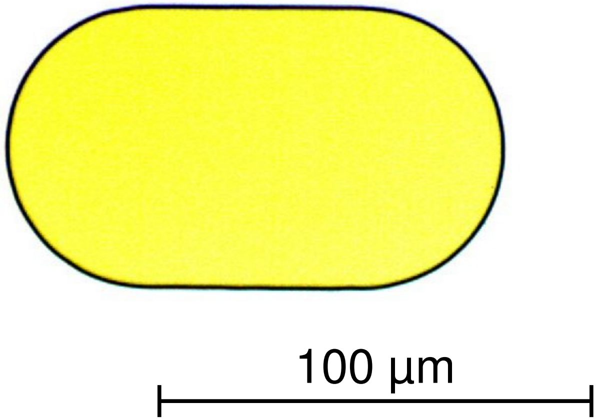
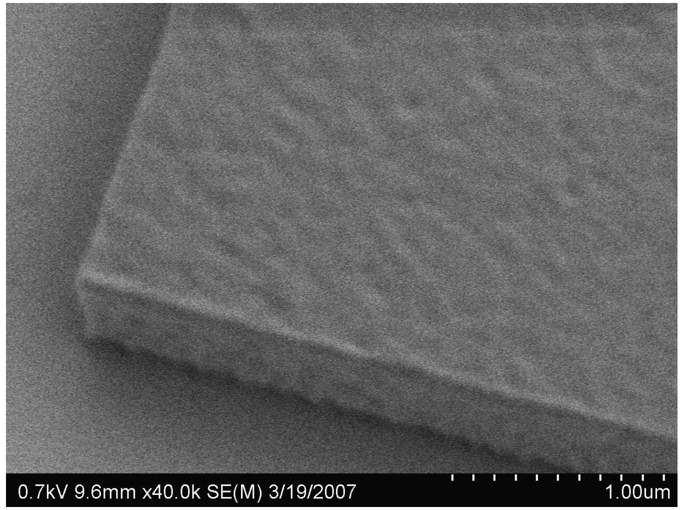
Organic micro-lasers

Melanie LEBENTAL





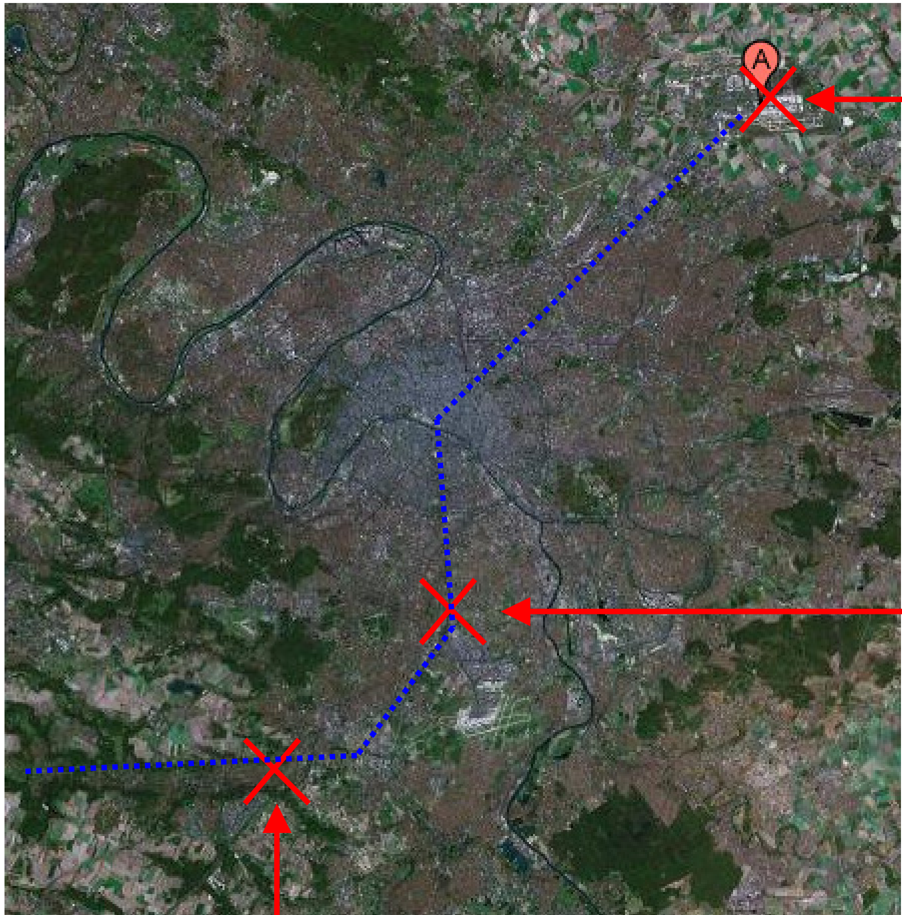
N. Djellali, S. Lozenko, I. Gozhyk, J. Lautru, I. Ledoux, and J. Zyss

Laboratory for Quantum and Molecular Photonics (LPQM)

ENS of Cachan

Resonances in Mathematical Physics, January 2009

To put Cachan on the map…



Charles-de-Gaulle Airport

RER B (urban train)

ENS of Cachan

Orsay University

Coll: E. Bogomolny, R. Dubertrand, C. Schmit (LPTMS)

Outline

Organic micro-**lasers** as test-beds
for wave chaos of **open** systems

I Micro-lasers and wave chaos

II Existing tools *(what we can do)*

III Open questions

I Wave chaos for closed systems

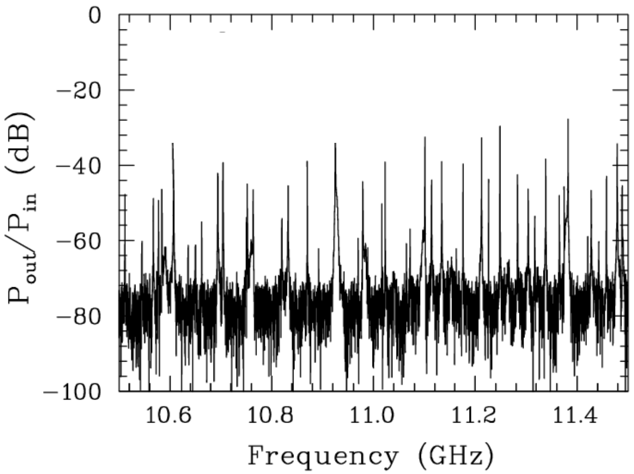
Conjectures

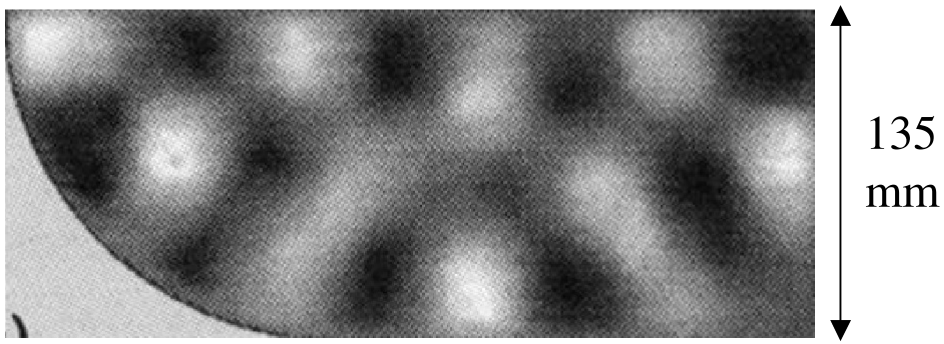
Spectra: random matrix theory

*Bohigas et al. , PRL **52** 1 (1984)*

Wavefunctions: random superposition

*Berry, J. Phys. A **10** 2083 (1977)*

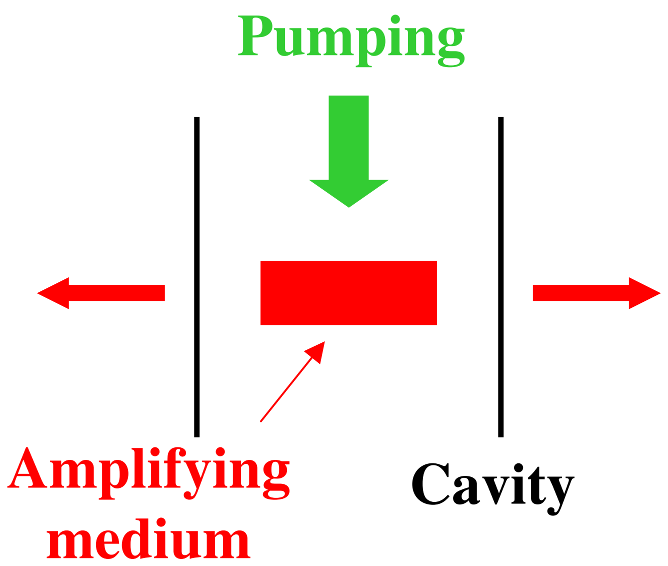




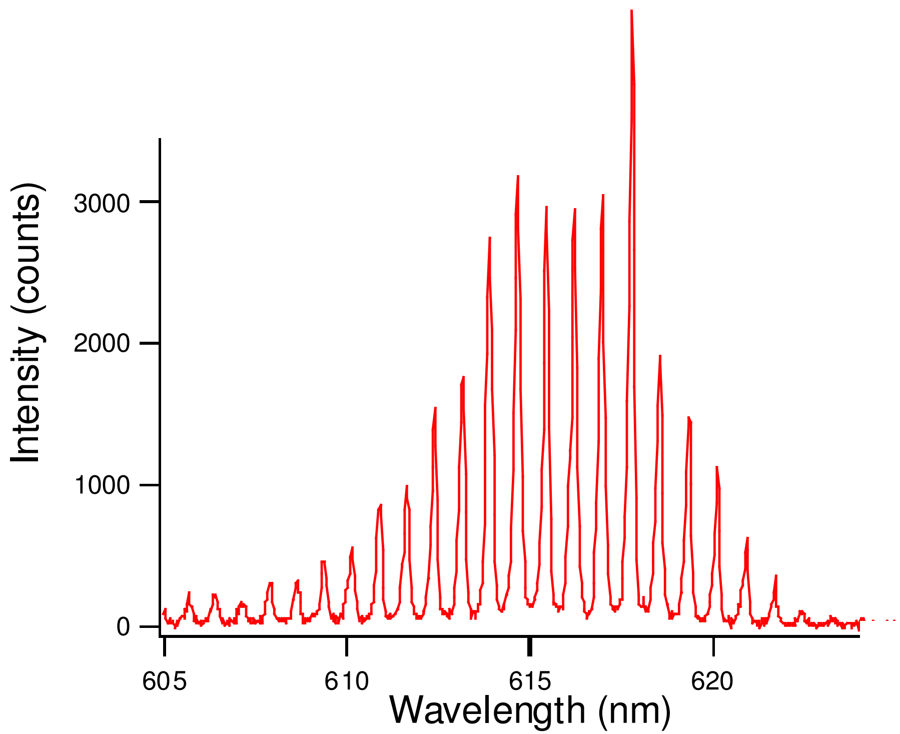
Experiments with metallic stadium-shaped microwave cavities

*Alt et al., PRE **60**, 2851-2857 (1999)* *Stein et al., PRL **75**, 53-56 (1995)*

I Lasing: basic ingredients



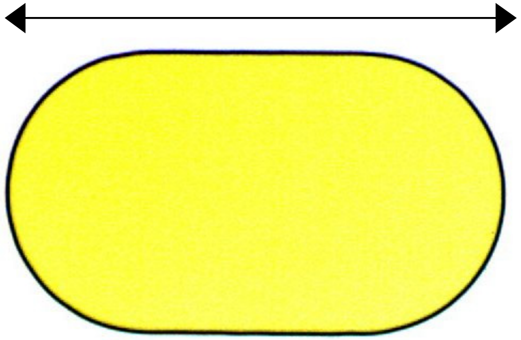
No direct connexion between pumping and emission



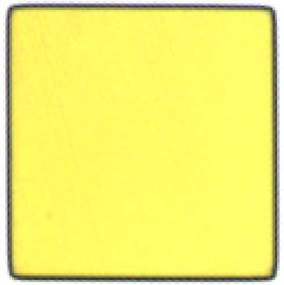
- Directions of emission ?
- Spectrum ?

Plastic micro-lasers

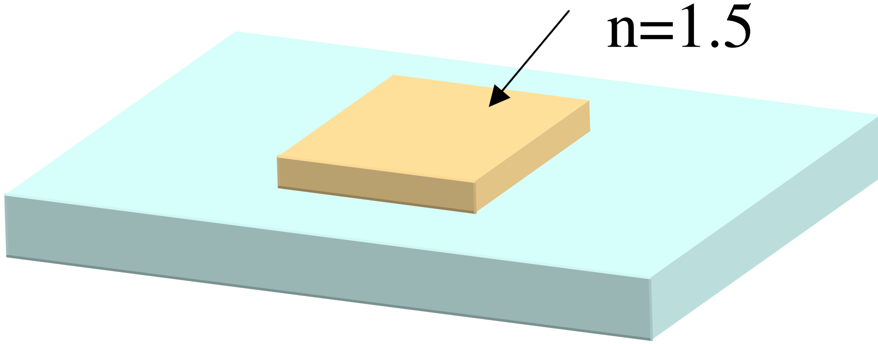
50-100 µm



Photography



A cavity
n=1.5

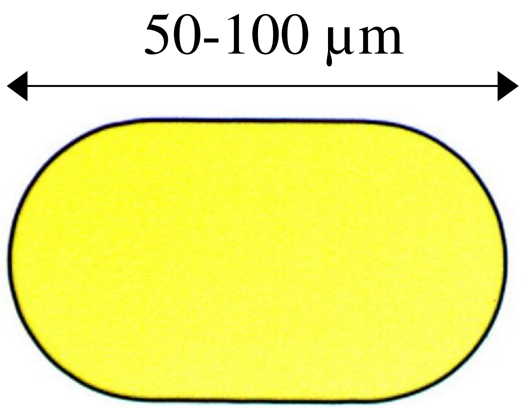


Matrix host: polymer (PMMA)

Guest: laser dye (DCM)

$\lambda \sim 0.6$ µm

Plastic micro-lasers



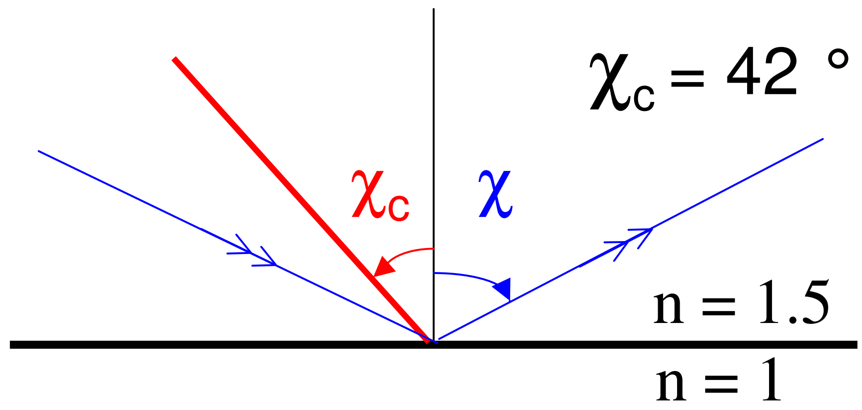
Photography

- Cheap
- Easy
- Low refractive index
- Modular (mask)

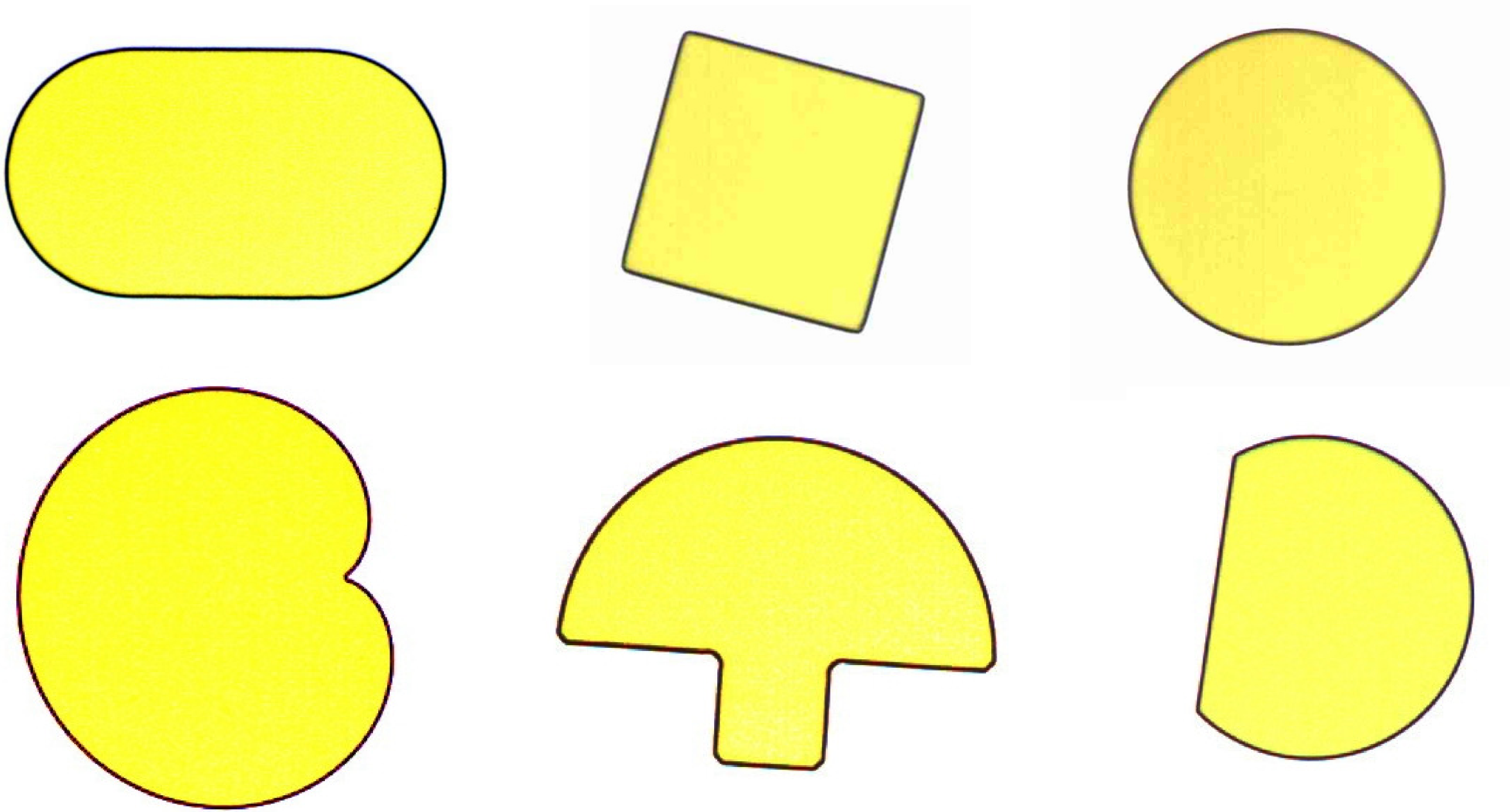
Matrix host: polymer (PMMA)

Guest: laser dye (DCM)

$\lambda \sim 0.6$ µm



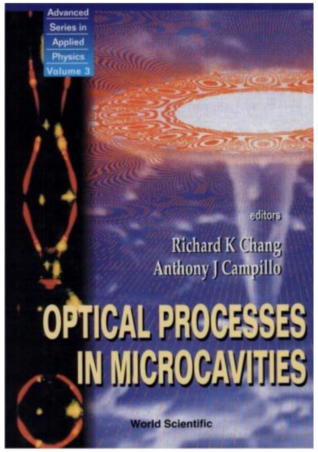
I Microlasers: cavity shapes



Photographies from an optical microscope

I Practical applications

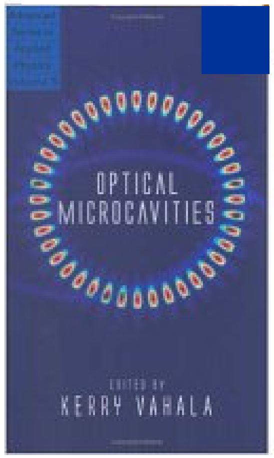
Chang
Campillo
1996



Optical telecommunications

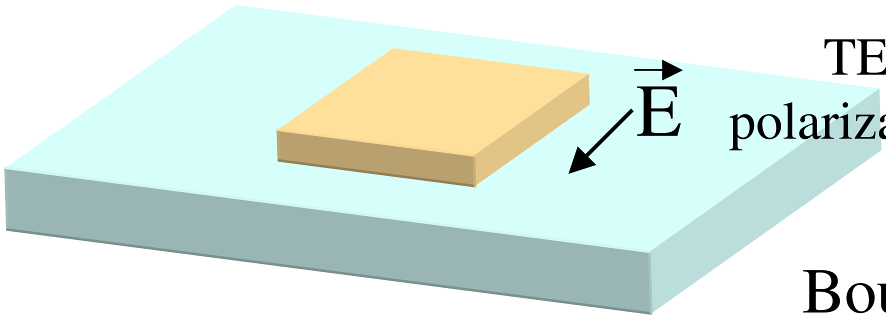
Chemical/biological sensors

Vahala
2004

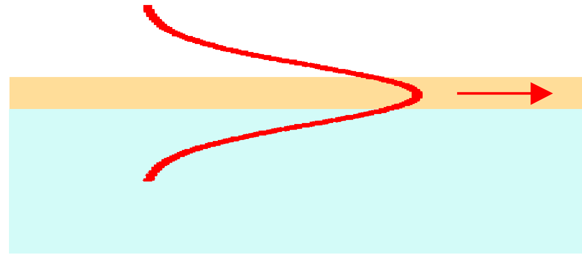


Practical applications of micro-resonators in optics and photonics, Matsko, 2009.

I From electromagnetism to wave chaos



TE polarization



Boundary conditions

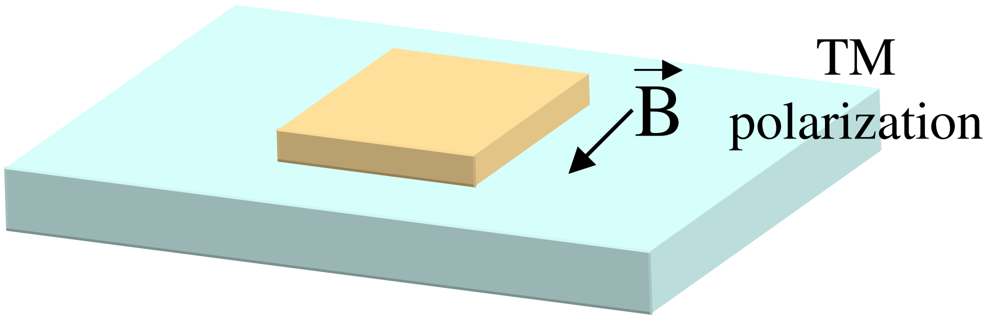
Inside	Outside
$(\Delta + n^2 k^2) \left\| \begin{matrix} \vec{E} \\ \vec{B} \end{matrix} \right. = 0$	$(\Delta + k^2) \left\| \begin{matrix} \vec{E} \\ \vec{B} \end{matrix} \right. = 0$

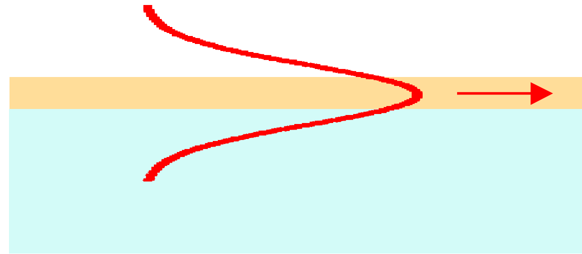
TE $\Rightarrow$ $\boxed{\Psi = B_z}$

Effective index approximation

Passive cavity (no laser)

I From electromagnetism to wave chaos





Inside

$$(\Delta_{xy} + n_{eff}^2 k^2)\ \Psi = 0$$

Outside

$$(\Delta_{xy} + k^2)\ \Psi = 0$$

Effective index approximation

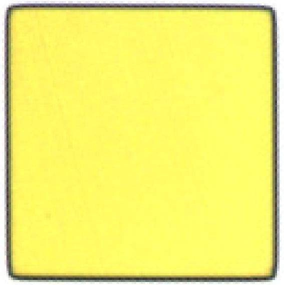
TE $\Rightarrow$ $\Psi = B_z$

TM $\Rightarrow$ $\Psi = E_z$

Passive cavity (no laser)

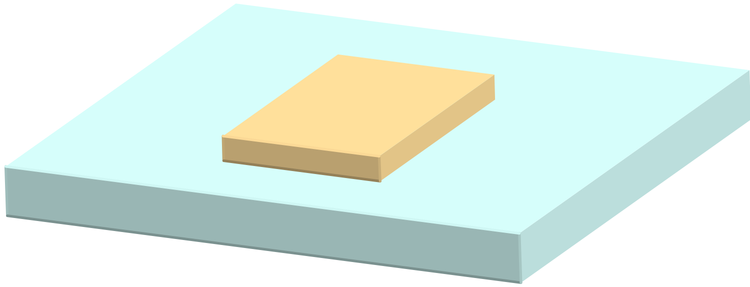
Outline

I Micro-lasers and wave chaos



Cavity shape → Billiard *(open)*

Laser effect → To fill the resonances with photons



II Existing tools *(what we can do)*

III Open questions

Outline

I Micro-lasers and wave chaos

II Existing tools *(what we can do)*

Numerics & Theory

- Wavefunctions
- Directions of emission
- Spectra

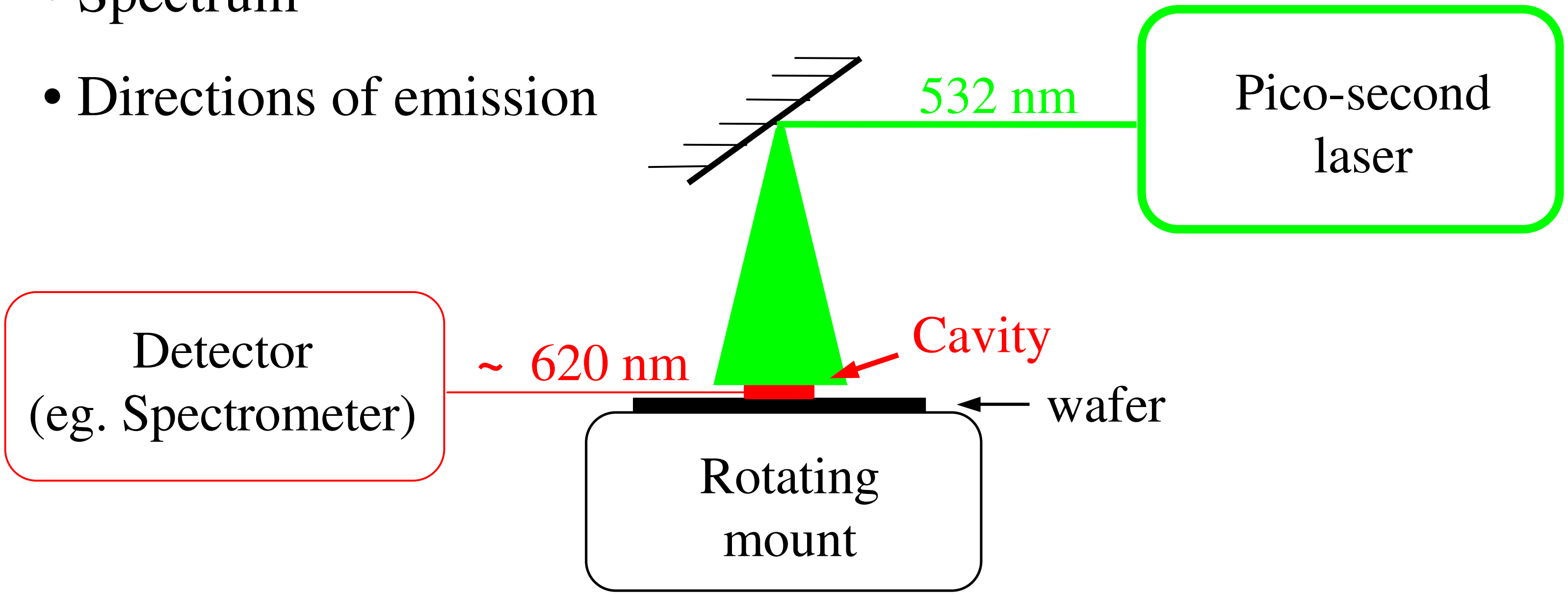
Experiments

III Open questions

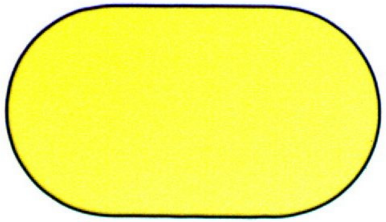
II Experimental set-up

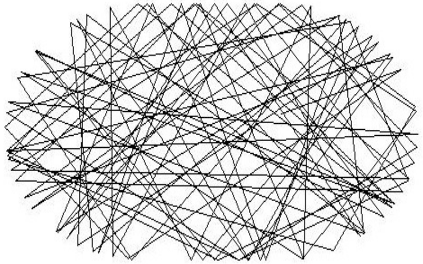
Information about :

- Lasing
- Spectrum
- Directions of emission

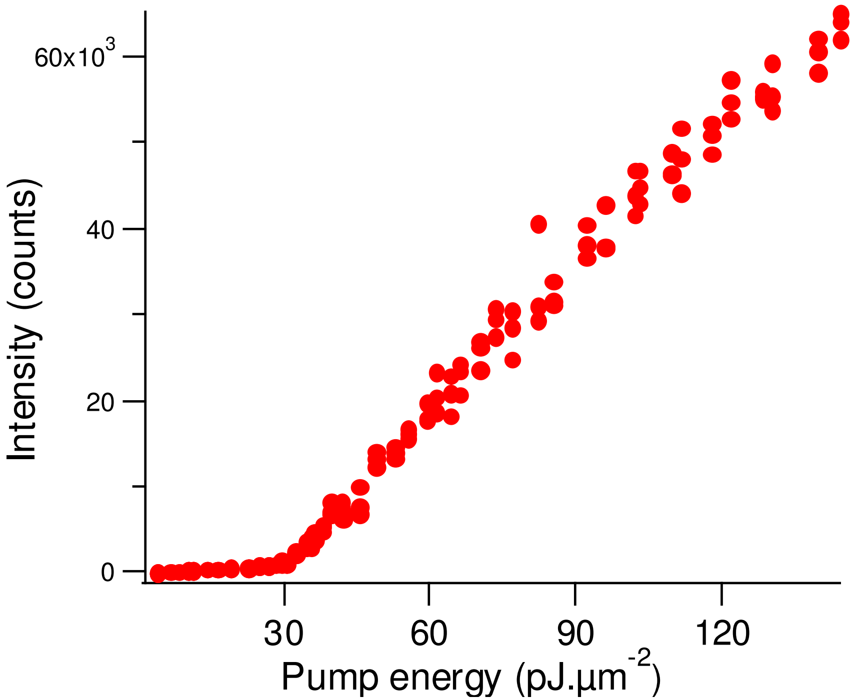


II Lasing ?





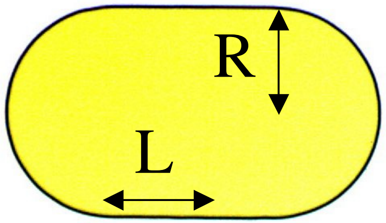
Laser threshold

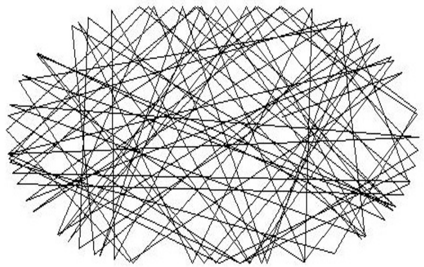


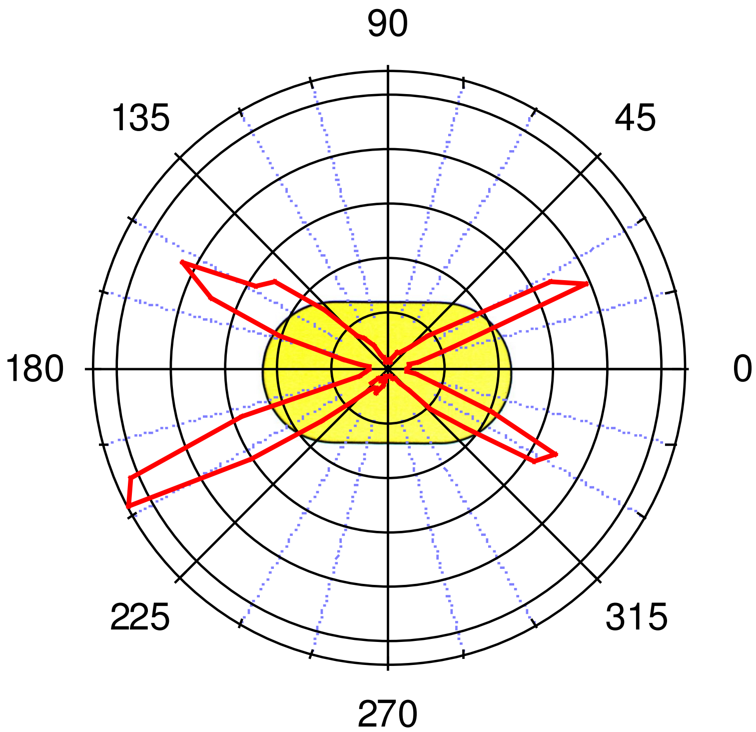
- Ease for detection
- Coherence

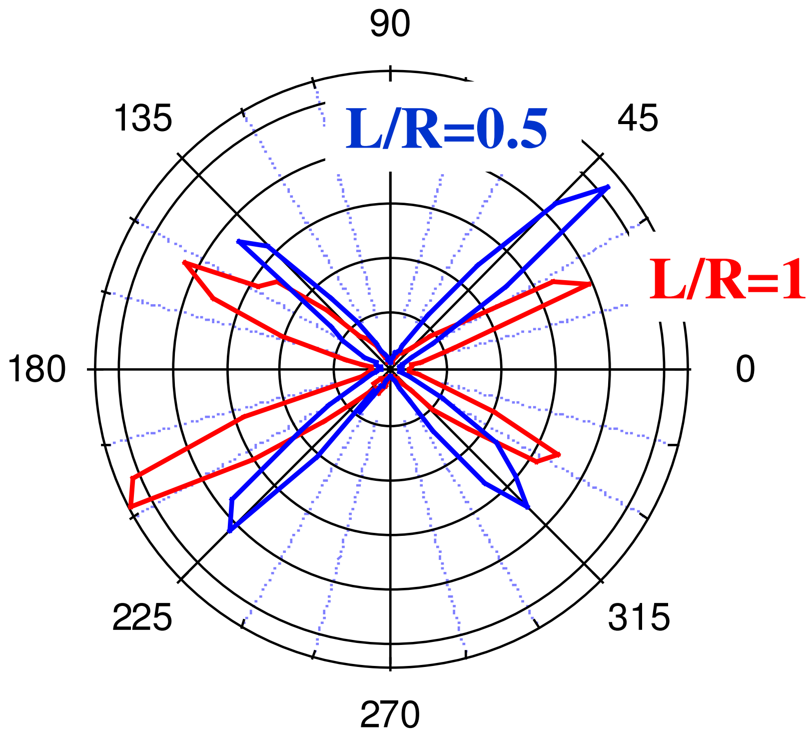
$$kR_{exp} \sim 200 - 1000$$

II Stadium: directions of emission



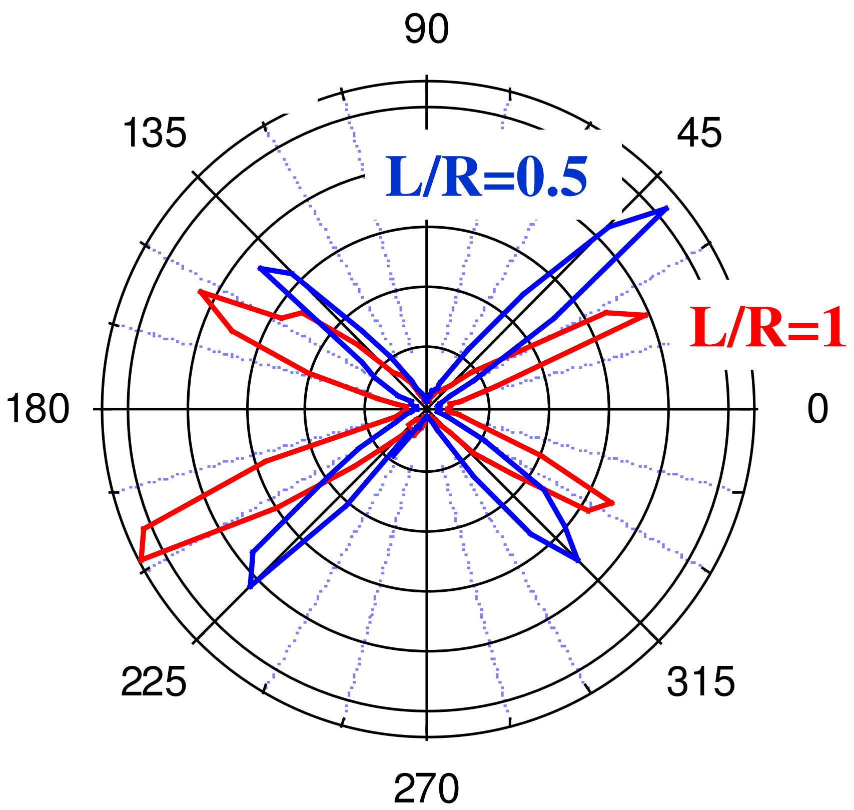


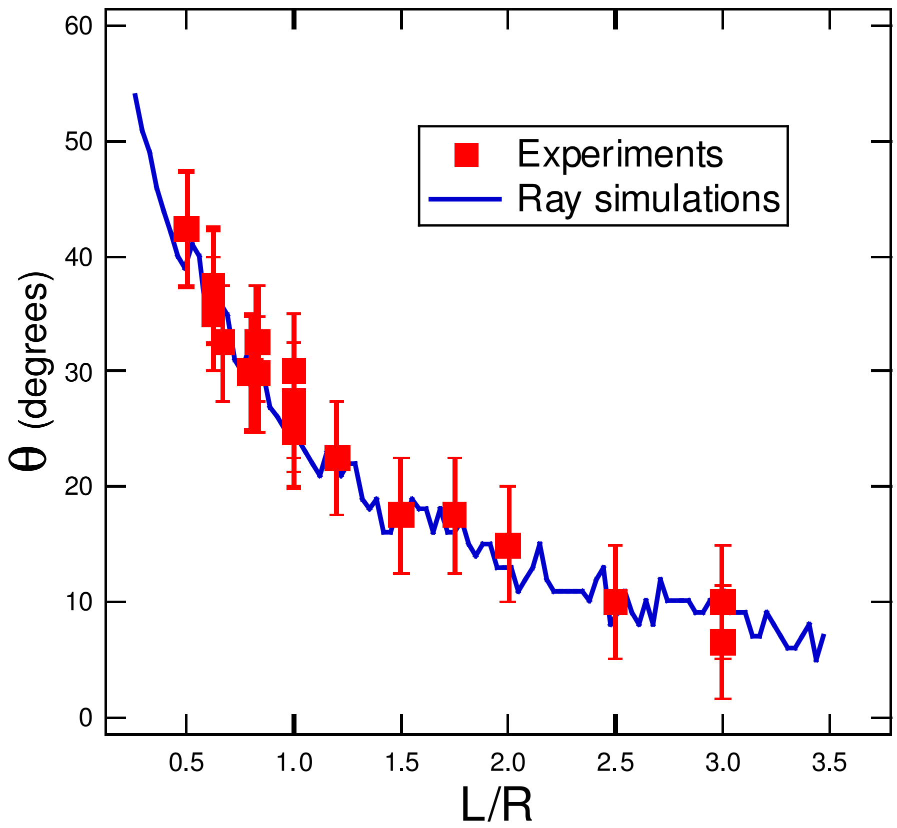




II Stadium: directional emission

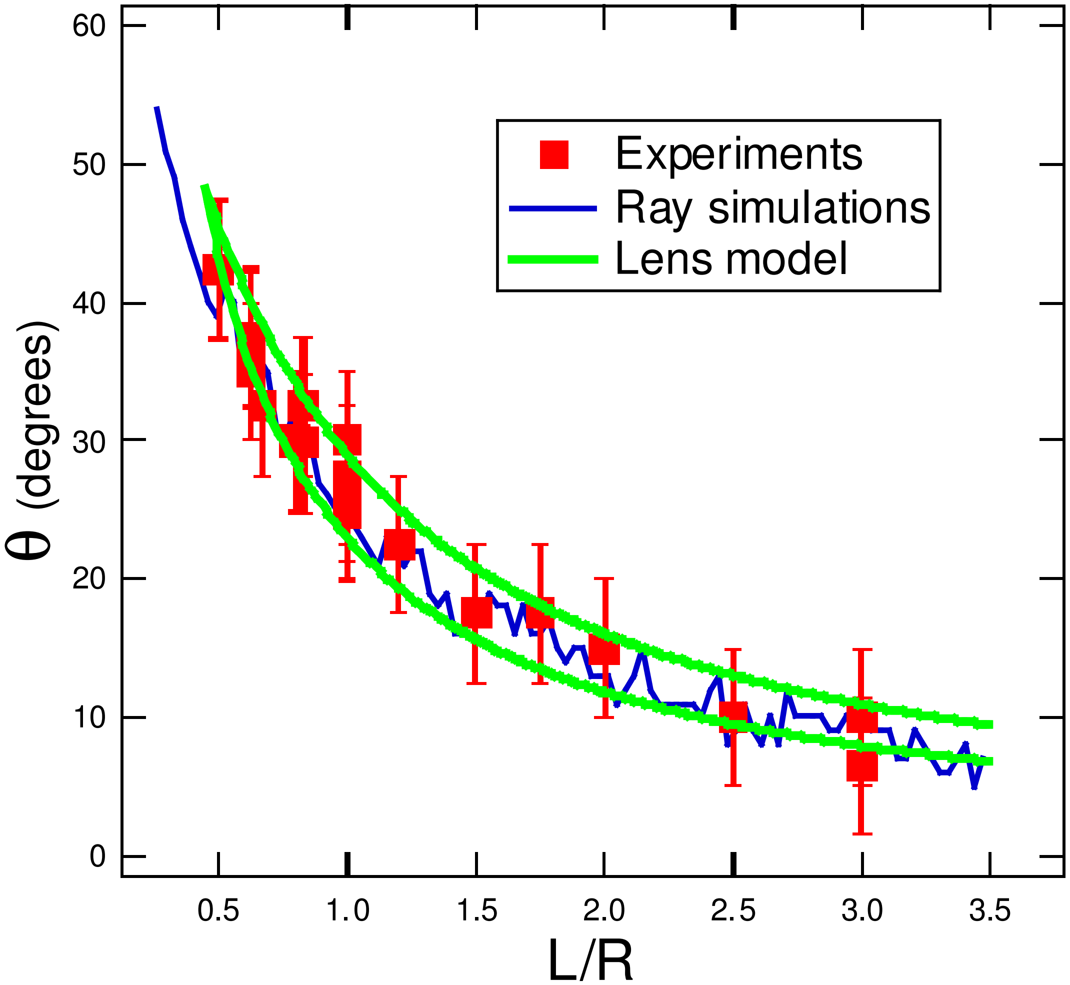
Emission in the far-field pattern





II Chaotic cavity: lens model

ANALYTIC



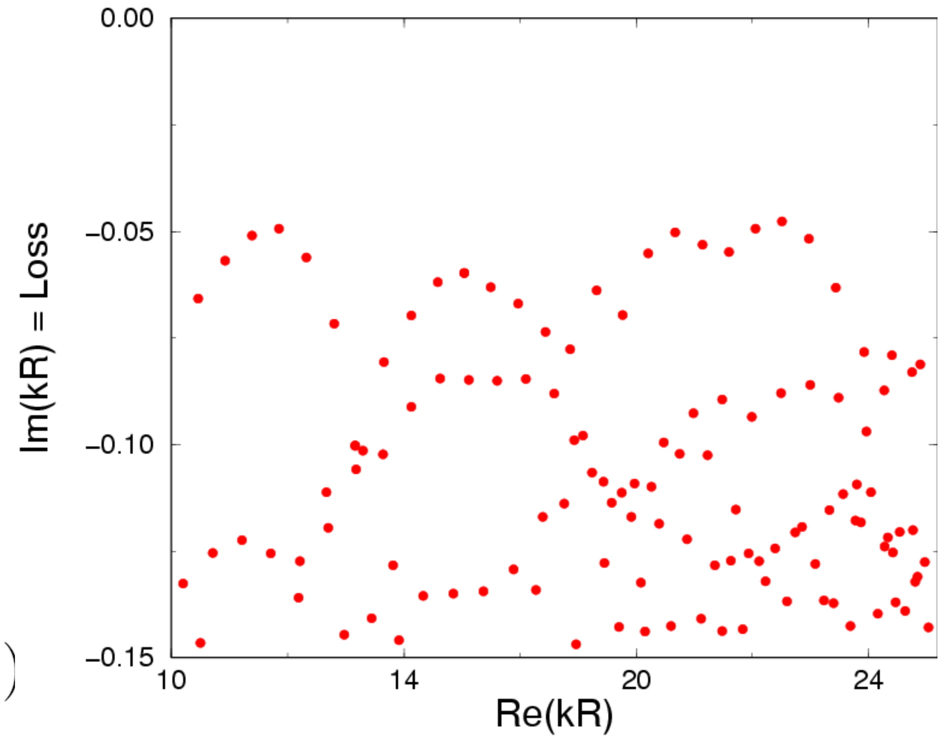
II Wave numerical simulations

<u>Helmholtz equations</u> inside and outside **+**
dielectric <u>boundary conditions</u>

Boundary element method

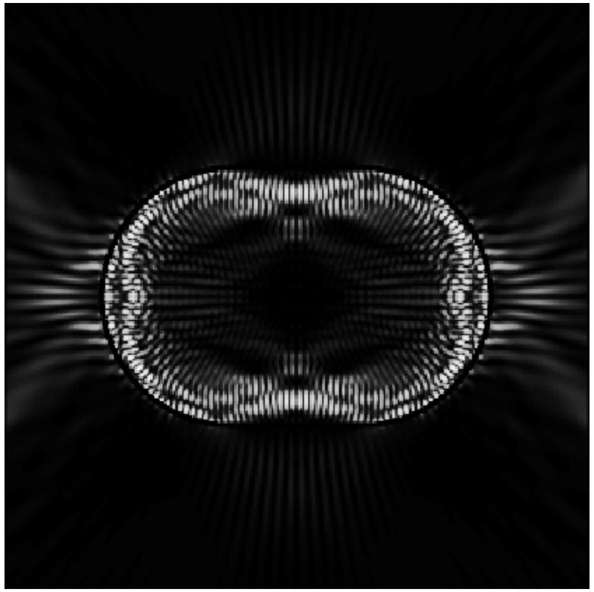
$$\psi_{int}(\vec{r}) = \oint \mathrm{d}s \; \mu_{int}(s) \; G_{int}(\vec{r} - \vec{r}_s)$$

$$\psi_{ext}(\vec{r}) = \oint \mathrm{d}s \; \mu_{ext}(s) \; G_{ext}(\vec{r} - \vec{r}_s)$$

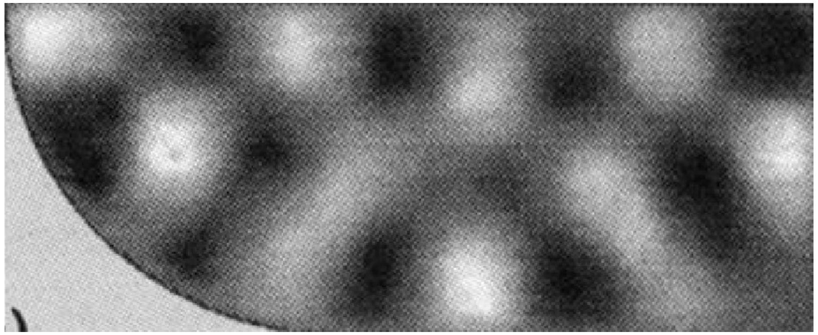


II Wave simulations

Open cavity



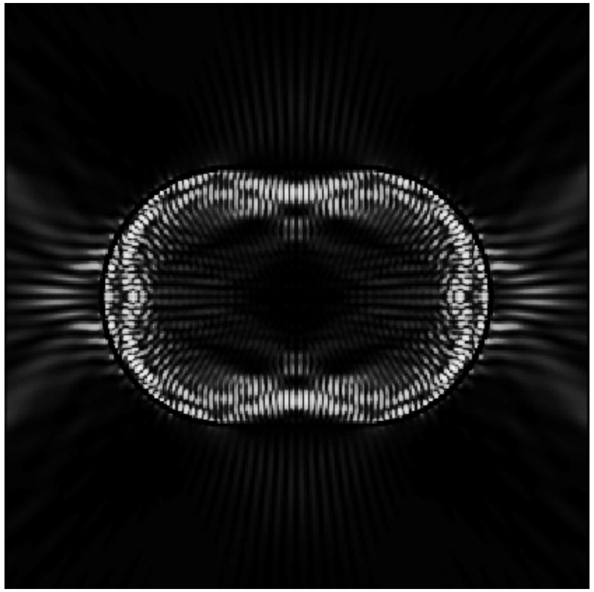
Closed cavity

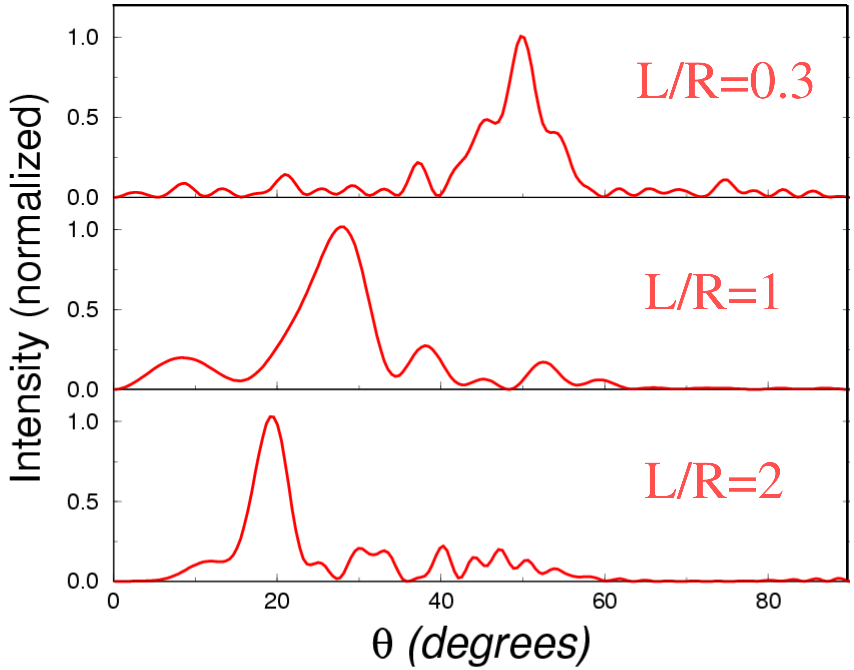


*Stein et al., PRL **75**, 53-56 (1995)*

II Wave simulations

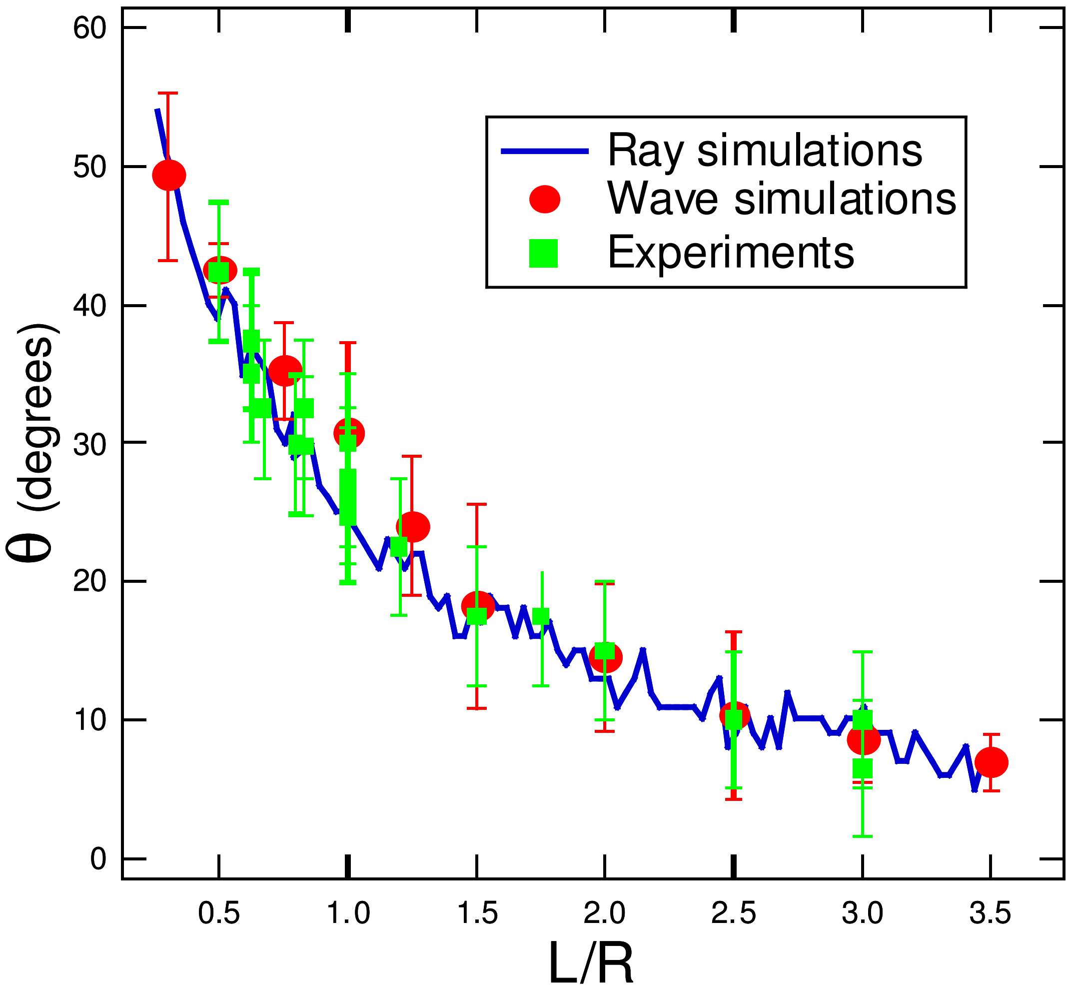
Far-field pattern





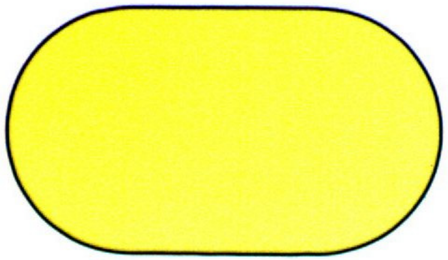
Individual well confined wavefunctions

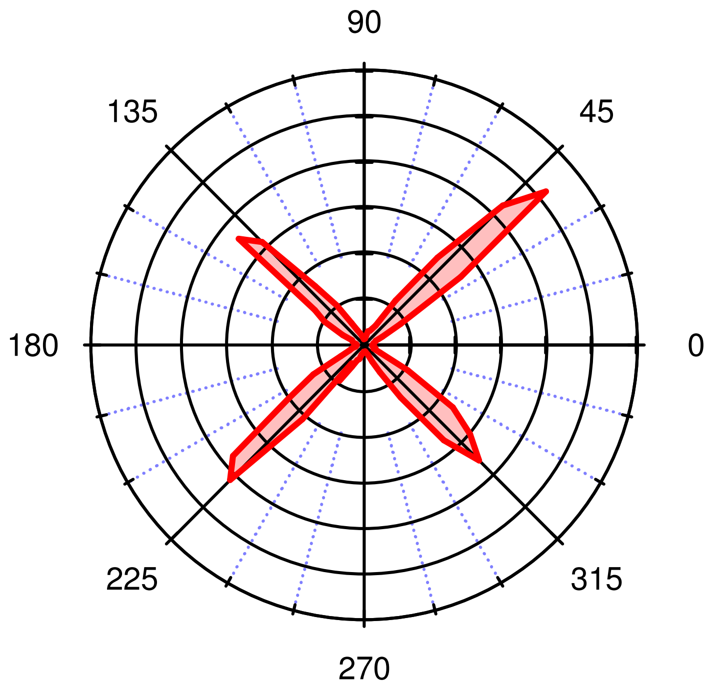
II Refractive escape: Rays or waves ?

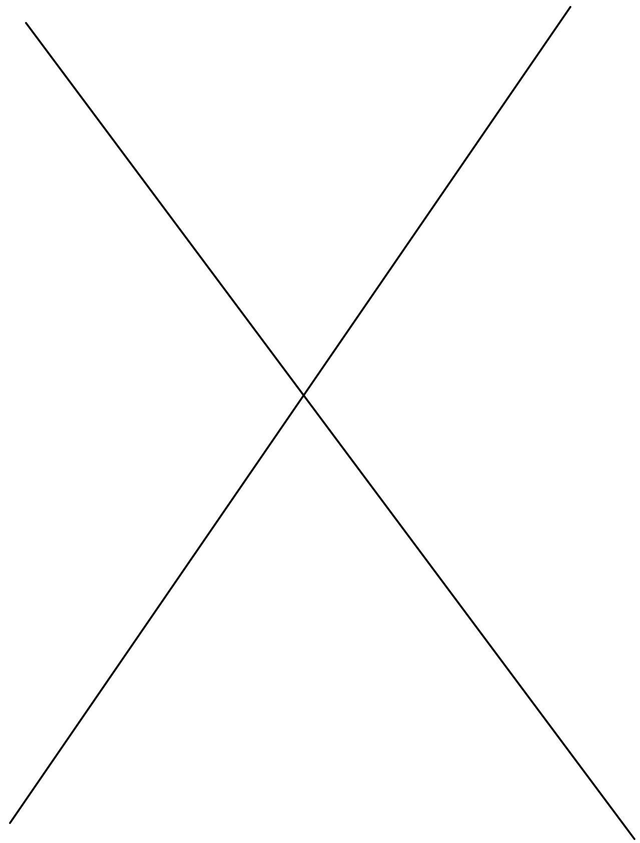


PRA **75**
033806
(2007)

II Consequences of the lens model







II Polygons

II Polygons

Outline

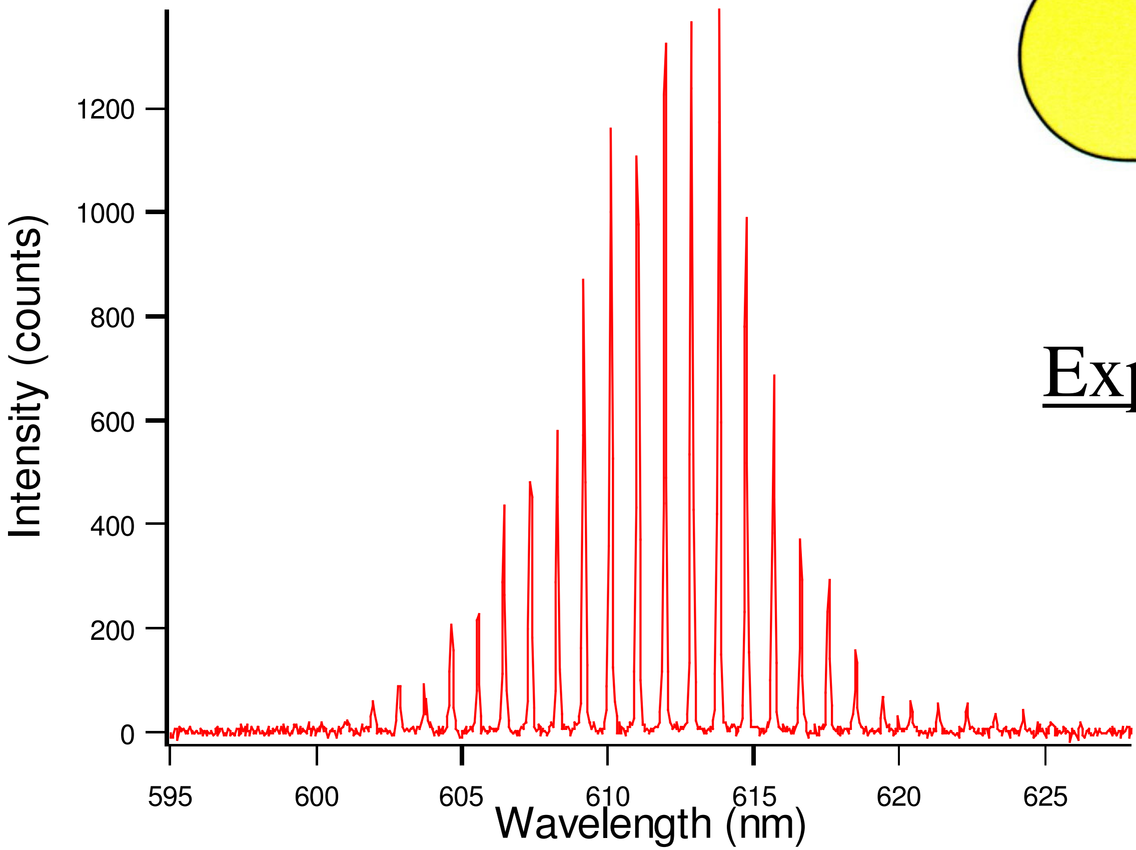
I Micro-lasers and wave chaos

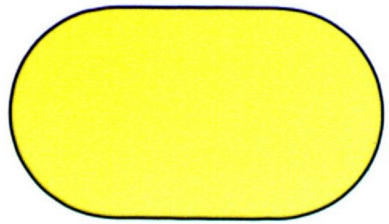
II Existing tools *(what we can do)*

- Wavefunctions
- Directions of emission
- Spectra

III Open questions

II Spectra

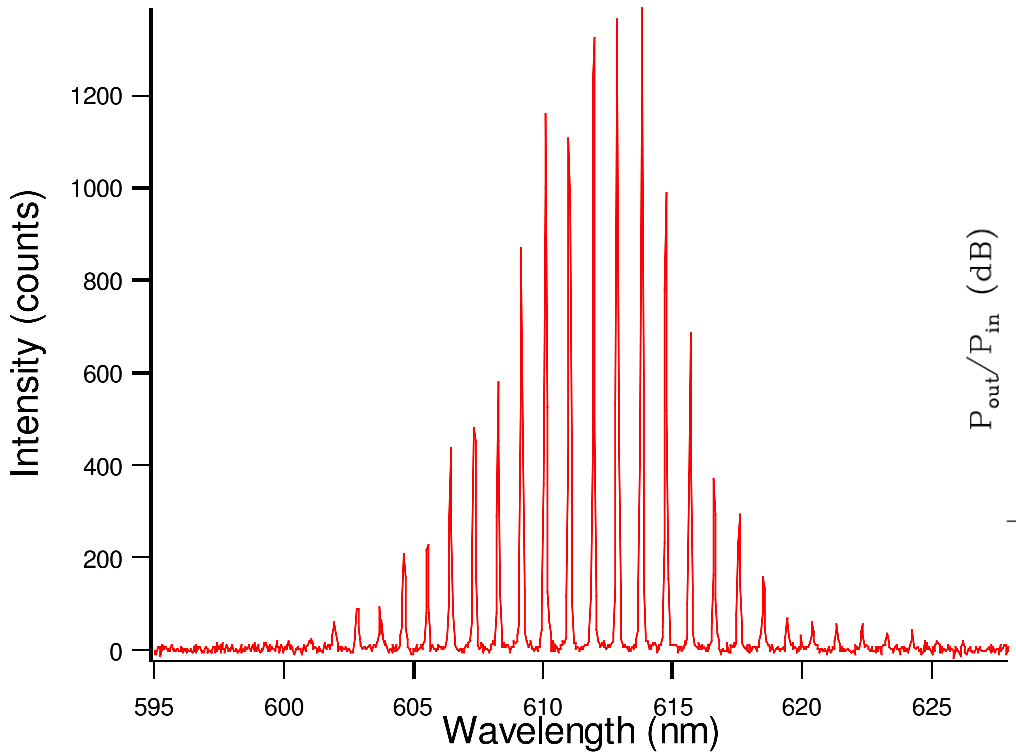




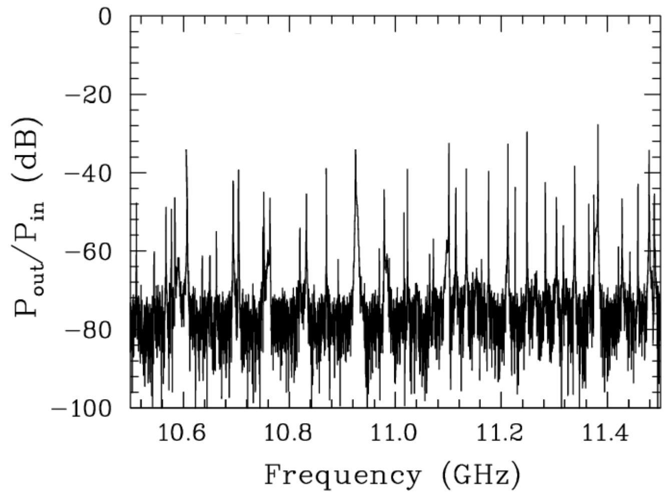
Experiments

II Spectra

Open cavity

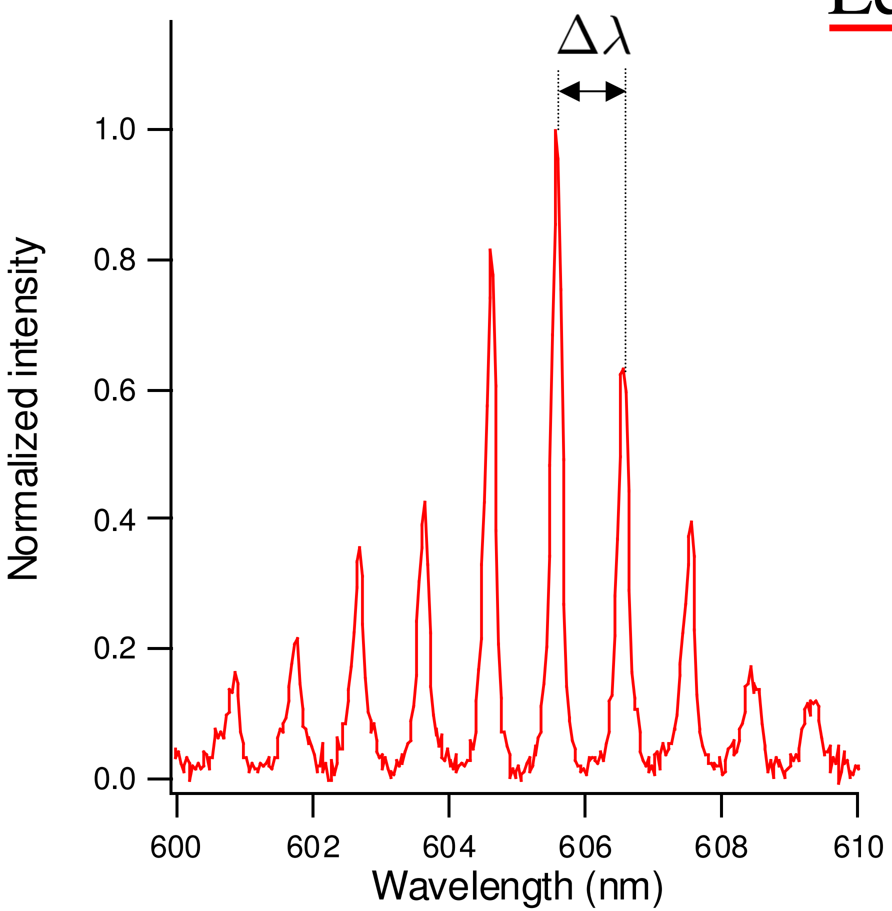


Closed cavity



*Alt et al., PRE **60**, 2851-2857 (1999)*

II Spectra: periodic orbit



Length L of the periodic orbit ?

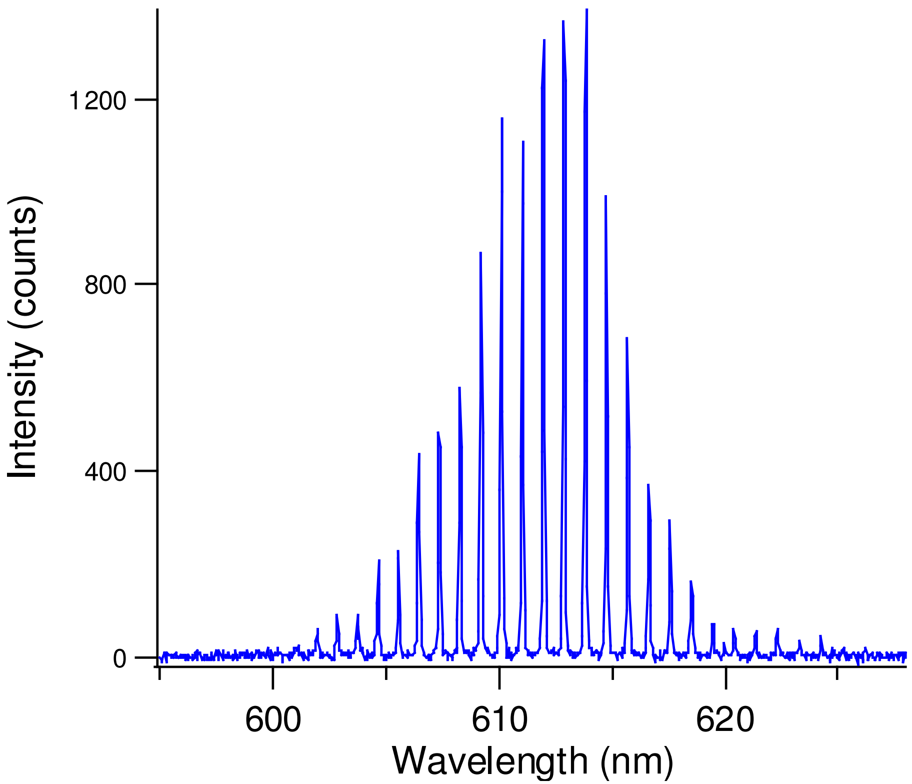
$$\frac{2\pi}{\lambda} n L = 2\pi m$$

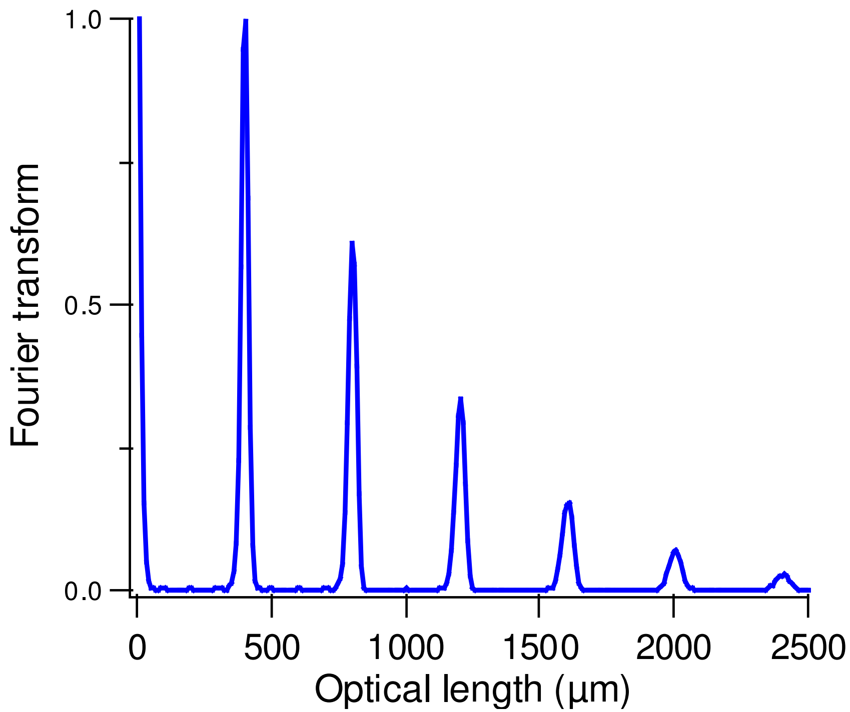
$$\Downarrow$$

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

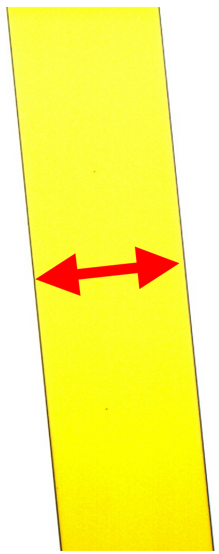
II Spectra: periodic orbit

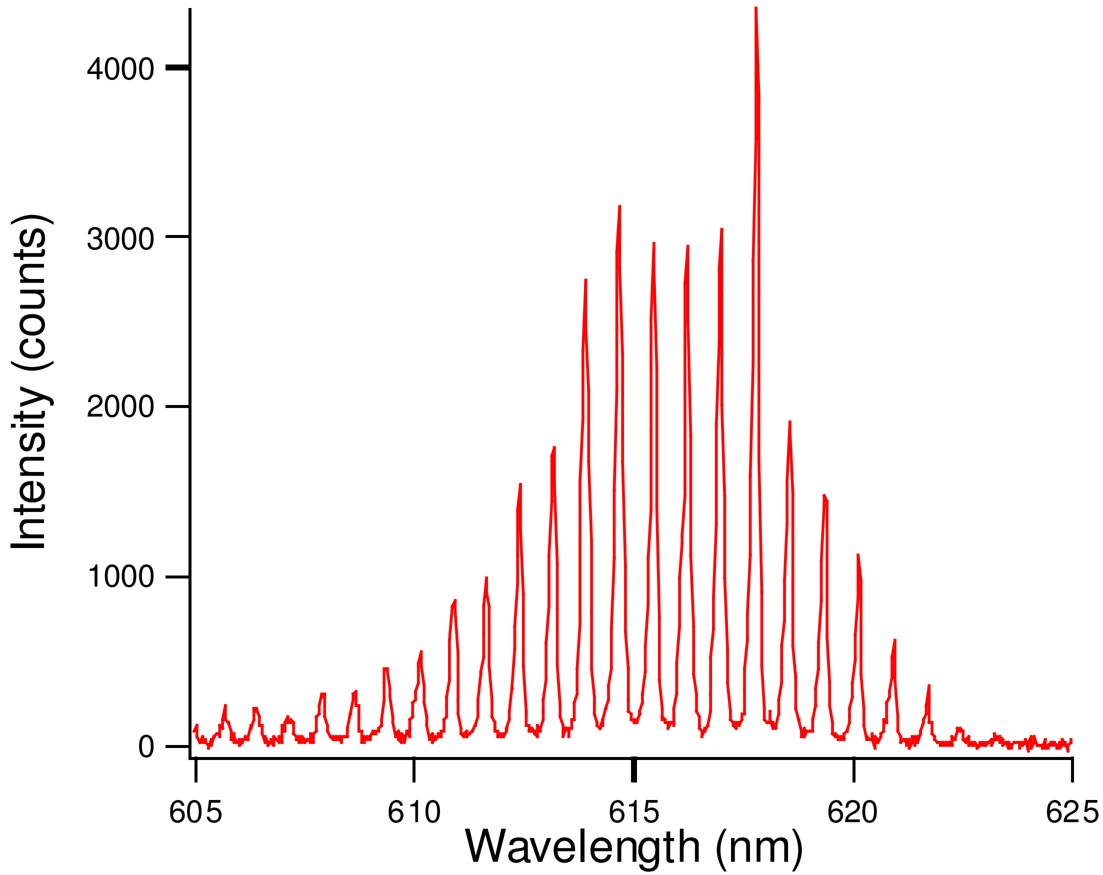
Fourier transform



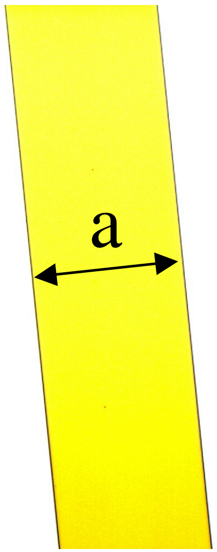


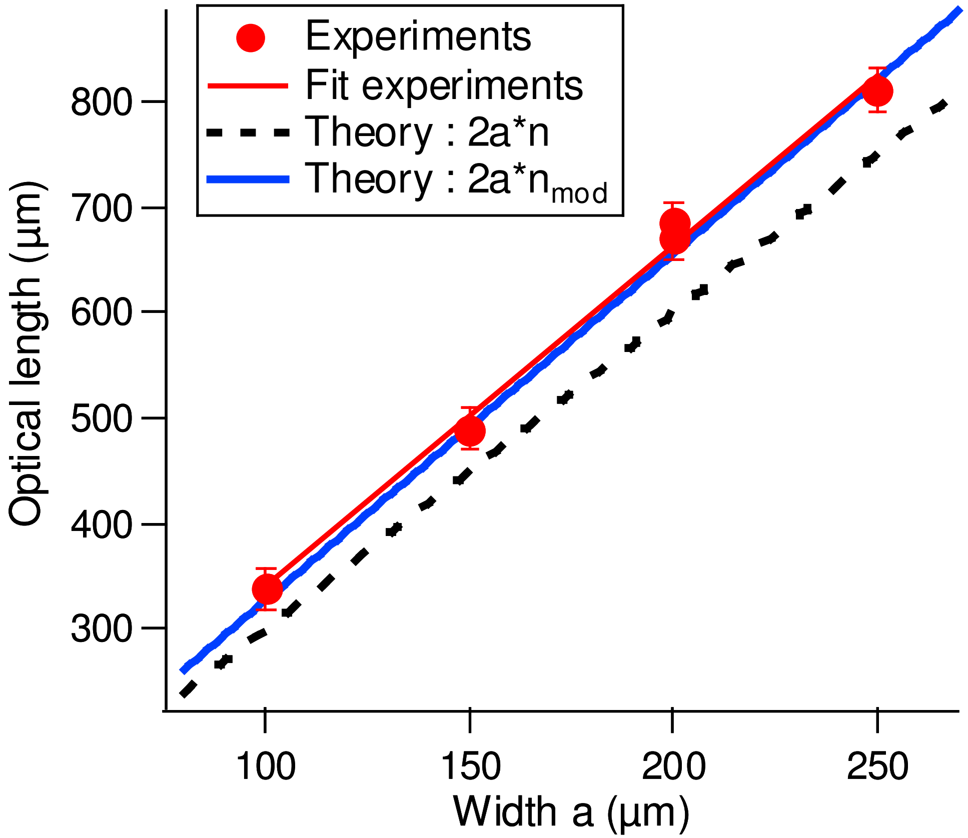
II Test: Fabry-Perot resonator





II Spectra: periodic orbit





n (with group velocity correction) = 1.64

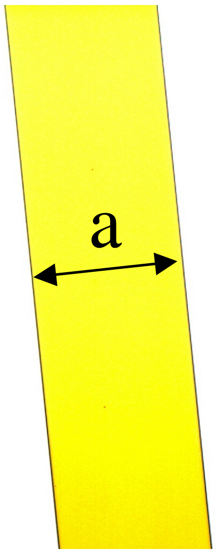
⇧

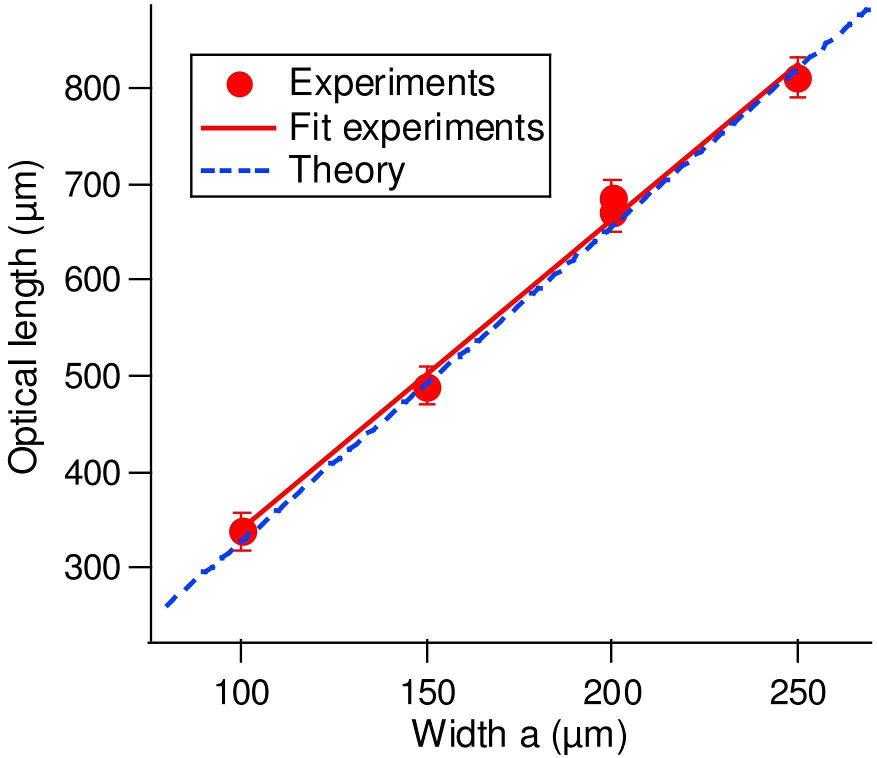
Inferred independently

Without any adjusted parameter

II Spectra: periodic orbit

Direct **measure** of the **geometrical** length



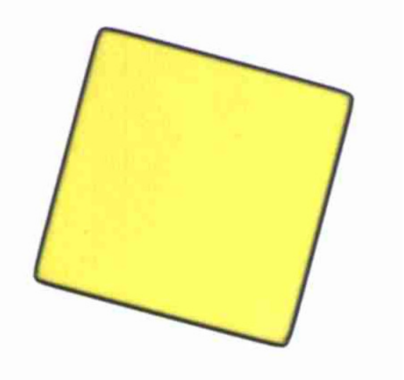


n = 1.64

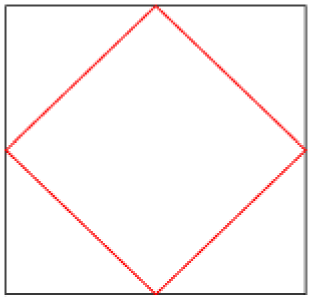
Without any adjusted parameter

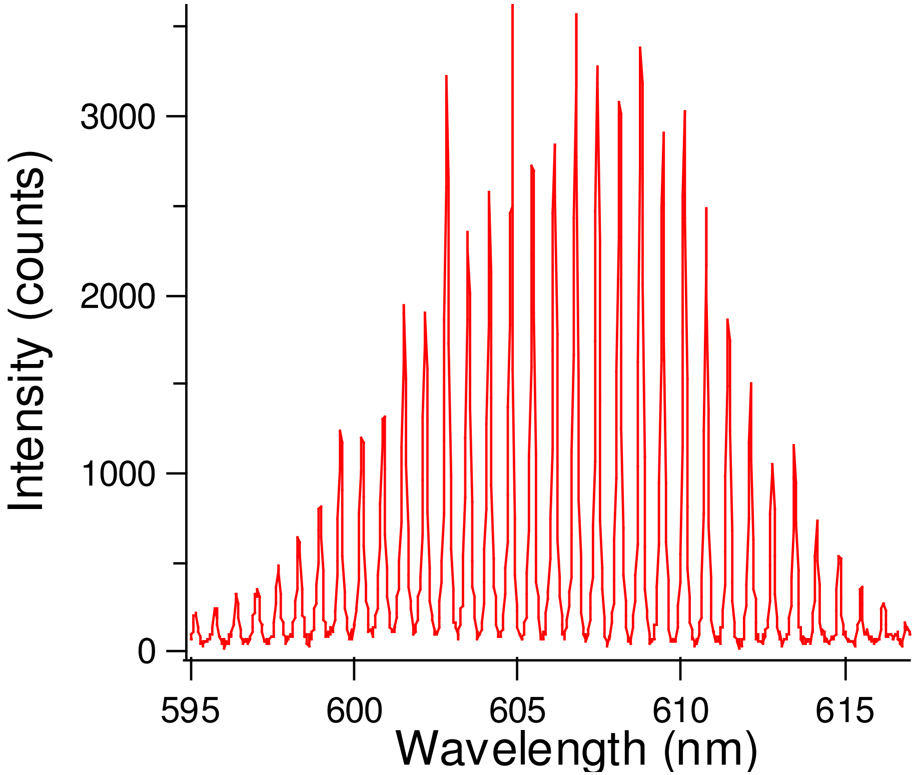
PRA ***76*** *023830 (2007)*

II Spectra: square

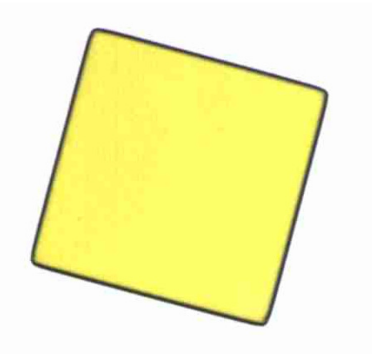


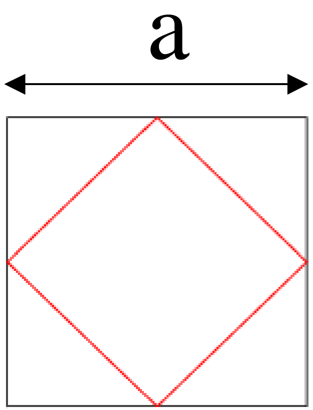
Diamond

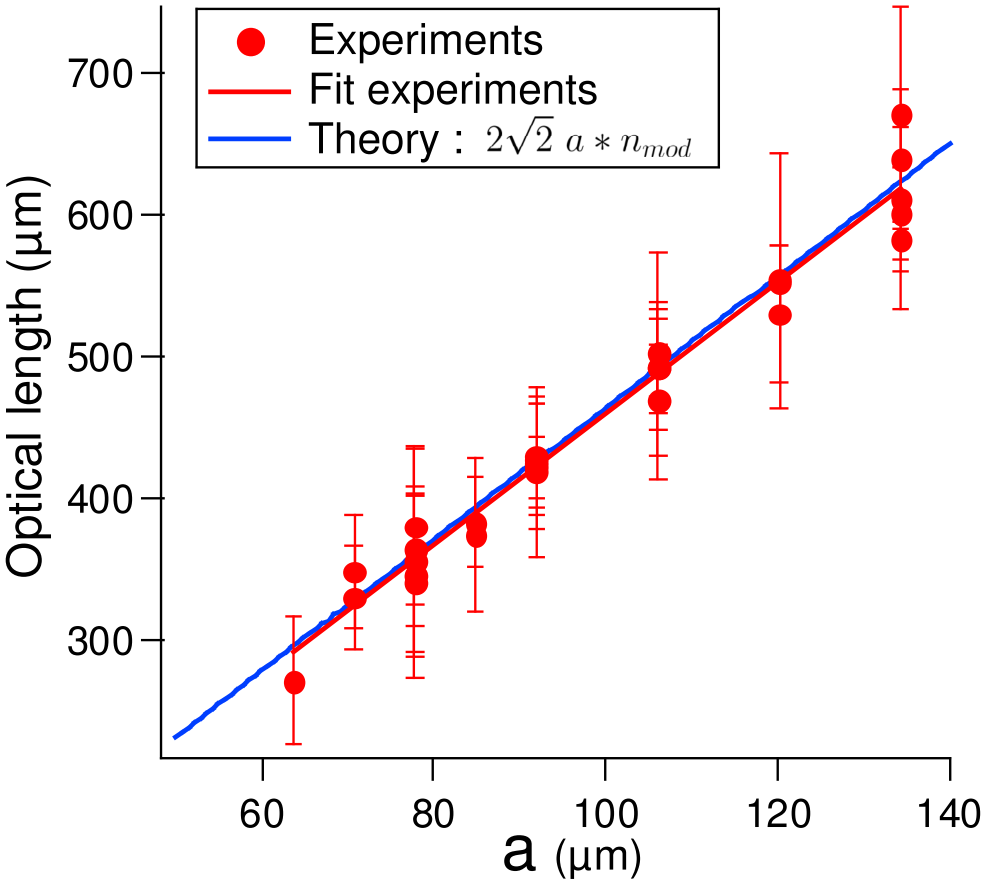




II Spectra: square



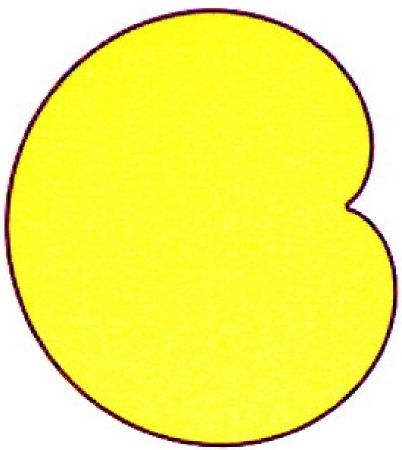


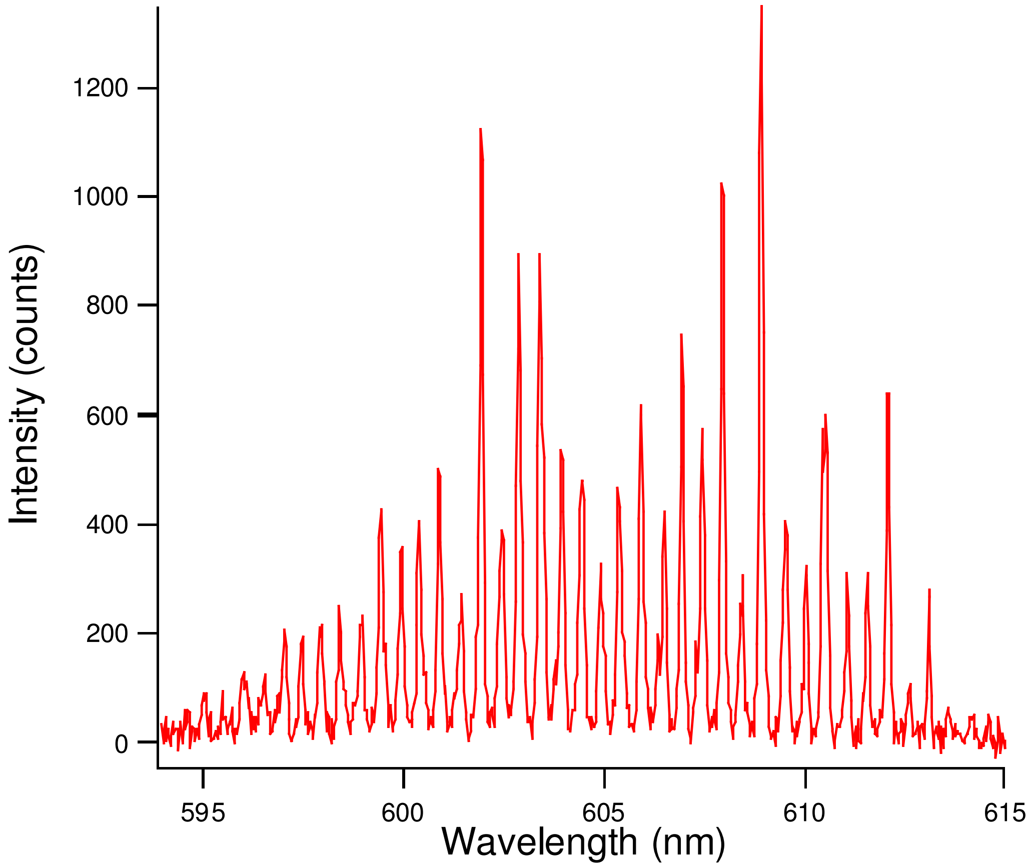


<u>Without any adjusted parameter</u>

II Spectra: periodic orbits

Cardioid





Outline

I Micro-lasers and wave chaos

II Existing tools *(what we can do)*

III Open questions

- Prediction of the dominant periodic orbit
- Resonances & lasing modes
- Diffraction on a dielectric corner

III Spectra: trace formula

Density of states

$$d(k) \propto \sum_m \frac{\mathrm{Im}\ k_m}{(k - \mathrm{Re}\ k_m)^2 + (\mathrm{Im}\ k_m)^2}$$ Wave physics

Integrable
Chaotic

⇕ ???

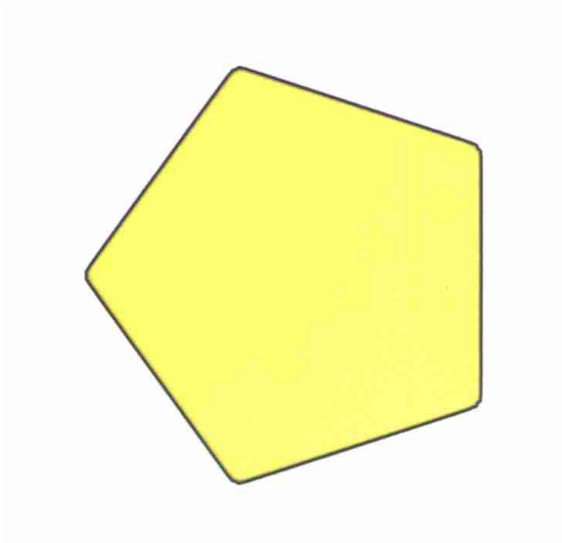
Semi-classical limit $k \to \infty$

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

⤷ Proved for Fabry-Perot and disk

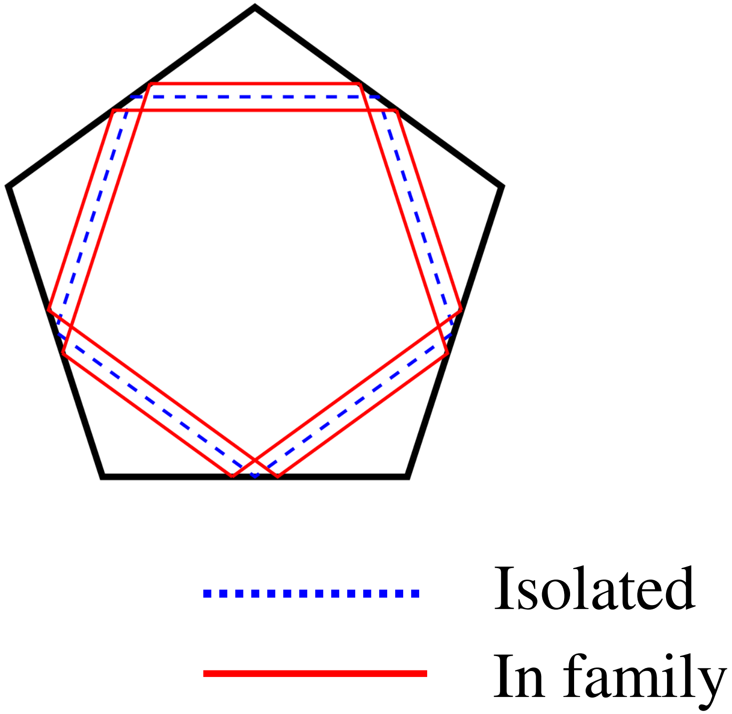
III Spectra and trace formula (a)

Periodic orbit: isolated or in family ?

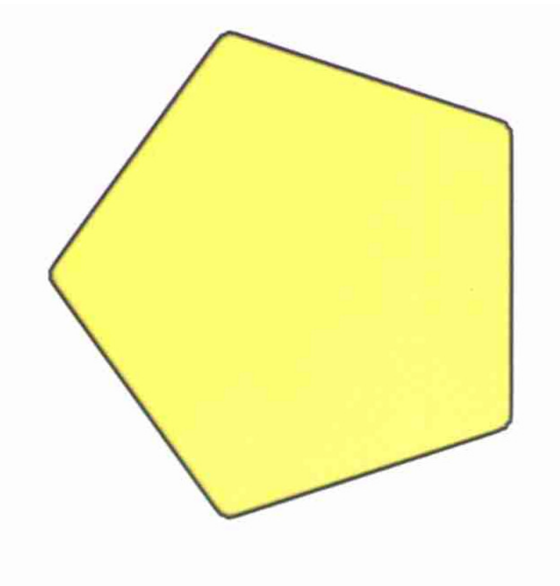


Photography

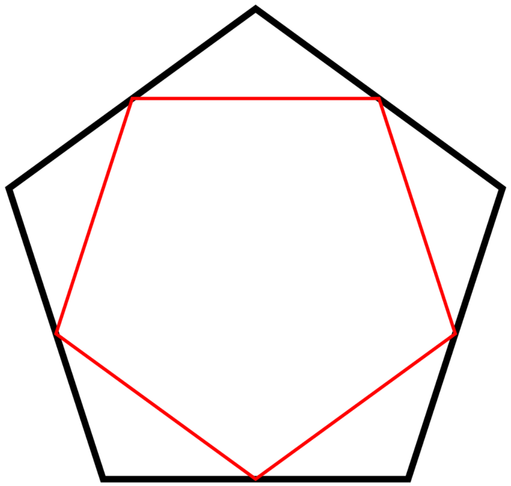
Odd number of sides



III Spectra and trace formula (a)

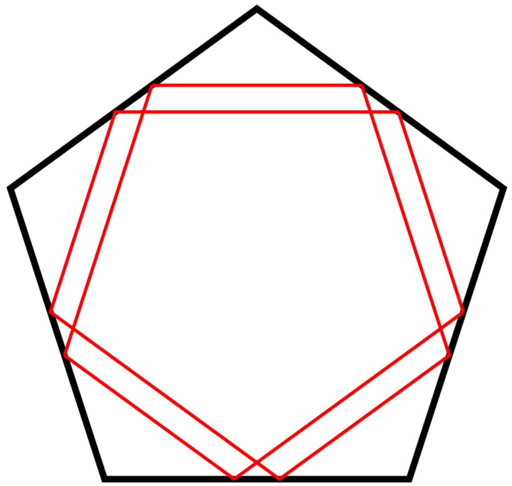


Isolated



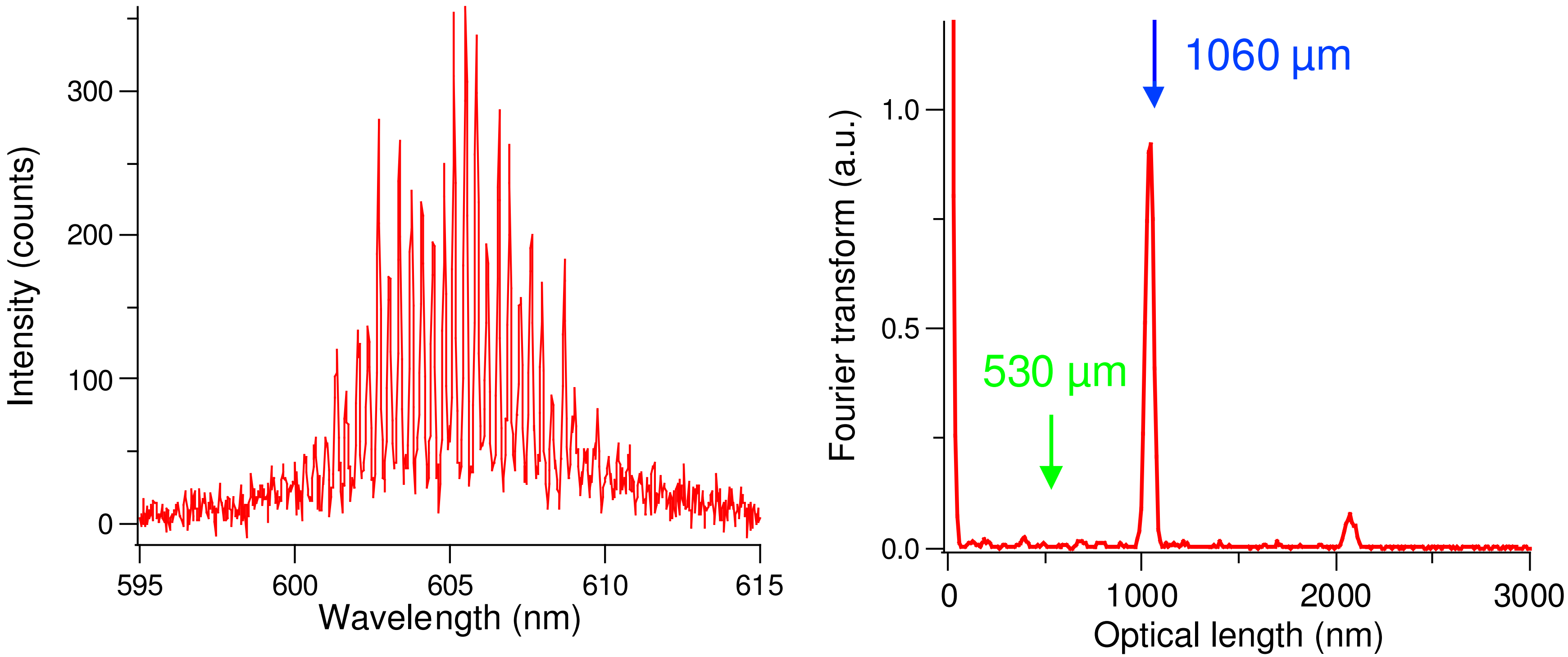
Single pentagon

In family



Double pentagon

III Spectra and trace formula (a)

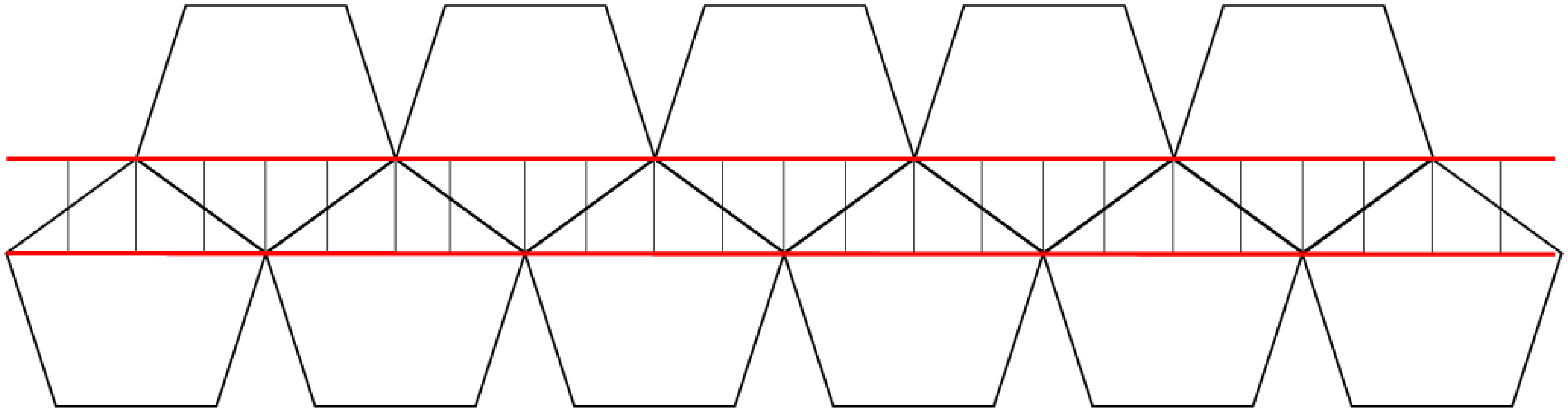


$a = 80\ \mu m$

Single pentagon ⇨ $5\ a\cos(\frac{\pi}{5})\ n_{full} = 530\ \mu m$

Double pentagon ⇨ $10\ a\cos(\frac{\pi}{5})\ n_{full} = 1060\ \mu m$

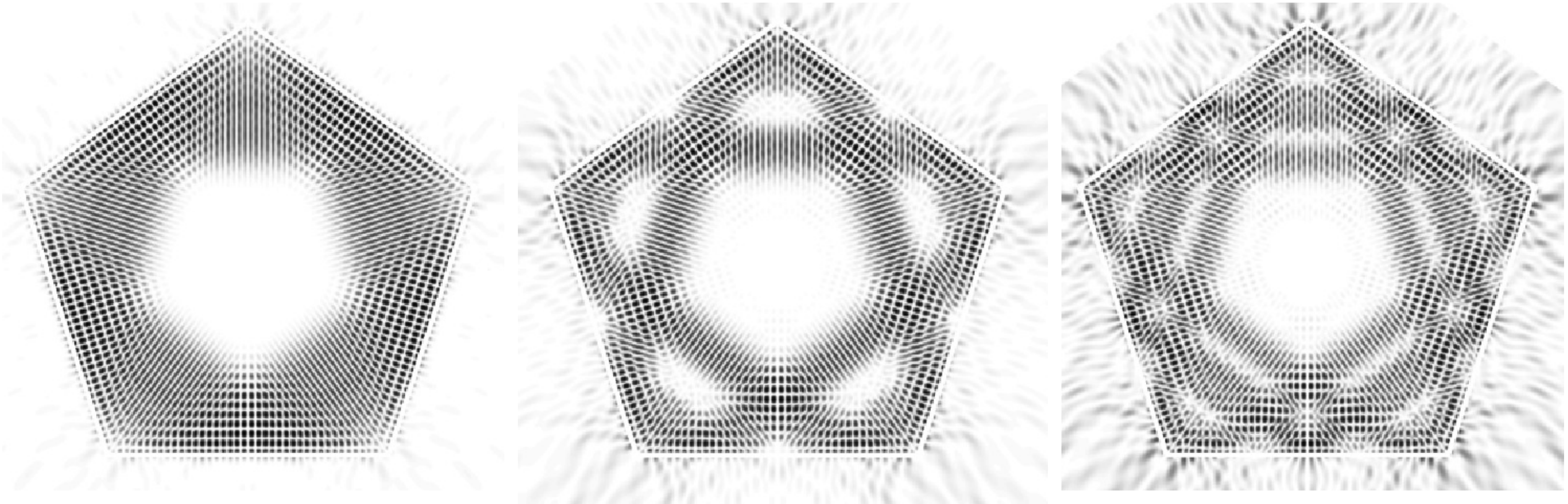
III [Superscars]



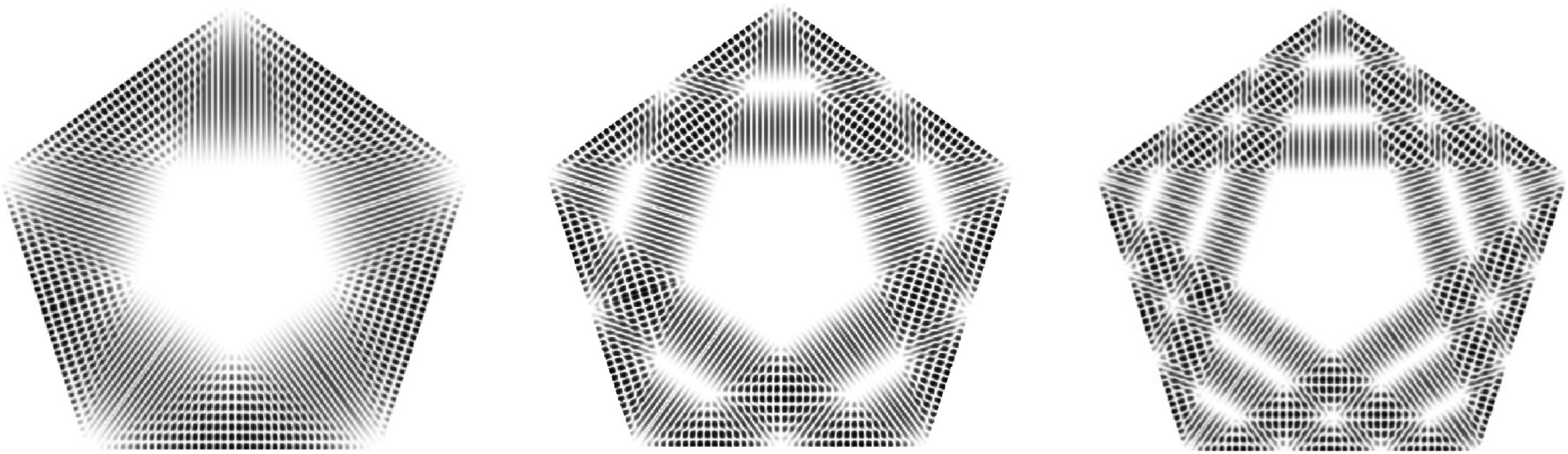
Superscar model ⇨ no light in the center

PRL **92** *244102 (2004)* *PRA* **76** *023830 (2007)*

Numerical simulations



Superscar model



III Spectra and trace formula (b)

Change of dominant periodic orbit with a parameter

III Spectra (b): experiments

III Trace formula: summary

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

Semi-classical limit $k \longrightarrow \infty$

- Proved for Fabry-Perot and disk
- Evidenced by experiments and numerical simulations

How to see the sub-dominant periodic orbits ?

Outline

I Micro-lasers and wave chaos

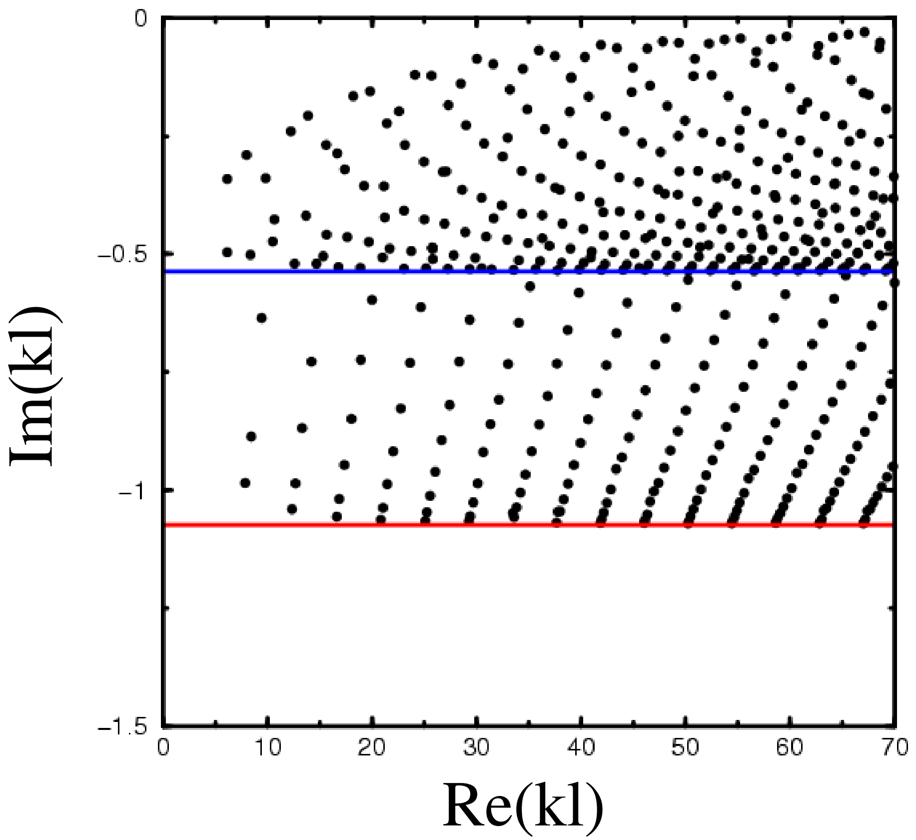
II Existing tools *(what we can do)*

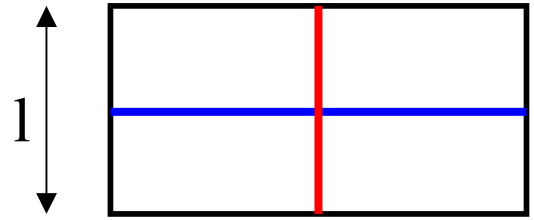
III Open questions

- Prediction of the dominant periodic orbit
- Resonances & lasing modes
- Diffraction on a dielectric corner

III Lasing and losses

Rectangle



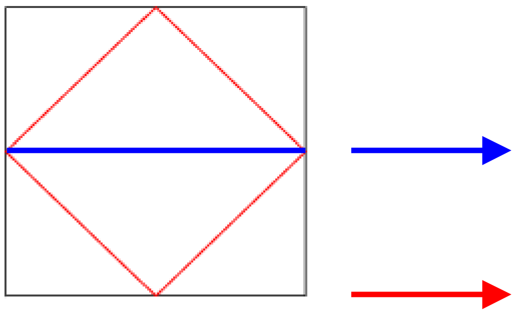


$$r^2 \; e^{iknL} = 1$$

⇩

$$|r|^2 \; e^{-k_i n L} = 1$$

III Lasing and losses



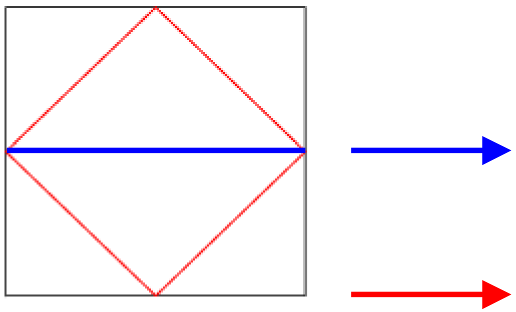
Question

- Diamond disappears when Fabry-Perot appears.

or

- Diamond and FP coexist, but the out-coupling of FP is too big to see diamond.

III Lasing and losses



III Lasing and losses

For a periodic orbit

Laser threshold ⟺ Losses *Experimental evidences*

Questions

- Which connexion with trace formula (c_p) ?
- Which meaning for resonances ?

III Models for micro-lasers

Laser effect → To fill the resonances with photons

(second quantization)

Resonances are not orthogonal

III Models for micro-lasers

- <u>Helmholtz equations with n complex</u>

$$\left(\Delta + n^2 k^2\right) \psi = 0 \qquad n = n_0 - i\gamma$$

Nosich et al. JOSAA ***25*** *2884 (2008)*

- <u>Maxwell-Bloch equations</u>

$$\ddot{E}^+ = \frac{1}{\epsilon(\mathbf{x})} \nabla^2 E^+ - \frac{4\pi}{\epsilon(\mathbf{x})} \ddot{P}^+$$

$$\dot{P}^+ = -(i\omega_a + \gamma_\perp) P^+ + \frac{g^2}{i\hbar} E^+ D$$

$$\dot{D} = \gamma_\parallel (D_0 - D) - \frac{2}{i\hbar} \left(E^+ (P^+)^* - P^+ (E^+)^* \right)$$

Türeci, Stone et al. Nonlinearity ***22*** *C1 (2009)*

Harayama et al. PRL ***82*** *3803 (1999)*

Outline

I Micro-lasers and wave chaos

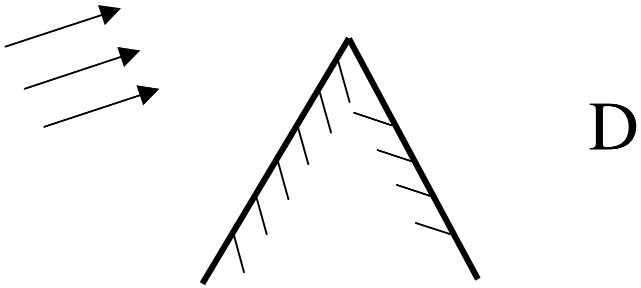
II Existing tools *(what we can do)*

III Open questions

- Prediction of the dominant periodic orbit
- Resonances & lasing modes
- Diffraction on a dielectric corner

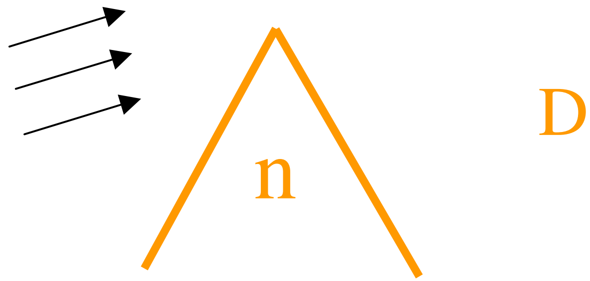
III Diffraction

<u>Metallic</u>



Sommerfeld (1896)

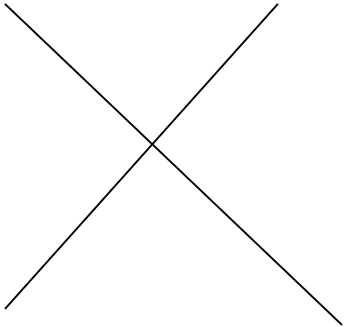
<u>Dielectric</u>

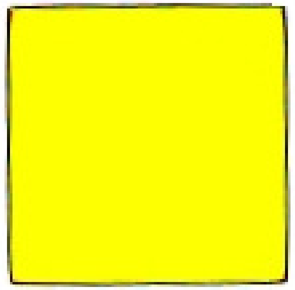


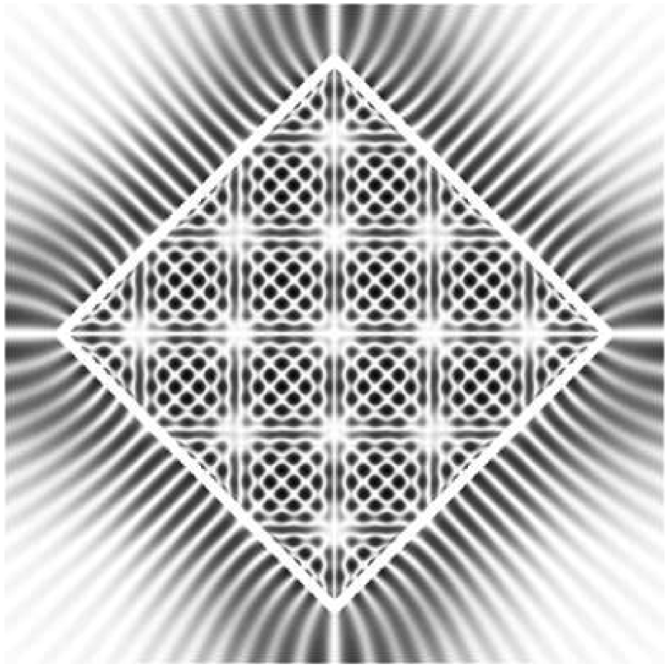
???

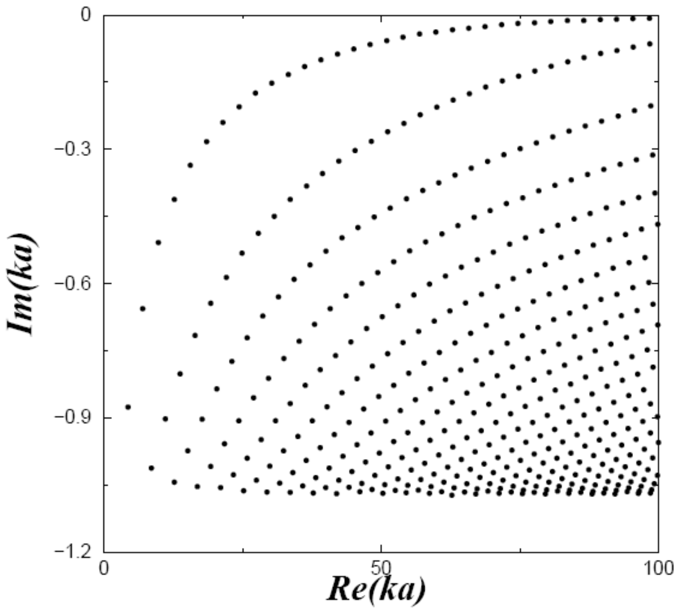
III Diffraction

Square: not (yet) integrable



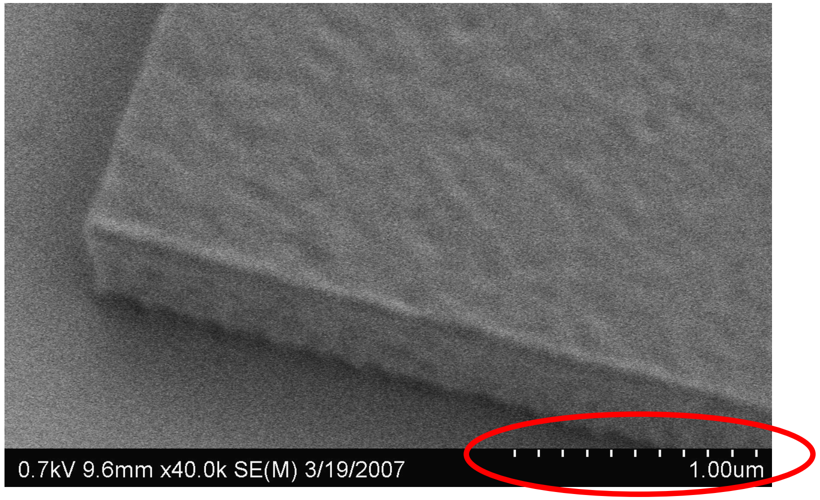






Rémy Dubertrand, Thesis.

III Diffraction



Collaboration with C. Ulysse (LPN)

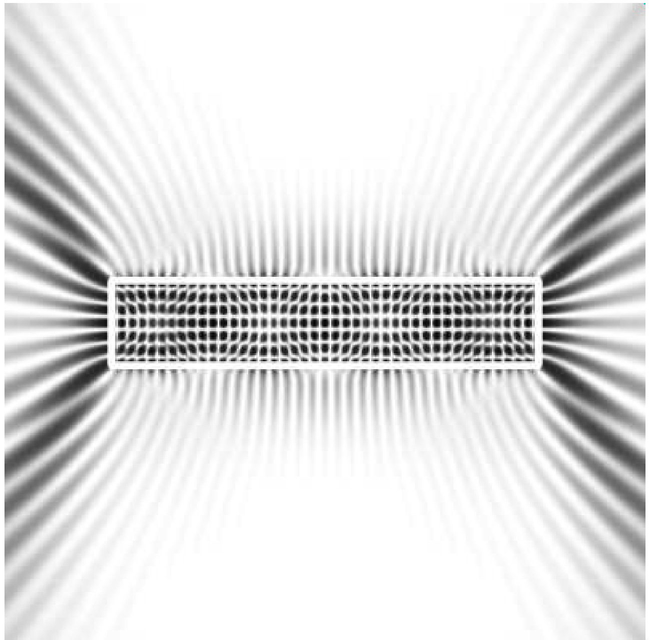
Summary & Perspectives

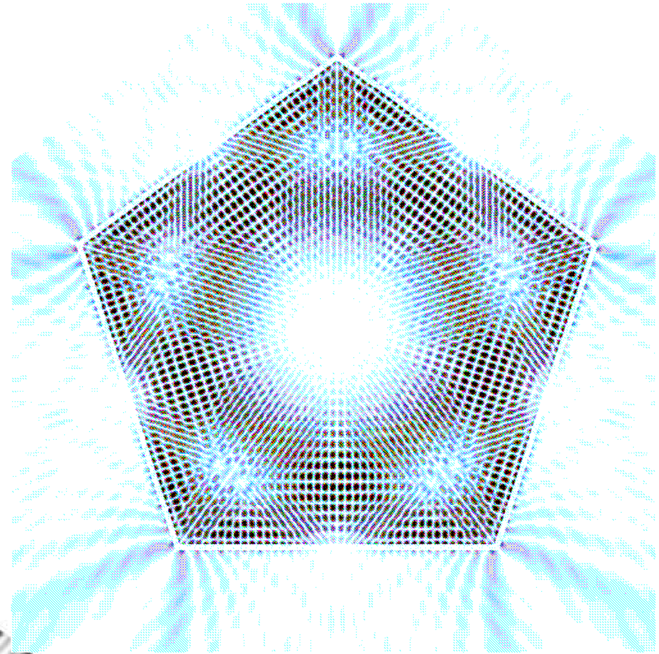
Organic micro-lasers

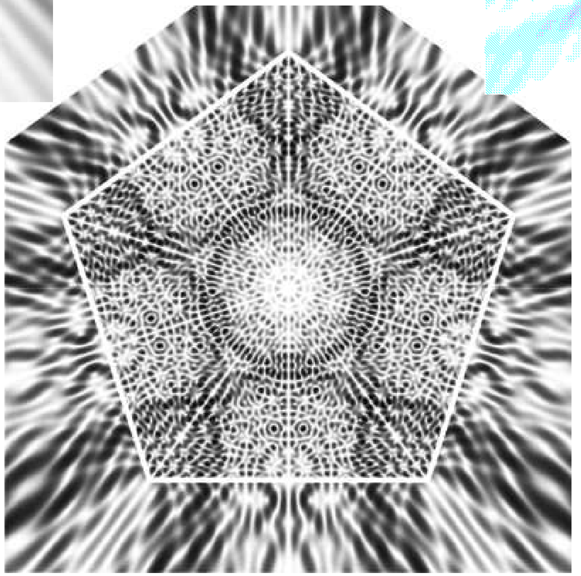
- Well-behaved microlasers → Practical applications (*sensors*)
  Open billiards
- Existing tools for wave chaos → Far-field patterns
  Periodic orbits
  Losses

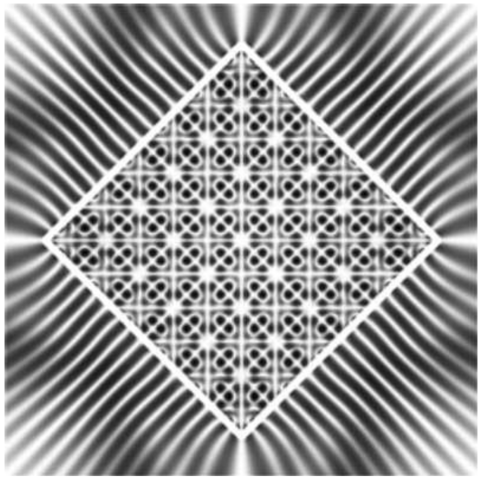
Open questions

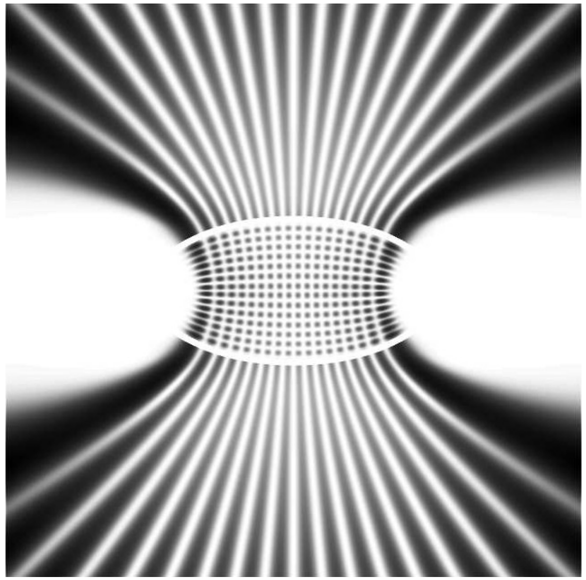
- Trace formula for dielectric billiards
- Resonances & lasing modes
- Diffraction on a dielectric corner











C. Schmit &
R. Dubertrand