# Experimental study of the transition to coherent emission in a semiconductor laser with optical feedback

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UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

*Campus d'Excel·lència Internacional*

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# Research group: Dynamics, nonlinear optics and lasers

www.donll.upc. edu



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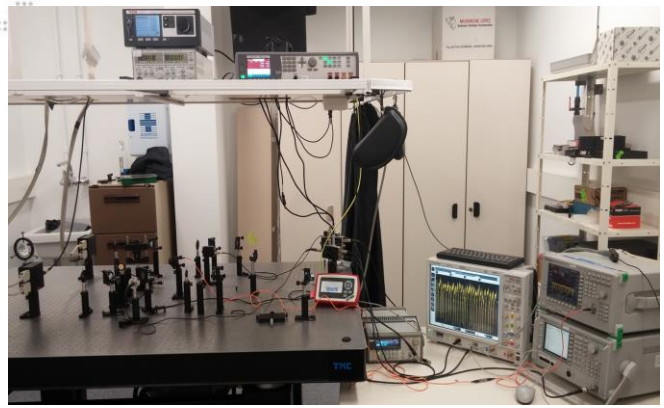
# Where are we? UPC Campus Terrassa


Viernes, 25 de septiembre de 2009 Diari de Terrassa

El edificio Gaia centraliza grupos científicos consolidados y emergentes.



Laser lab in Gaia Building,
UPC Campus Terrassa



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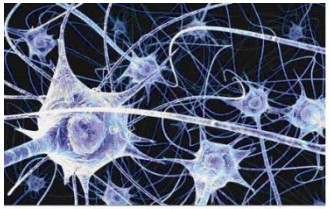
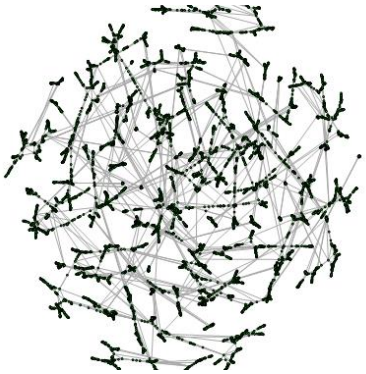
# Research lines

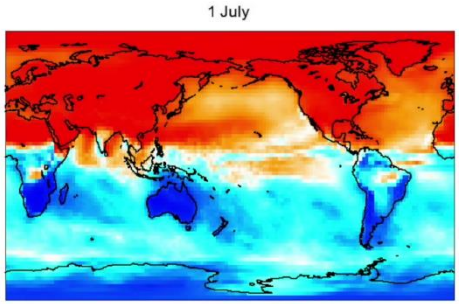
- Laser dynamics

- Neural dynamics



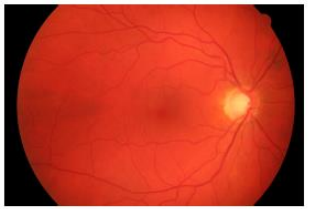


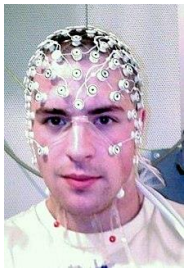
- Complex systems

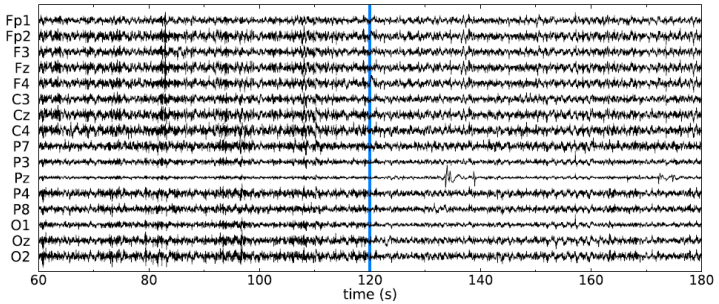



- Climate data analysis

- Biomedical data analysis







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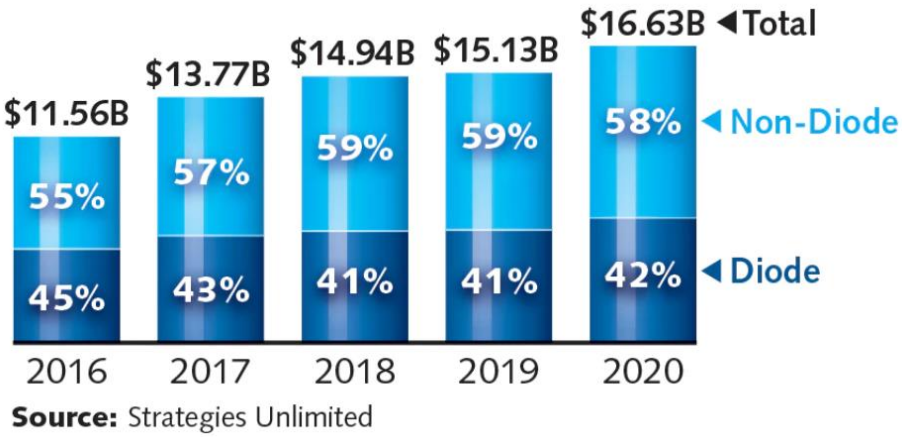
# Semiconductor lasers & photonic technologies

- Inexpensive, compact, efficient
- Emit a wide range of wavelengths (optical communications, biomedical applications),
- Emit a wide range of powers (μWs-KWs).



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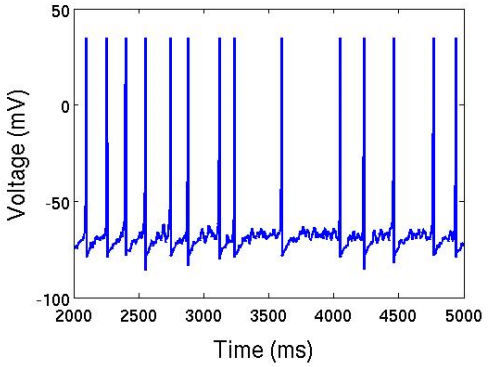
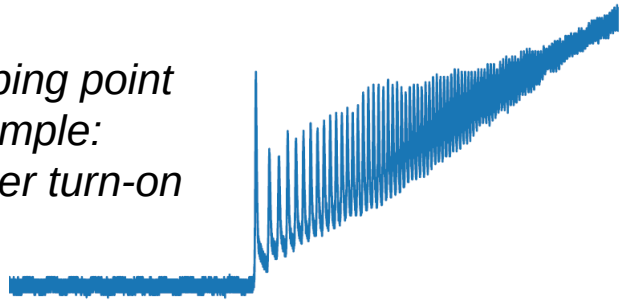
# Semiconductor lasers: experiments allow to understand complex phenomena

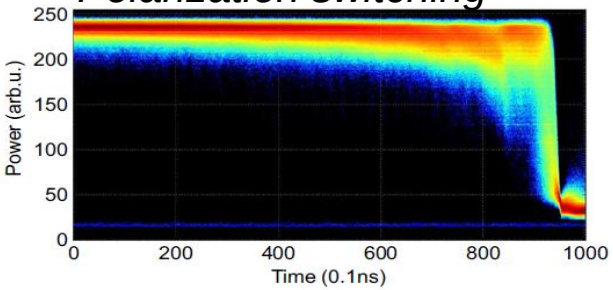
*Laser & neuronal spikes*



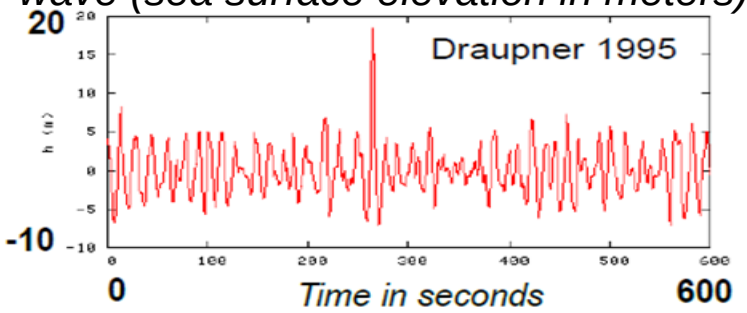

*Tipping point example: Laser turn-on*



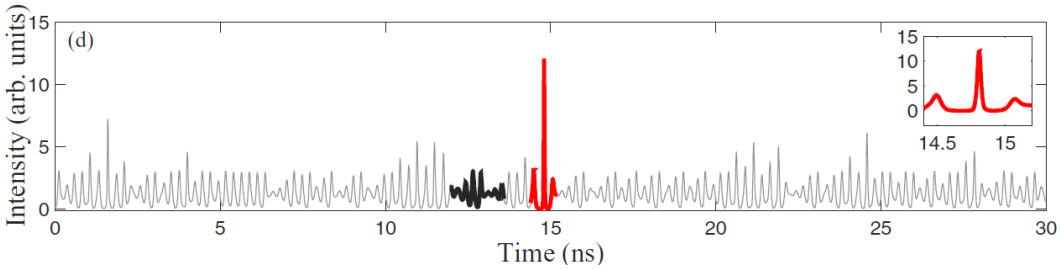
*Polarization switching*




*Extreme event example: ocean rogue wave (sea surface elevation in meters)*




*High laser pulse (optical rogue wave)*



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# In this talk: “explosive” phenomena

PRL **105,** 264101 (2010) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2010

## Crowd Synchrony and Quorum Sensing in Delay-Coupled Lasers

Jordi Zamora-Munt, C. Masoller, and Jordi Garcia-Ojalvo
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Rajarshi Roy
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(Received 24 September 2010; published 22 December 2010)

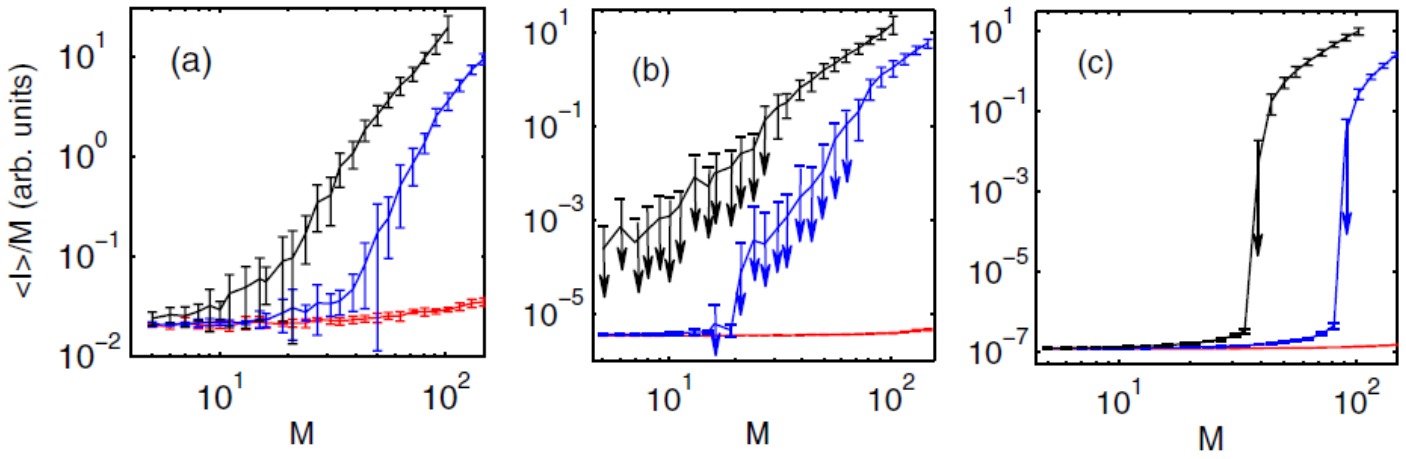


FIG. 3 (color online). Ratio between the averaged coherent intensity $\langle I \rangle$ and the number of star lasers $M$, as a function of $M$



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# Explosive Synchronization Transitions in Scale-Free Networks

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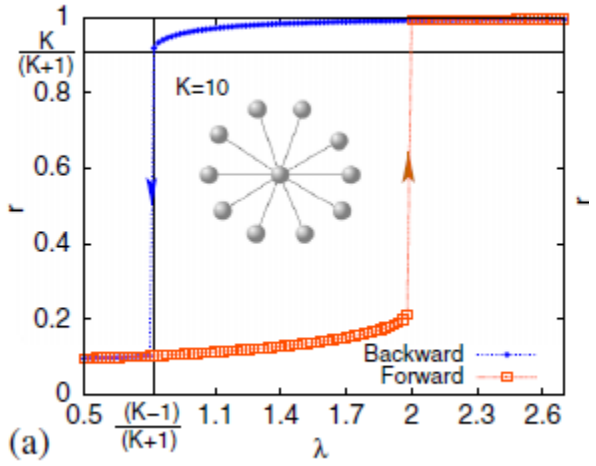
[1]*Departamento de Física de la Materia Condensada, Universidad de Zarag*
[2]*Institute for Biocomputation and Physics of Complex Systems (BIFI), University o*
[3]*Departament d'Enginyeria Informàtica i Matemàtiques, Universitat Rovira i*
[4]*Departamento de Física Teórica, Facultad de Ciencias, Universidad de Zar*
(Received 30 December 2010; published 23 March






# Explosive First-Order Transition to Synchrony in Networked Ch

I. Leyva,[1,2] R. Sevilla-Escoboza,[3] J. M. Buldú,[1,2] I. Sendiña-Nadal,[1,2] J. Gómez-Ga
Y. Moreno,[5,7] S. Gómez,[6] R. Jaimes-Reátegui,[3] and S. Boccale
[1]*Complex Systems Group, Universidad Rey Juan Carlos, 28933 Móstoles, M*
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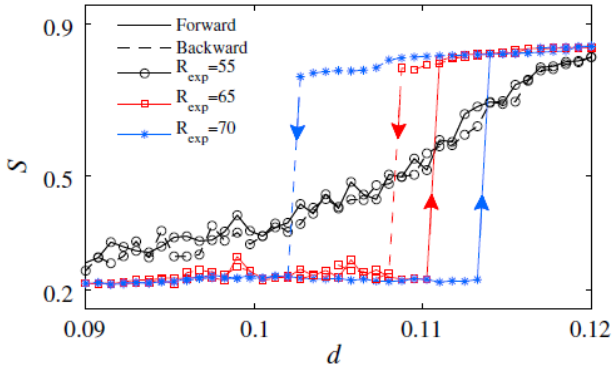
[3]*Centro Universitario de Los Lagos, Universidad de Guadalajara, Lagos de Moreno, J*
[4]*Departamento de Física de la Materia Condensada, Universidad de Zaragoza, Zar*
[5]*Institute for Biocomputation and Physics of Complex Systems (BIFI), Universidad de Zarag*
[6]*Departamento d'Enginyeria Informàtica i Matemàtiques, Universitat Rovira i Virgili, 4*
[7]*Departamento de Física Teórica, Universidad de Zaragoza, Zaragoza 50009, Spain*
(Received 17 January 2012; published 20 April 2012)



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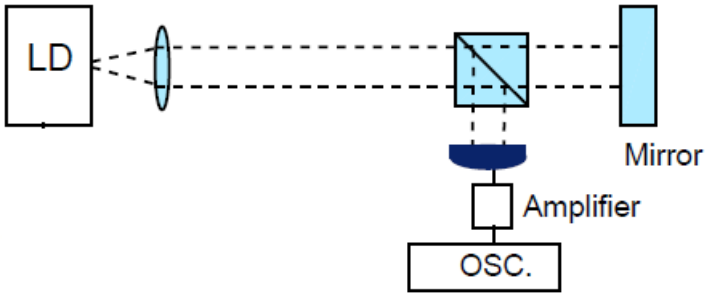
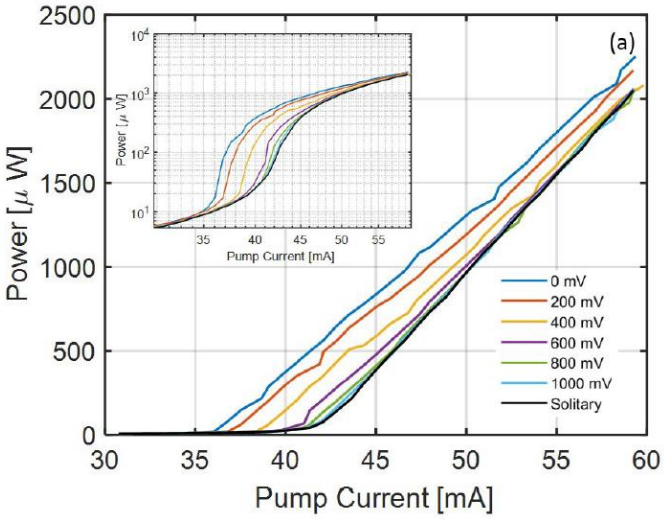
# Optical feedback and laser dynamics

How does the intensity of light grow during the laser turn on?




Well-known optical feedback-induced threshold reduction

How is the *coherence* of the light affected by feedback?



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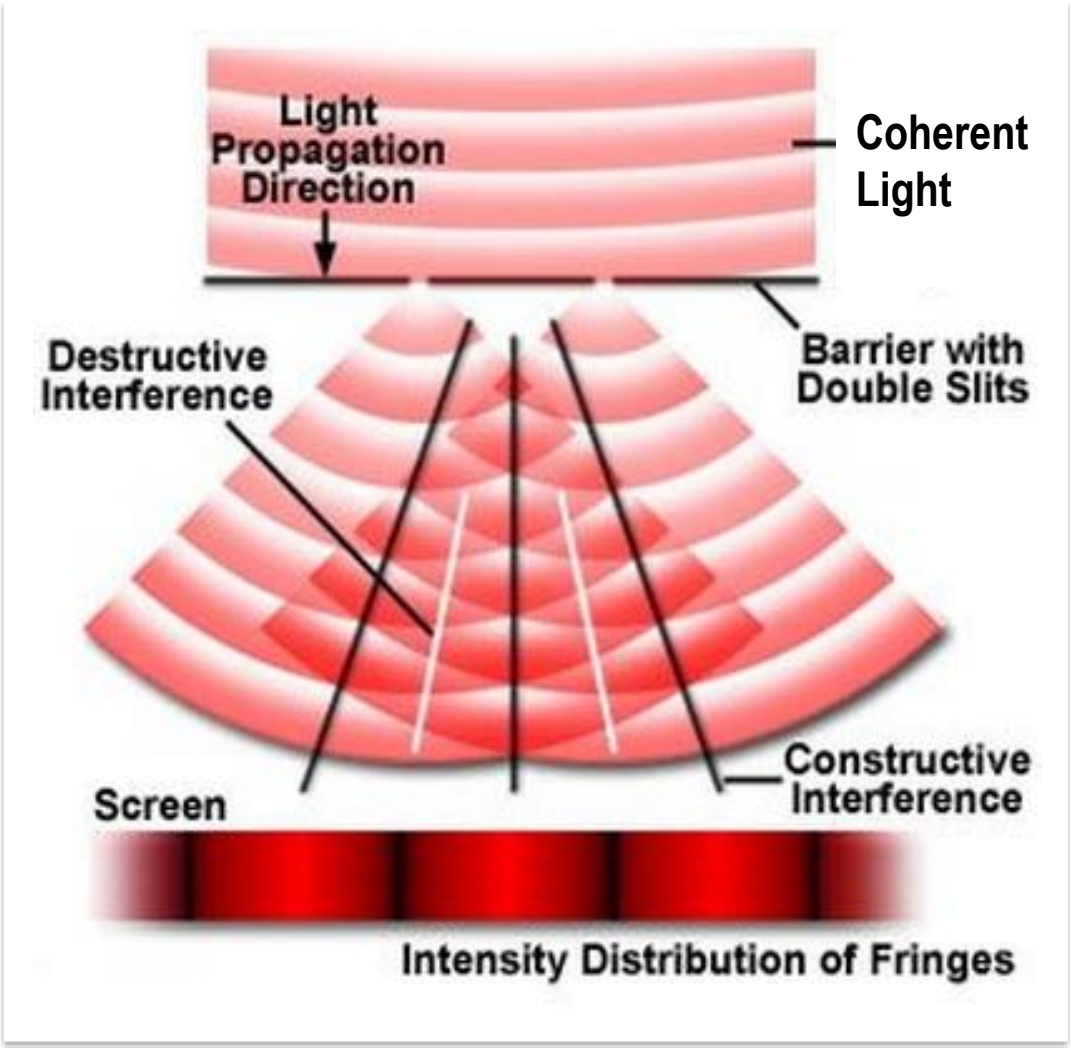
# Quick review on the interference of coherent waves



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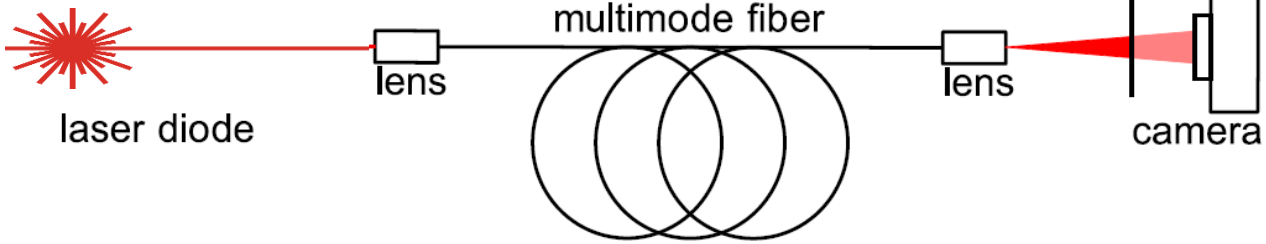
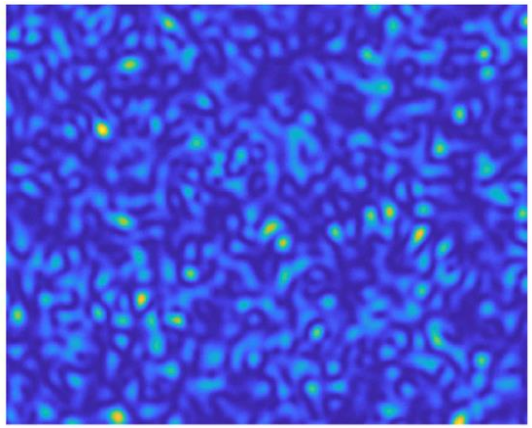
# Speckle pattern: generated by random interference / scattering of coherent waves



Many applications. Two main types

- Extract information of the light (wavemeters)
- Extract information of the medium that generates the speckle (speckle-based spectroscopy)

But

Speckle is a drawback in laser-based illumination and imaging application.



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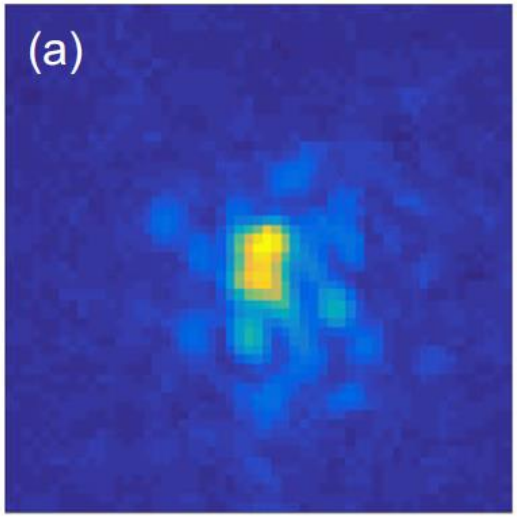
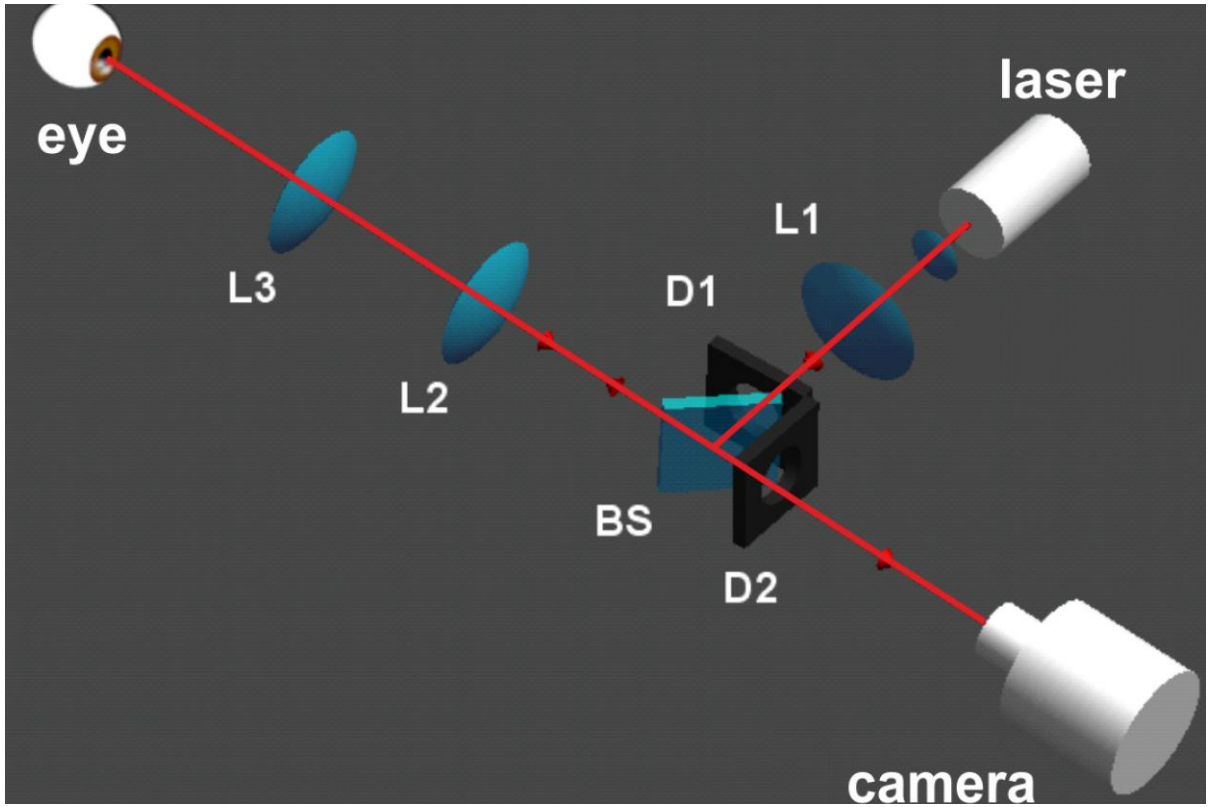
# Speckle reduction in double-pass retinal imaging

Problem:
The retina reflectivity is about 4%




D. Halpaap, C. E. Garcia-Guerra, M. Vilaseca, C. Masoller, "*Speckle reduction in double-pass retinal images*", Sci. Rep. 9, 4469 (2019)



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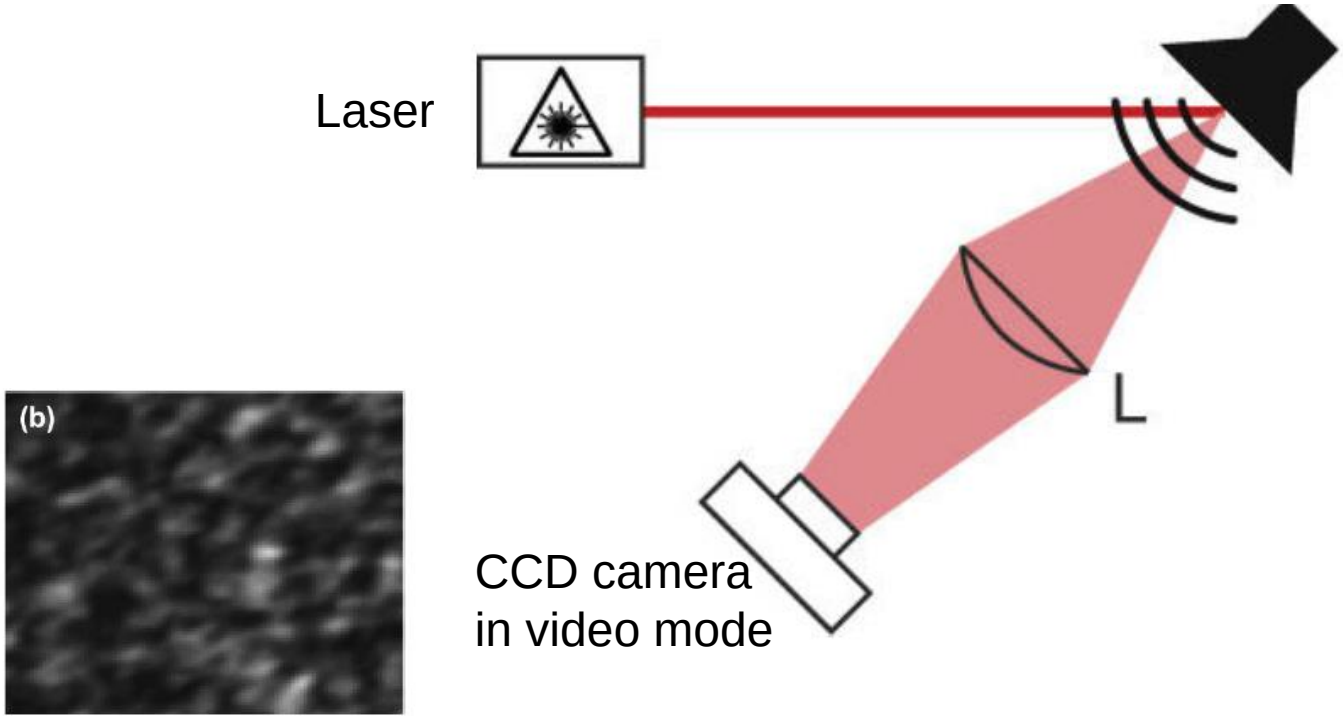
# An example of application of speckle pattern analysis

Recovery of audio signals from silent videos of speckle patterns




C. Barcellona, D. Halpaap, P. Amil, A. Buscarino, L. Fortuna, J. Tiana, C. Masoller, "*Remote recovery of audio signals from videos of optical speckle patterns: a comparative study of signal recovery algorithms*", Opt. Exp. 28, 8716 (2020).



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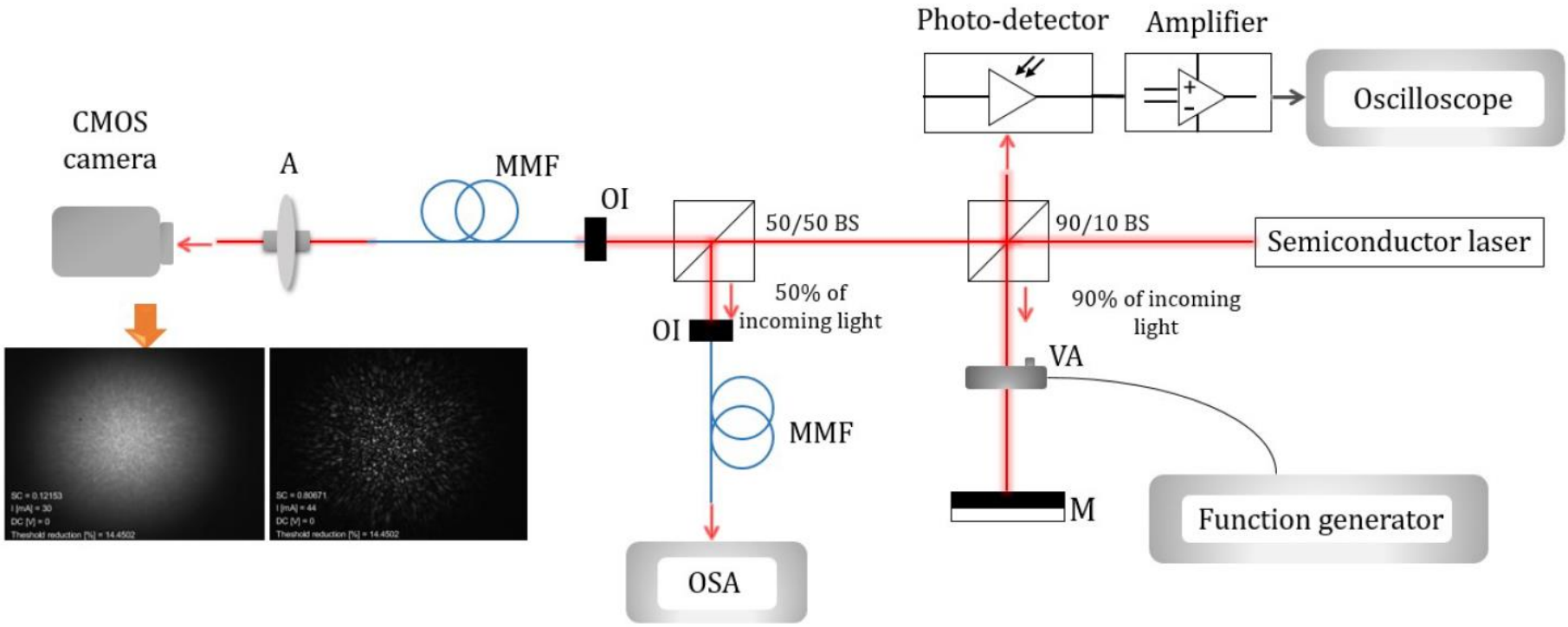
# Experimental setup for the analysis of optical-feedback induced dynamics using speckle analysis




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, "*Abrupt transition from low-coherence to high-coherence radiation in a semiconductor laser with optical feedback*," Opt. Exp. 31, 3857 (2023).



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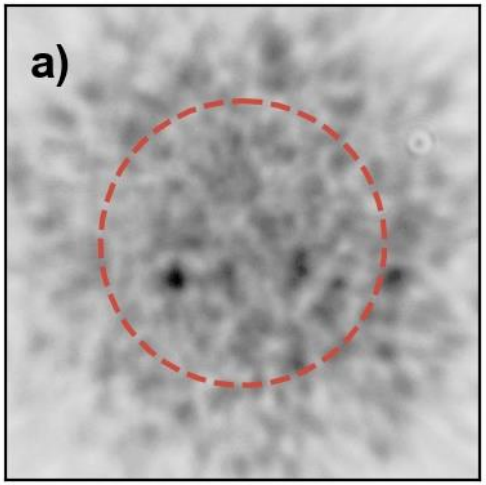
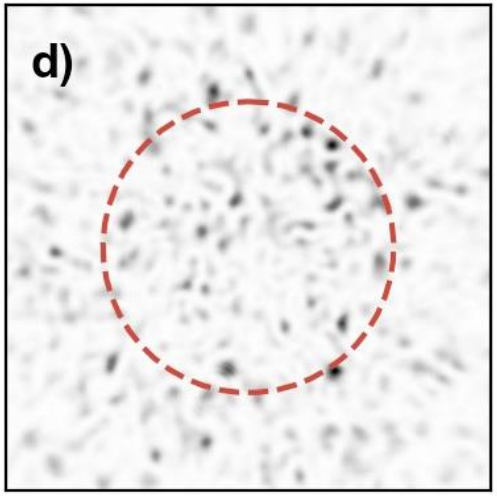
# Examples of speckle images

**Below threshold**




**Above threshold**




Quantification of speckle contrast: $SC = \sigma/\langle I \rangle$



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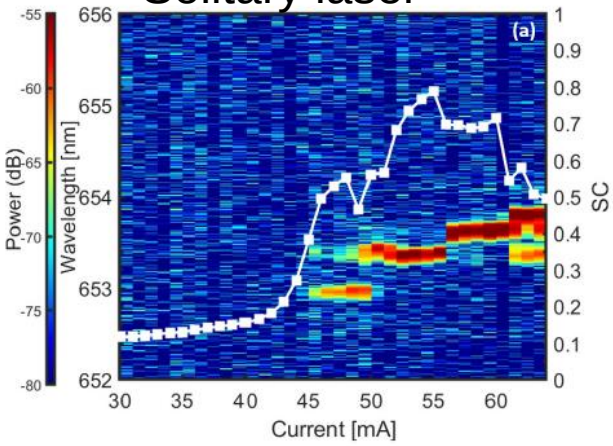
# Analysis of the laser turn-on

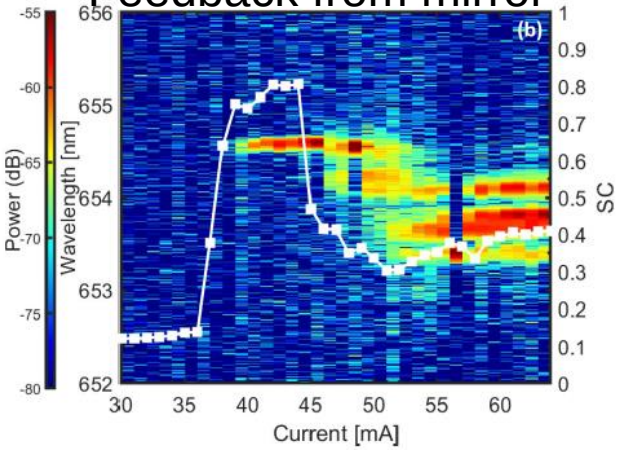
Speckle contrast (white) SC = $\sigma/\langle I \rangle$

Color code: optical spectrum

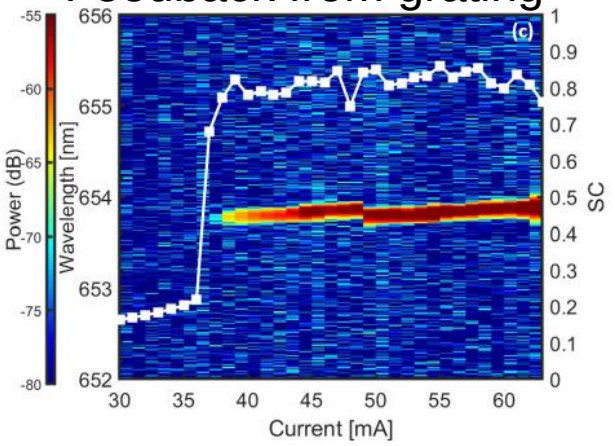
Solitary laser




Feedback from mirror




Feedback from grating




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, Opt. Exp. 31, 3857 (2023)



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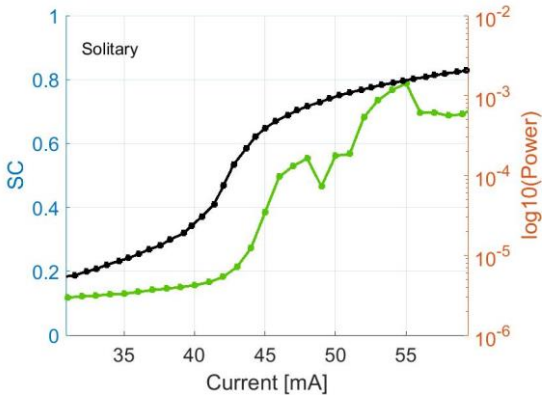
# Analysis of the laser turn-on

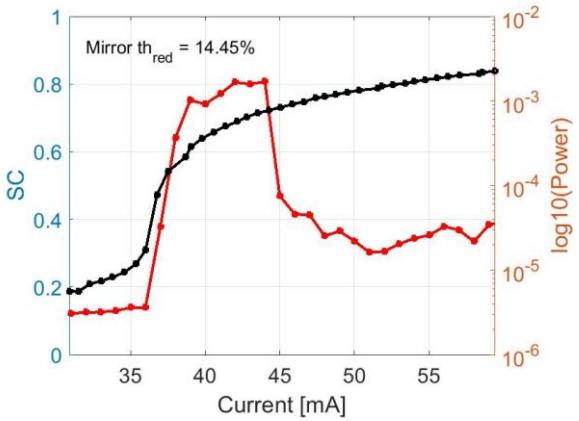
L-I curves: black, log scale

Speckle contrast curves (color)  SC = $\sigma/\langle I \rangle$

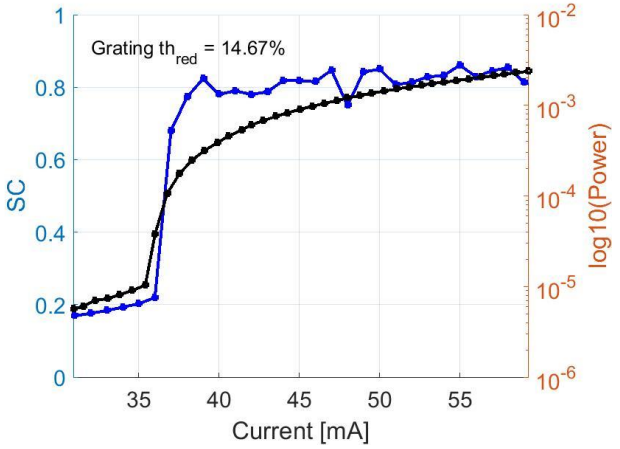
Solitary laser




Feedback from mirror




Feedback from grating




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, "*Abrupt transition from low-coherence to high-coherence radiation in a semiconductor laser with optical feedback*," Opt. Exp. 31, 3857 (2023).



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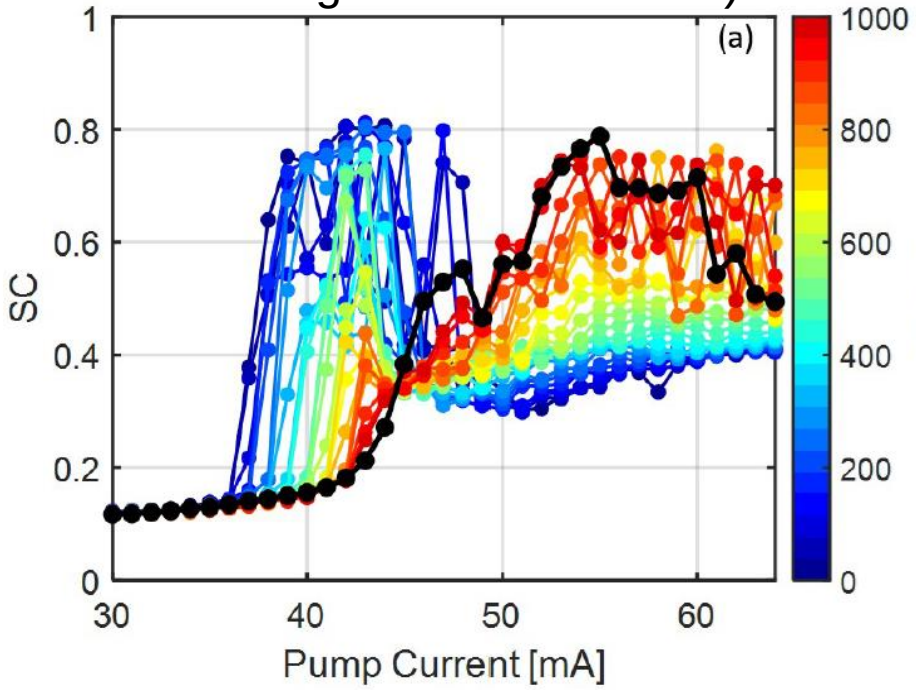
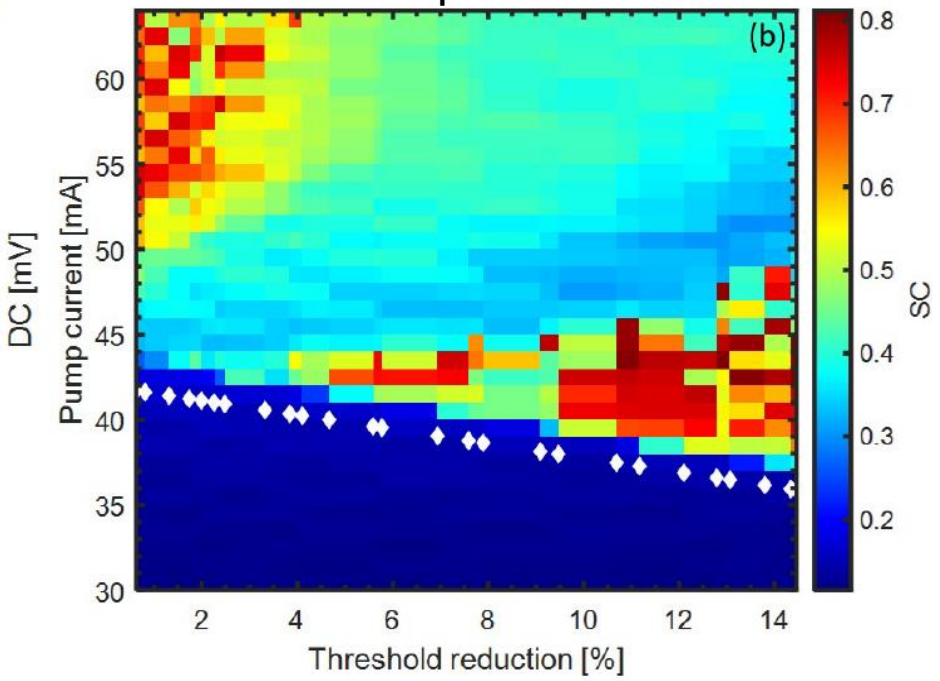
# Influence of the optical feedback strength

Color code: voltage in the variable attenuator (mV, controls the strength of the feedback)




Color code: speckle contrast




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, Opt. Exp. 31, 3857 (2023)



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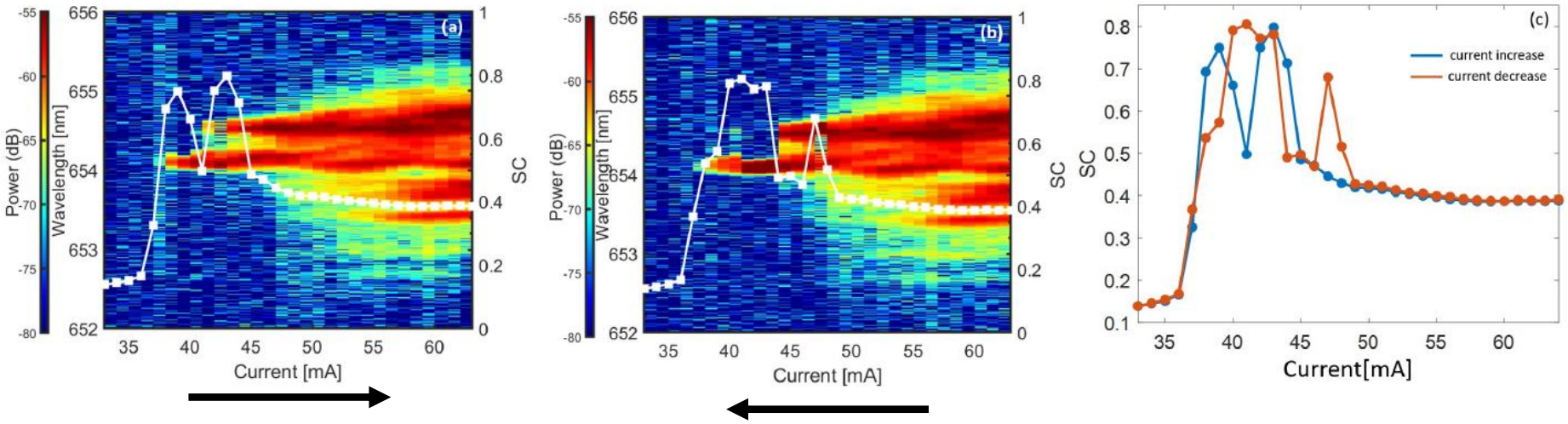
# Hysteresis?




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, Opt. Exp. 31, 3857 (2023)



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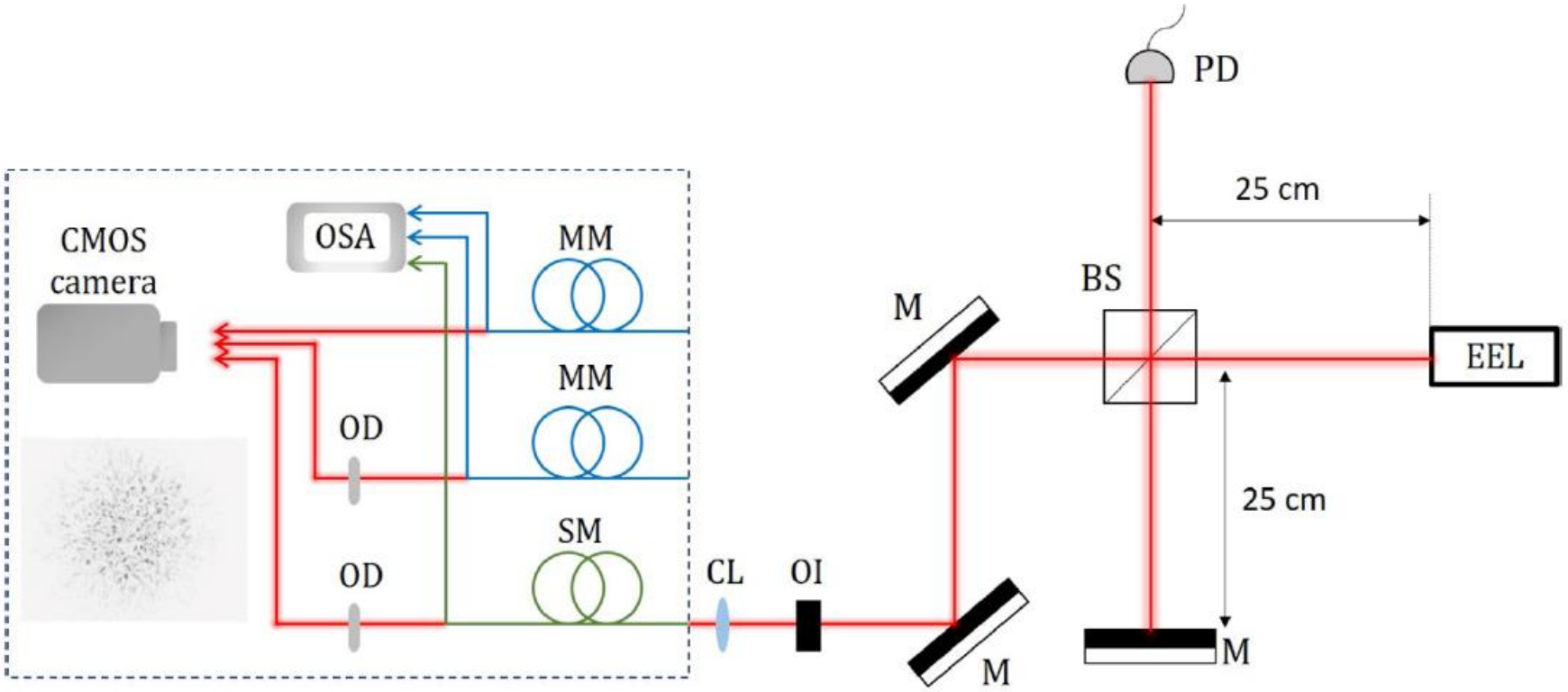
# Role of the medium that generates the speckle pattern?




M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, "*Experimental study of spatial and temporal coherence in a semiconductor laser with optical feedback*," Optics Express 31, 21954 (2023)



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# Comparing MM fiber, MM + Diffuser, SM fiber + Diffuser

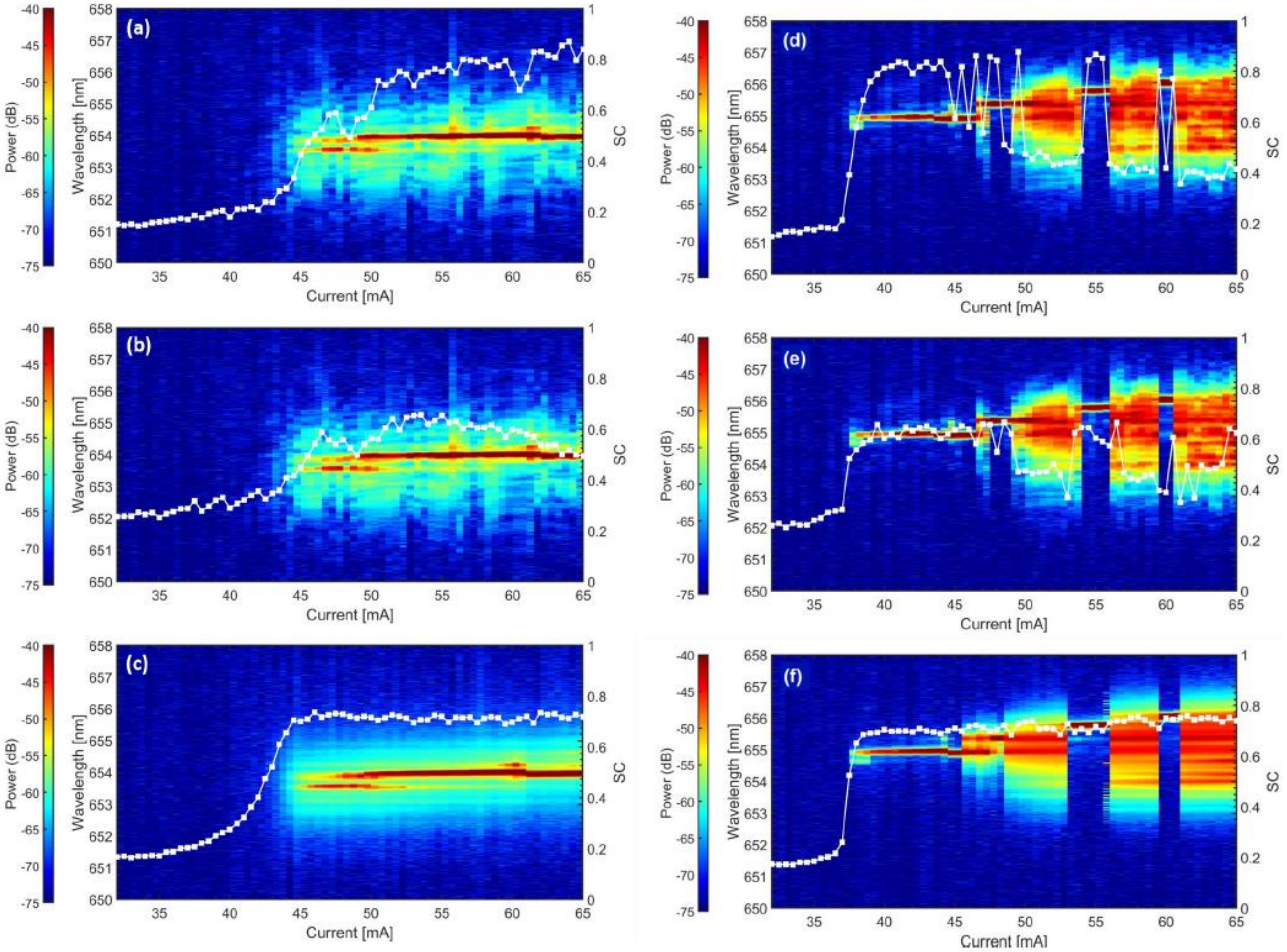
Solitary laser

Laser with optical feedback

MM

MMD

SMD



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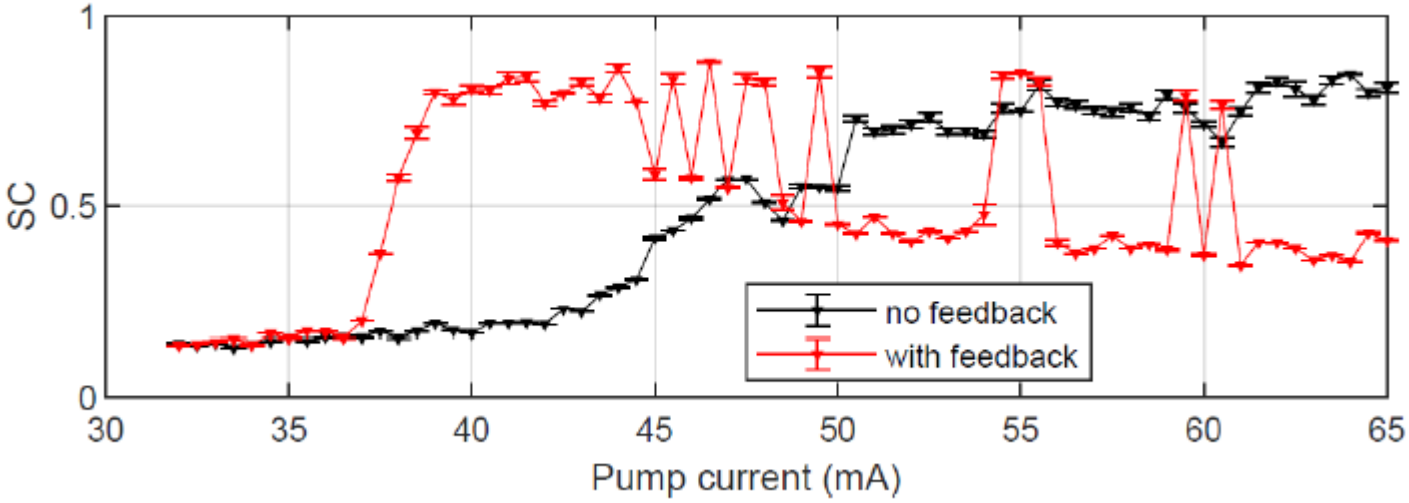
# Research question: can we try to anticipate regime transitions, from the analysis of speckle images?




We tried the permutation entropy, a well-known time-series analysis tools that has been adapted for image analysis.



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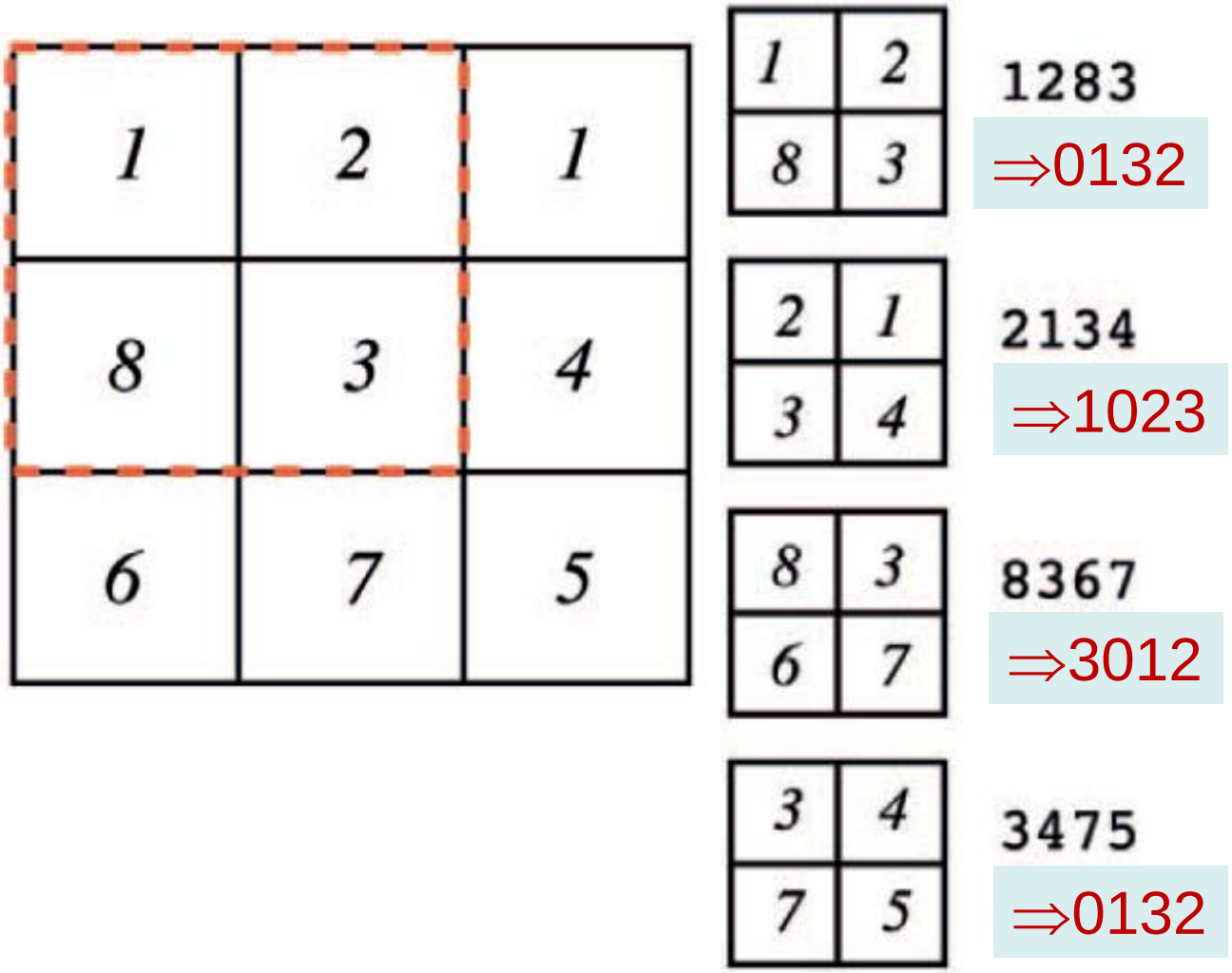
# Ordinal analysis of two-dimensional patterns




Spatial permutation entropy

$$H = -\sum_{i=1}^{N} p_i \ln p_i$$

2x2 pixels: 24 possible patterns

SC and PE computed in a circular region with 70692 pixels.

H. V. Ribeiro et. al, PLoS ONE 7, e40689 (2012).



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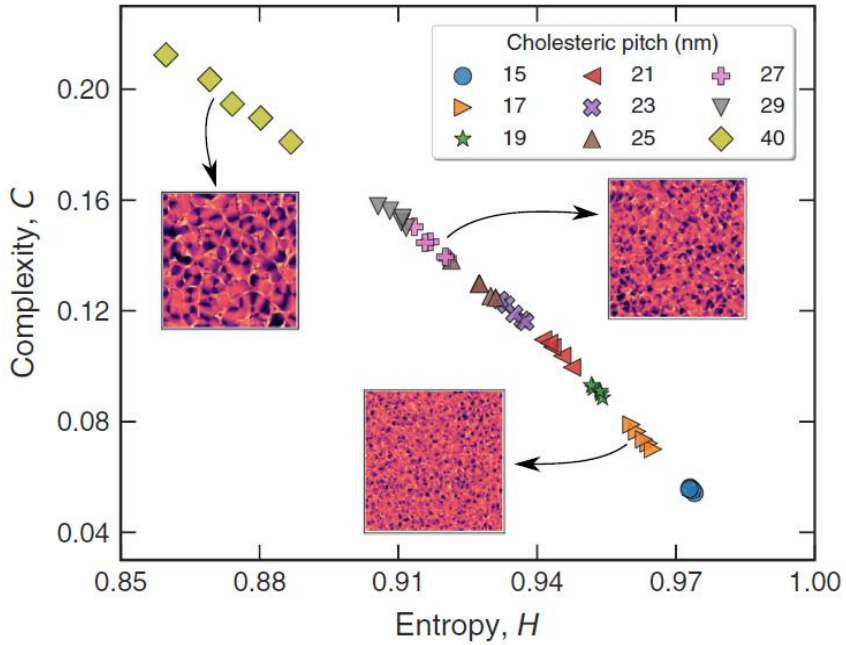
# The “spatial” permutation entropy was proposed to characterize two dimensional patterns and images.

PHYSICAL REVIEW E **99**, 013311 (2019)

**Estimating physical properties from liquid crystal textures via machine learning and complexity-entropy methods**

H. Y. D. Sigaki,[1] R. F. de Souza,[1] R. T. de Souza,[1,2] R. S. Zola,[1,2,*] and H. V. Ribeiro[1,†]
[1]*Departamento de Física, Universidade Estadual de Maringá, Maringá, PR 87020-900, Brazil*
[2]*Departamento de Física, Universidade Tecnológica Federal do Paraná, Apucarana, PR 86812-460, Brazil*



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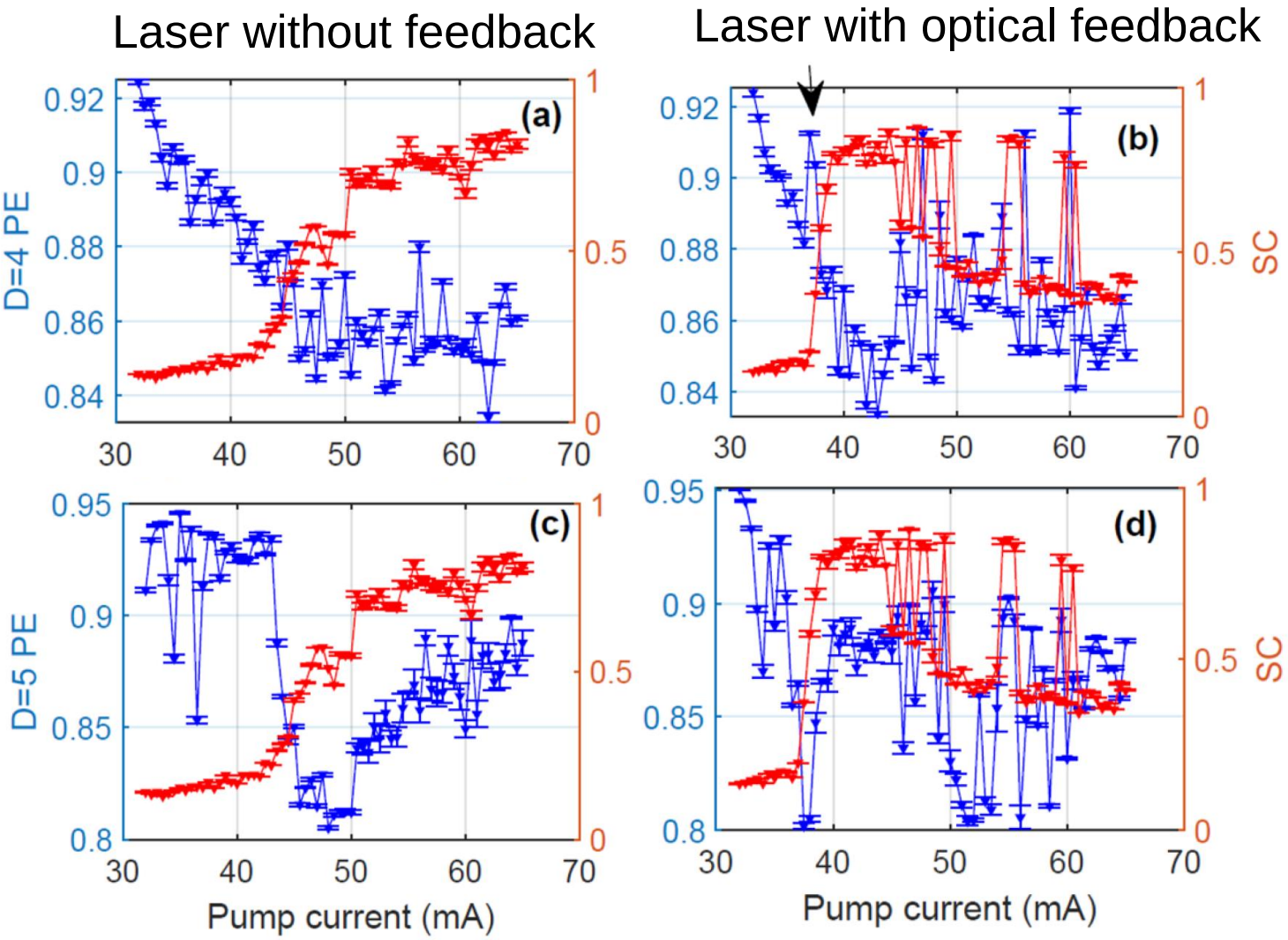
# Results

Pattern:
x x
x x

SC = σ/⟨I⟩

$$H = -\sum_{i=1}^{N} p_i \ln p_i$$

Pattern: x
x x x
x




*G. Tirabassi et al., "Permutation entropy-based characterization of speckle patterns generated by semiconductor laser light", APL Photonics 8, 126112 (2023).*



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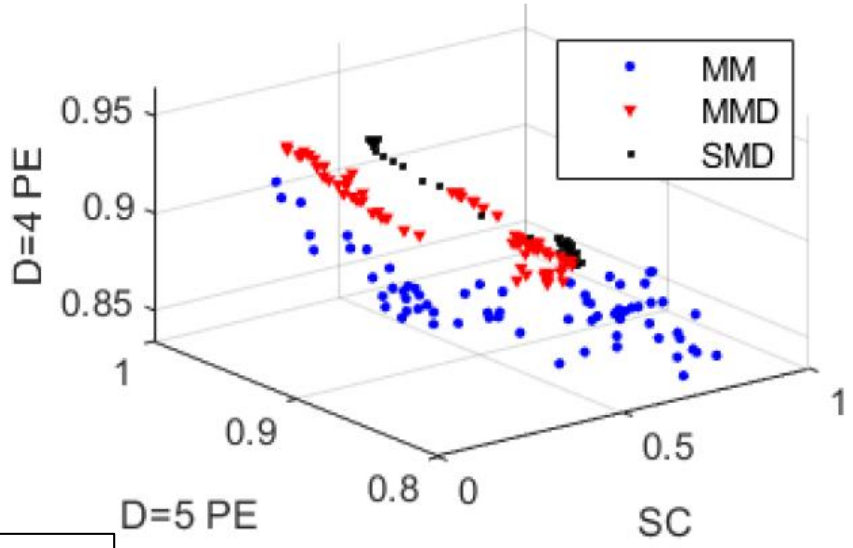
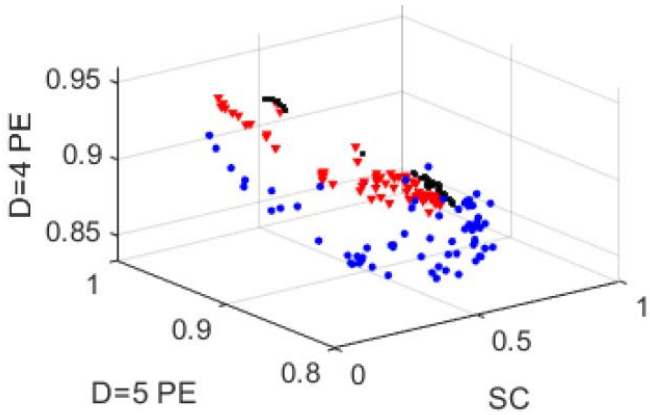
# Three features allow to classify the speckle patterns according to the configuration used to generate speckles

Solitary laser

Laser with optical feedback

Pattern: x x
x x




Pattern: x
x x x
x

Accuracy of random forest classifier

Solitary laser: 99.4 % ± 0.4 %

Laser with optical feedback: 97.1 % ± 1.3 %



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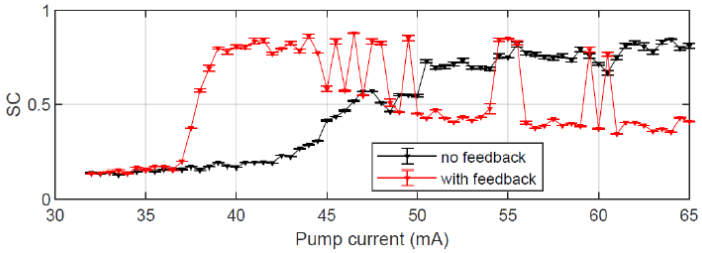
# Take home messages and outlook

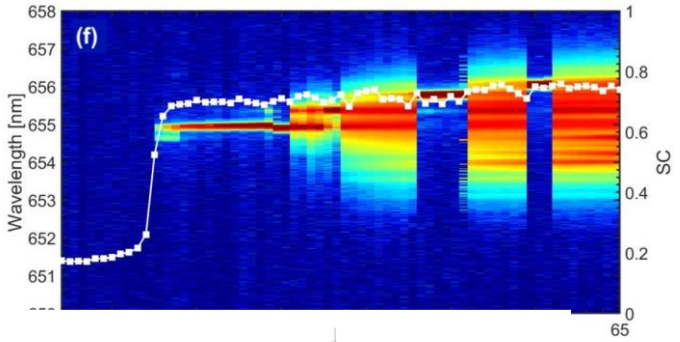
1. Optical feedback induces an abrupt, "*explosive*" transition to coherent emission.

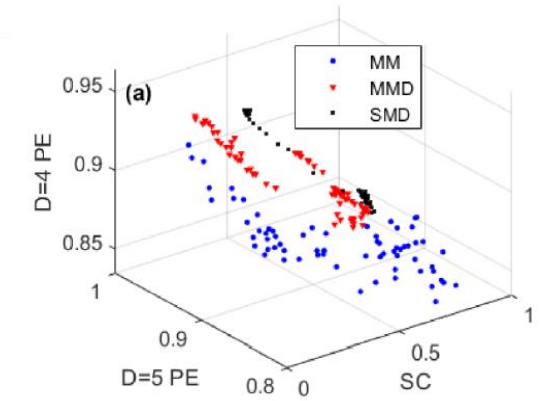
2. Combining speckle and spectral analysis we can differentiate spatial and temporal coherence.

3. Permutation entropy extracts usable information of the speckle patterns.

Ongoing and future work: how to model this system?

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# Funding, co-authors and references

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## Thank you for your attention!


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