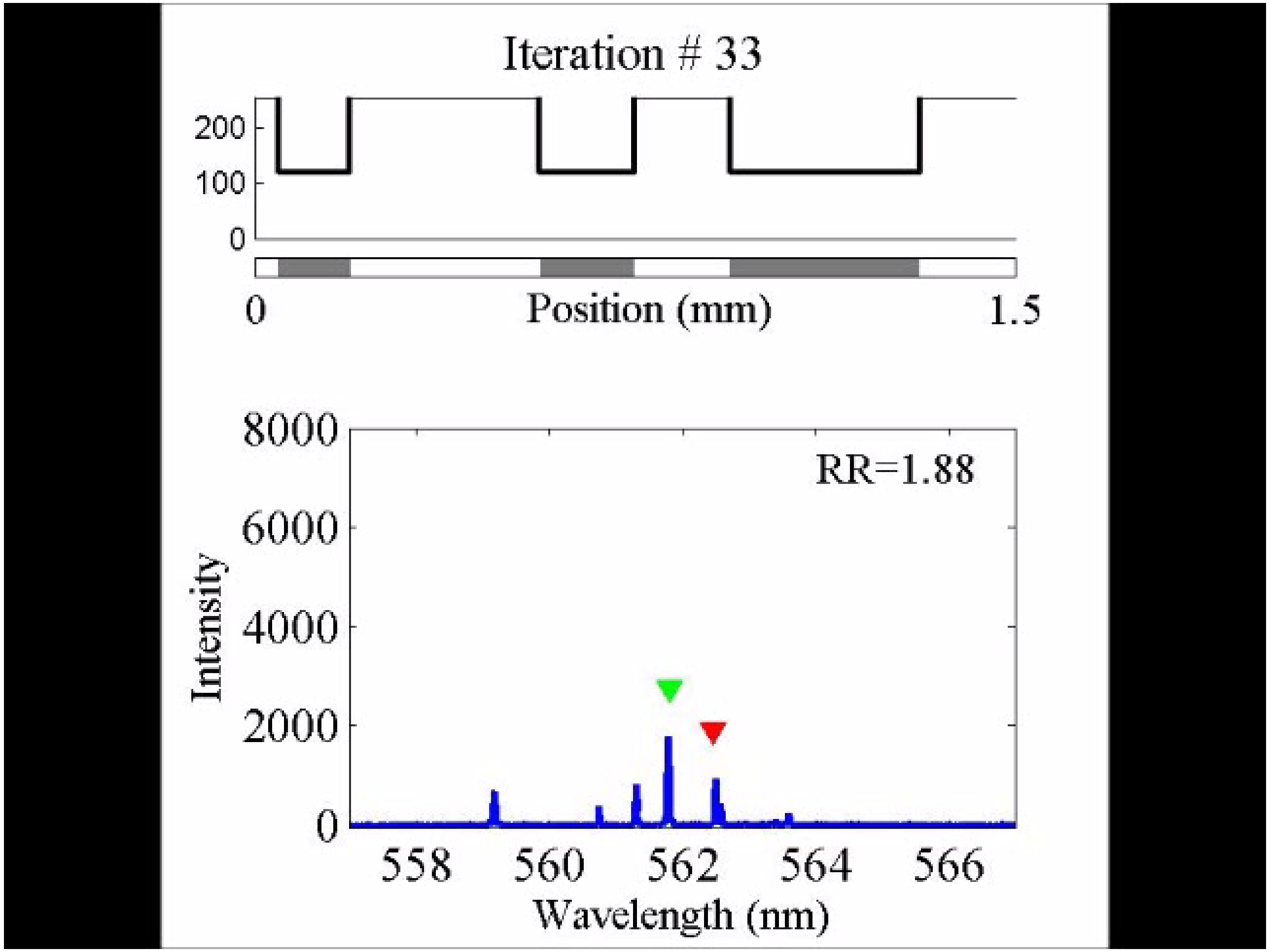
Hadamard matrices
(Each column shows a basis vector)

EXPERIMENTAL DEMONSTRATION



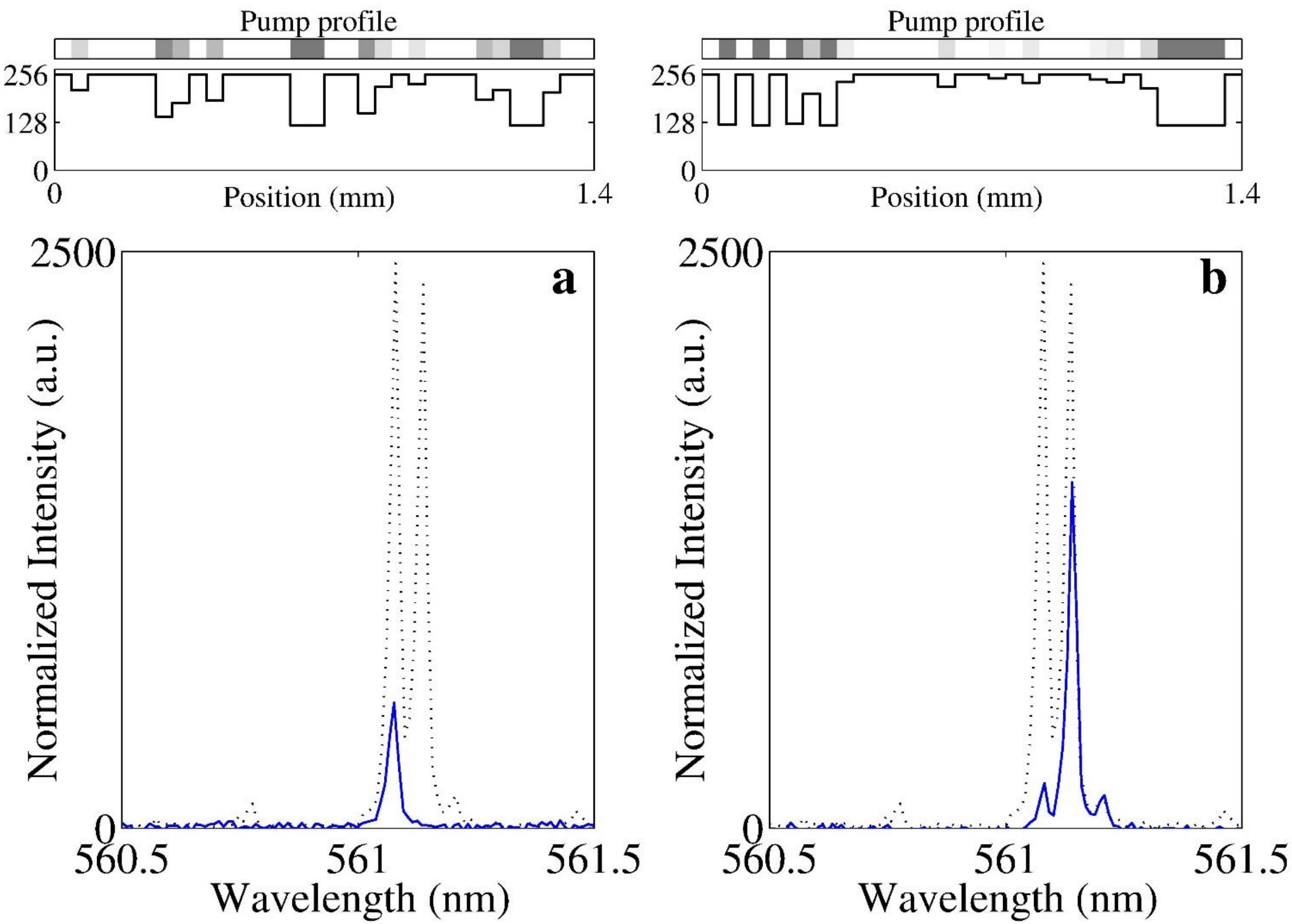
N. Bachelard *et al.*,
"Adaptive pumping for spectral control of random lasers",Nature Physics 10, 426–431 (2014).

"LIVE" EXPERIMENT



N. Bachelard *et al.*,
"Adaptive pumping for spectral control of random lasers",Nature Physics 10, 426–431 (2014).

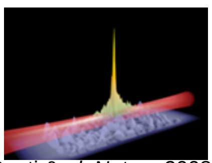
SPECTRAL SELECTIVITY



N. Bachelard *et al.*,
"Adaptive pumping for spectral control of random lasers",Nature Physics 10, 426–431 (2014).

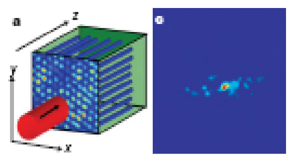
DISORDER-INDUCED LOCALIZATION

- Some Fundamental questions:
  - Anderson Localization — "Absence of diffusion in certain random lattices", P.W. Anderson, *Phys. Rev 109(1958)*.

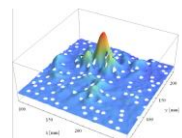


Roati & *al. Nature* 2008

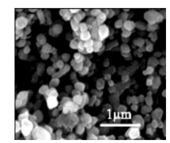
Hu & *al., Nature P 2008*



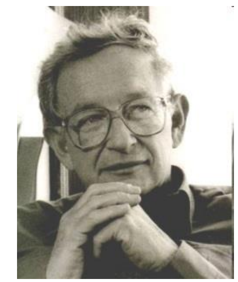
Schwartz & *al. Nature 2007*

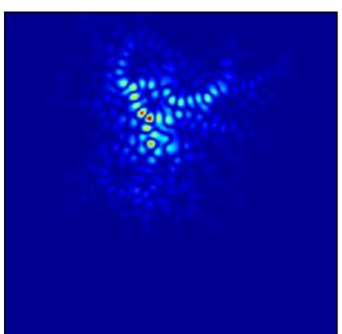


Laurent & *al., PRL 2007*

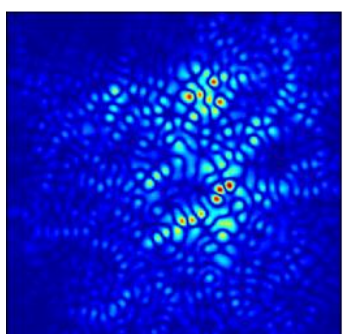


Störzer & *al., PRL 2006*

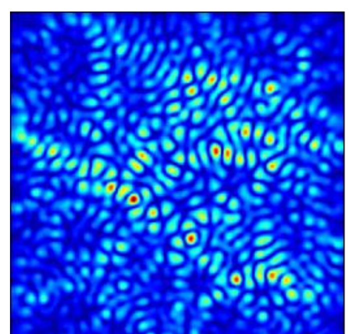




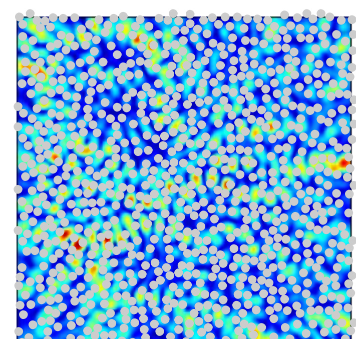
Δn=1.00



Δn=0.85

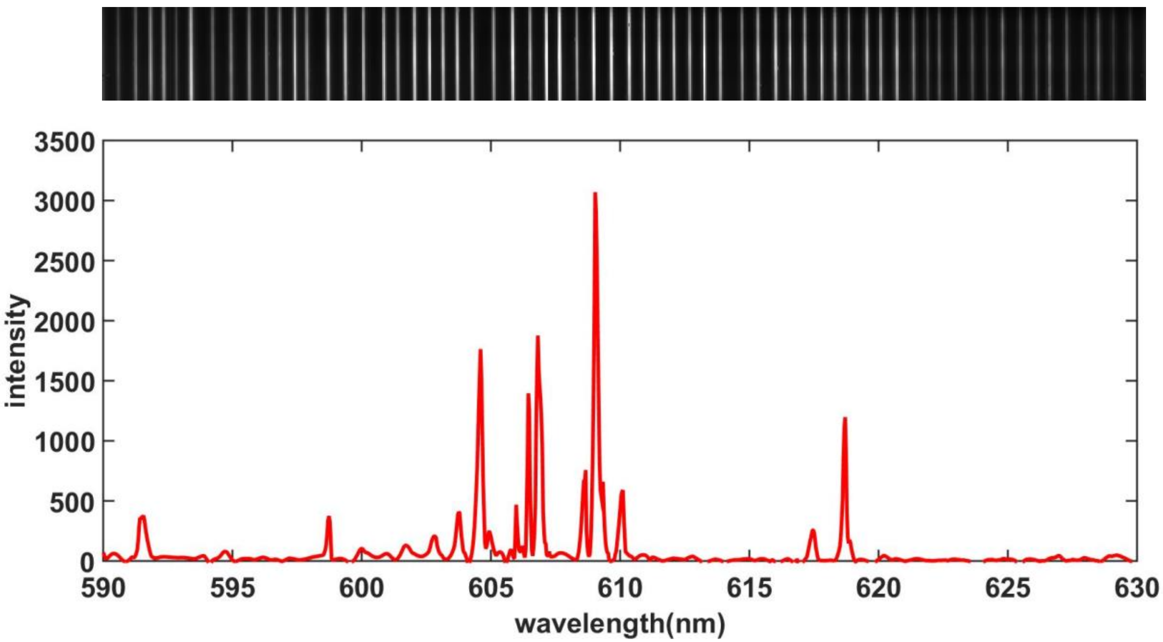


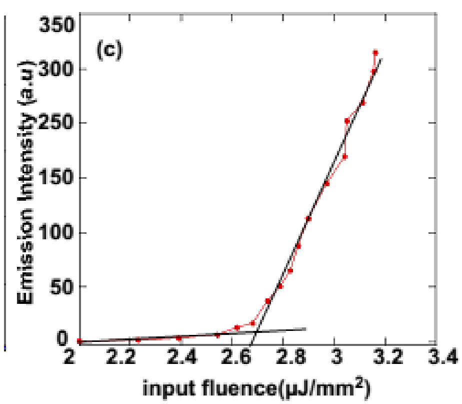
Δn=0.50



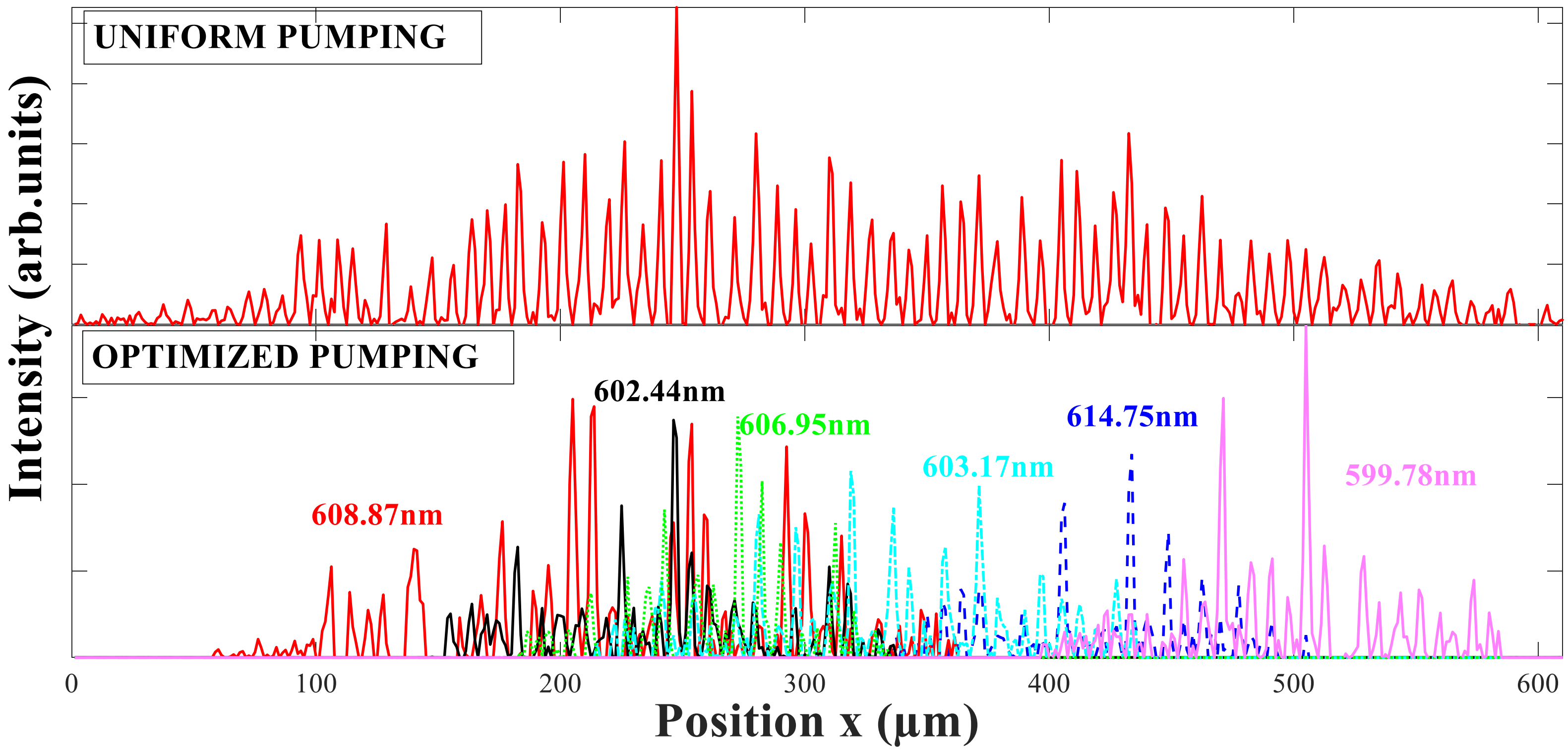
Δ=0.25

RANDOM LASING

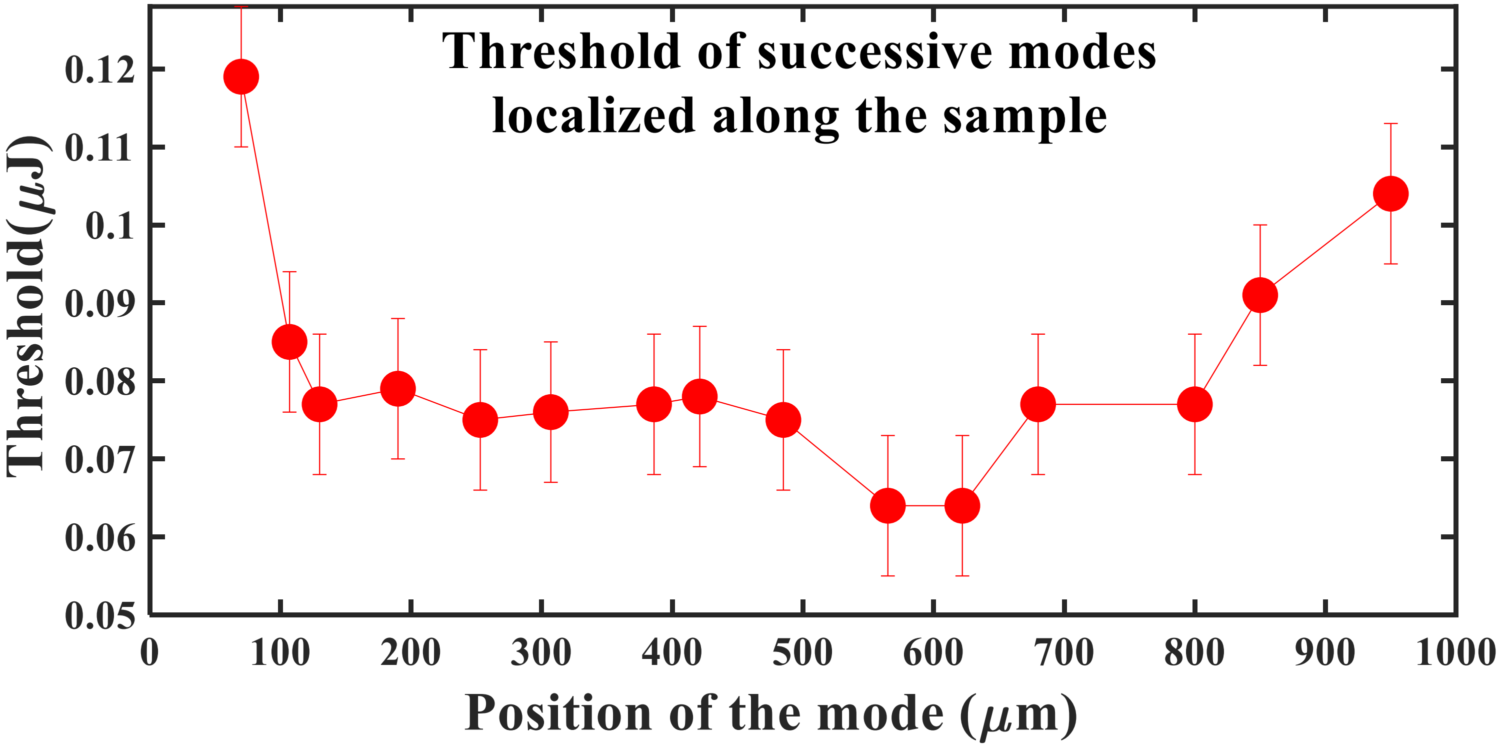




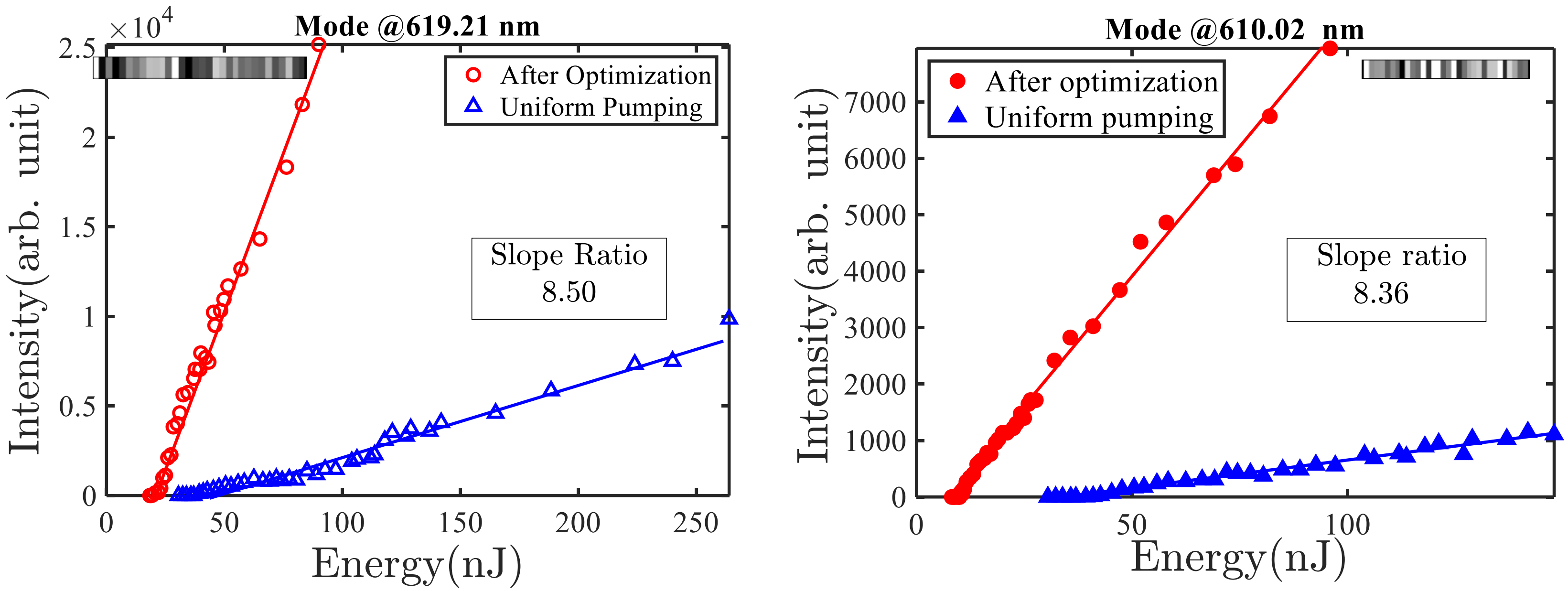
INVESTIGATING LOCALIZATION



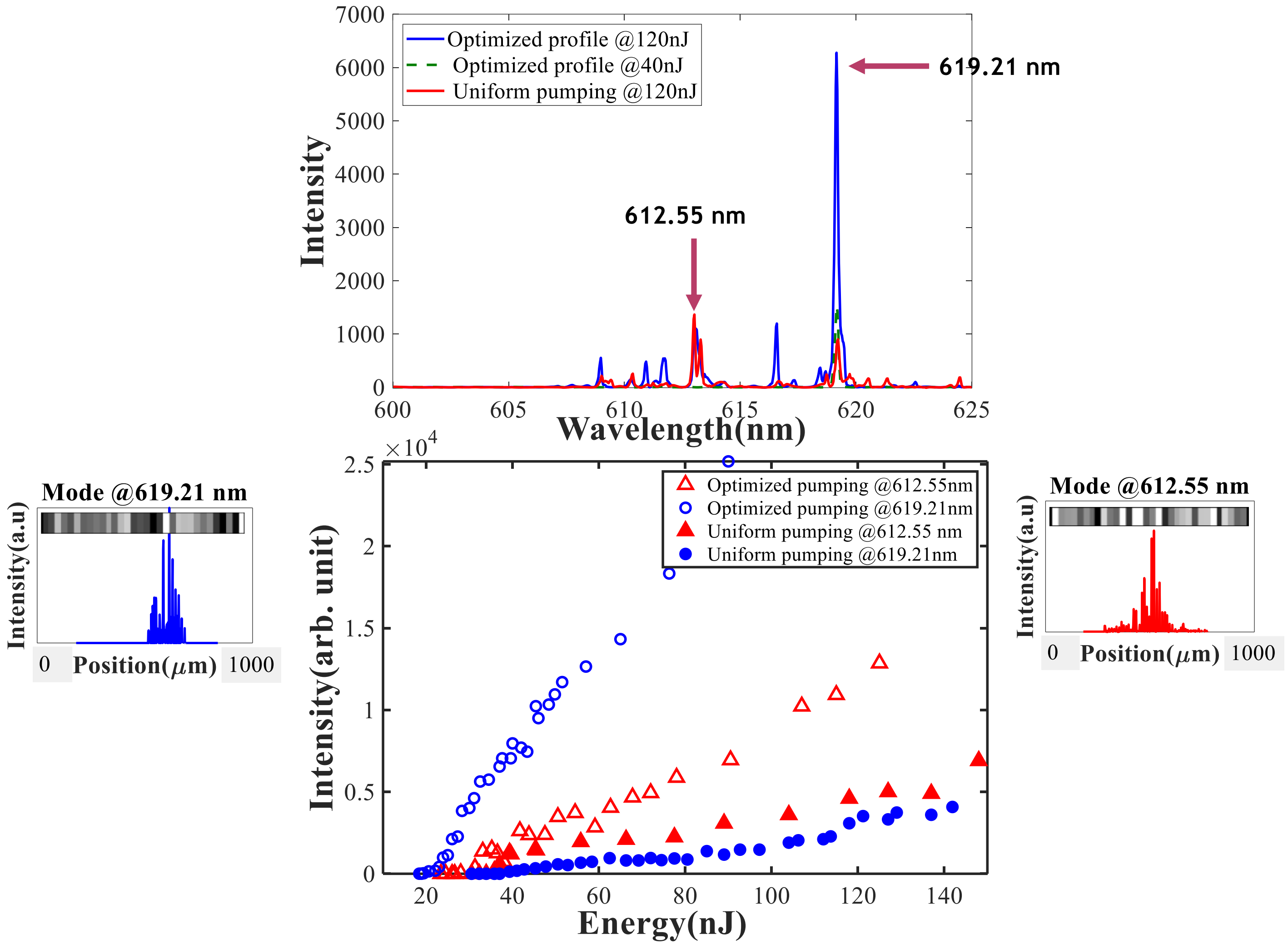
THRESHOLD DEPENDENCE WITH MODE POSITION



THRESHOLD AND THROUGHPUT ENHANCEMENT

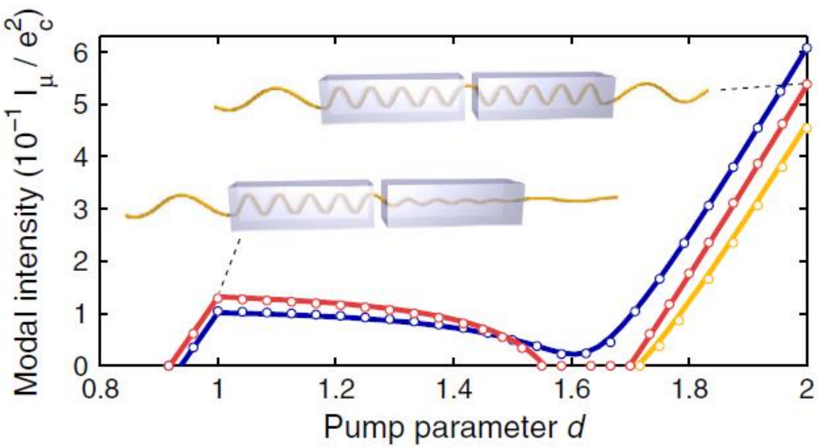


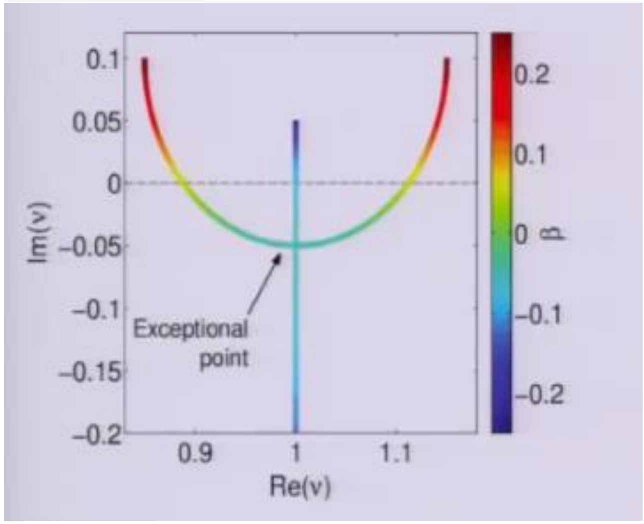
SELECTING THE MODE WITH OPTIMAL OUTPUT EFFICIENCY

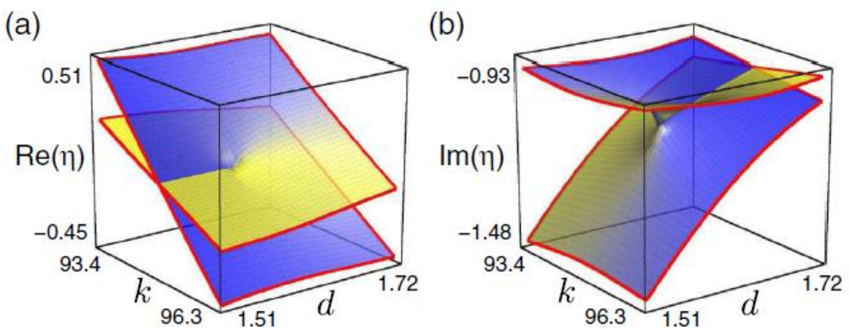


EXCEPTIONAL POINTS:

- Spatial properties of non Hermitian complex matrix
- Operator/ matrix become defective
- Eigen value become identical (both real and im part) and eigenstate become parallel.

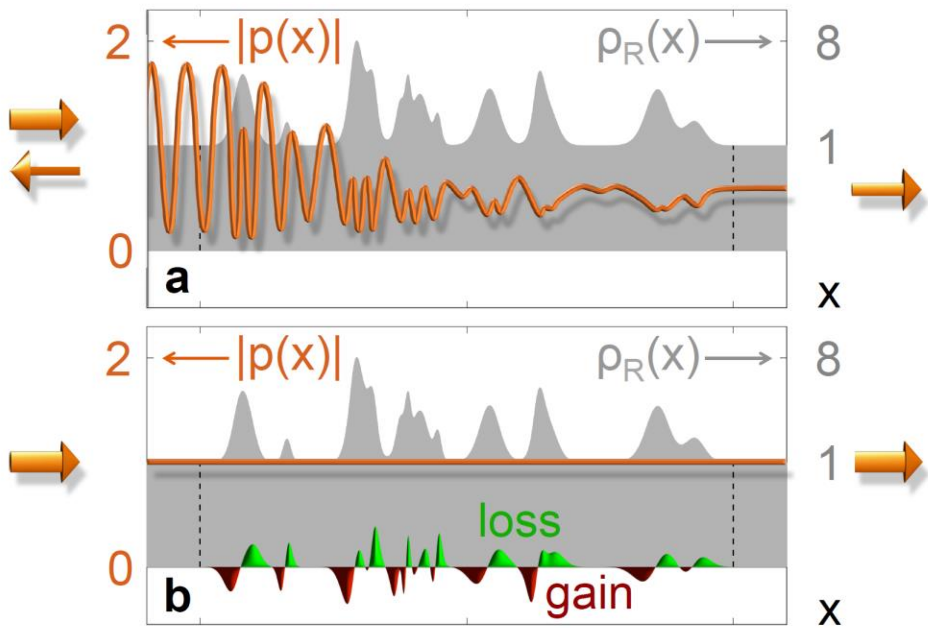


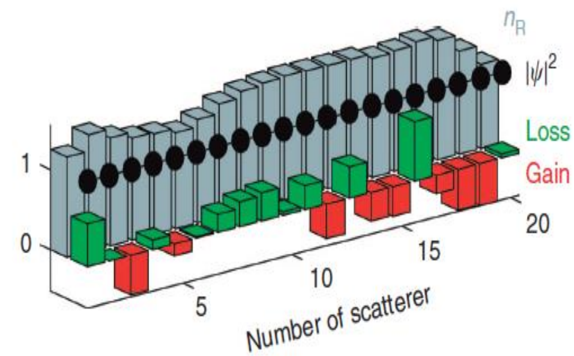




Pump induced exceptional point in laser (PRL,2012)

CONSTANT INTENSITY WAVES THROUGH A DISORDER MEDIA WITHOUT BACK SCATTERING

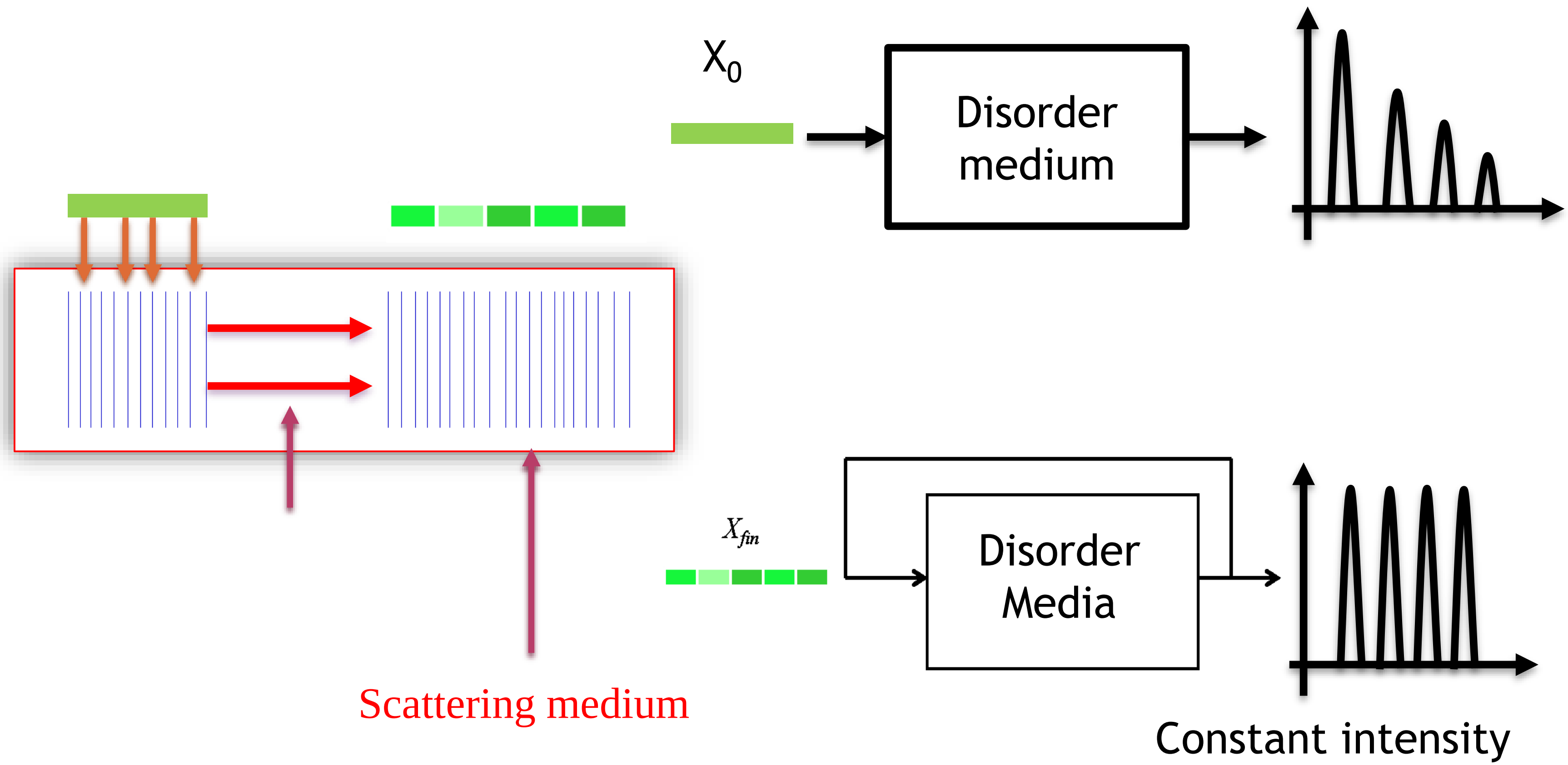




K.G.Makris *et al.*
Light Science and Applicaations(2017)

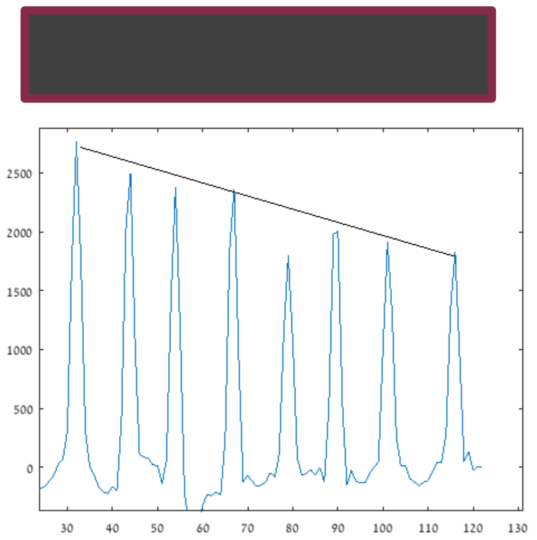
Concept of continuous constant-pressure waves.
E Rivet et. al (Nature physics ,2018)

CONSTANT INTENSITY WAVES THROUGH A DISORDER MEDIA WITHOUT BACK SCATTERING

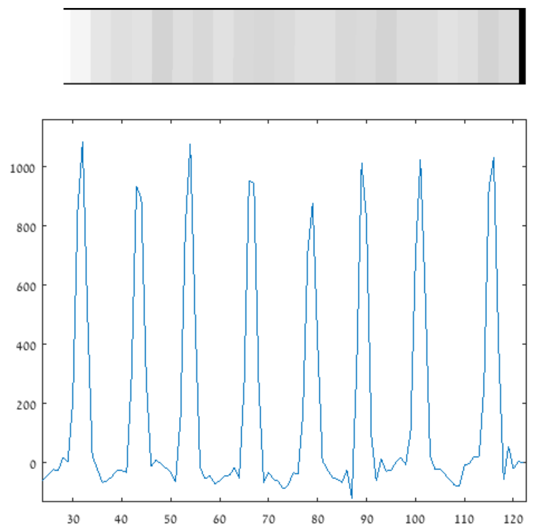


PRELIMINARY RESULTS ON CONSTANT INTENSITY WAVES

Uniform pumping



Optimized pumping after 187 iterations

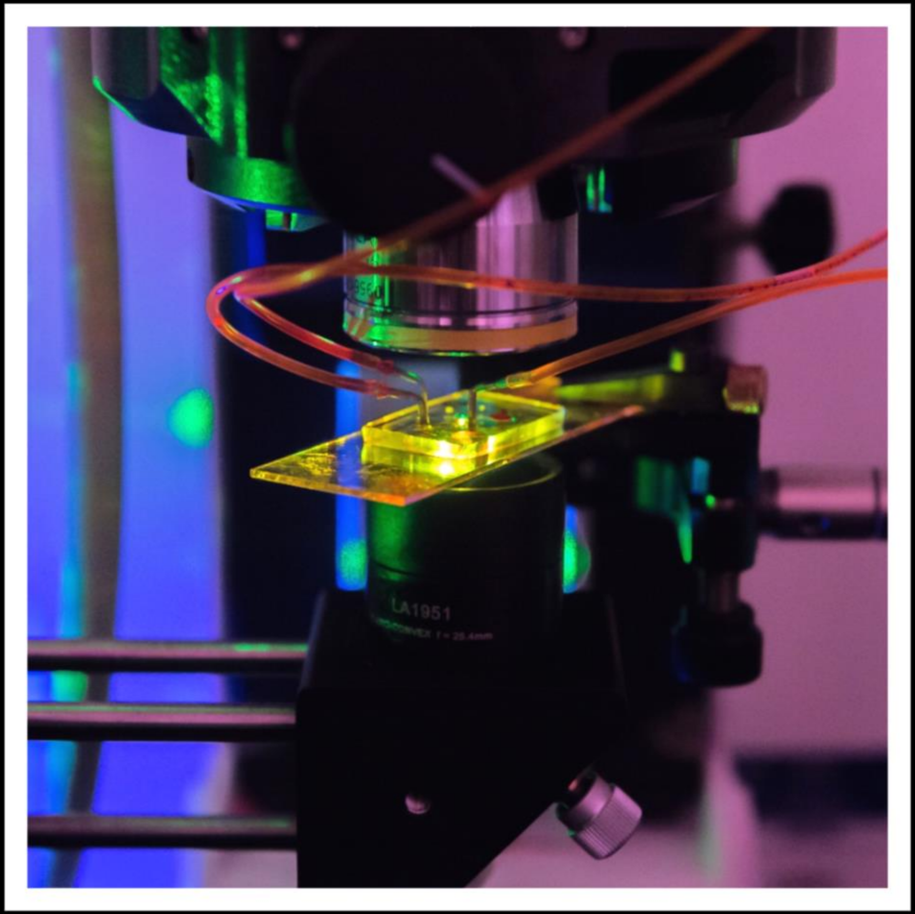


Input source from random lasing @604.05nm

SUMMARY

- Single mode operation at any desired lasing mode in case of both strong and weak scattering system with gain
- Individual imaging of localized modes

- Enhancement of total output power of a Random laser with selective pumping.



THANK YOU FOR YOUR ATTENTION