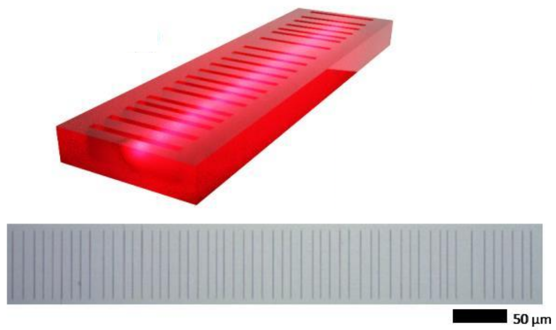
Organic microlasers
Two mechanisms for wave localization

Mélanie LEBENTAL

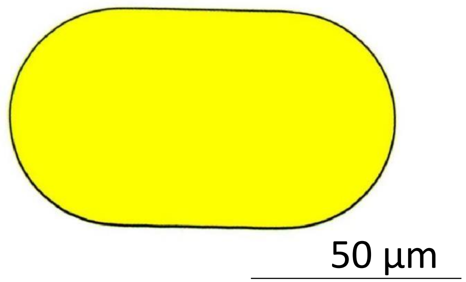
① Localization induced by disorder



⇨ **Random laser**

Patrick Sebbah & Bhupesh Kumar
Bar Ilan University (Israel).

② Localization induced by an open system



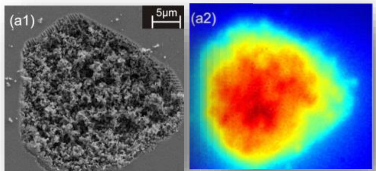
⇨ **Quantum chaos**

Clément Lafargue, Joseph Zyss, ENS Paris-Saclay.
Stefan Bittner, LMOPS, Metz.
Dominique Decanini, Xavier Chécoury, C2N.

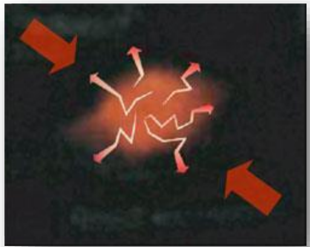
GdR complexe, December 2022

I Localization induced by disorder

“Absence of diffusion in certain random lattices”, P.W. ***Anderson****, Phys. Rev. vol. 109, 1492 (1958).* ⇨ **Random lasers**

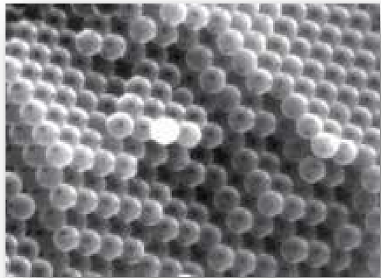


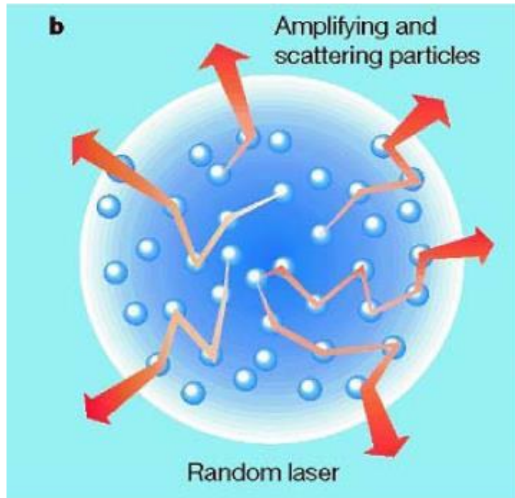
J. Fallert et al.
Nature Photonics, 279 (2009)



R. Kaiser, Cold atoms

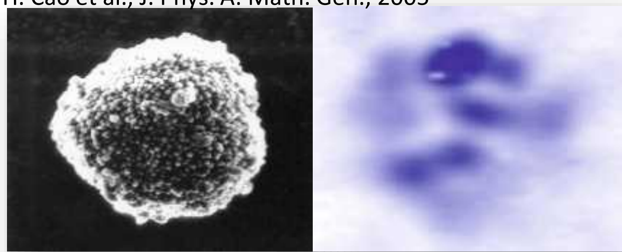
C. López
The Photonic Crystals Group



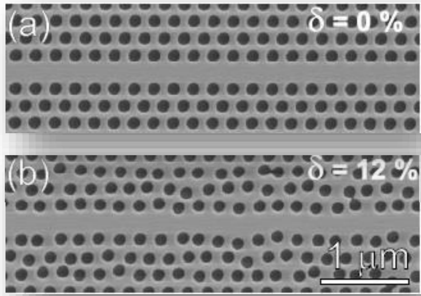


Wiersma, Nature, 406, 132(2000)

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



Sapienza et al., Science 327 (2010)



I Localization induced by disorder: the **landscape**

Filoche & Mayboroda, PNAS 37, 14761 (2012)

$$(-\Delta + V)\psi = E\psi$$

Which consequence on ψ ?

$$(-\Delta + V)u = 1$$

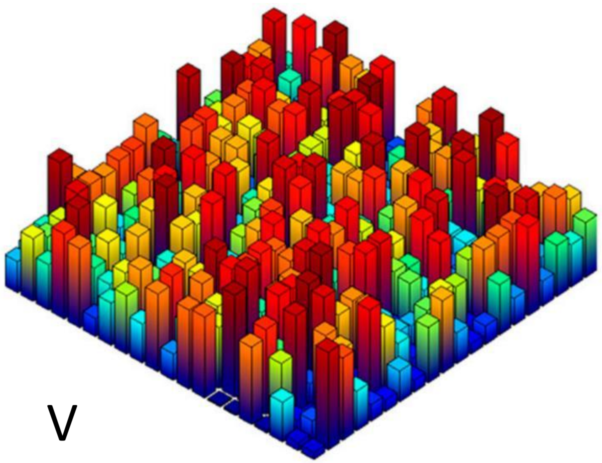
for V > 0

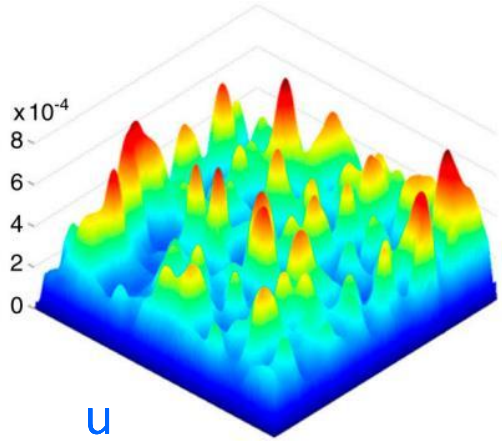
u is called « the landscape » and is more or less the Green function

$$\Longrightarrow \quad |\psi(\vec{x})| \leq E u(\vec{x})$$

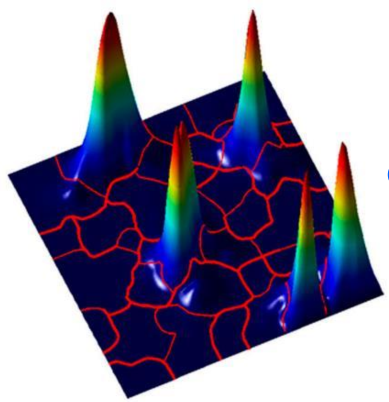
for all x

u is independent on the wavefunction



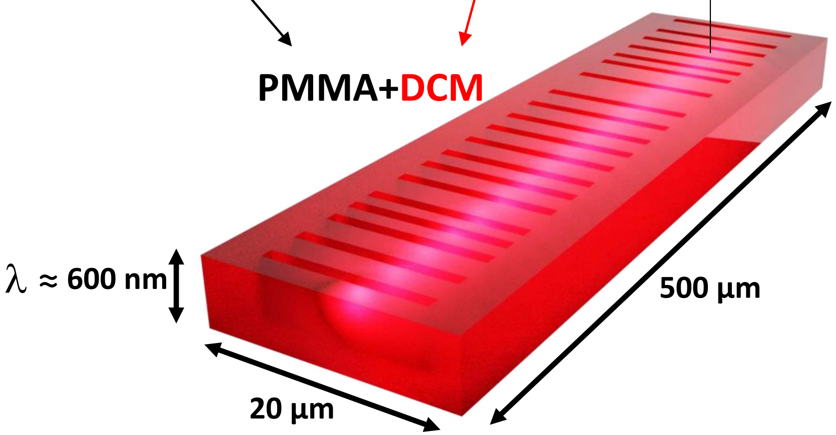


The red lines are the deeepest valleys of u.



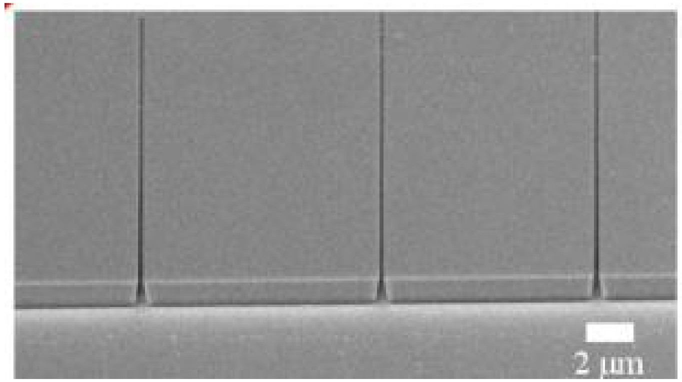
Five first eigenmodes

I Random lasers with a fixed disorder



Grooves etched by e-beam lithography

Random positions of the grooves with an averaged pitch 8 µm.

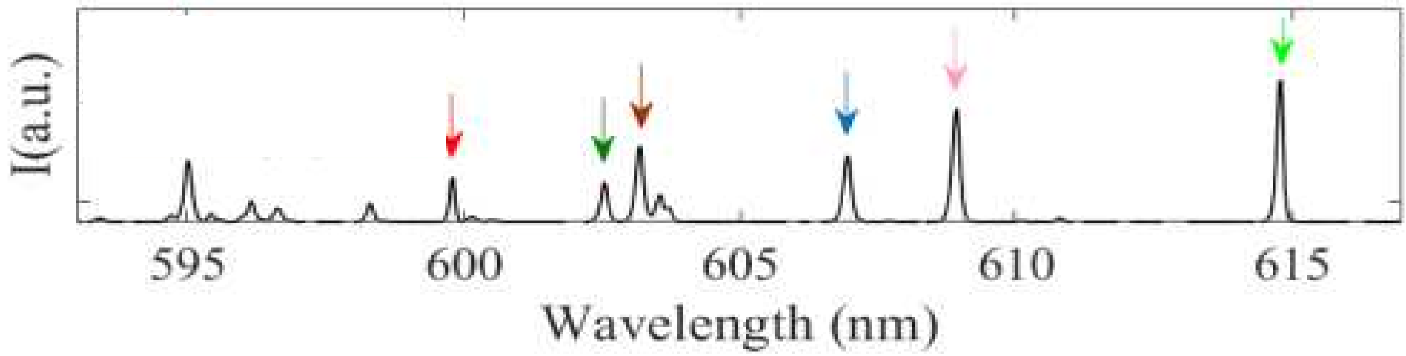


The light propagates and is amplified in the PMMA-DCM. It is scattered by the grooves.

⇨ **Random lasers**

I Random lasers with a fixed disorder

Typical experimental spectrum: a multimode spectrum



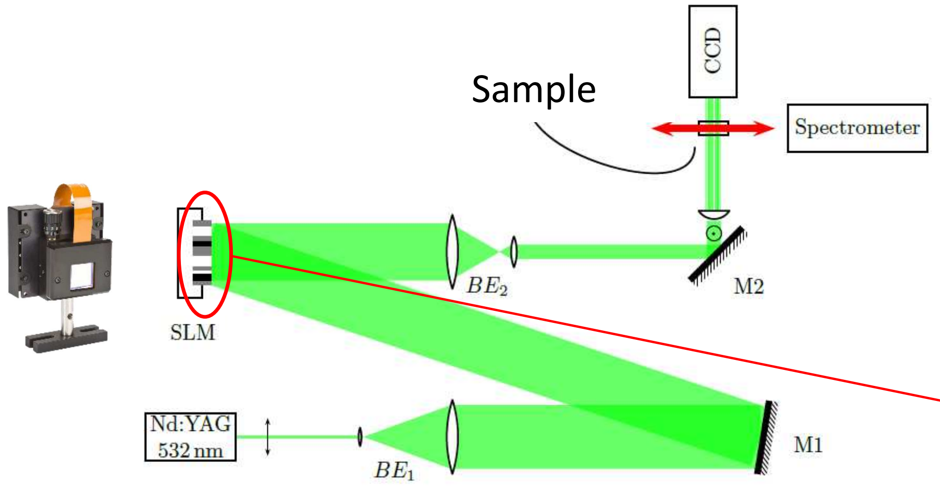
How to study each laser mode individually ?
without non-linear interactions between modes (like spatial hole-burning)

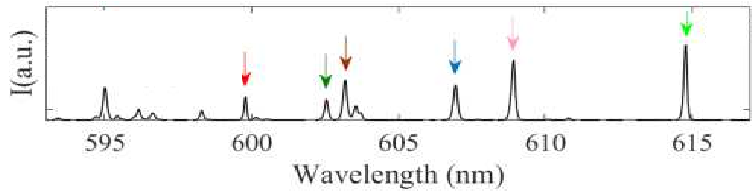
⇨ <u>Optimization of the spatial profile of the pump</u>
to select a single laser mode

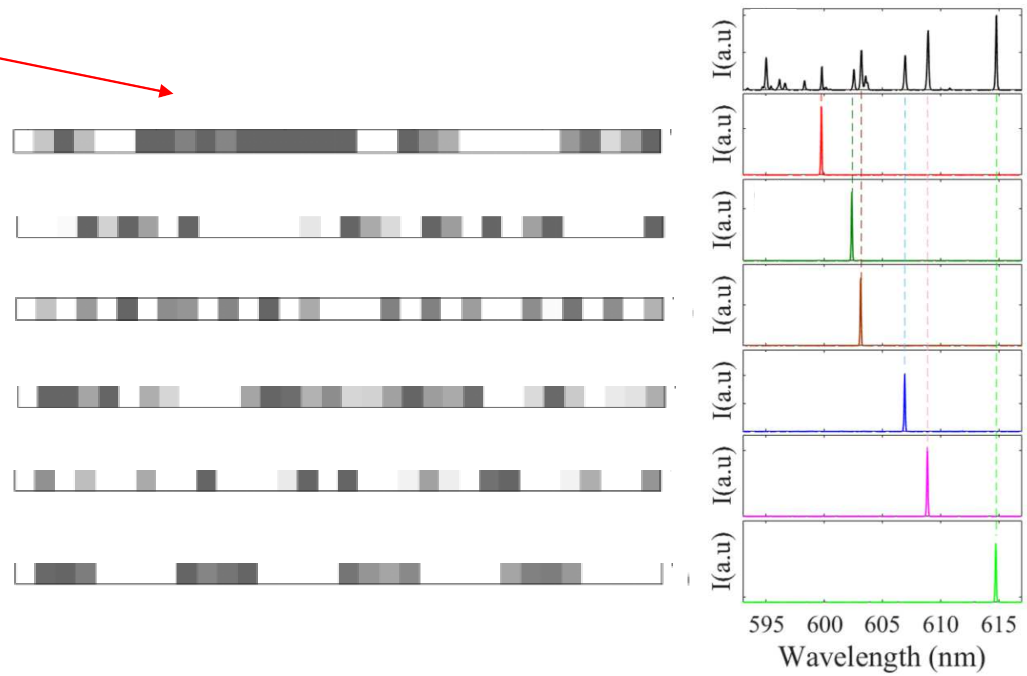
with a Spatial Light Modulator (SLM) and a specific algorithm.

N. Bachelard, S. Gigan, X. Noblin, P. Sebbah, Nat. Phys. <u>*10*</u>*, 426 (2014).*

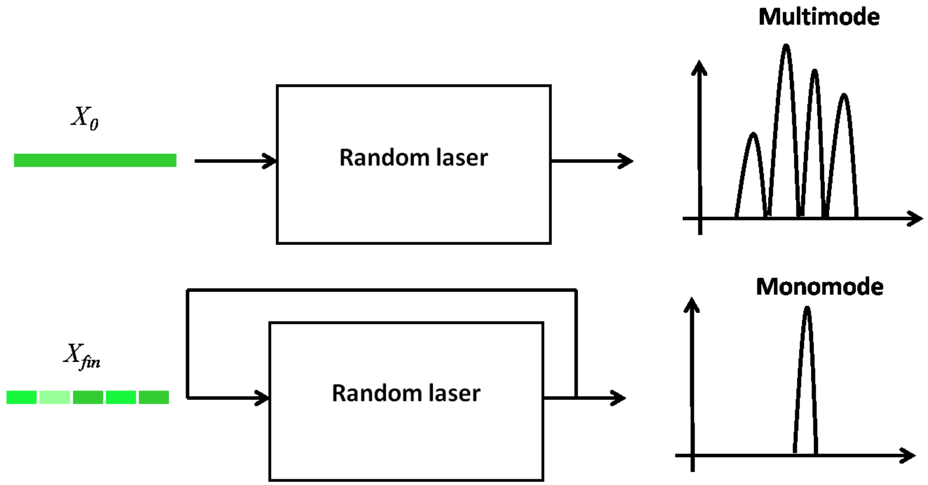
I Random lasers with a fixed disorder



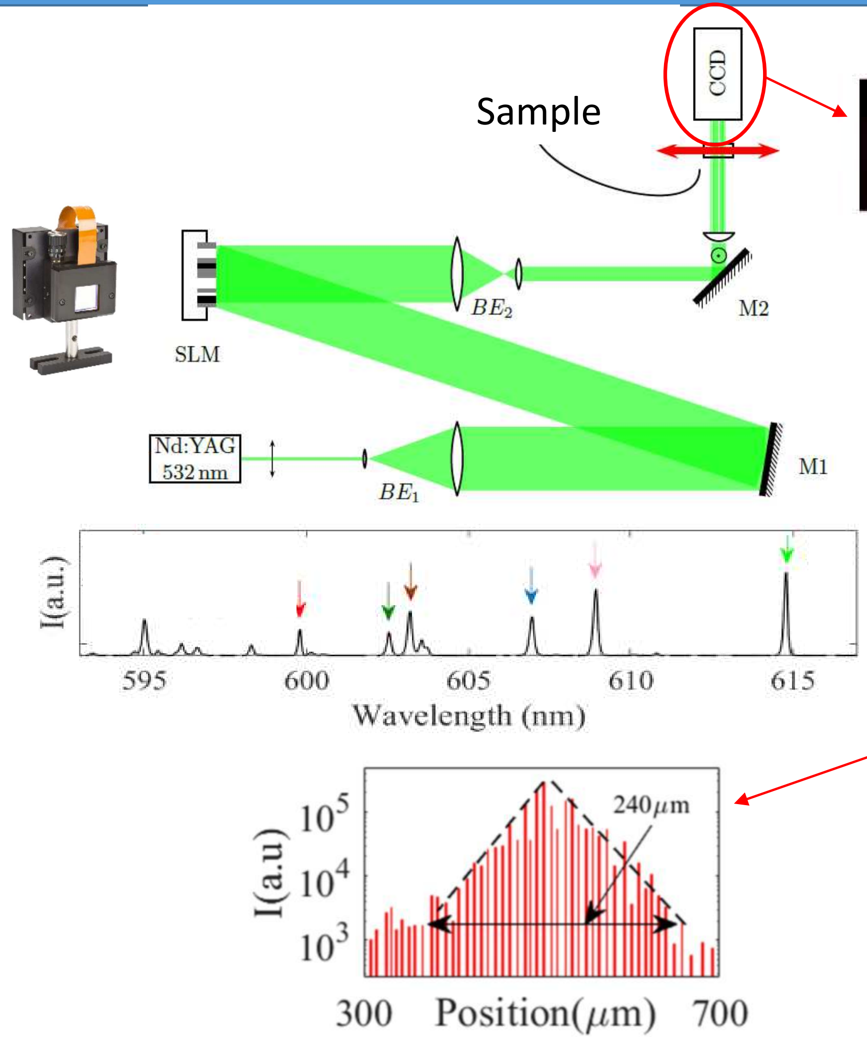




Spatial shaping of the pump beam

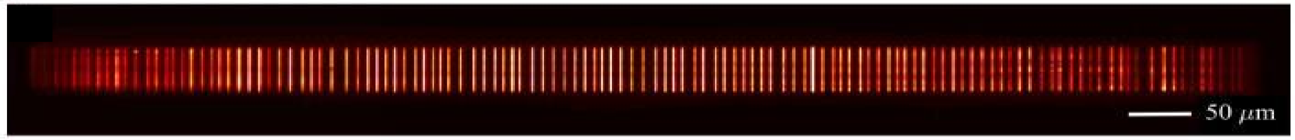


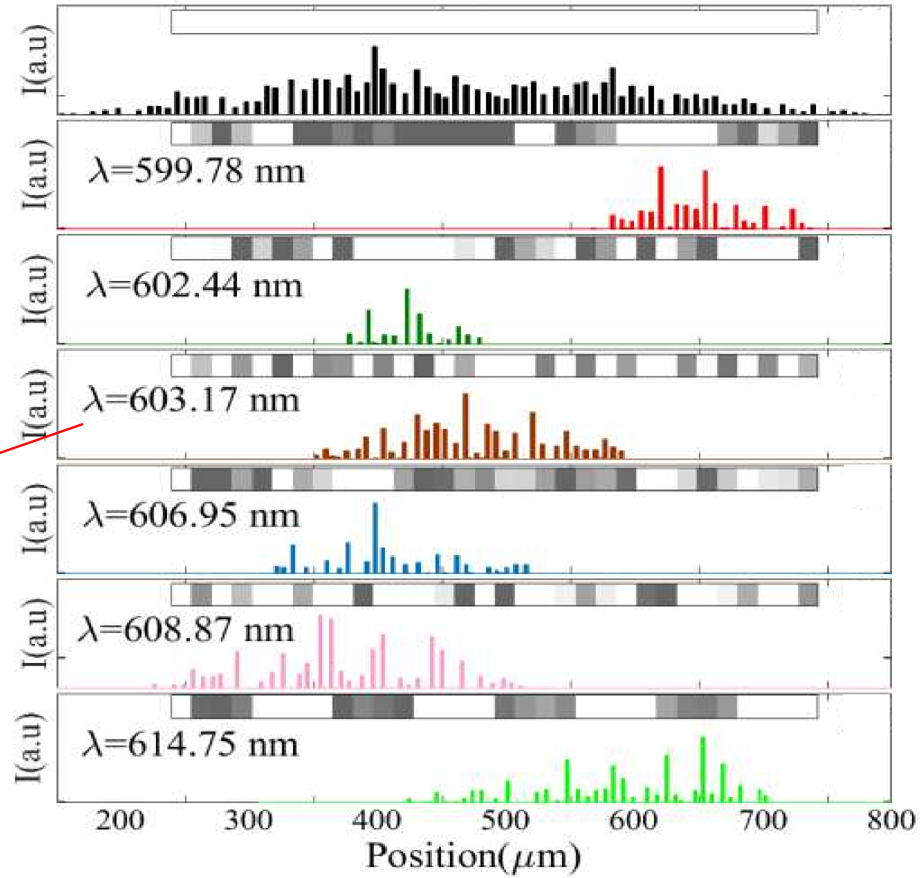
I Random lasers: localization length



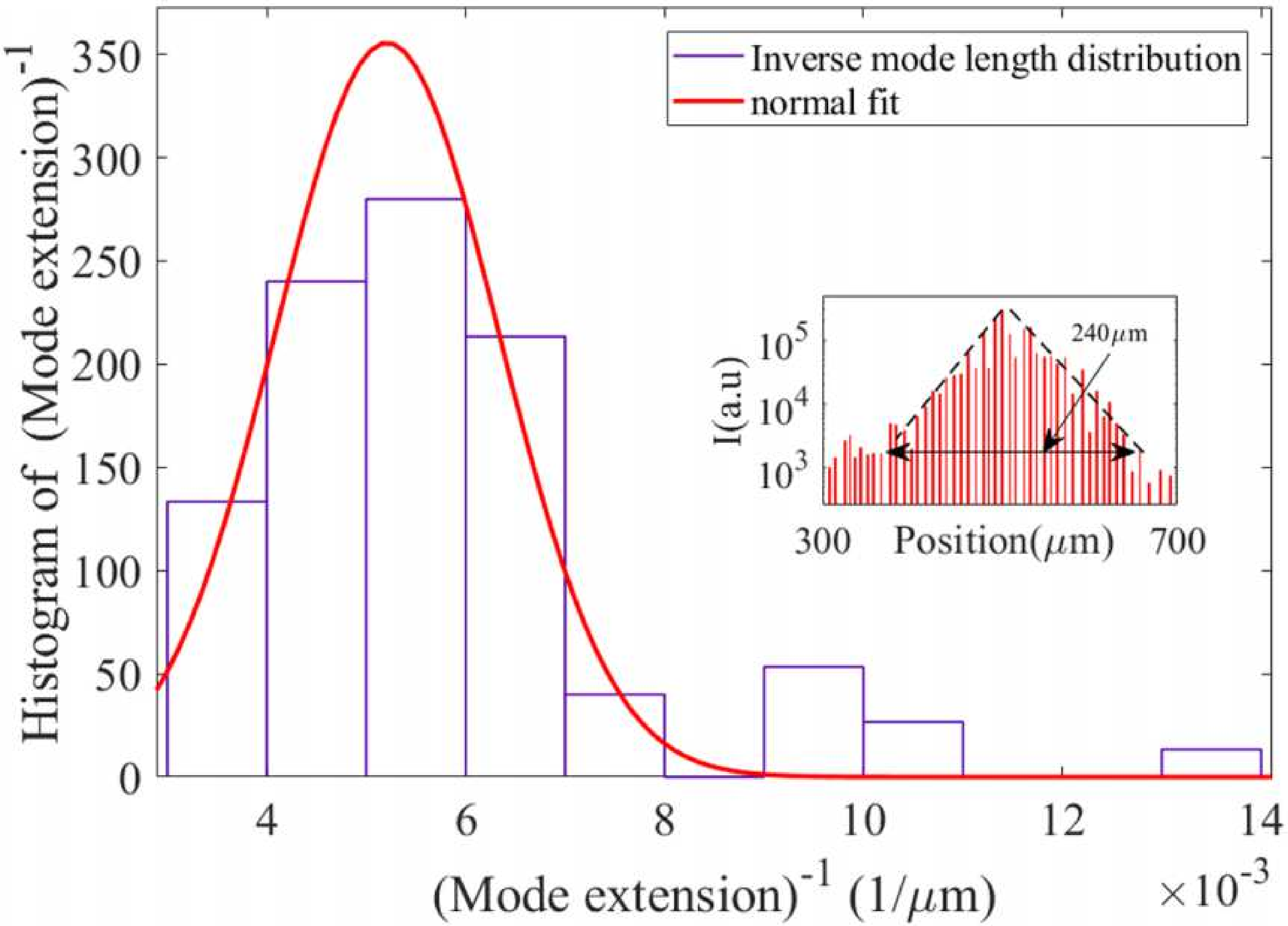
The localization length of this mode is about 120 μm.

Scattering by the grooves. Spatial profile of the laser modes.





I Random lasers: localization length



Histogram calculated from 75 individual laser modes of 10 different samples

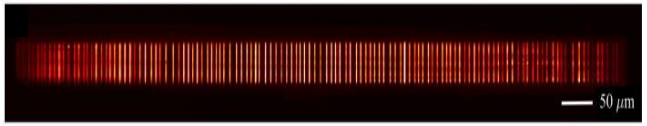
Mean localization length: about 100 µm

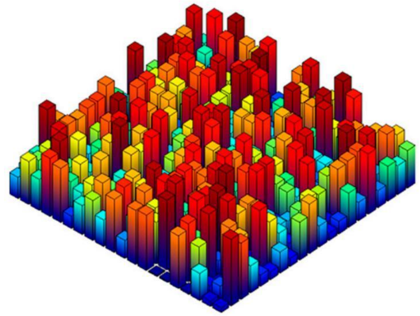
Optica 8 1033 (2021)

Outline

I Random lasers: Localization induced by disorder

Anderson localization





Optica 8 1033 (2021)

II Quantum chaos: localization induced in open systems

Periodic orbits

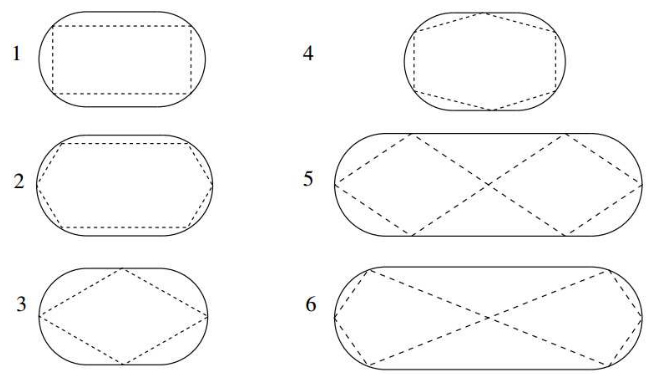
Outline

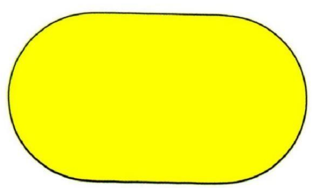
I Random lasers: Localization induced by disorder

Anderson localization

II Quantum chaos: localization induced in open systems

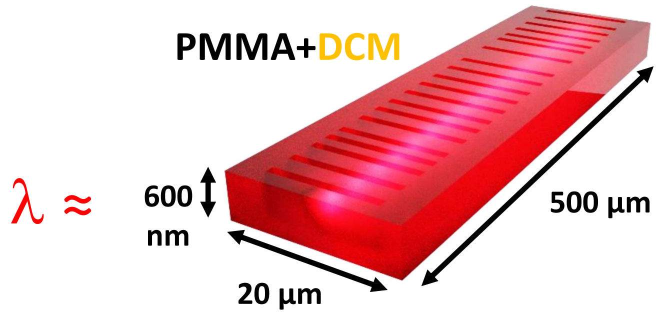
Periodic orbits = classical periodic trajectories

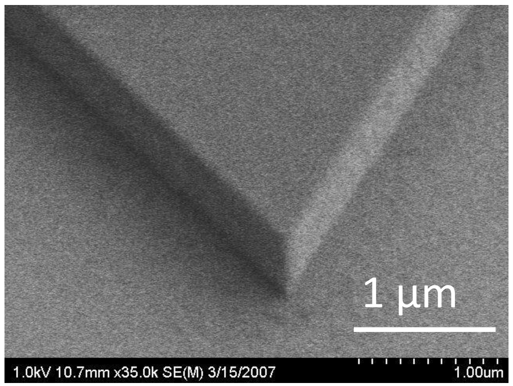




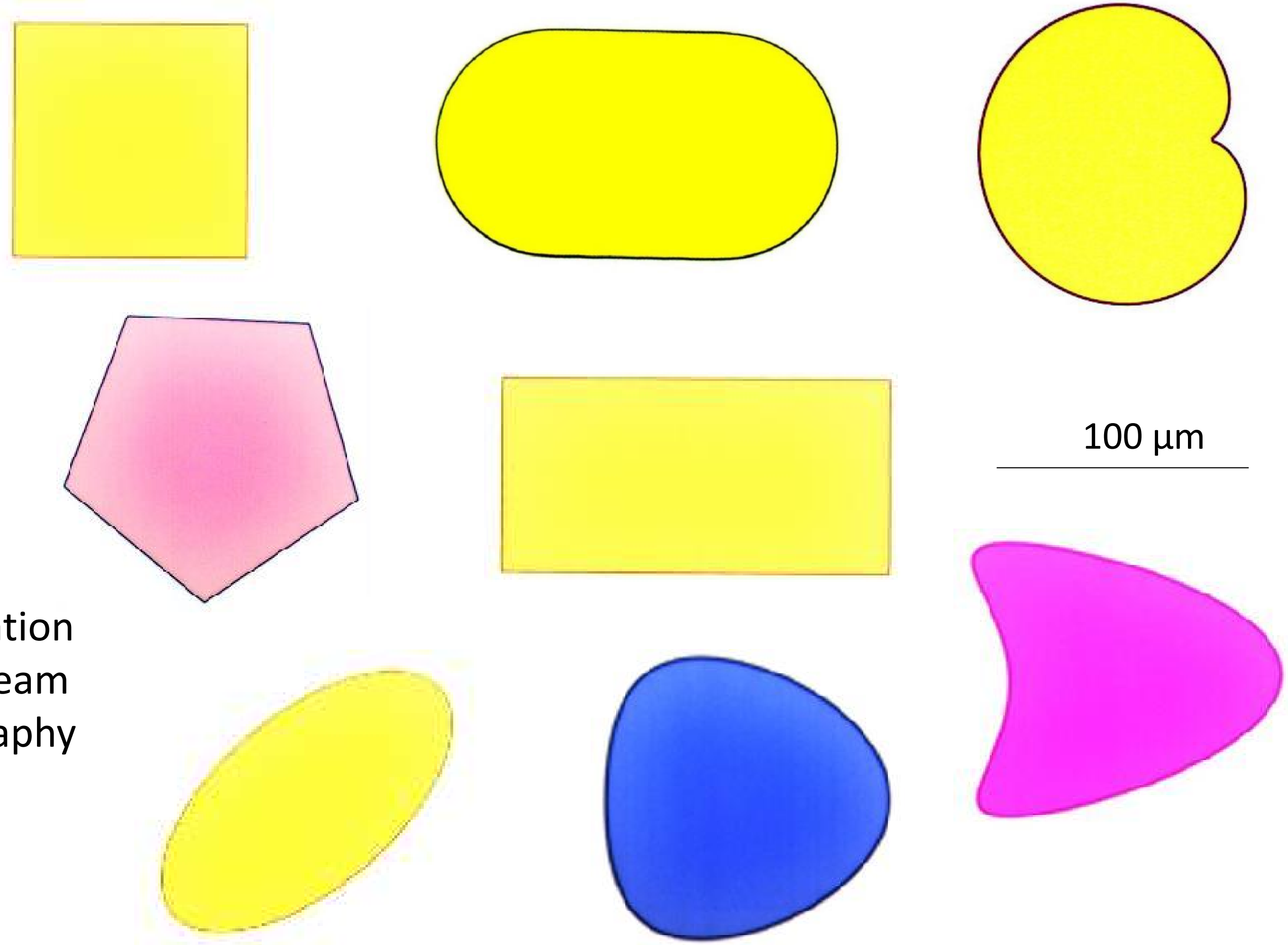
II 2D microlasers

Photographs with an optical microscope, real colors

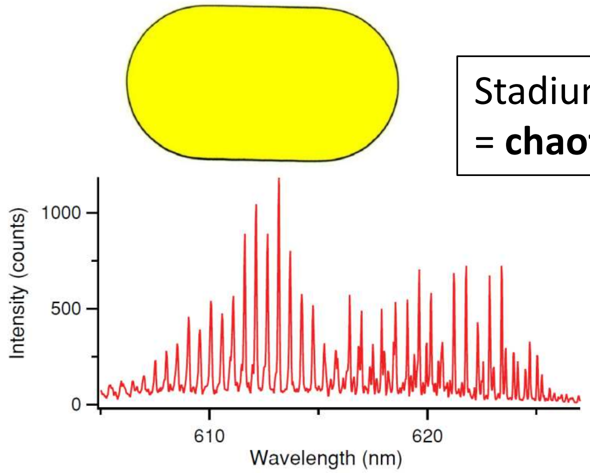




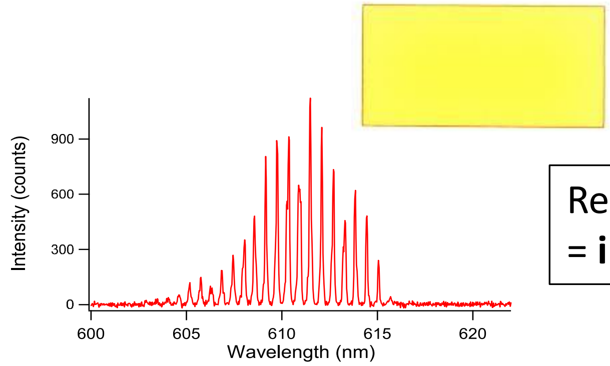
Fabrication by e-beam lithography



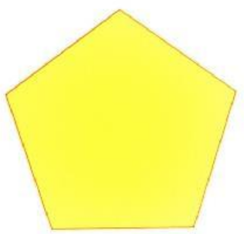
II Quantum chaos:= relationship between a quantum (or wave) system and its classical counterpart



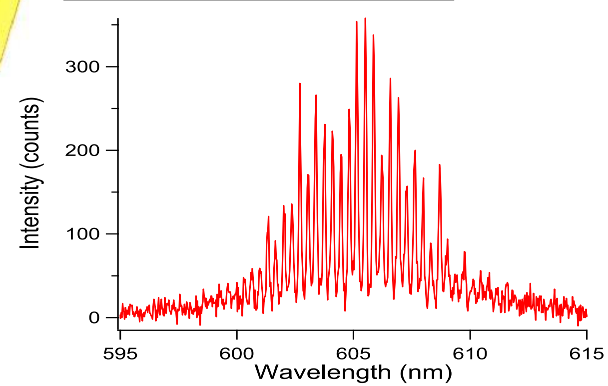
Stadium billiard
= **chaotic**

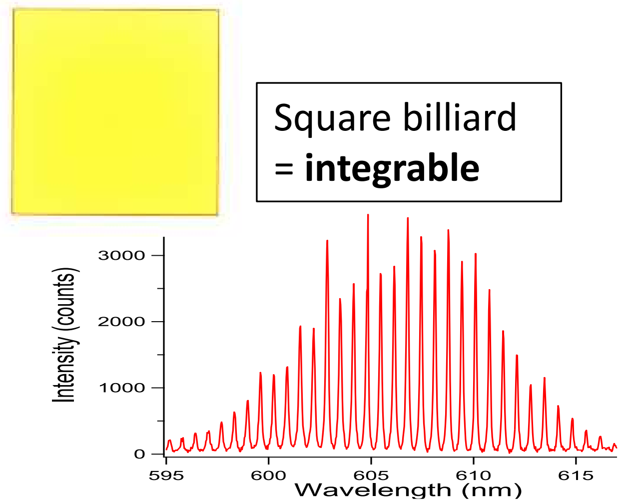


Rectangle billiard
= **integrable**



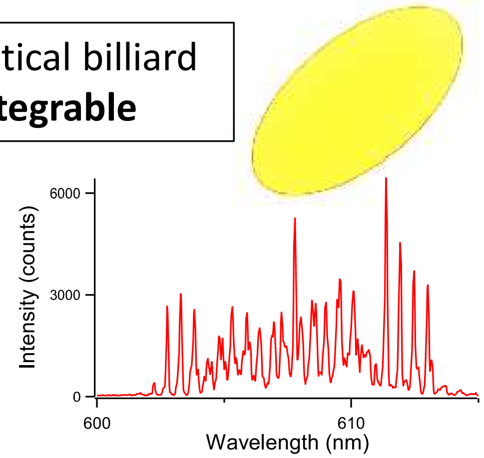
Pentagon billiard
= **pseudo-integrable**





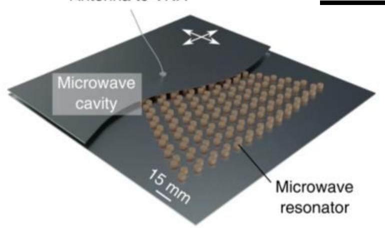
Square billiard
= **integrable**

Elliptical billiard
= **integrable**



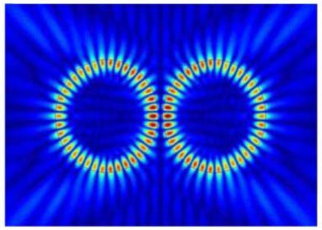
II Quantum (wave) chaos: classical ⟷ quantum

Microwave billiards



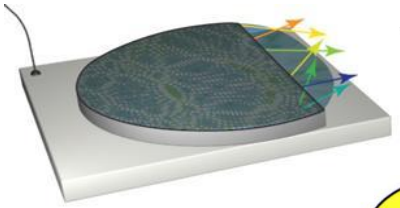
Light: Science & Applications 9 146 (2020)

Tera-Hertz resonators

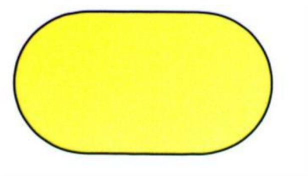


OE 16, 7339 (2010)

Optical cavities



Science 361, 1225 (2018)



PRE ***83*** *032608 (2011)*

Acoustics

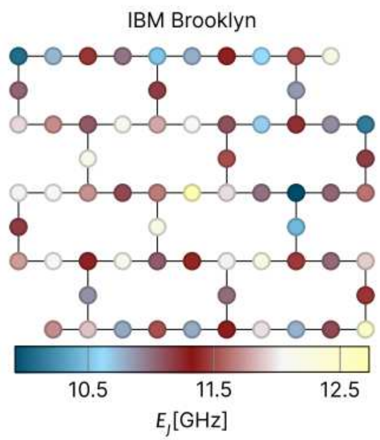
PRL 104 164101 (2010)

Loop quantum gravity

http://olemiss.edu/depts/physics_and_astronomy/research/gravitation.html

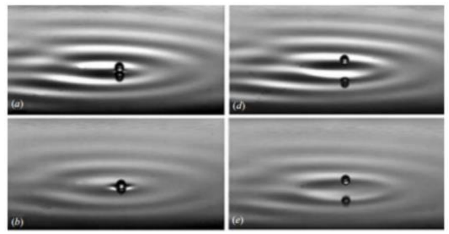
PRL 107, 011301 (2011)

Coupled Qbits



Nat. Com. 13 2495 (2022)

Fluid dynamics



New J. Phys. 18, 113037 (2016)

II Quantum chaos: **trace formula**

Density of states $d(k) = \sum_m \delta(k - k_m)$ Wave physics

Semi-classical limit

$k \to \infty$

Integrable

Balian & Bloch, Ann. Phys. 60 401 (1970)

Chaotic

Gutzwiller, Chaos in classical and quantum physics, Springer (1980)

$$d(k) \propto \sum_p \mathbf{r_p} C_p \cos(\mathbf{n} k L_p + \varphi_p)$$ Classical physics

Periodic orbits
Geometric features

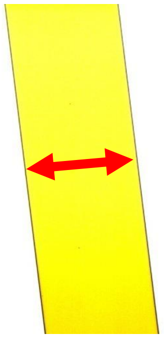
For a convex **dielectric** resonator
PRE 83 032608 (2011)

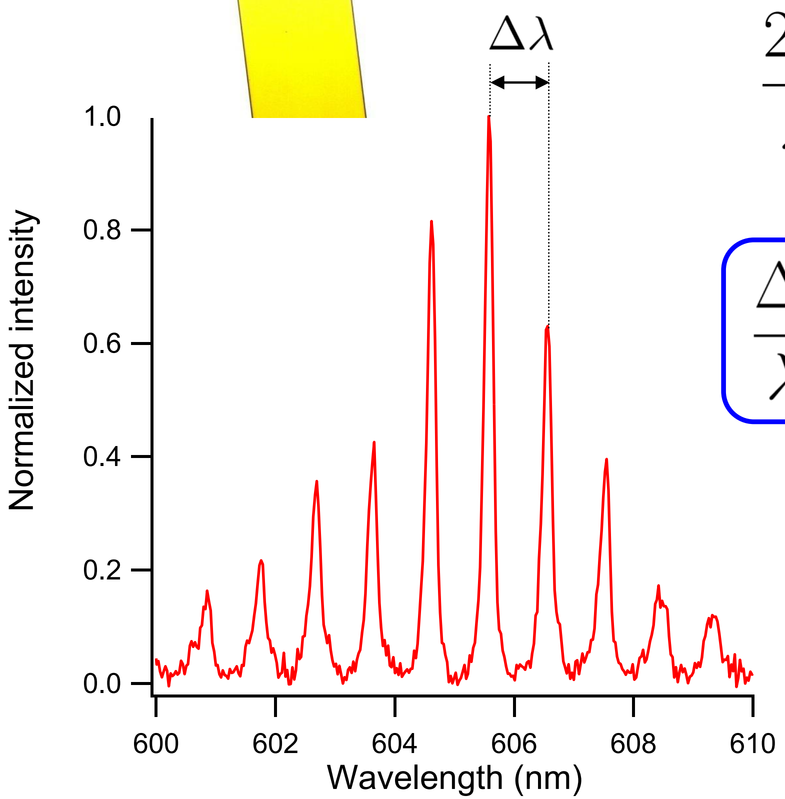
If only one or two low-loss periodic orbits ⇒ The modes are located along these periodic orbits.

*T. Harayama & S. Shinohara Physical Review E **92**, 042916 (2015)*

II Periodic orbits:= periodic classical trajectories

Length *L* of the periodic orbit ?

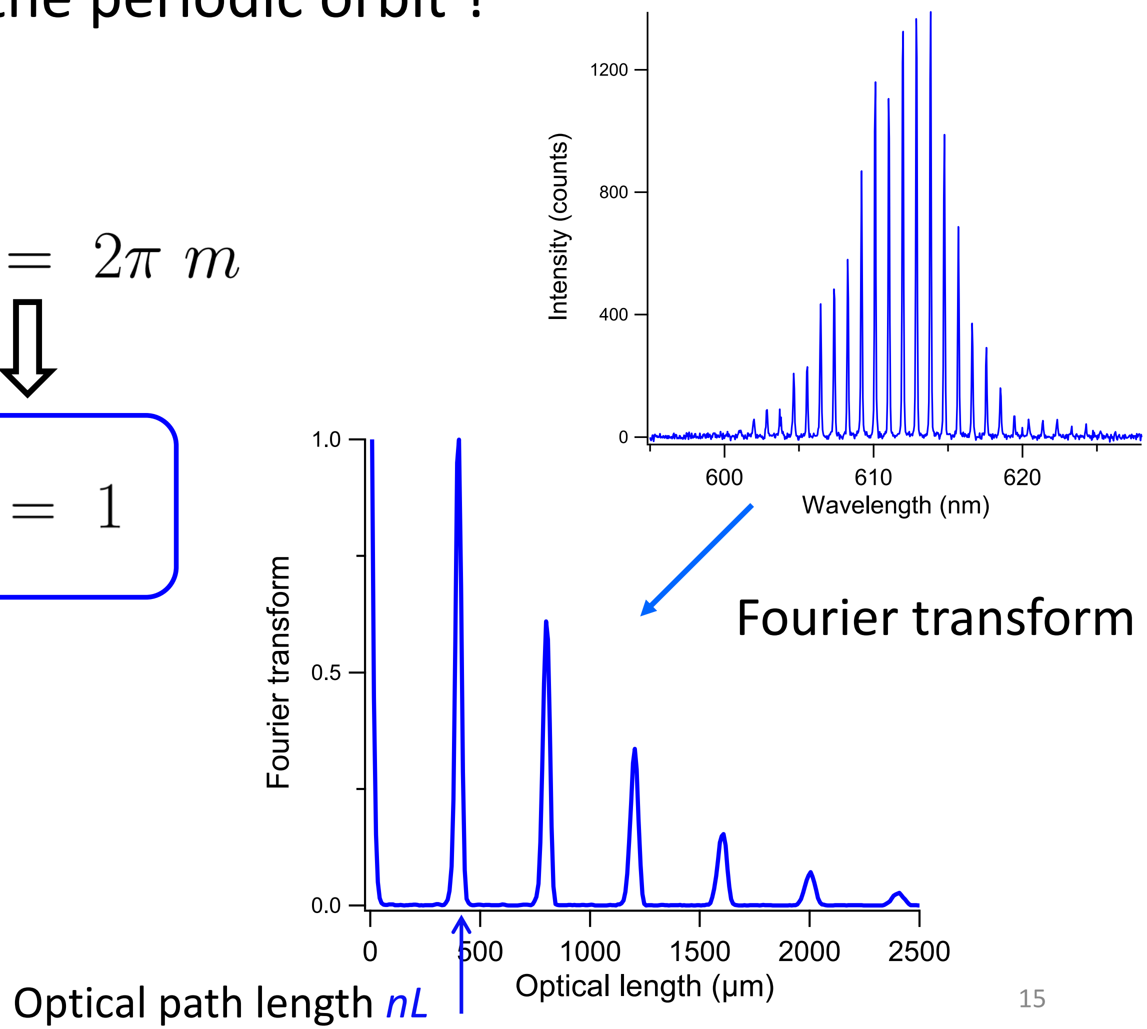




$$\frac{2\pi}{\lambda} n\, L = 2\pi\, m$$

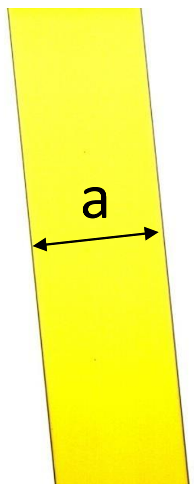
$$\Downarrow$$

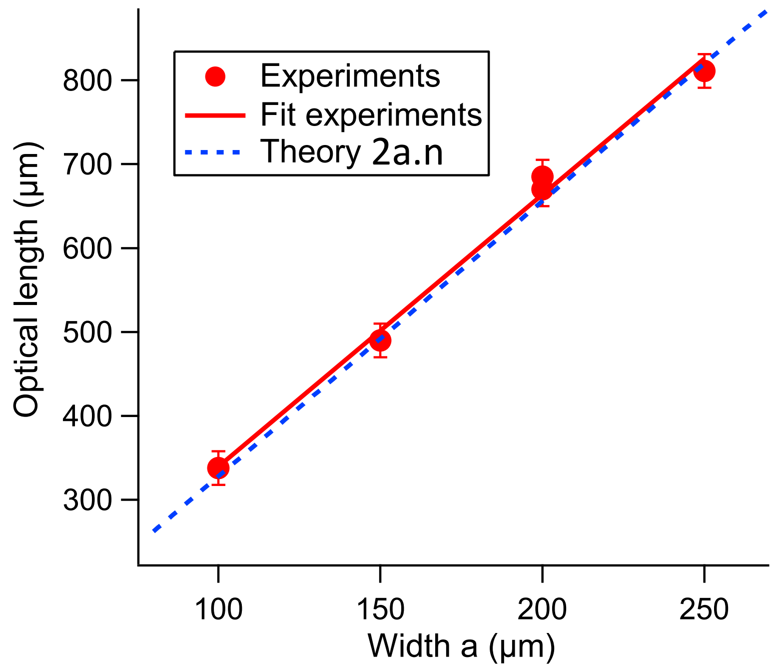
$$\frac{\Delta\lambda}{\lambda^2} n\, L = 1$$



II Periodic orbits

Test: the Fabry-Perot resonator



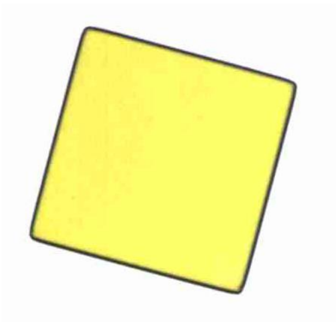


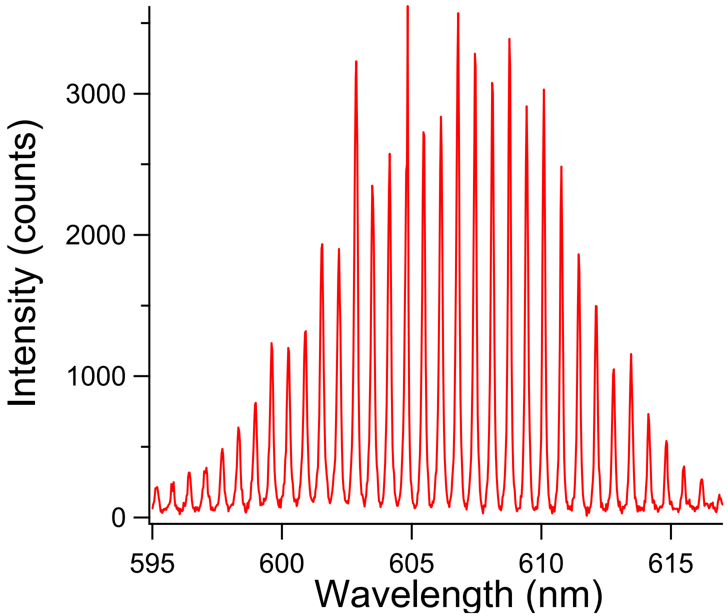
n = 1.64

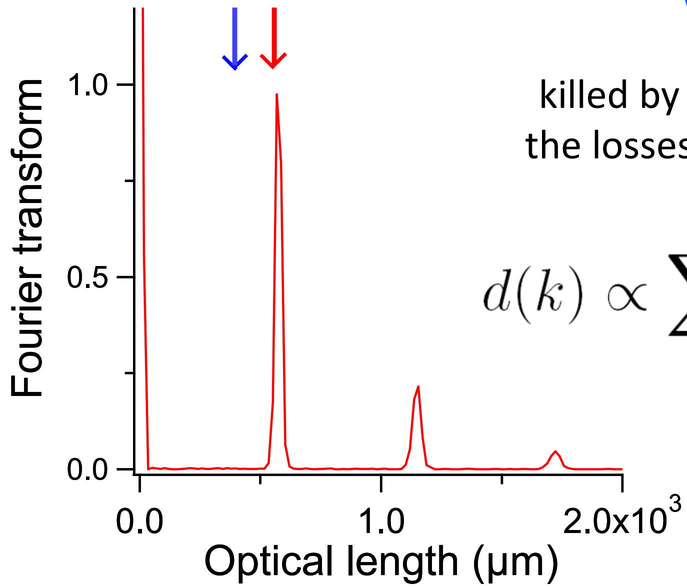
Effective index
+
dispersion

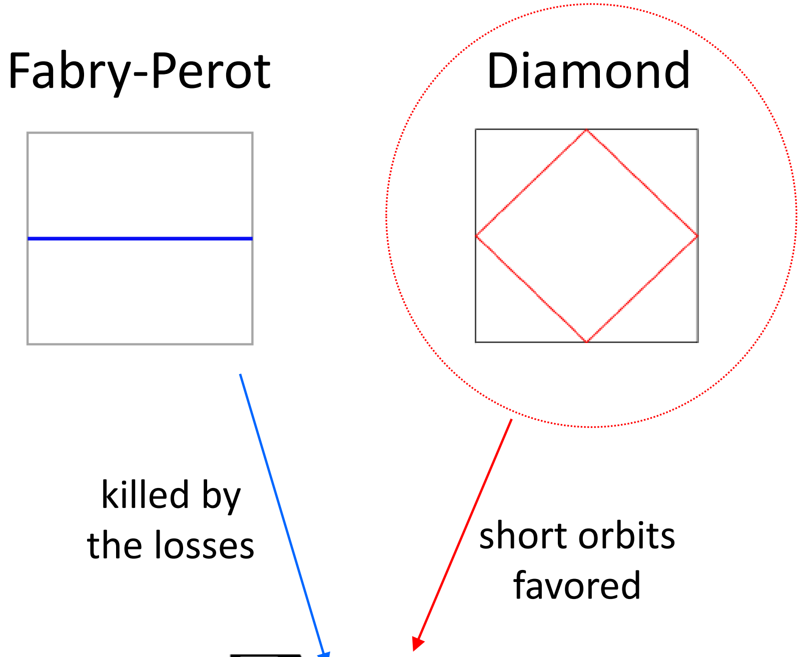
II Periodic orbits

Square microlaser: Several periodic orbits



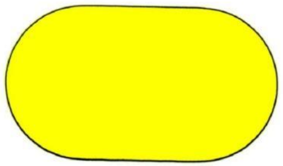


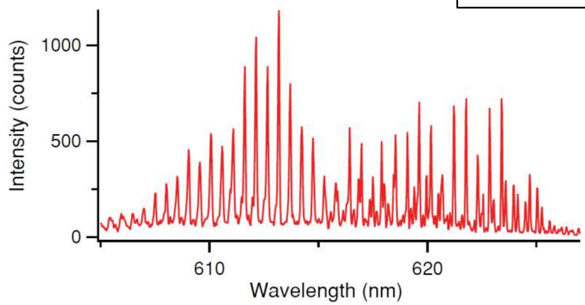




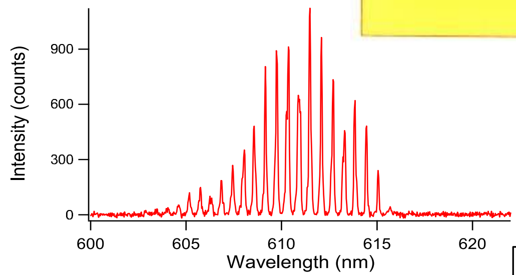
$$d(k) \propto \sum_p \mathbf{r_p} C_p \cos(\mathbf{n} k L_p + \varphi_p)$$

II Quantum chaos:= relationship between a quantum (or wave) system and its classical counterpart



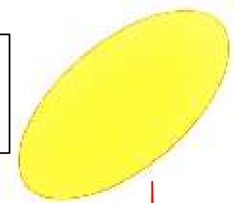


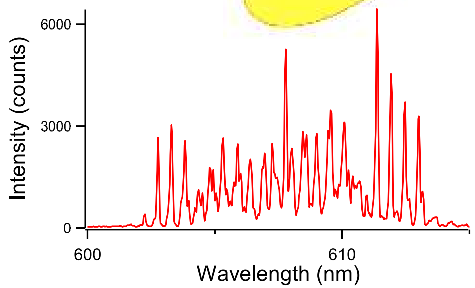
Stadium billiard
= **chaotic**

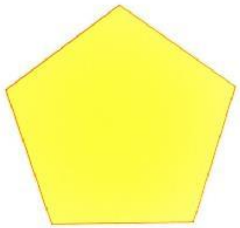


Rectangle billiard
= **integrable**

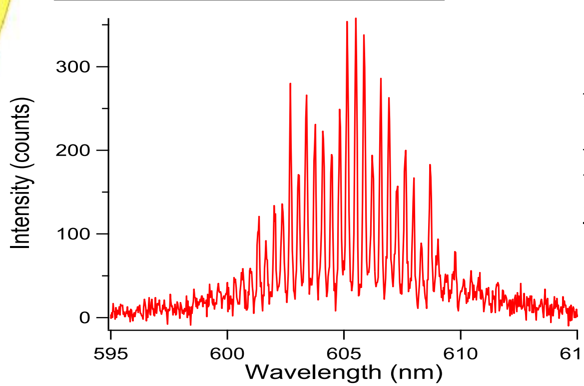
Elliptical billiard
= **integrable**

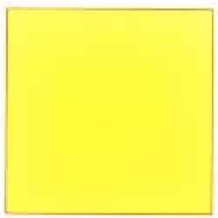




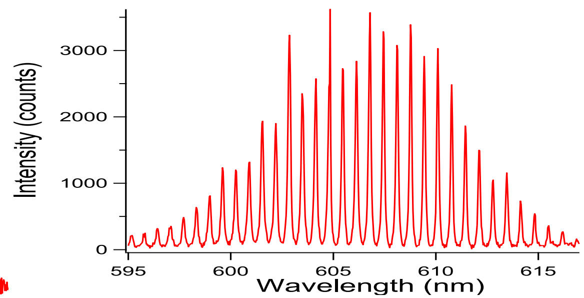


Pentagon billiard
= **pseudo-integrable**





Square billiard
= **integrable**

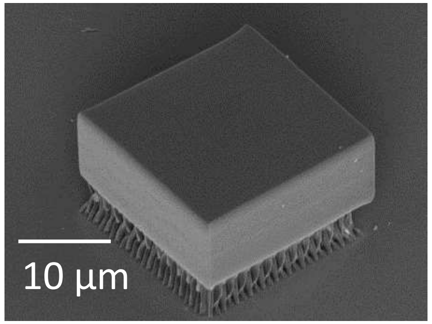


$$d(k) \propto \sum_p \mathbf{r_p} C_p \cos(\mathbf{n} k L_p + \varphi_p)$$

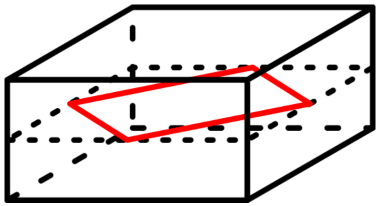
*Physical Review E **83** 032608 (2011)*

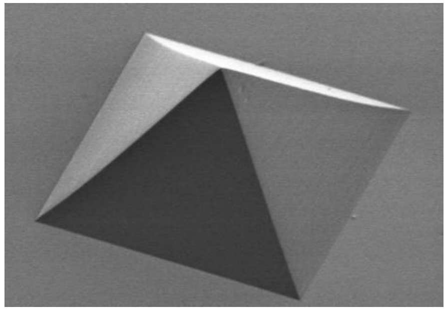
II Quantum chaos with 3D microlasers

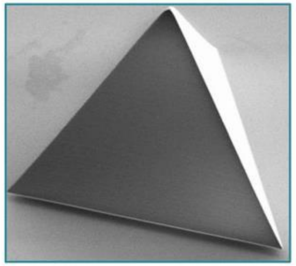
Fabrication by Direct Laser Writing with 2 photons
by Dominique Decanini C2N

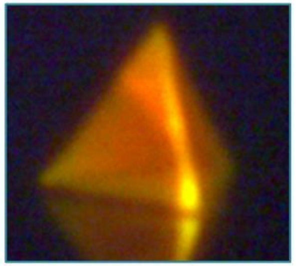


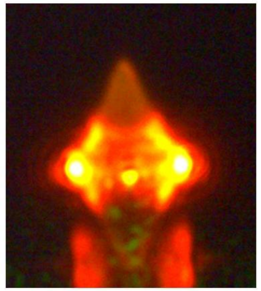
*Optics Express, **22** 12316 (2014)*

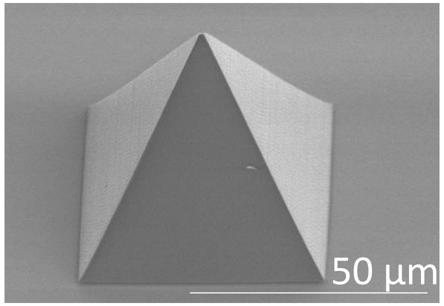


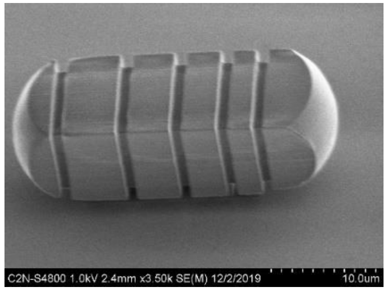


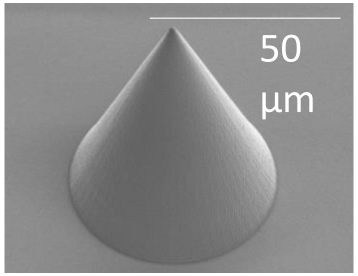












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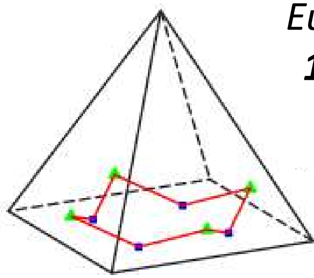
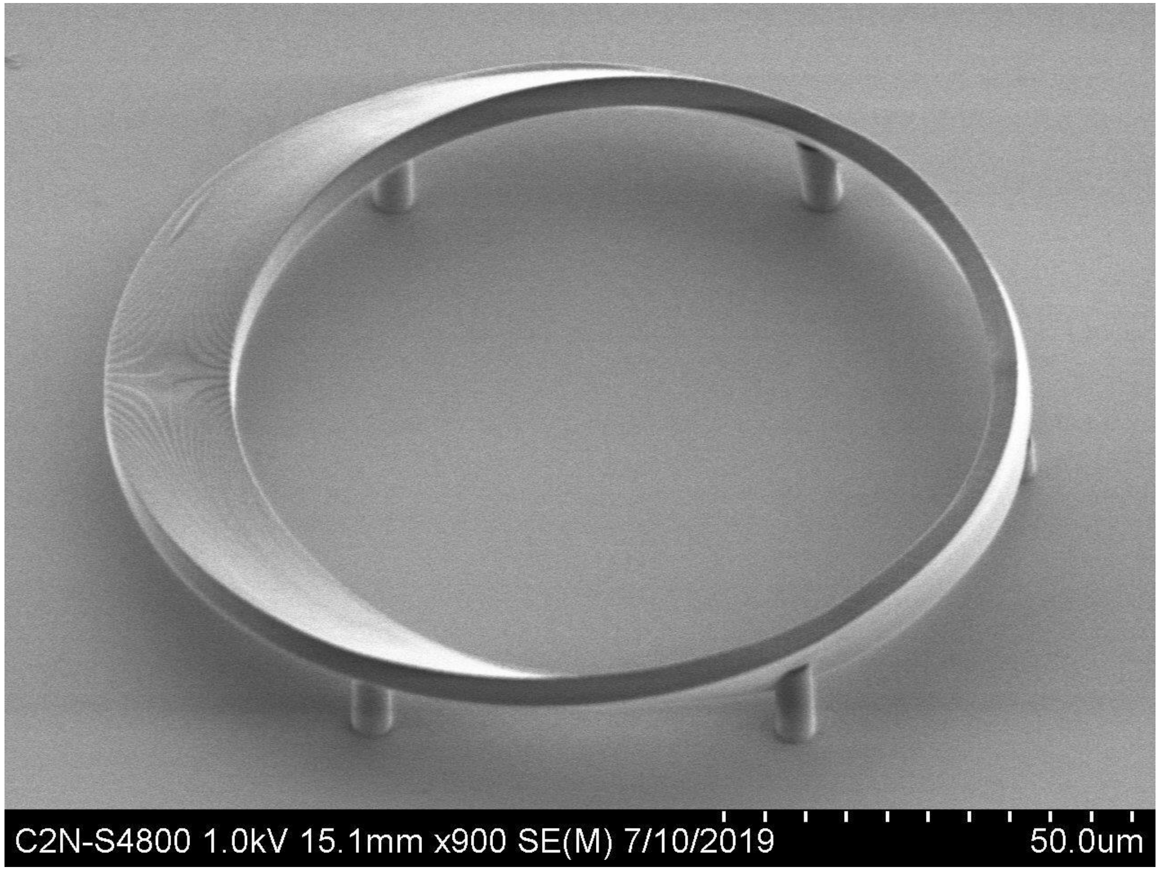
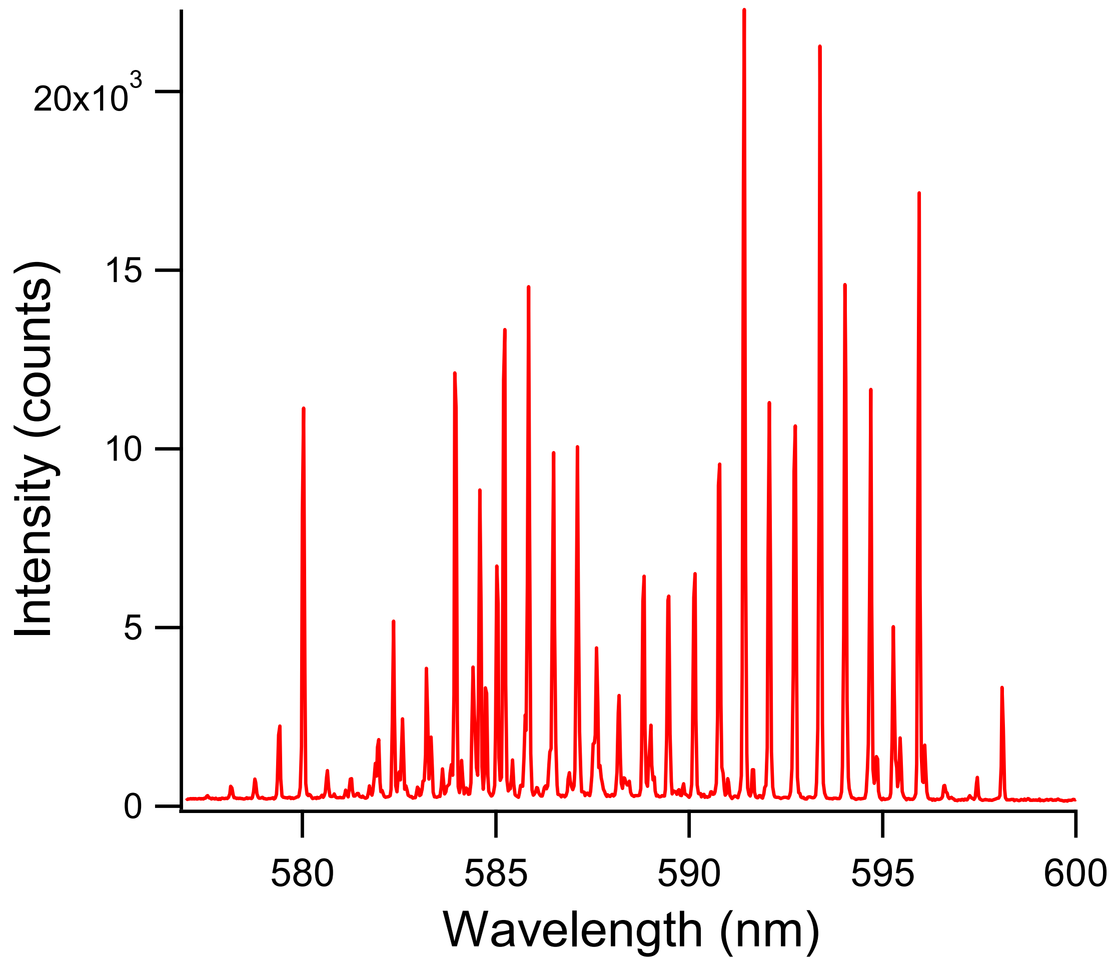


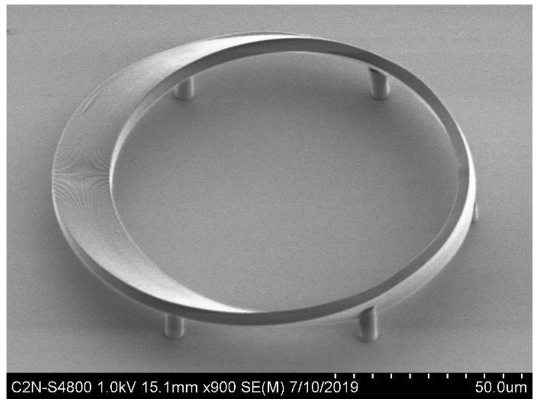
II Quantum chaos with 3D microlasers



Dominique Decanini

II Quantum chaos with 3D microlasers



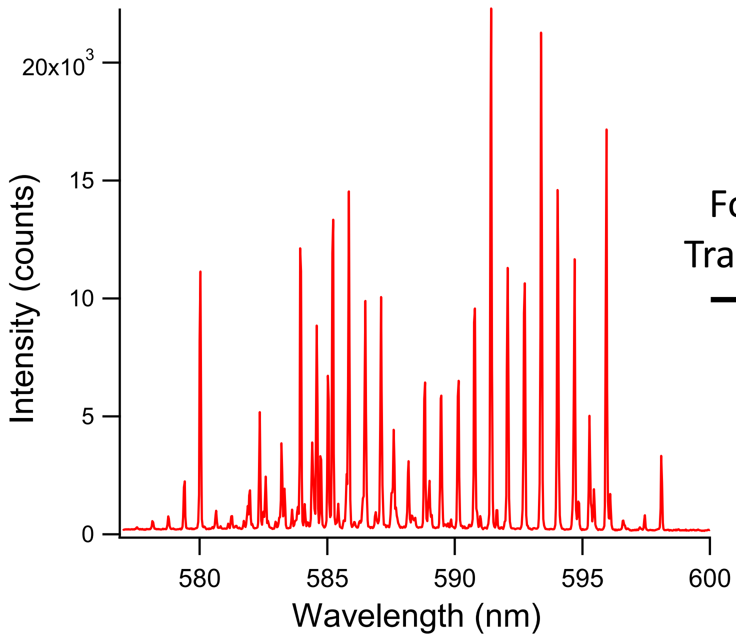


$$d(k) \propto \sum_{p} \mathbf{r_p} C_p \cos(\mathbf{n} k L_p + \varphi_p)$$

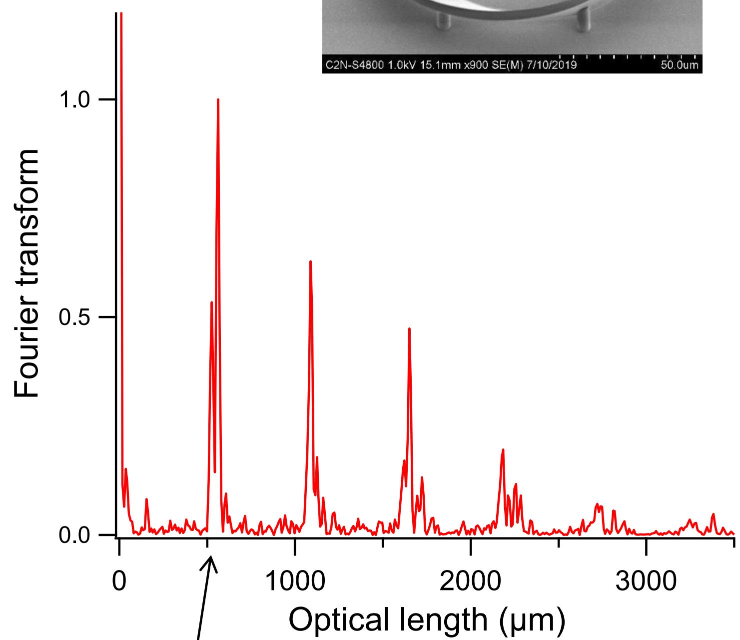
Periodic geodesics

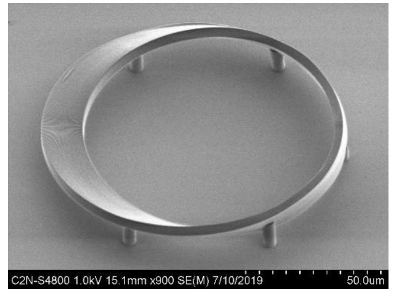
A geodesic:= The shortest path
between two points on the surface.

II Möbius strip microlaser: Spectrum and geodesics



Fourier Transform →





Optical length of the geodesic: nL

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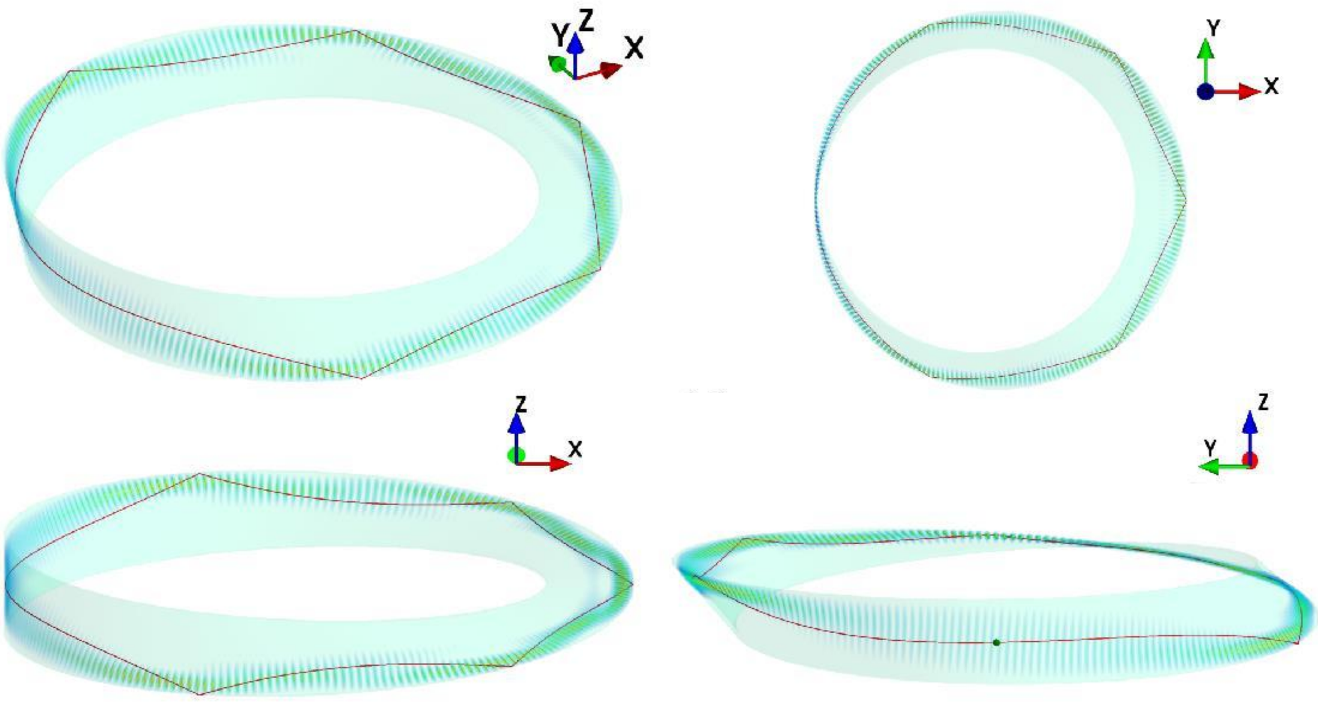
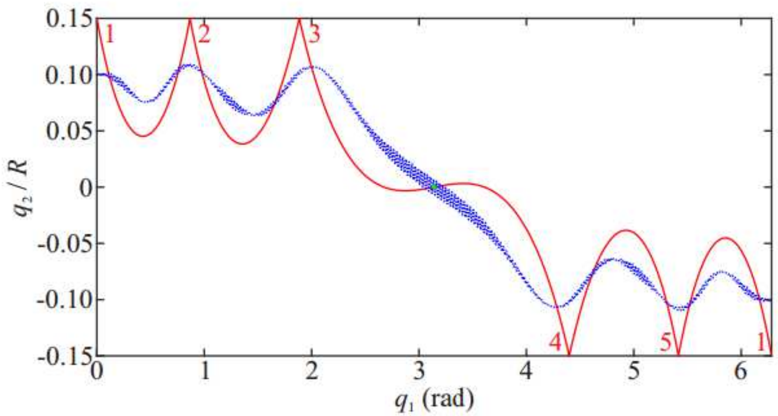
II Möbius strip microlaser: 3D FDTD simulations

Different views of a <u>single wavefunction</u> with Re(kR) = 88.0 and Im(kR) = -0.00022



$$\langle w\rangle(\varphi) = \frac{\iint_{\text{Half-plane}} w\,\rho(w,\varphi,q_3)\,dw\,dq_3}{\iint_{\text{Half-plane}} \rho(w,\varphi,q_3)\,dw\,dq_3}\,,$$

$$\rho = \frac{1}{2}\epsilon_0\epsilon_r|\vec{E}|^2 + \frac{1}{2}\mu_0|\vec{H}|^2$$



⇨ Red line = a periodic geodesic

Average position of the wavefunction along W

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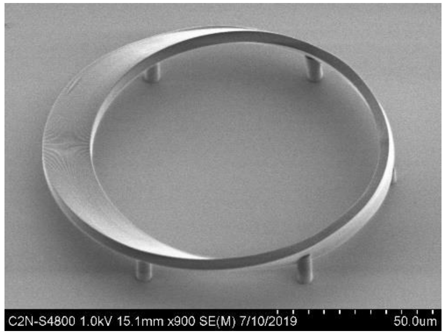
Xavier Chécoury

II Non-Euclidean Photonics (NEP)



The laser modes propagate along periodic geodesics.

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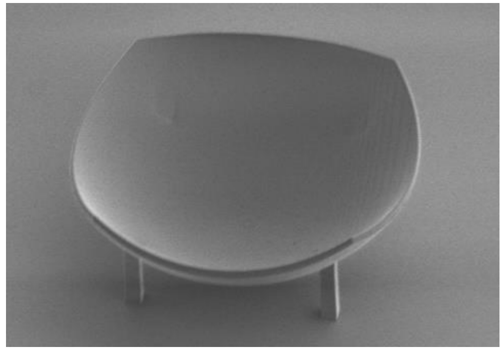
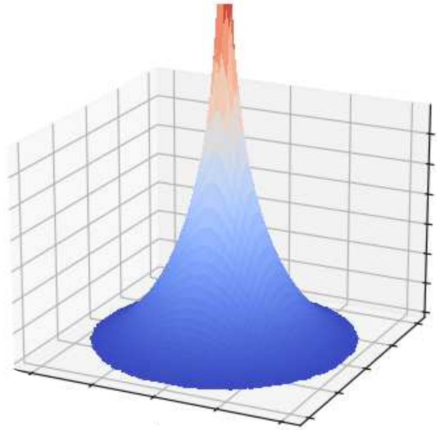
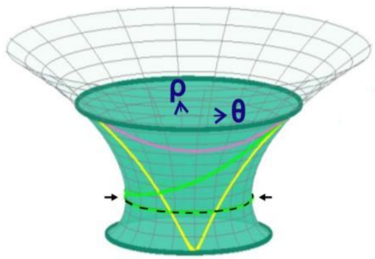


Spherical square
Gaussian curvature K=1
Stable



Pseudo-sphere
K=-1
Unstable



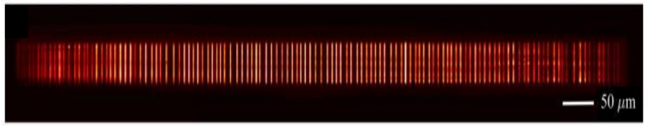
Schwarzshild metric + black hole
Light is trapped

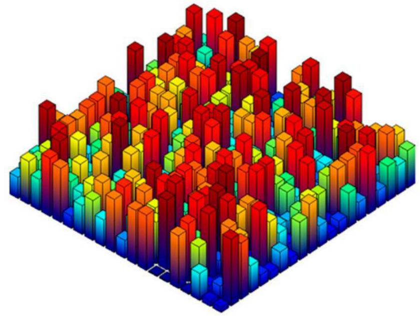
⟹ A black hole laser

Conclusion

I Random lasers: Localization induced by disorder

Anderson localization



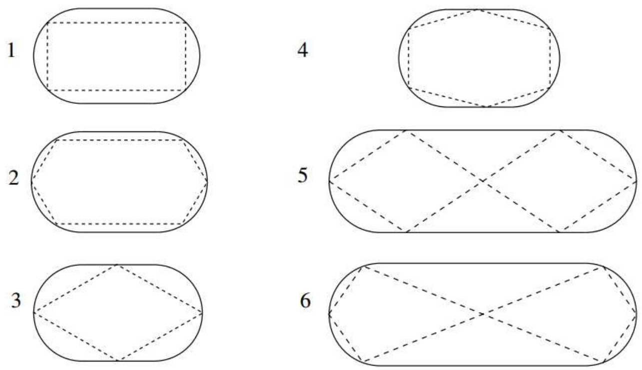


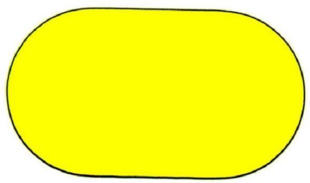
Patrick Sebbah
Bhupesh Kumar

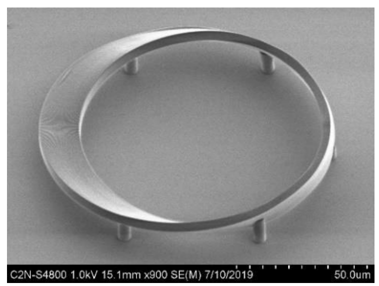
Optica 8 1033 (2021)

II Quantum chaos: localization induced in open systems

Periodic orbits







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Clément Lafargue, Joseph Zyss, Stefan Bittner, Dominique Decanini, Xavier Chécoury