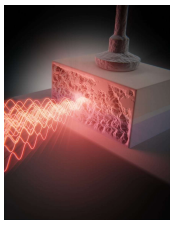
Nanolight, 7 March 2022

cheap electrically driven random lasers



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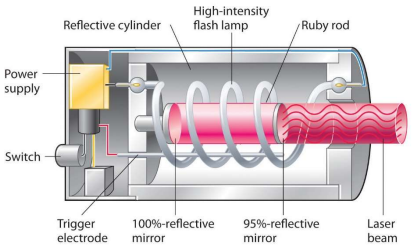
Summary

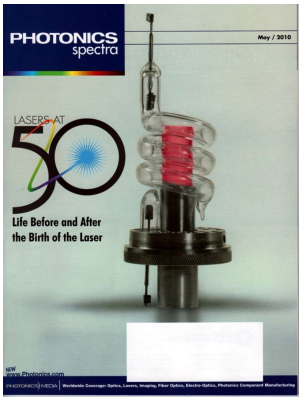
- lasers, random lasers
- random laser resonators
- diode random lasers
  - Fabrication
  - Characterization

Conventional laser

Rubi laser

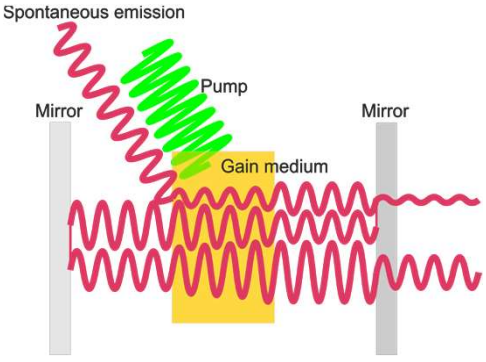
- First laser:
  - $Cr:Al_2O_3$
  - Flash lamp

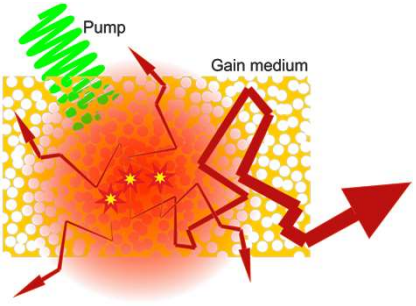




Random lasers

Disorder* and non-linearity likely to bring about complexity





*in the interactions is enough

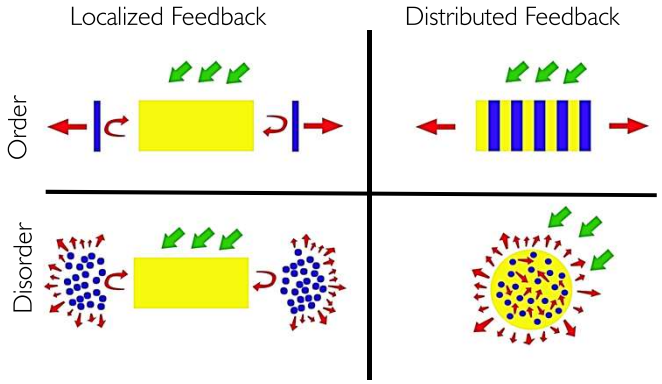
Requirement: feedback

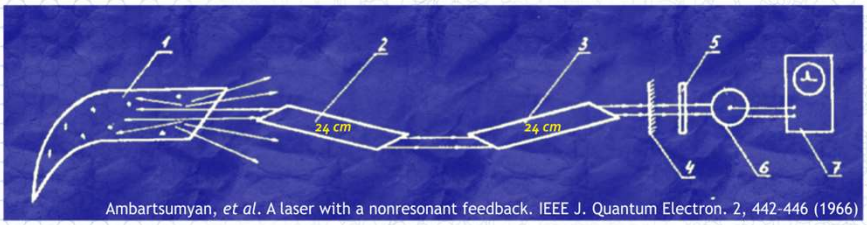
Cavity or Bragg stack

cavity modes

Scattering diffuser

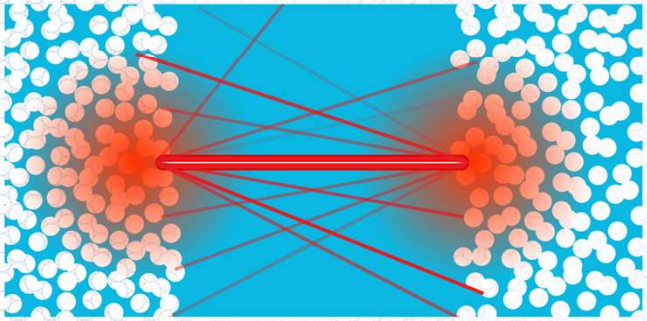
quasi modes





Ambartsumyan, *et al*. A laser with a nonresonant feedback. IEEE J. Quantum Electron. 2, 442-446 (1966)

Non-resonant lasers were initially proposed and realized by substituting one of the cavity mirrors by a diffusing material. The cavity thus formed was non-resonant.

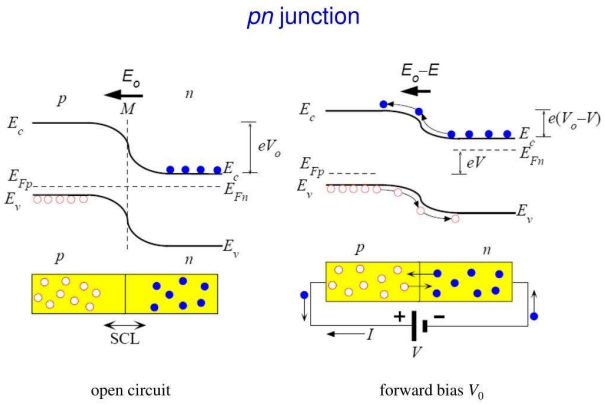


A micro random laser is built by placing two scattering barriers (powder) at the edges of a thin layer of gain material (dye).
Little gain material is contained in the scattering mirrors so that gain occurs only in the dye.
This design decouples scattering from gain and permits to manipulate them separately.

Non-resonant laser

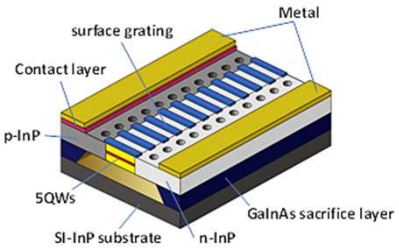
Gain mechanism

- Fermi level
  - near CB in *n* region
  - near VB in *p* region
- Gap at junction prevents e^- and h^+ to tunnel
- Applied bias flattens bands
  - recombination allowed

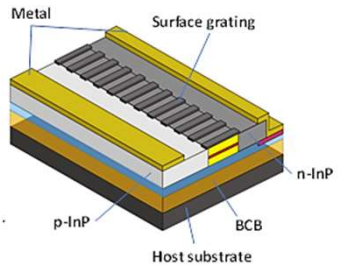


Feedback mechanism

Distributed feedback



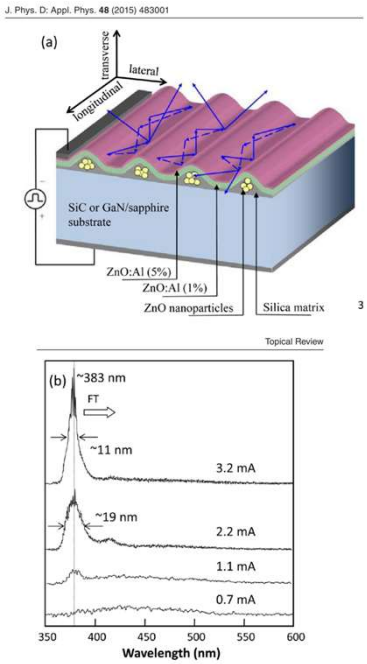
(a) Membrane DFB laser with Airbridge structure



(b) Membrane DFB laser with Airbridge structure

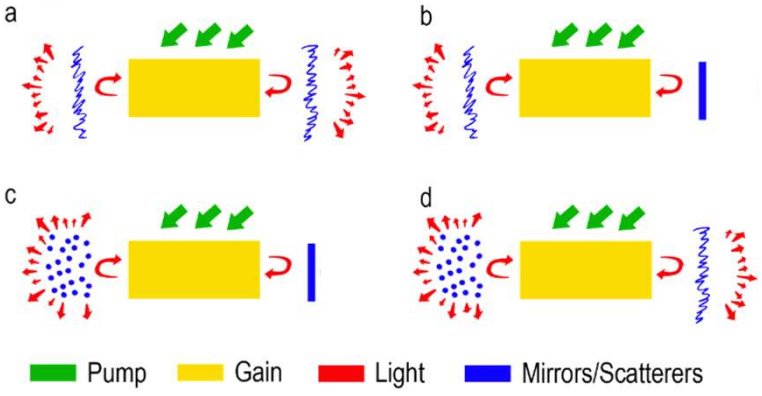
Electrical pumping RL

- Materials
  - GaN
  - ZnO
- Fabrication
  - Sputtering
  - Nanocrystals
  - Granular



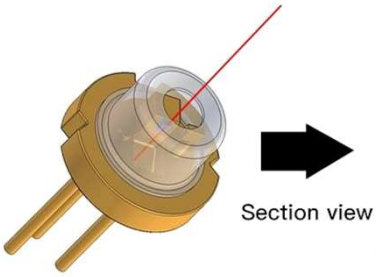
Non-distributed feedback

Combinations of volume, surface scattering, ordered mirror

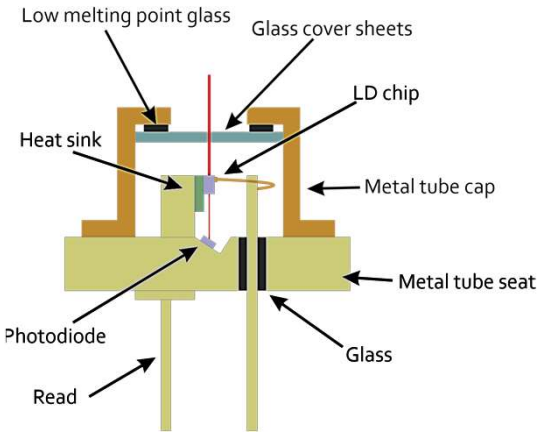


In-plane Fabry-Perót laser diode

Vertical current



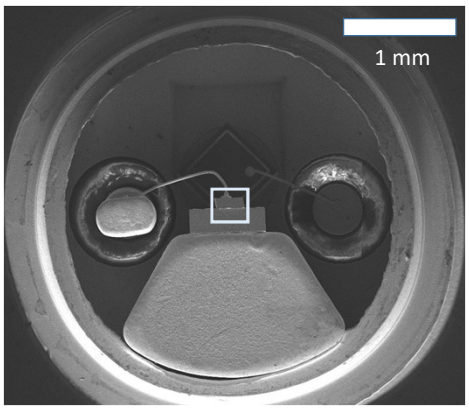
Section view



Fabry-Perót laser diode

Removing the capsule exposes the electronic device

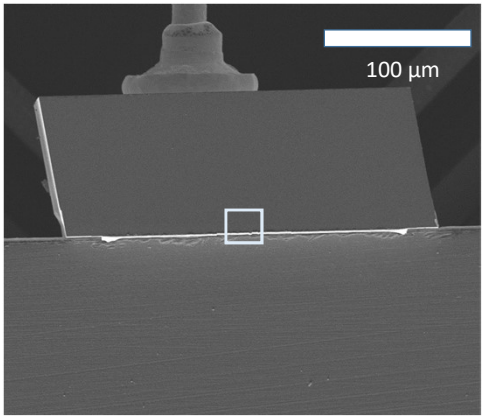
- Metal base
- Electrodes
- Back diode



Fabry-Perót laser diode

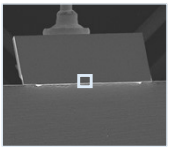
Active región close to surface

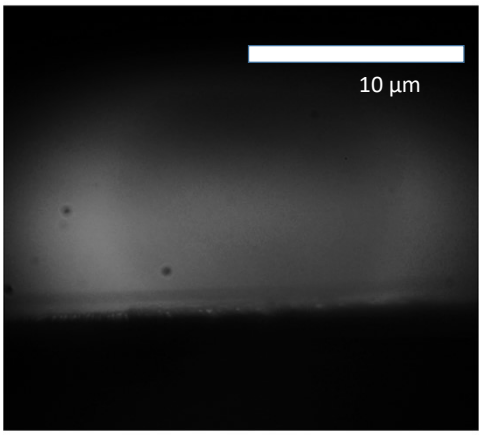
- Dice
- Heat sink



Fabry-Perót laser diode

Active regionnear surface

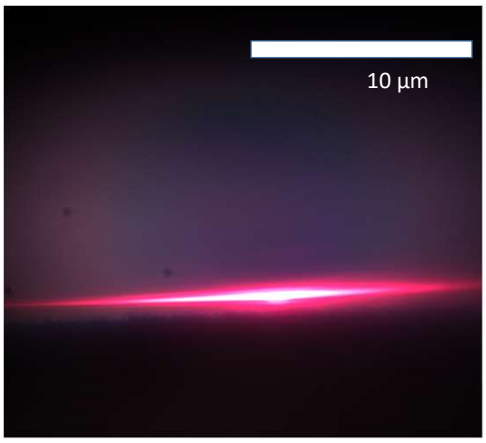


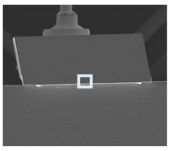


Fabry-Perót laser diode

Optical microscope image

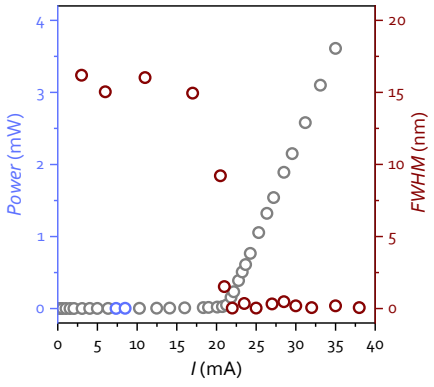
Active region

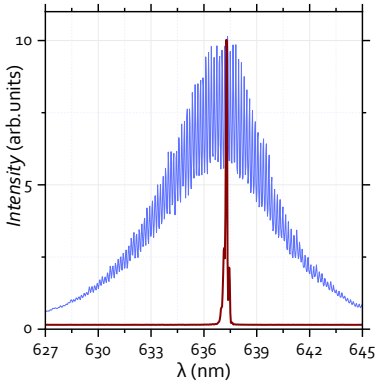




Fabry-Perót laser diode performance

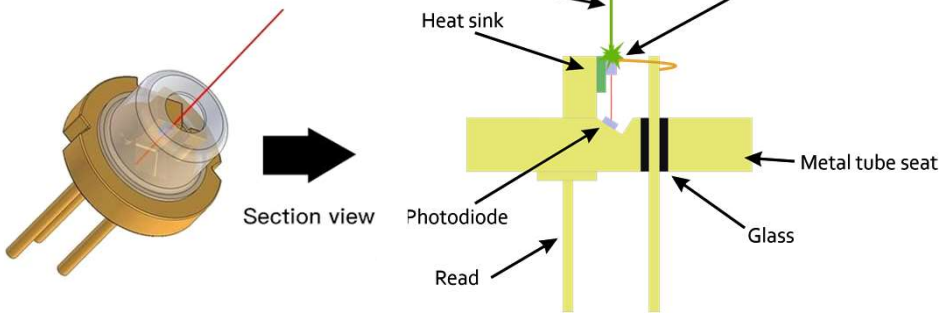
- Below lasing threshold:
  - Broad spectrum (many FP modes)
  - Spontaneous emission
- Above lasing threshold:
  - Single FP
  - Stimulated emission





Ablation

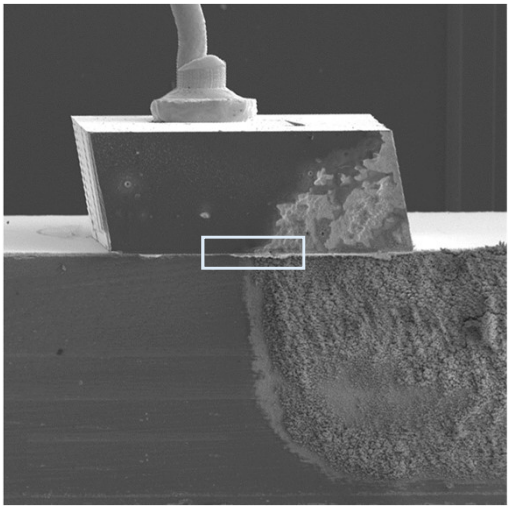
Vertical current



Random laser diode

Ablation

- 800 nm
- 100 femtosecond
- 100 µJ
- 200 pulses
- spot 350 µm



Random laser diode

Ablation

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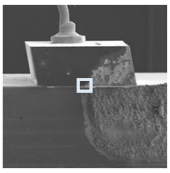
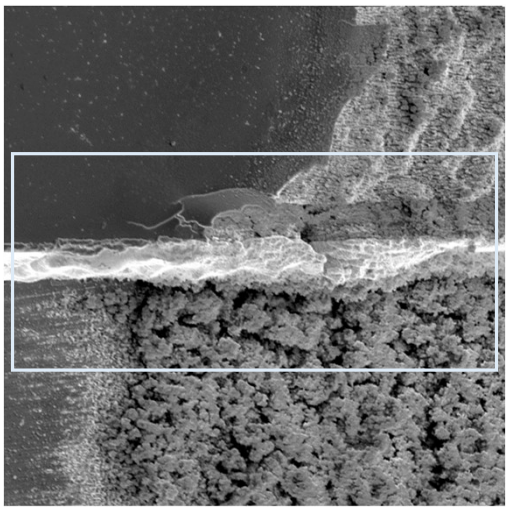
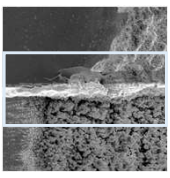
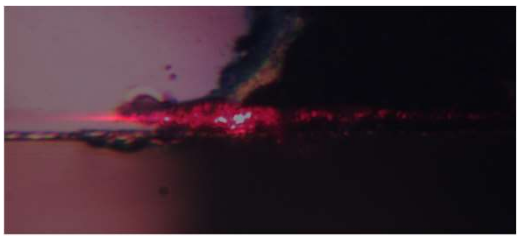


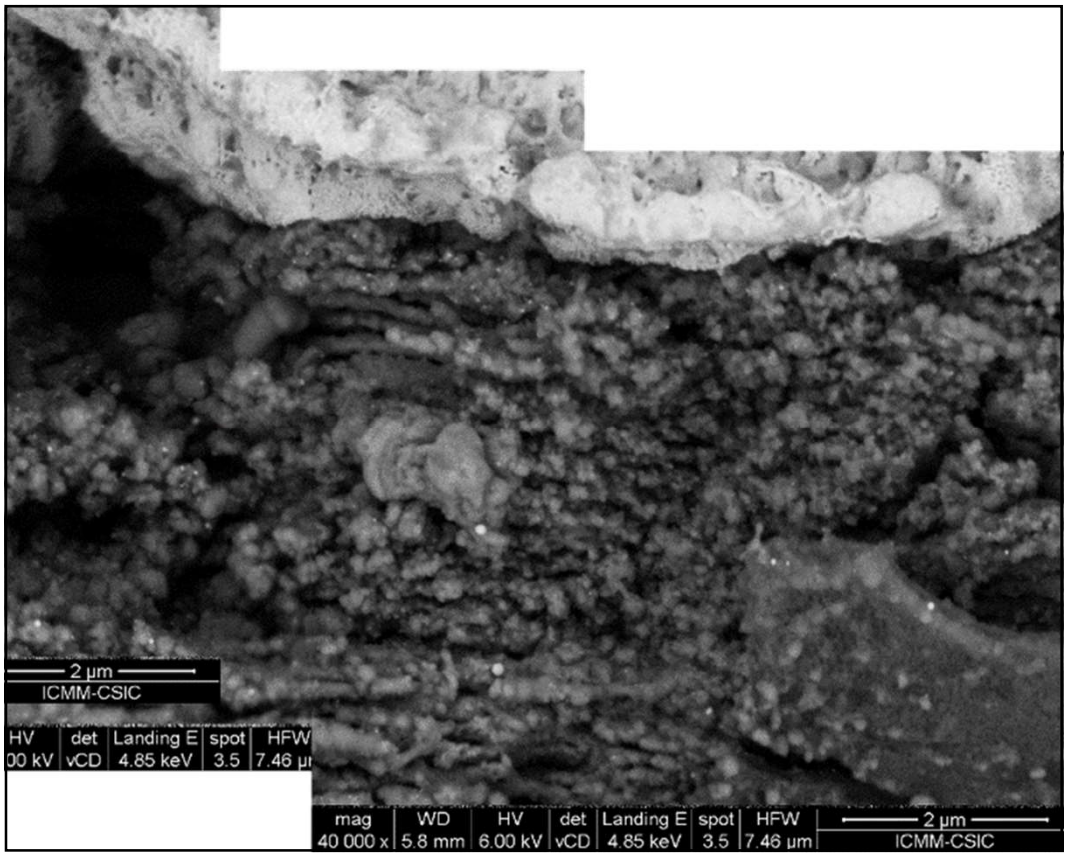


Random laser diode

Emission región under pumping





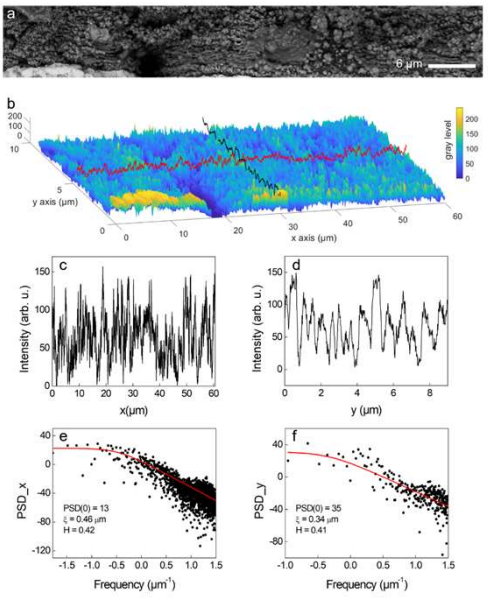


Ablated surface

SEM images help analyse roughness:

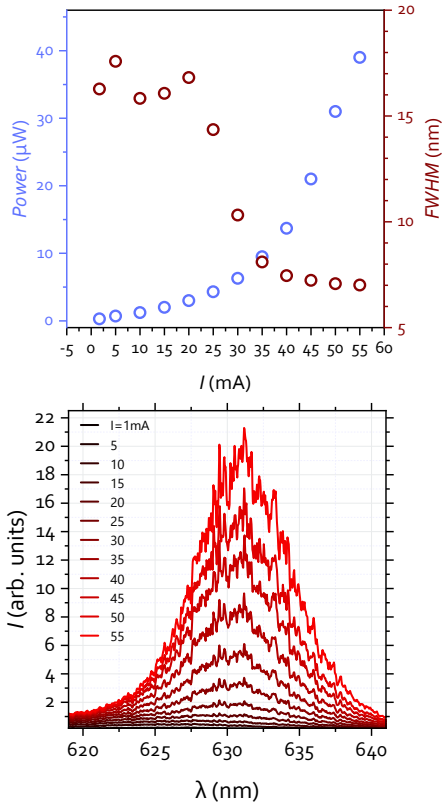
correlation length

$\xi \sim 0.3\text{-}0.4\ \mu m$



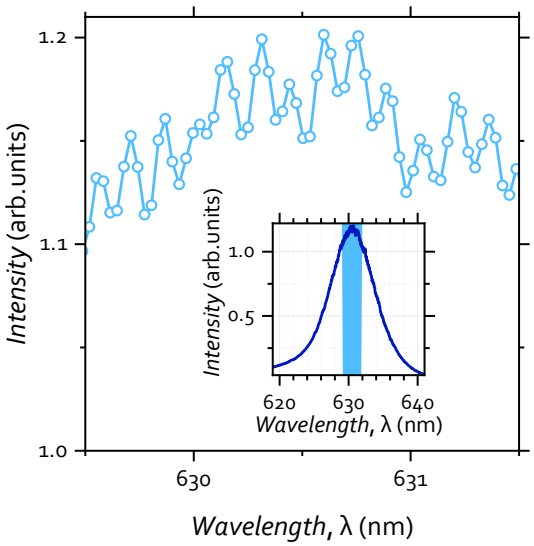
Random laser diode

- Below lasing threshold:
  - Broad spectrum (no FP modes)
    - Spontaneous emission
- Above lasing threshold:
  - Line narrowing
  - Stimulated emission



RL cavity length

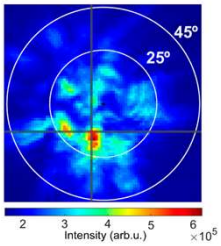
Fourier transformed emission retrieves cavity length

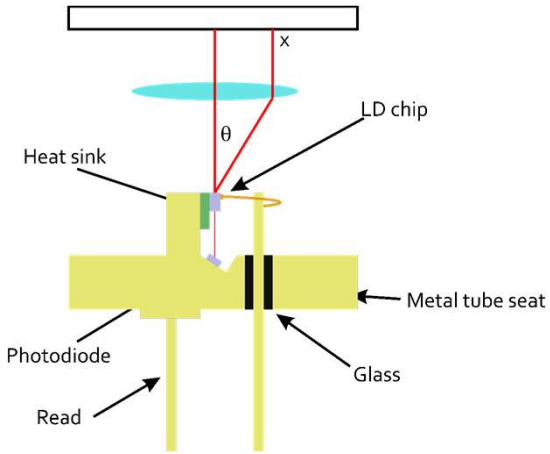


RL cavity length

Angular selection of emission

Integrated emission

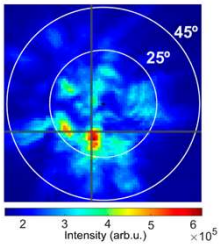


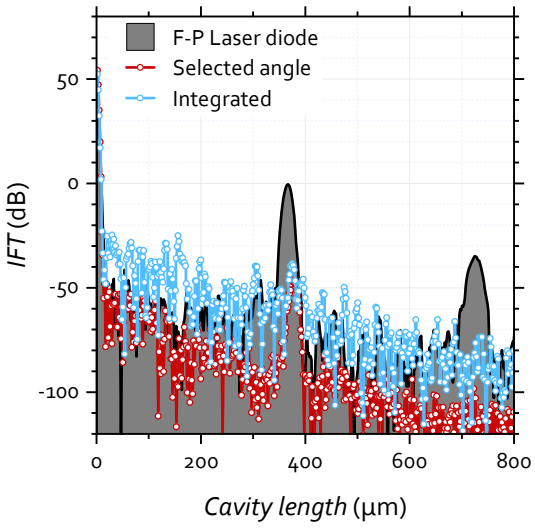


RL cavity length

Angular selection of emission

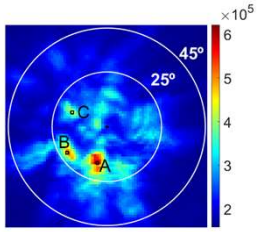
Integrated emission

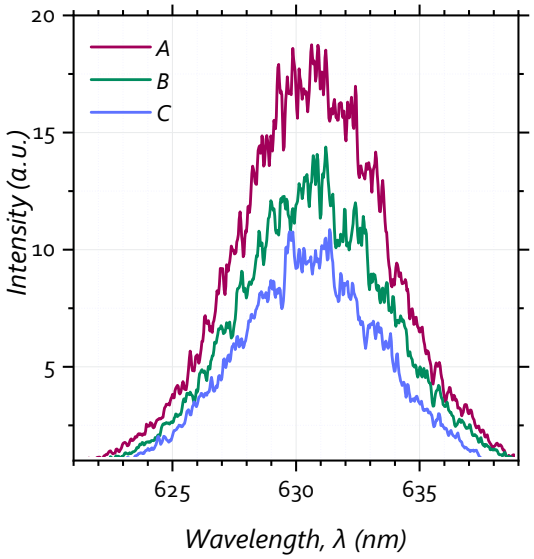




Mode mapping

Fourier imaging provides spatial distribution of intensity





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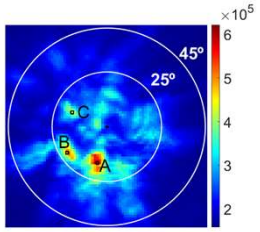
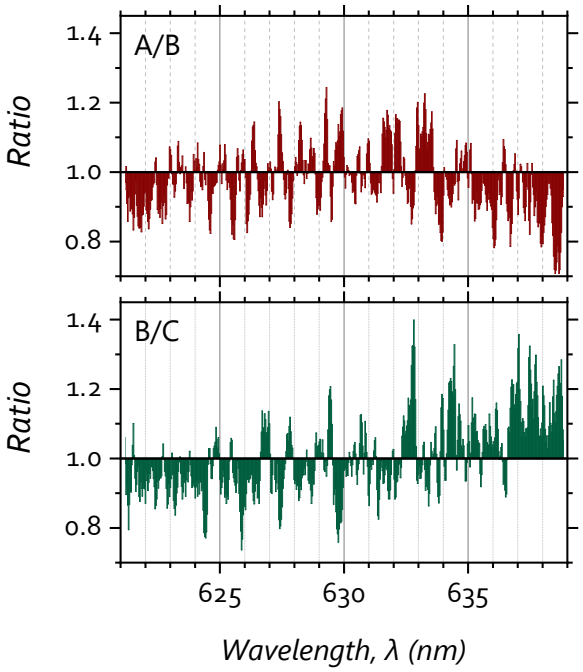
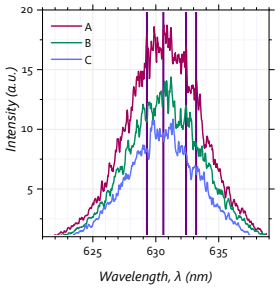
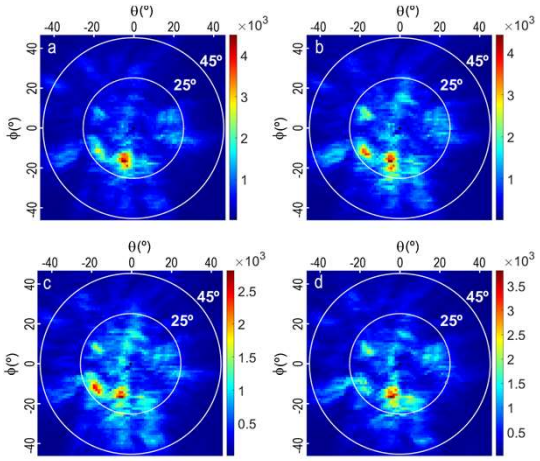




Random laser diode

Mode emission spatial distribution





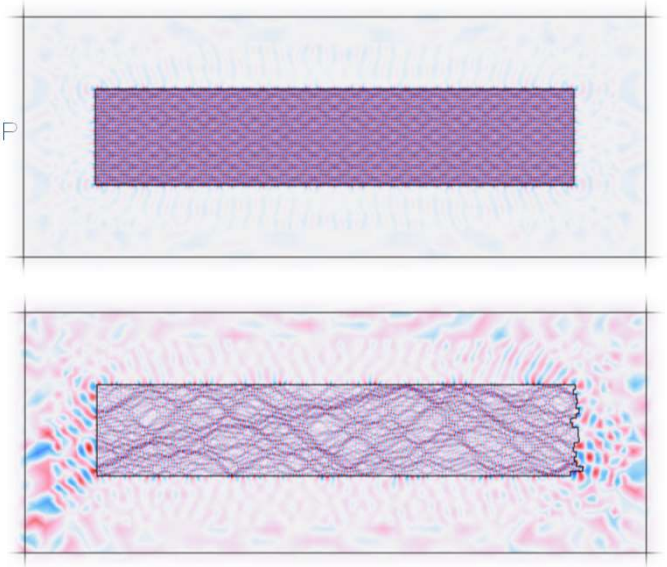
Mode modelling

Comparison between F-P cavity and RL cavity:

Roughness = 20 layers

(normally distributed

With σ = 300 nm)



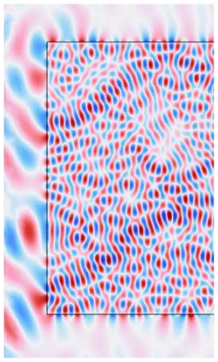
Mode modelling

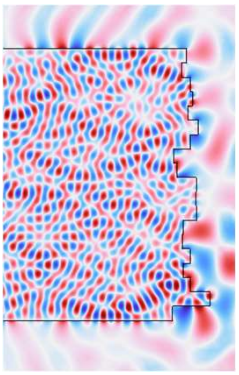
Comparison between perfect cavity and roughened RL:

Roughness = 20 layers

(normally distributed

With σ = 300 nm)





$$g^1(\mathbf{r}_1, \mathbf{r}_2, \tau) = \frac{|\langle \mathbf{E}^*(\mathbf{r}_1,t)\mathbf{E}(\mathbf{r}_2,t+\tau)\rangle|}{\langle \mathbf{E}^*(\mathbf{r}_1,t)\mathbf{E}(\mathbf{r}_1,t)\rangle^{1/2}\langle \mathbf{E}^*(\mathbf{r}_2,t+\tau)\mathbf{E}(\mathbf{r}_2,t+\tau)\rangle^{1/2}}$$

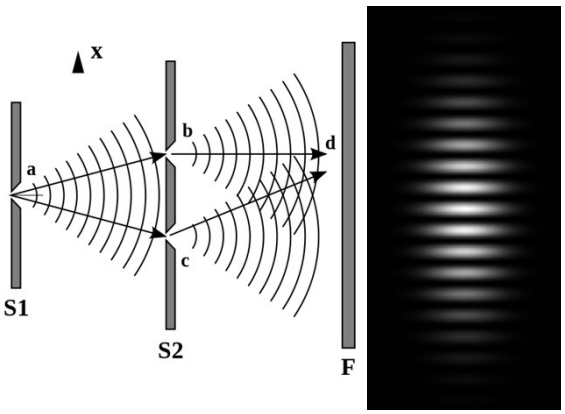
Spatial coherence

The width of $g^1(\mathbf{r}_1, \mathbf{r}_1, \tau)$ gives coherence *time*: number of longitudinal modes

Mach-Zehnder

The width of $g^1(\mathbf{r}_1, \mathbf{r}_2, 0)$ gives coherence *length*: number of transverse modes

visibility γ, defined as
$\gamma = (I_{\max} - I_{\min})/(I_{\max} + I_{\min})$



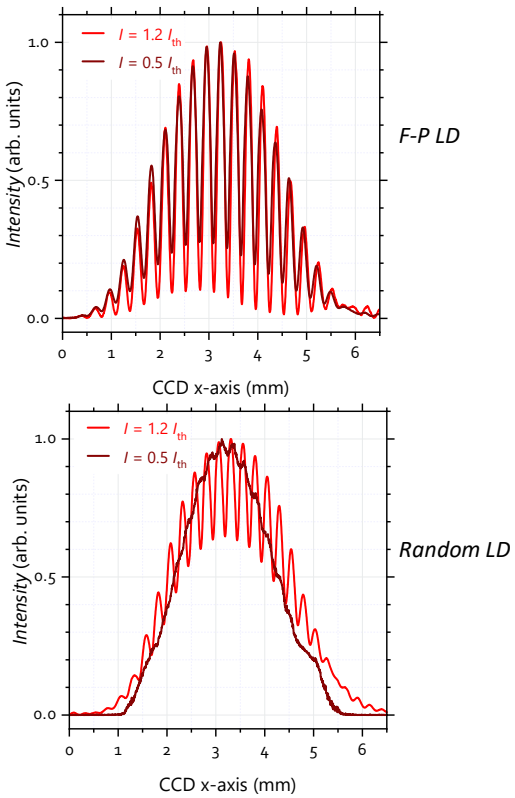
$$\mathbf{E}_d = K_\mathrm{b}\mathbf{E}(\mathbf{r}_\mathrm{b}, t + t_\mathrm{b}) + K_\mathrm{c}\mathbf{E}(\mathbf{r}_\mathrm{c}, t + t_\mathrm{c})$$

$$I_d = K_\mathrm{b}^2\langle|\mathbf{E}(\mathbf{r}_\mathrm{b}, t + t_\mathrm{b})|^2\rangle + K_\mathrm{c}^2\langle|\mathbf{E}(\mathbf{r}_\mathrm{c}, t + t_\mathrm{c})|^2\rangle + K_\mathrm{b}K_\mathrm{c}\mathrm{Re}[\langle\mathbf{E}^*(\mathbf{r}_\mathrm{c}, t + t_\mathrm{c})\mathbf{E}(\mathbf{r}_\mathrm{b}, t + t_\mathrm{b})\rangle]$$

RL diode operation

Spatial Coherence (transversal modes)

Double-slit fringes

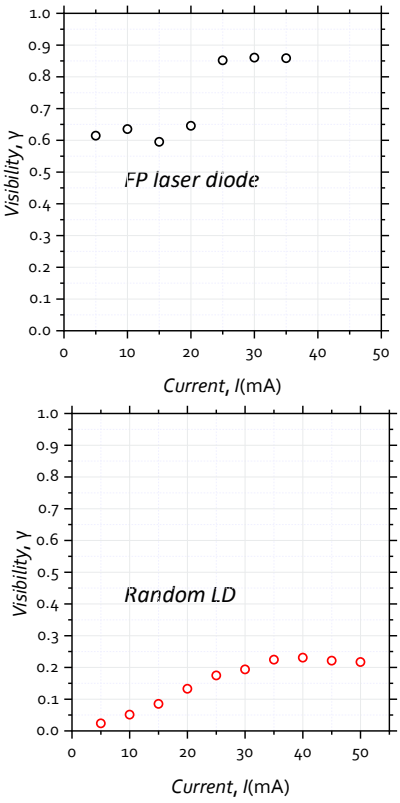


RL diode operation

Spatial Coherence (transversal modes)

Visibility of FP laser diode always above 0.6

Visibility of the RL barely surpasses 0.2

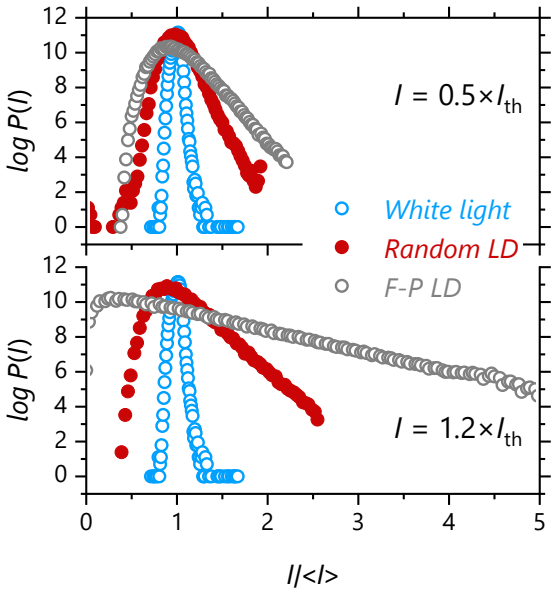


RL diode speckle

Speckle distribution monochromatic source:
$P(I) = e^{-I/\langle I\rangle}/\langle I\rangle$

dark pixels exponentially more probable

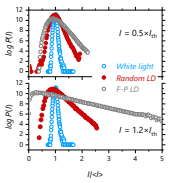
- White lamp
- Random LD
- F-P LD

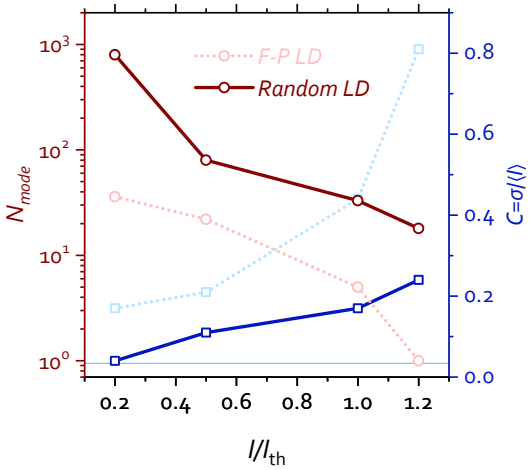


Number of modes

Number of modes from contrast:

$$C = \frac{\sigma}{\langle I\rangle}$$
$$N = C^{-2}$$

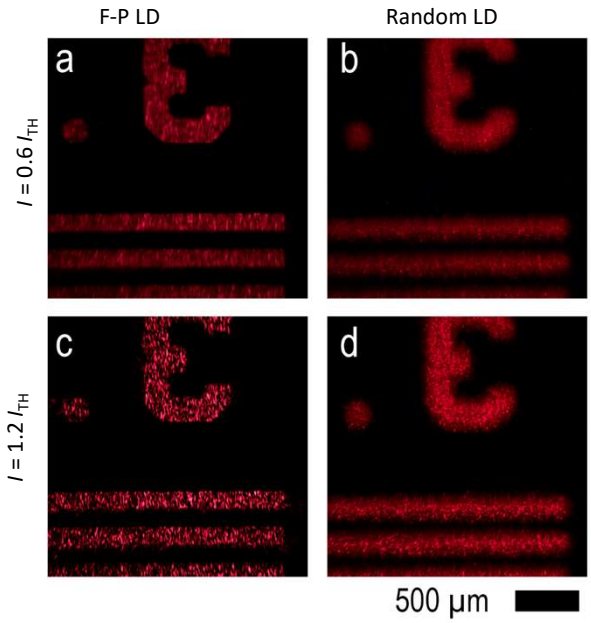




RL diode imaging

Speckle negatively affects imaging

RL mitigates speckle formation



Conclusions

Summary

- Electrical pump RL
  - Simple & cheap
  - Illumination without speckle
  - Still under improvement

A. Consoli, N. Caselli, and C. López, "Electrically driven random lasing from a modified Fabry–Pérot laser diode," *Nat. Photonics* **16** 2-19-225 (2022).

10.1038/s41566-021-00946-0

Outlook

- Optimization
  - Increased output power
  - Reduce coherence
- Other wavelengths
  - GaN laser diode

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