Optical feedback induces an abrupt transition to coherent emission during the turn on of a semiconductor laser

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XIX Instabilities and Nonequilibrium Structures:
Enrique Tirapegui 2023
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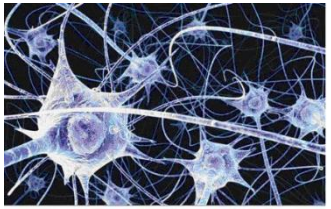
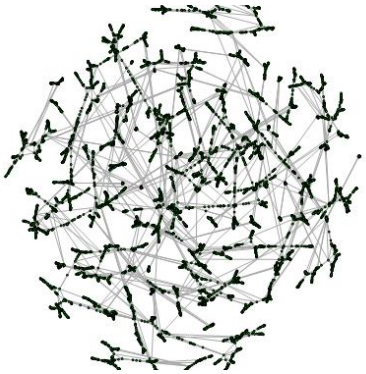
Research lines

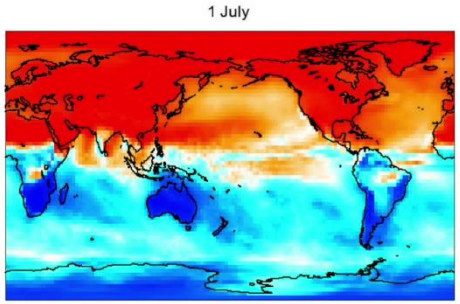
- Laser dynamics

- Neural dynamics



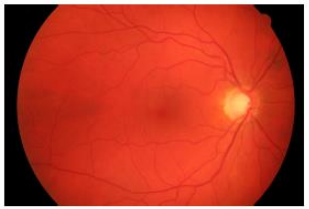


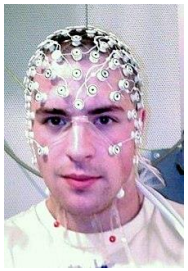
- Complex systems

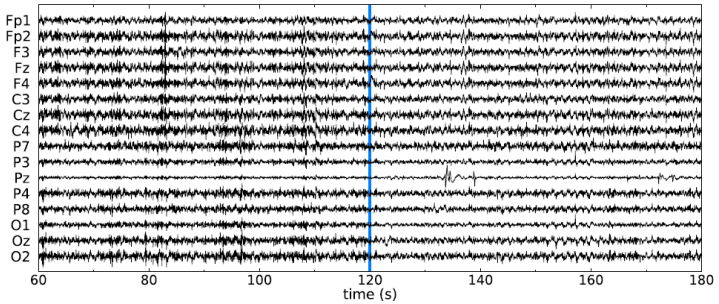


- Climate data analysis

- Biomedical data analysis







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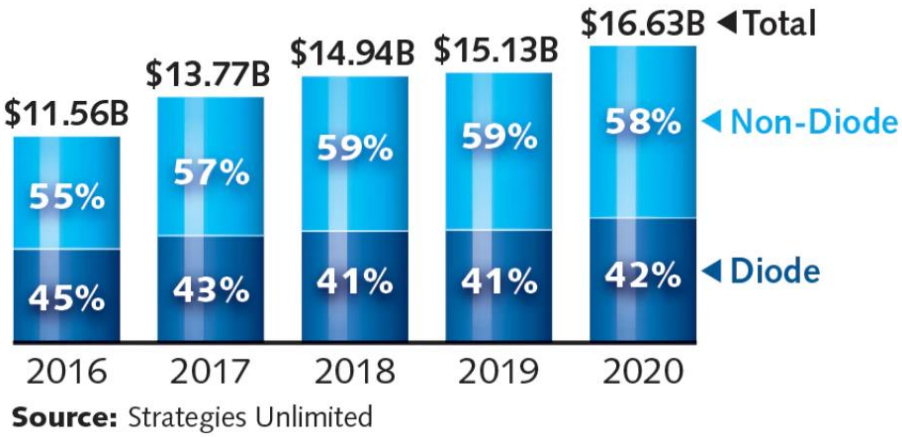
Semiconductor lasers play a crucial role in photonic technologies

- 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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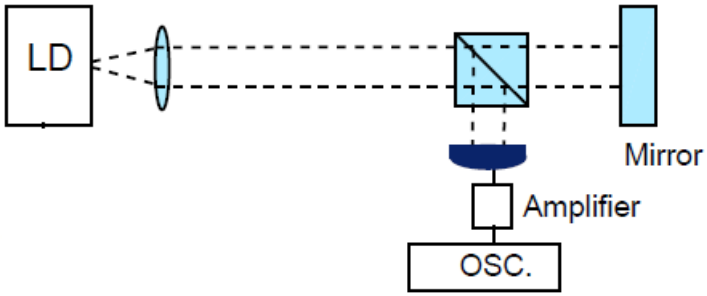
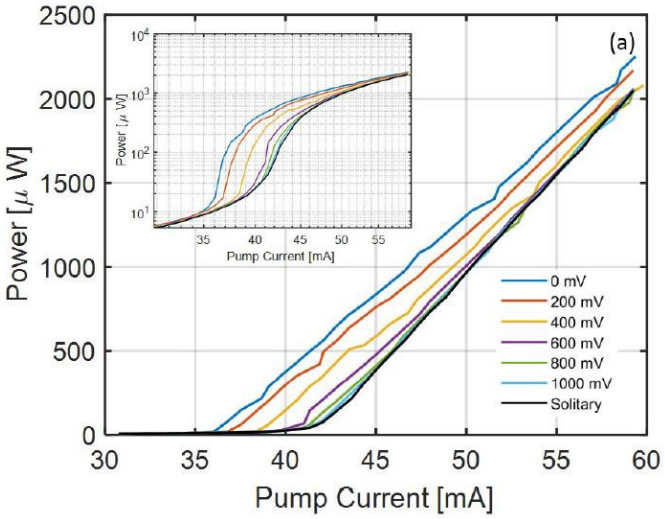
Optical feedback strongly affects the dynamics of the laser

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 laser light affected by feedback?

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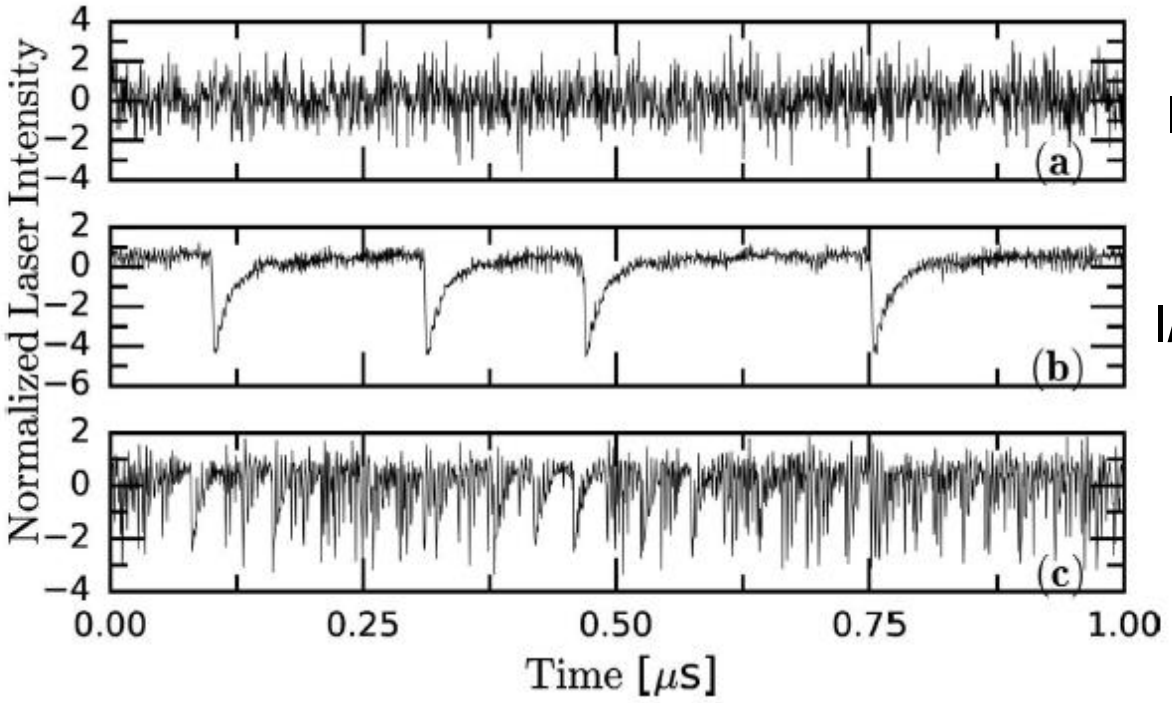
Optical feedback induces spiking and chaotic behavior



$I/I_{th} = 0.95$

$I/I_{th} = 1.02$

$I/I_{th} = 1.2$

C. Quintero-Quiroz et al, Sci. Rep. 6, 37510 (2016).

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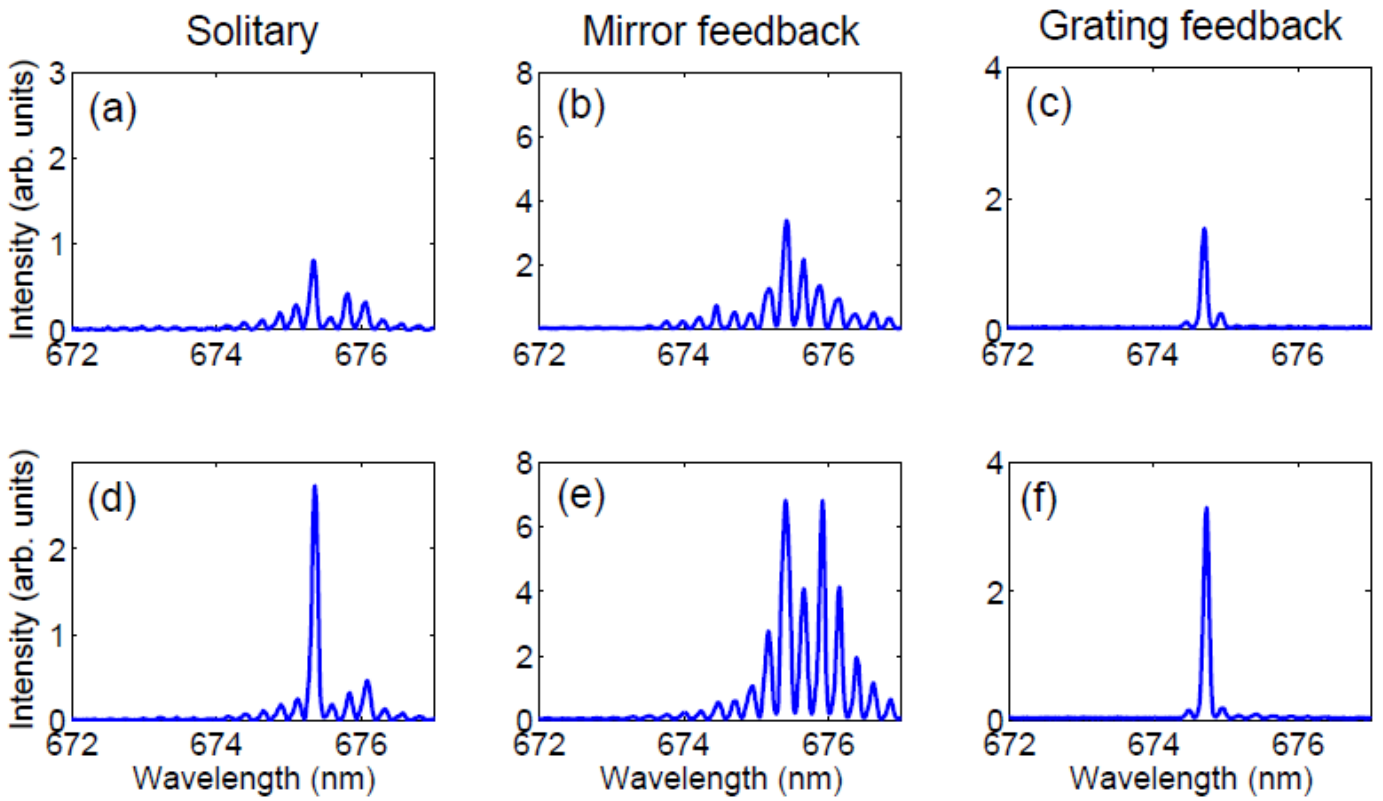
Optical feedback excites additional modes

Close to threshold

Above threshold



Andres Aragoneses PhD thesis (UPC 2014).

How about the **spatial** coherence of the laser light?

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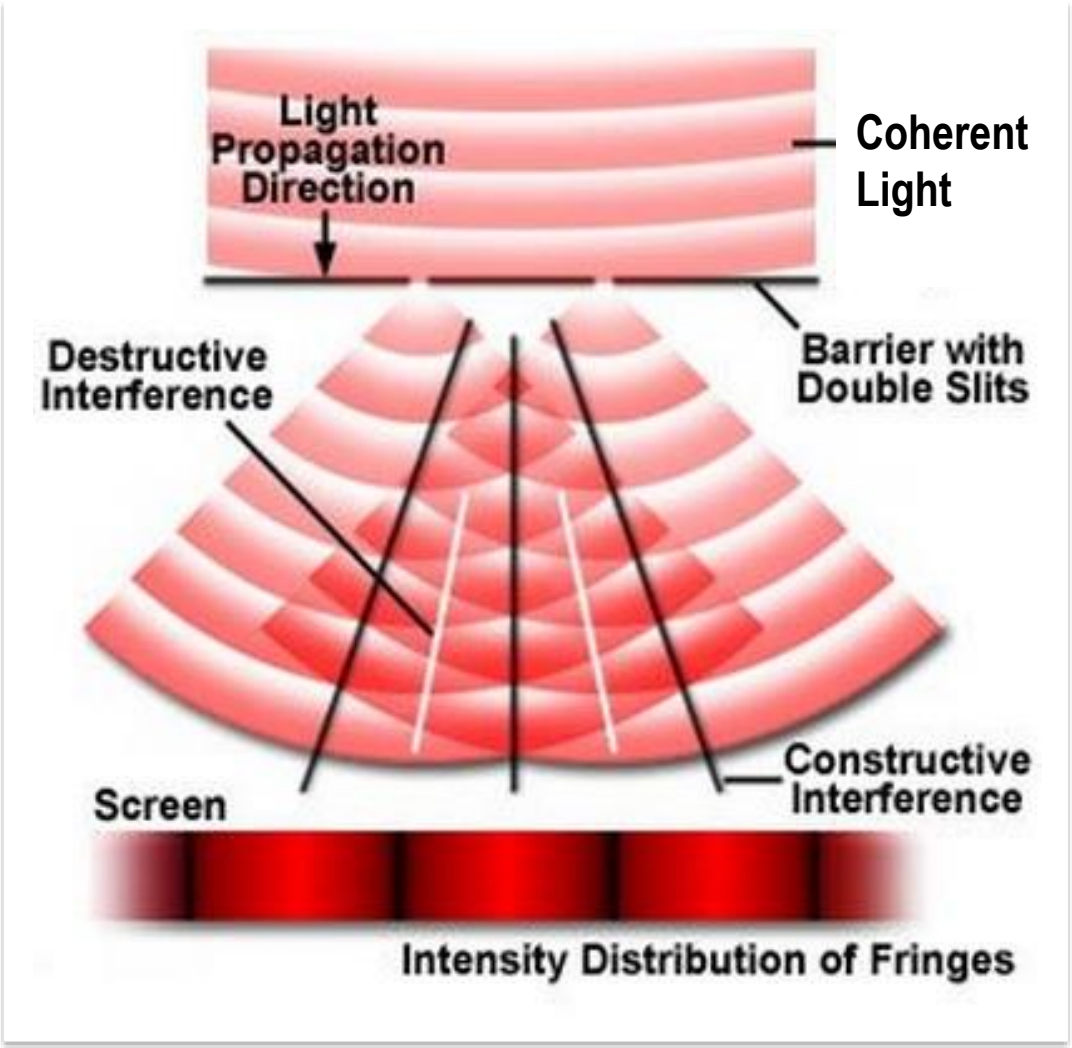
Quick review on the interference of coherent waves



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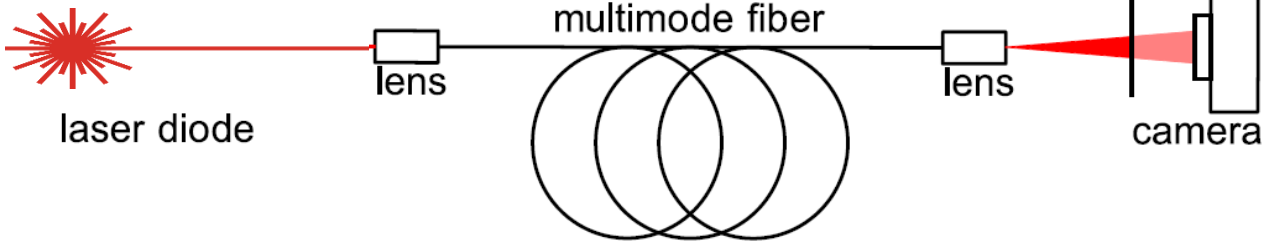
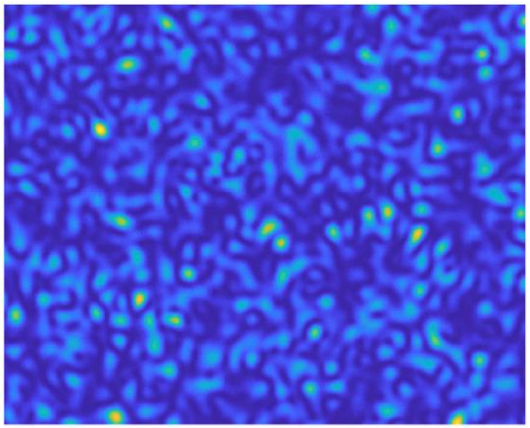
Speckle pattern: generated by random interference / scattering of coherent waves





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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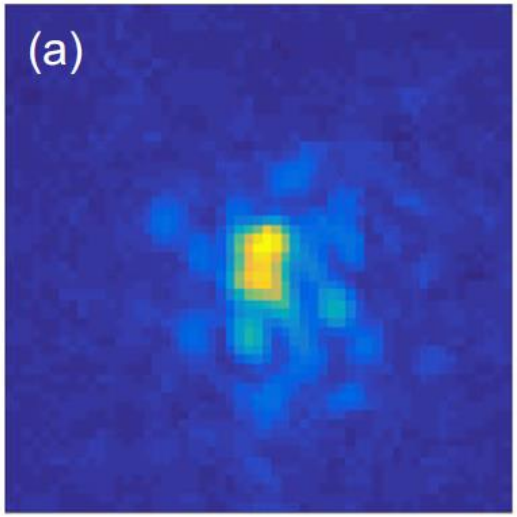
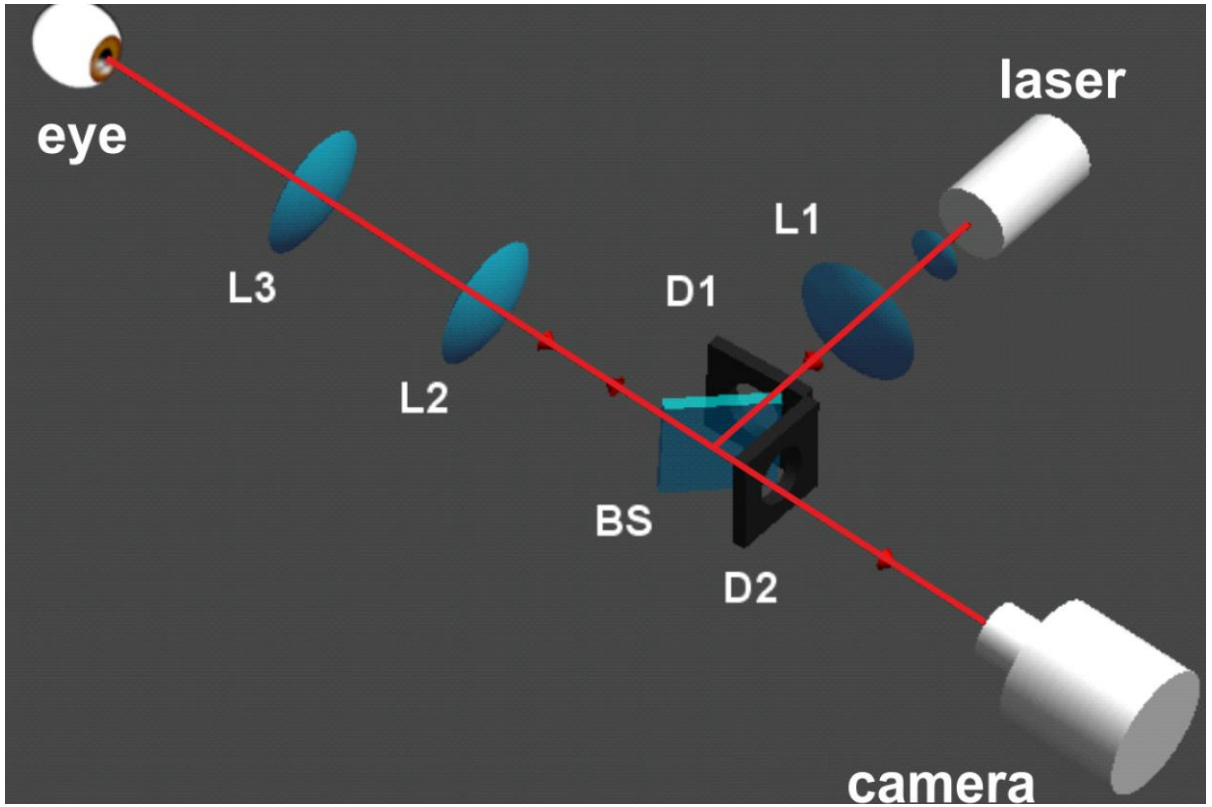
Speckle reduction in double-pass retinal imaging

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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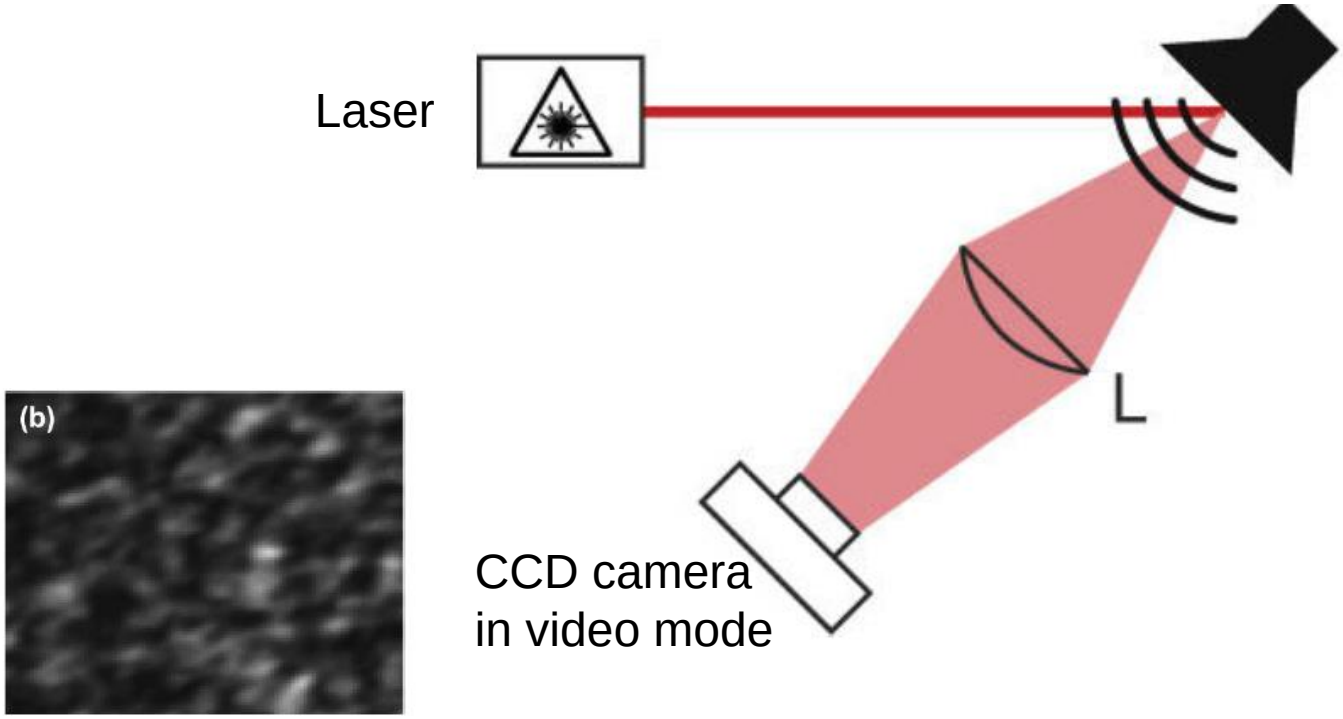
An example of application of speckle pattern analysis

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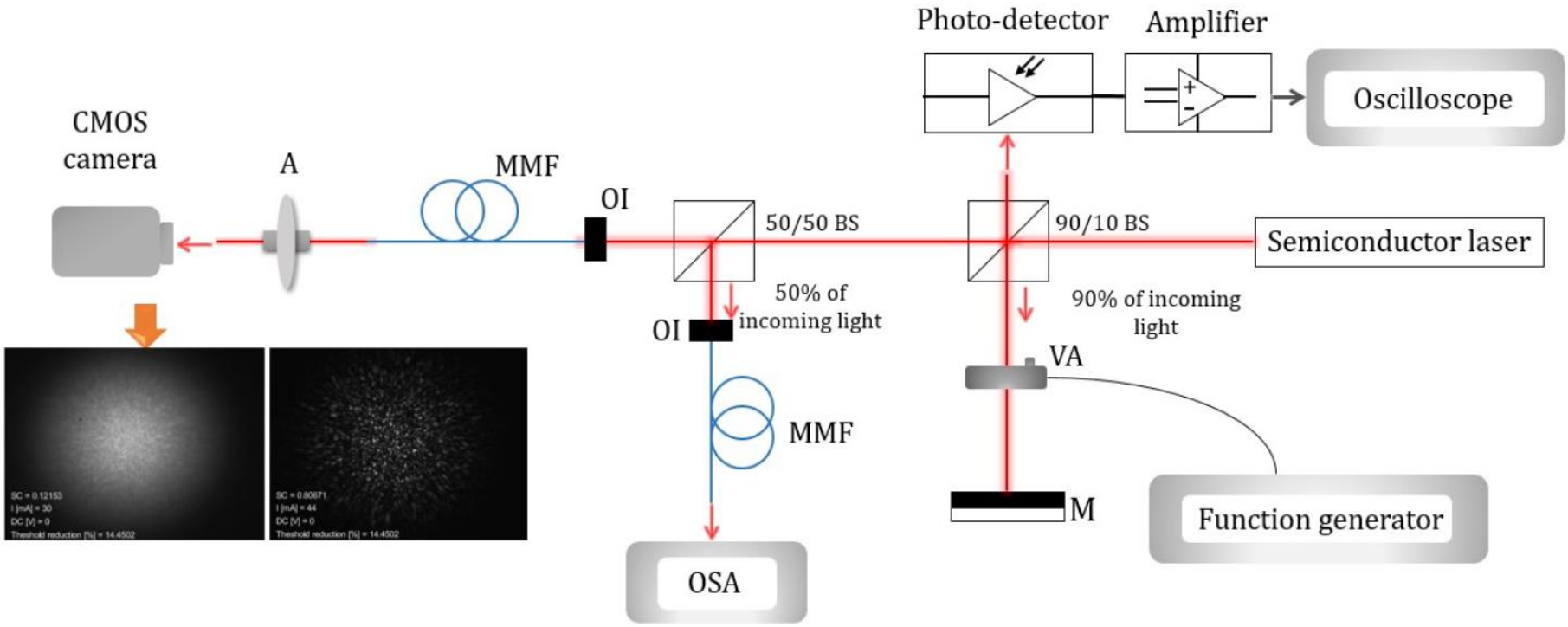
Experimental setup for the analysis of optical-feedback induced dynamics using speckle analysis



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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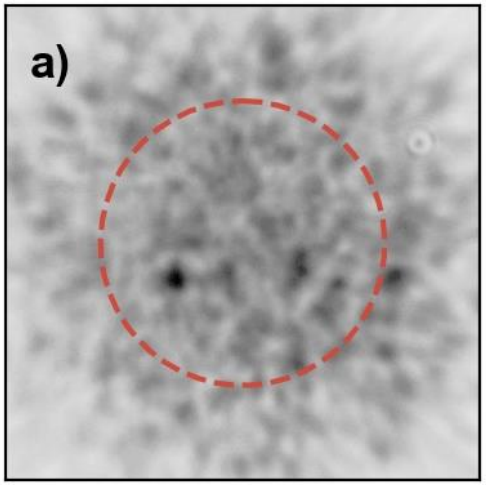
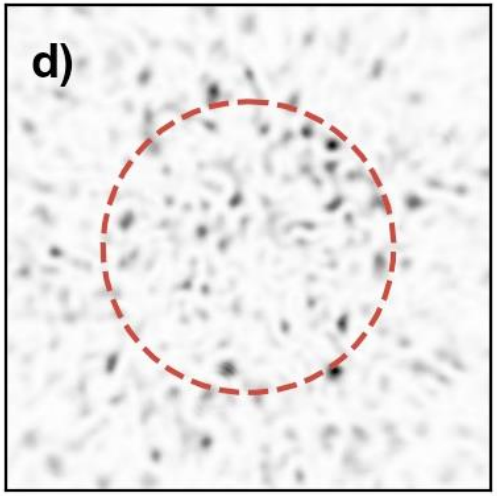
Examples of speckle images

Below threshold



Above threshold



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

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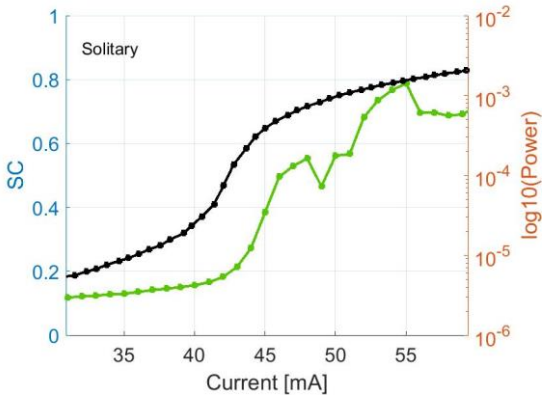
Speckle analysis of the turn-on transition

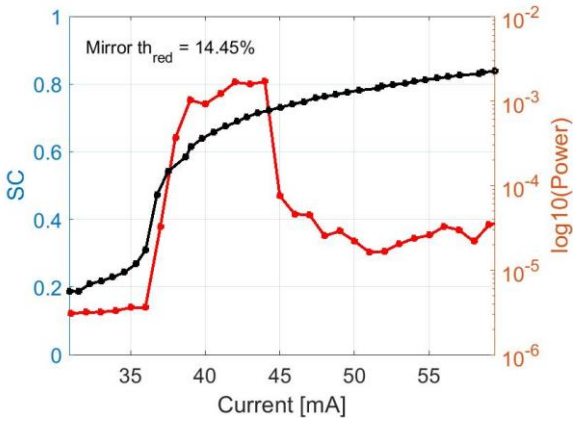
L-I curves: black, log scale

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

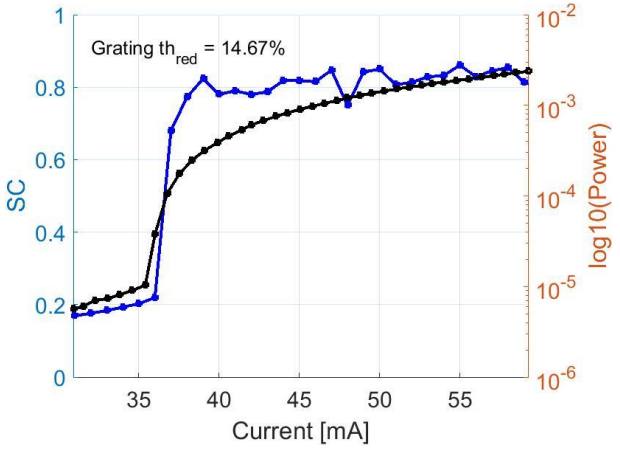
Solitary laser



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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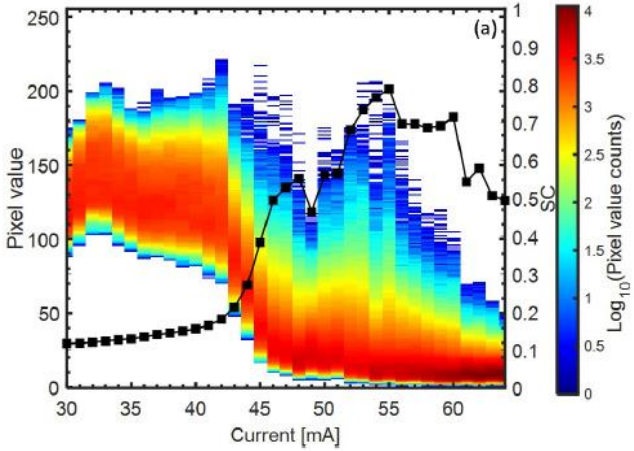
Distribution of pixel values during the turn-on transition

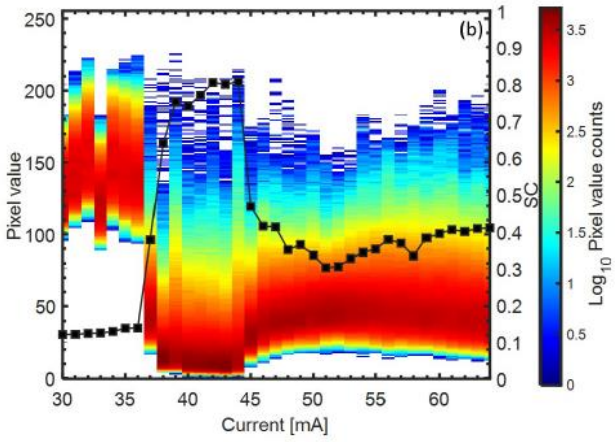
Speckle contrast (black) SC = $\sigma/\langle I \rangle$

Color: distribution of pixel values (log scale)

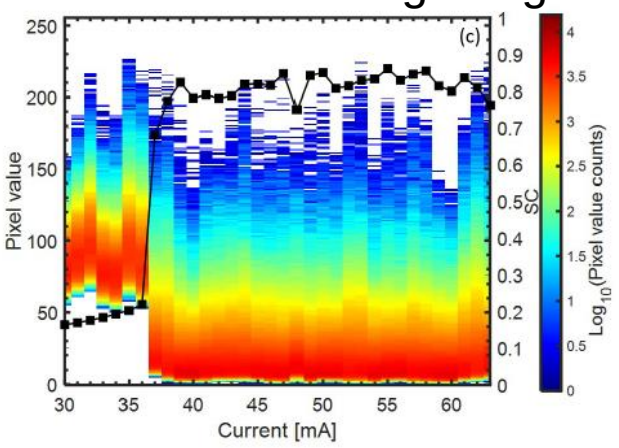
Solitary laser



Feedback from mirror



Feedback from grating



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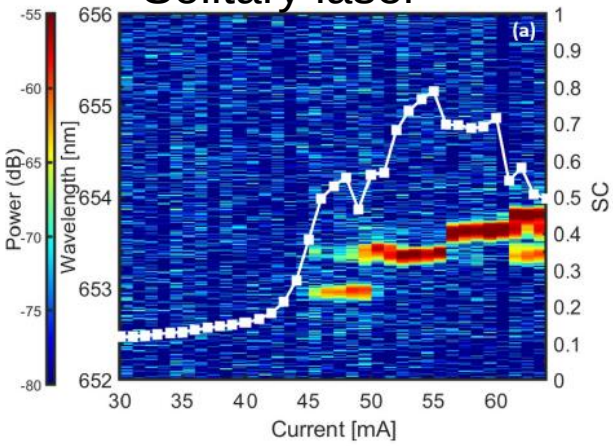
Spectral analysis

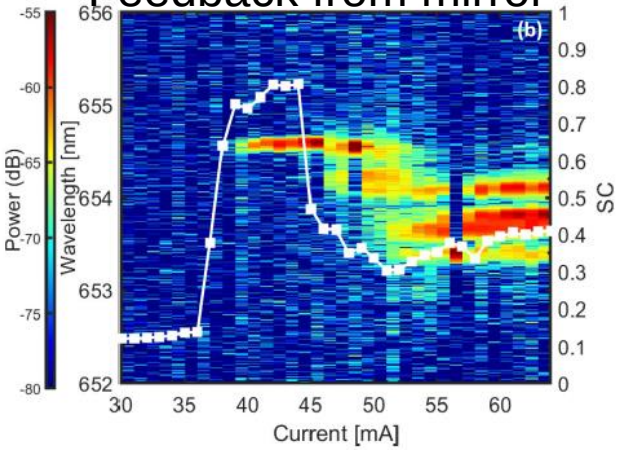
Speckle contrast (white) SC = $\sigma/\langle I \rangle$

Color code: optical spectrum

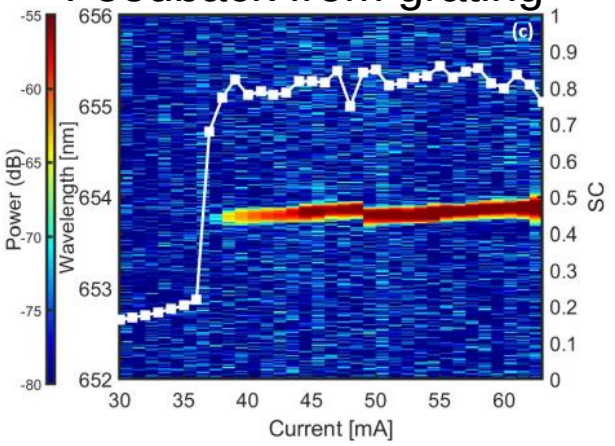
Solitary laser



Feedback from mirror



Feedback from grating



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

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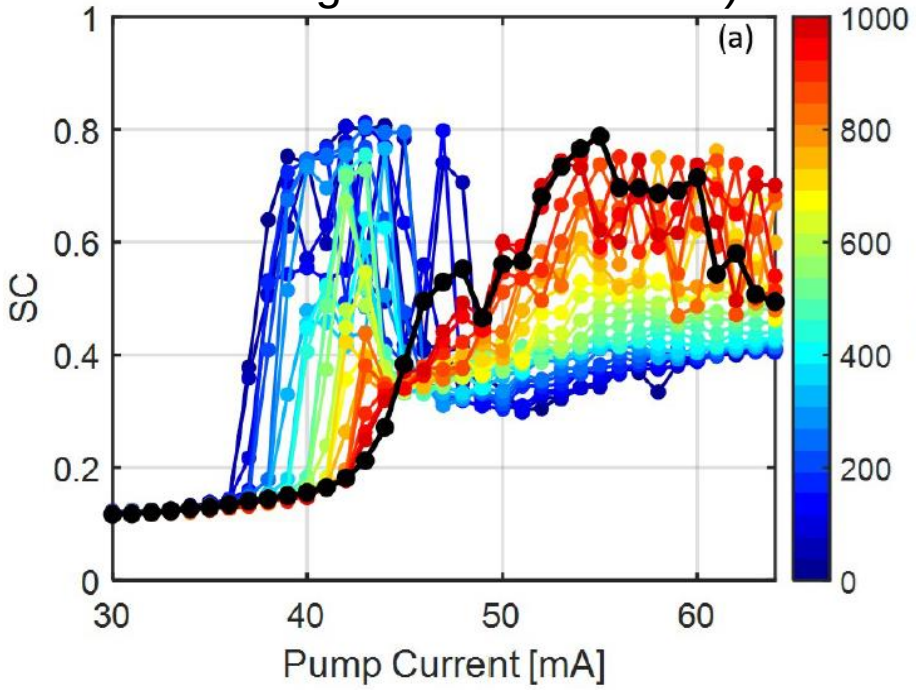
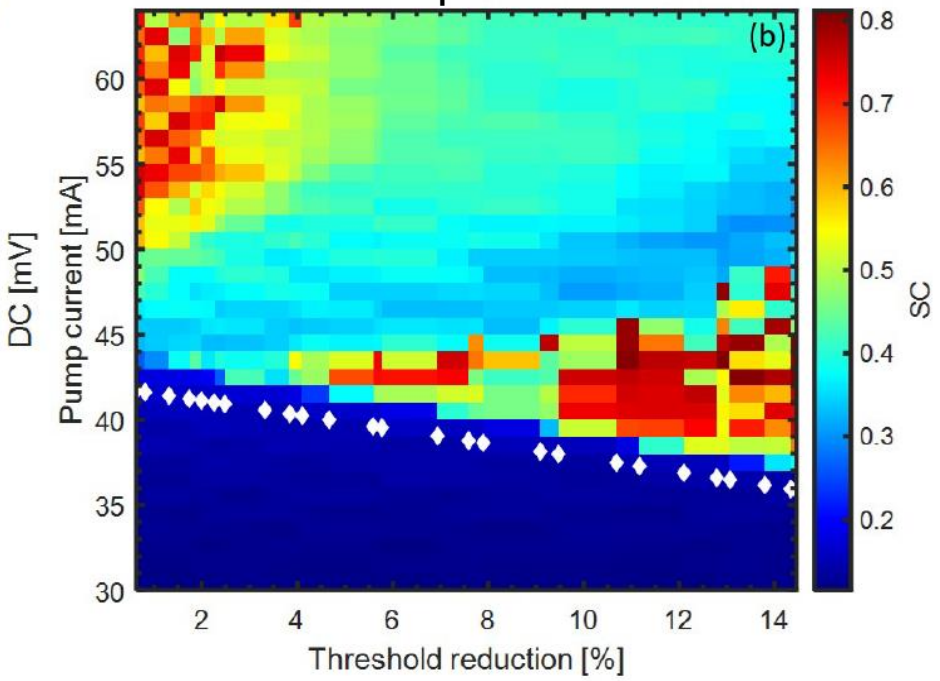
Influence of the optical feedback strength

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



Color code: speckle contrast



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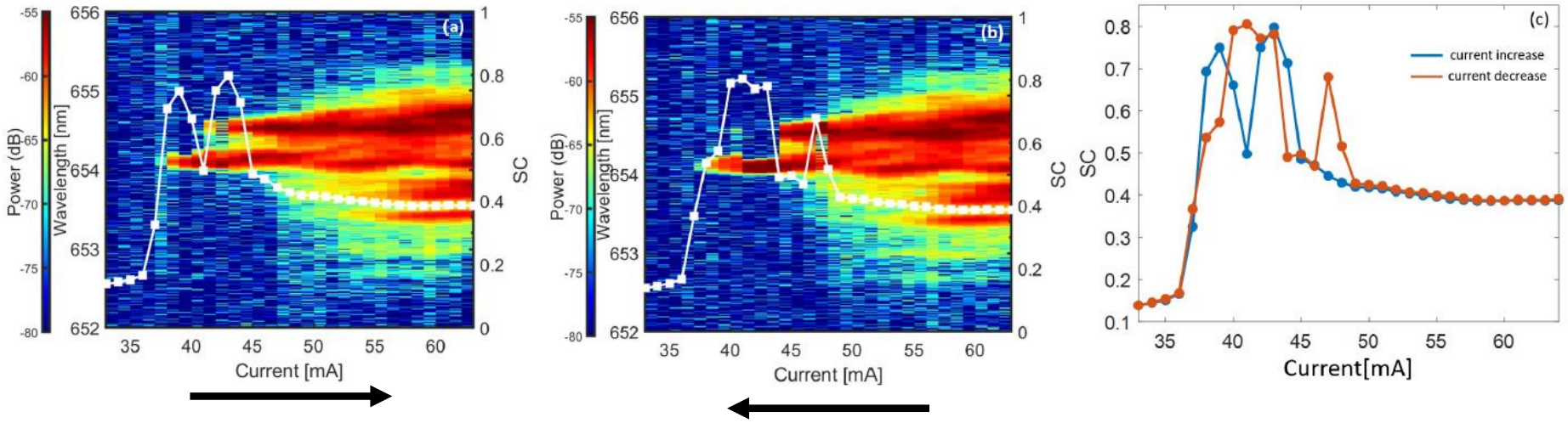
Hysteresis?



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

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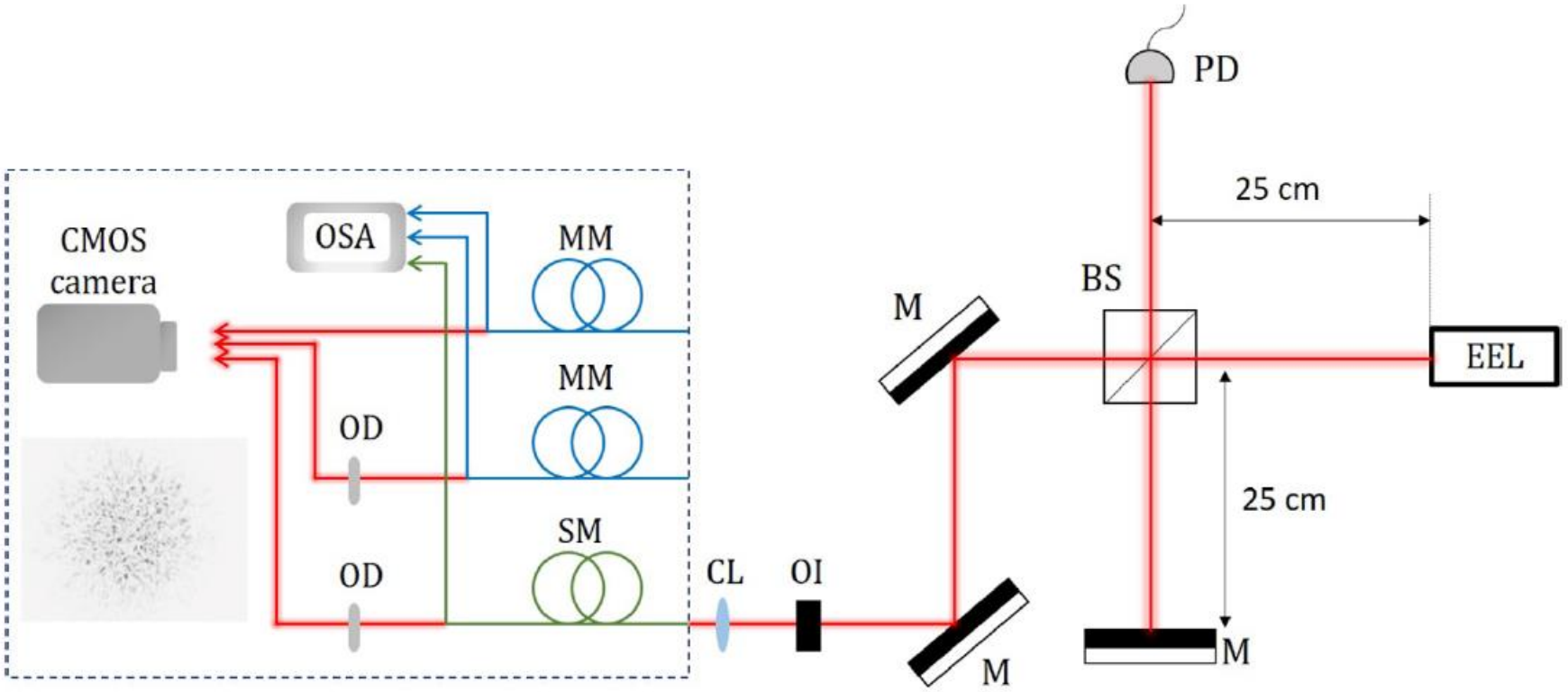
Role of the medium that generates the speckle pattern?



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

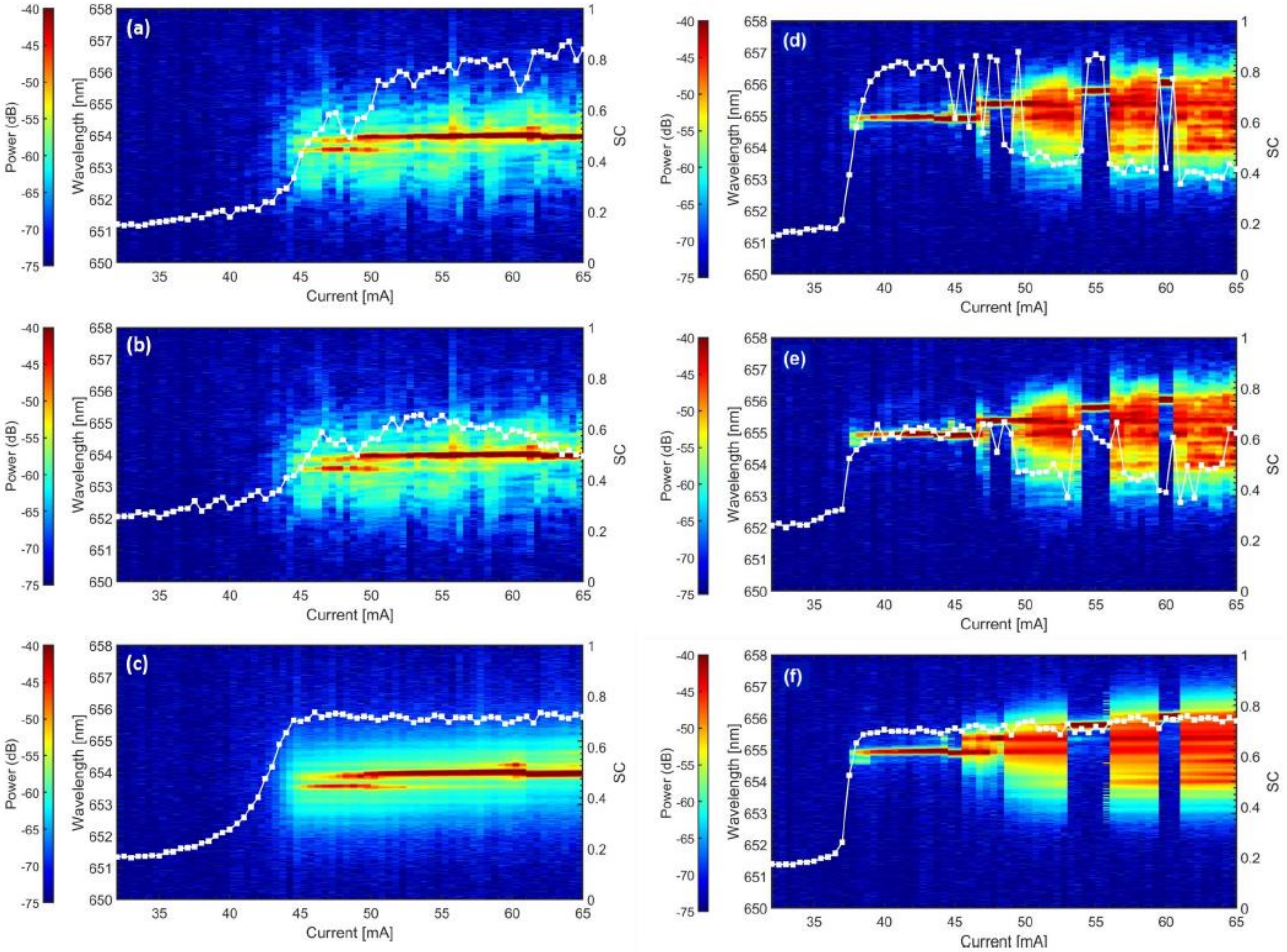
Solitary laser

Laser with optical feedback

MM

MMD

SMD



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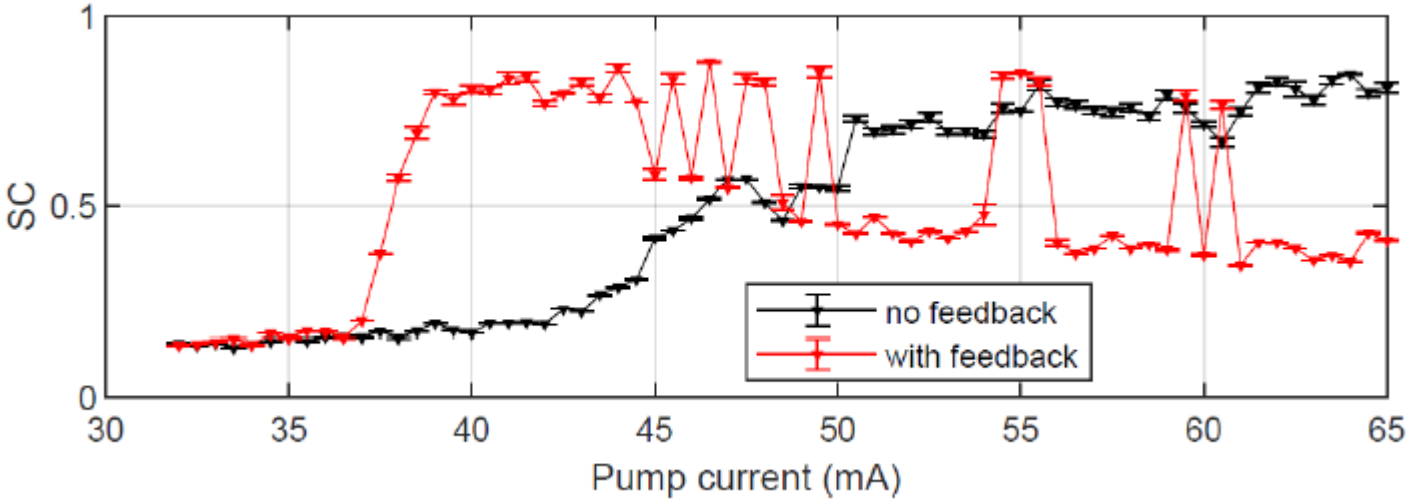
Research question: can we try to anticipate regime transitions, from the analysis of speckle images?



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

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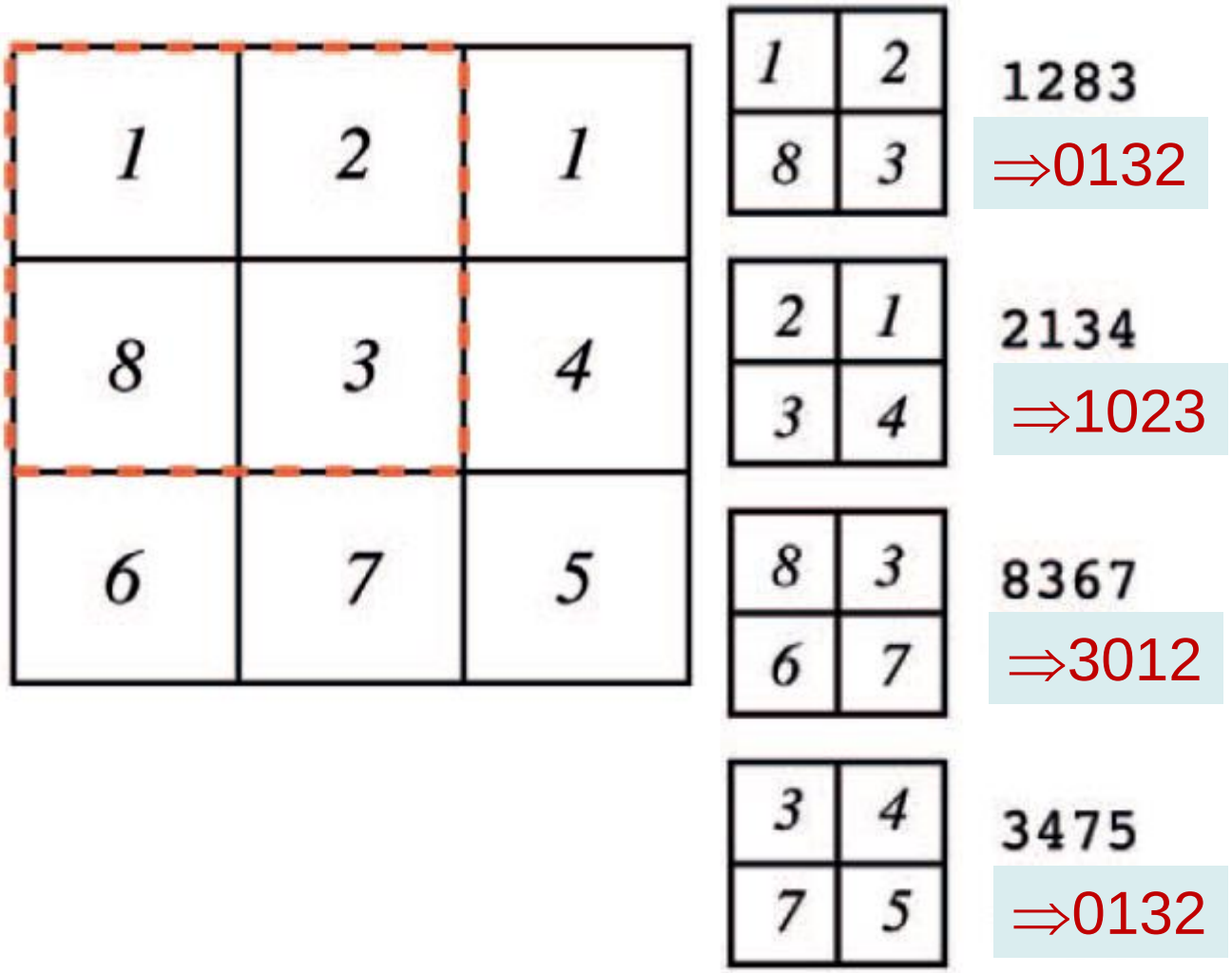
Ordinal analysis of two-dimensional patterns



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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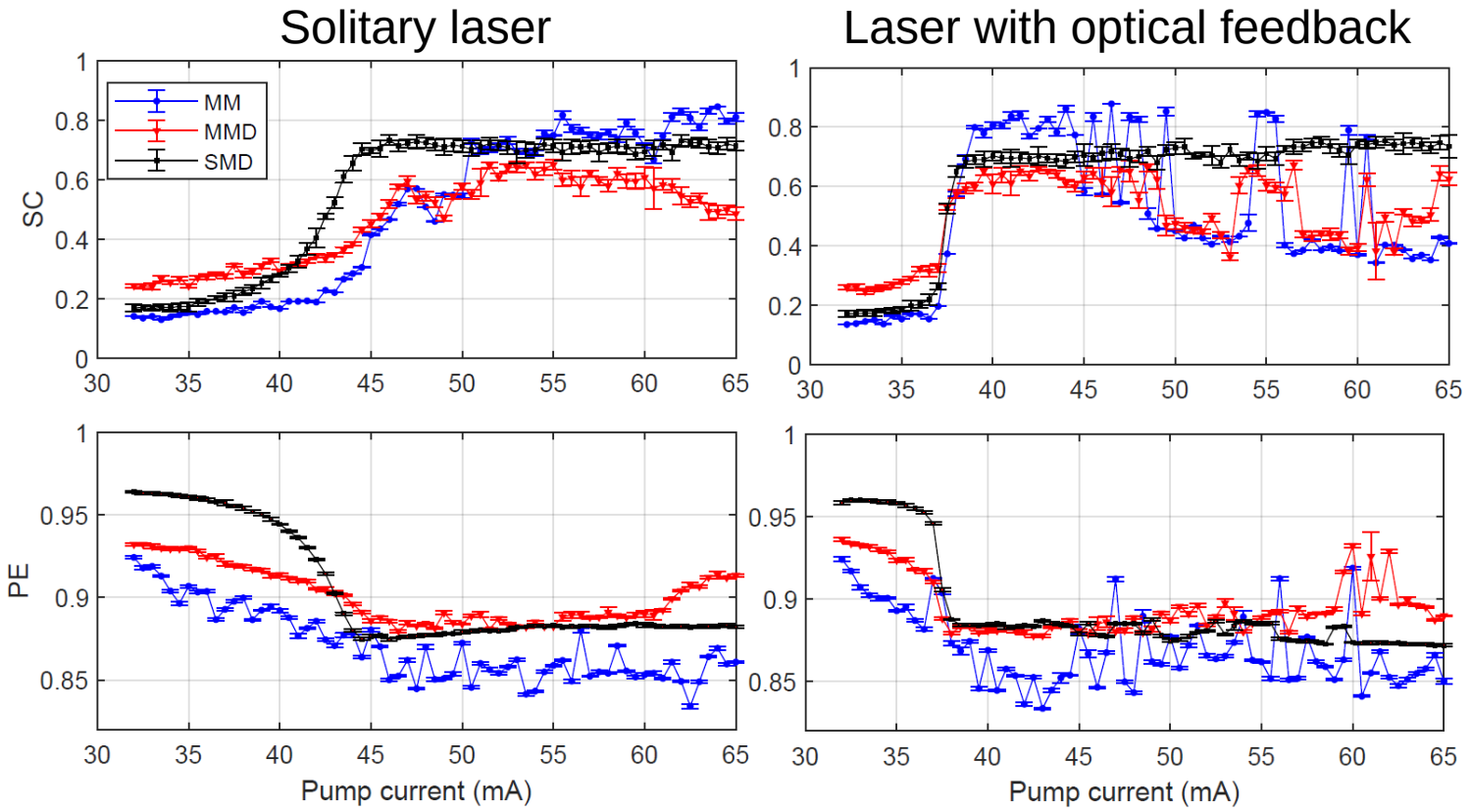
Results



67 currents x 3 conf. x 8 images = 1608 images (solitary / feedback laser)

G. Tirabassi, M. Duque-Gijon, J. Tiana-Alsina, C. Masoller, "*Permutation entropy-based characterization of speckle patterns generated by semiconductor laser light*", APL Photonics in press (2023).

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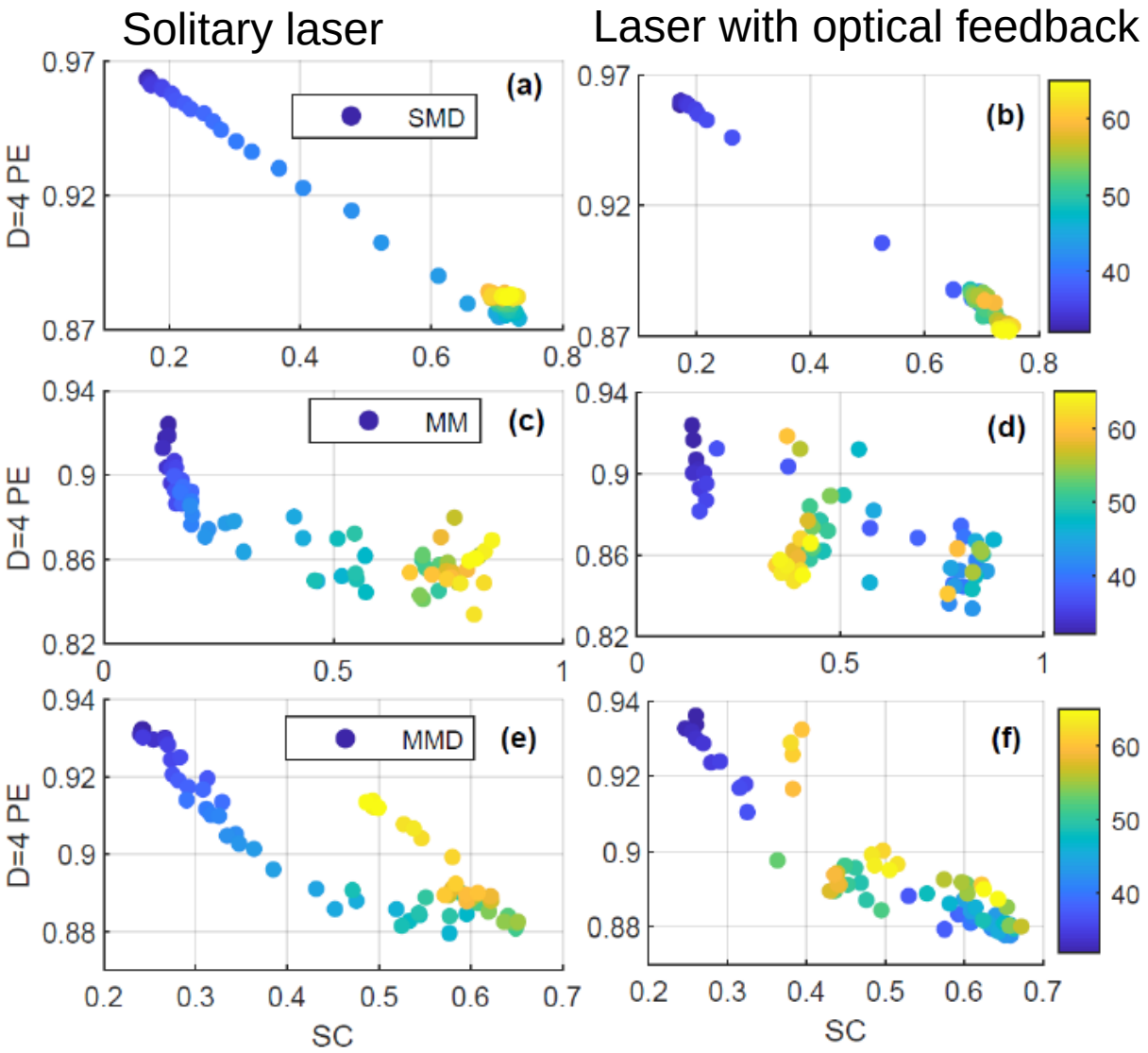
Results



Color code:
laser current

G. Tirabassi, M. Duque-Gijon, J. Tiana-Alsina, C. Masoller, APL Photonics in press.

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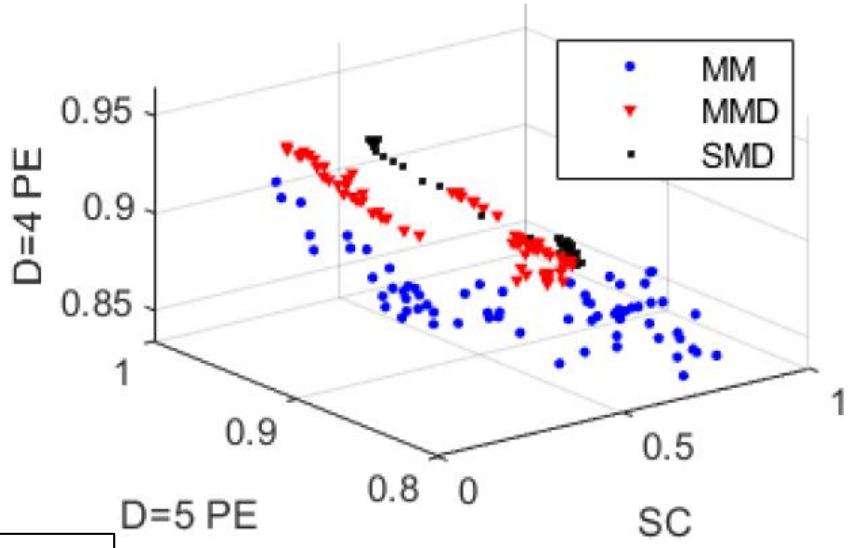
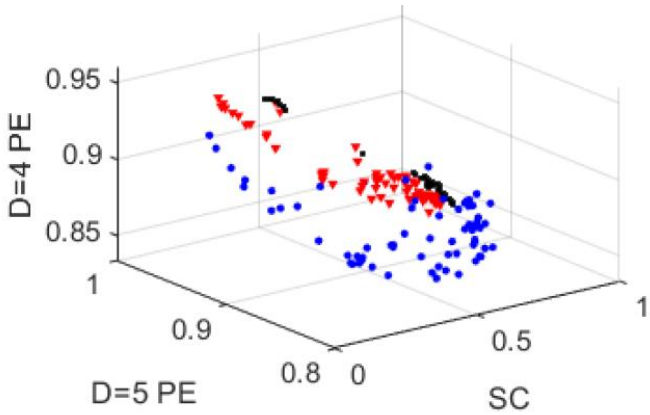
Three features allow to classify the speckle patterns according to the configuration used to generate speckles

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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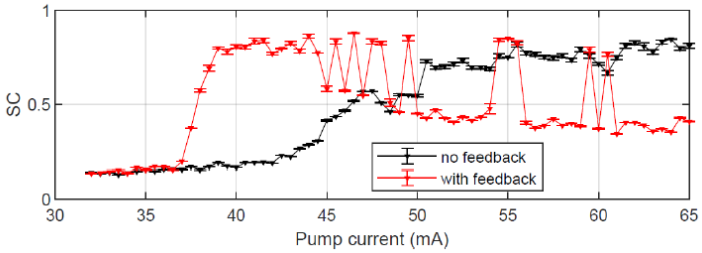
Take home messages and outlook

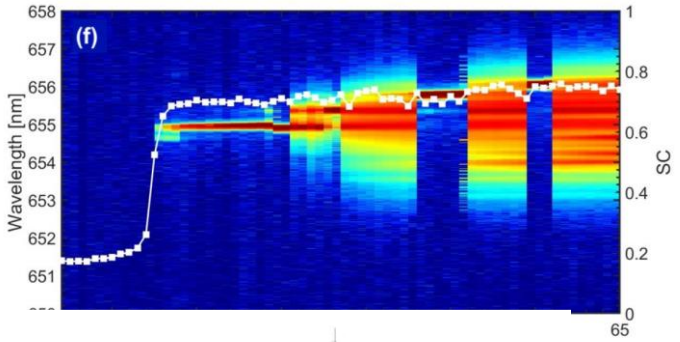
1. Optical feedback induces an abrupt transition to coherent emission.

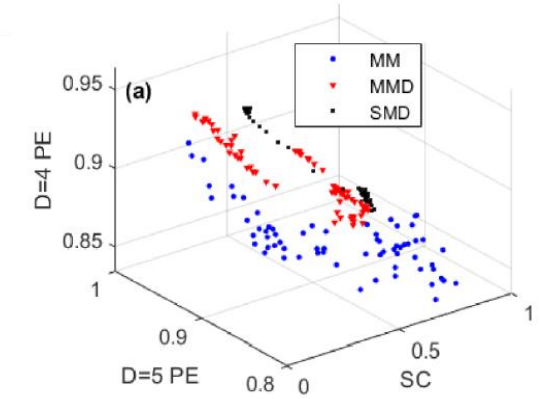
2. Combining speckle and spectral analysis we can differentiate spatial and temporal coherence.

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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Dr. Giulio Tirabassi

Dr. Jordi Tiana-Alsina

- M. Duque-Gijon, C. Masoller, J. Tiana-Alsina, "*Abrupt transition from low-coherence to high-coherence radiation in a semiconductor laser with optical feedback*," Optics Express 31, 3857 (2023).
- 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).
- G. Tirabassi, M. Duque-Gijon, J. Tiana-Alsina, C. Masoller, "*Permutation entropy-based characterization of speckle patterns generated by semiconductor laser light*", APL Photonics in press (2023).

Thank you for your attention!

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