Extreme intensity pulses in a semiconductor laser with a short external cavity

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Monday 16th September
ECCS'13
Barcelona (Spain)

People

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Outline

1. What are extreme events?.

   Why are we interested in them?.

2. Extreme pulses in lasers (semiconductor lasers with a short external cavity).

   Identification, characterization and robustness.

3. Summary.

Extreme events in nature and society

Sumatran earthquake 2007
(magnitude 8,5)

2004 Indian Ocean tsunami

CITY EDITION London Herald LATE PRICES

FRIDAY 25th OCTOBER 1929

WALL STREET CRASH!

Black Thursday in America

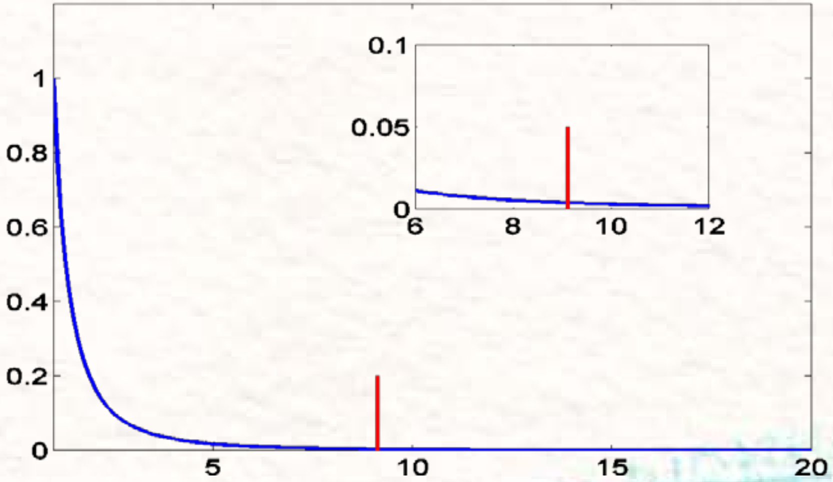
Stocks Plunge and Eleven Commit Suicide

What Went Wrong?

Wall Street crash of 1929

Concepts of extreme events

- Most relevant extreme events take high intensity values compared with the set of events. They are also rare and might have dramatic consequences.
- Quantitatively, it is very difficult to define the concept of e.e. without being arbitrary. For us, e.e. are those events with intensities that exceed a certain threshold (another approx. considers maxima in a block of time series).

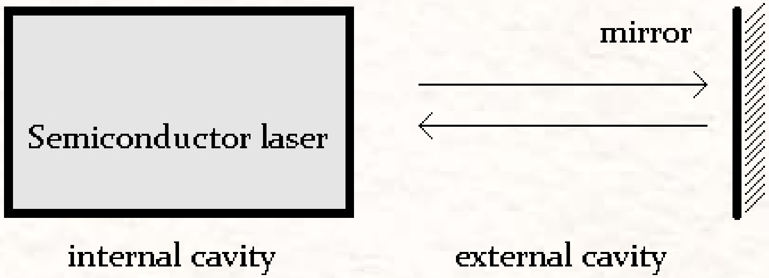


Pareto distribution

Lasers: high intensity pulses

- In general, lasers support 3 different dynamical regimes: continuous wave regime (c.w.), periodic regime and also in a chaotic regime.

- Lasers of class B such as semiconductor lasers (SL) are very stable [1]. However, they are destabilized by adding an external cavity that allows optical feedback. This device supports high intensity pulses observed in the short cavity regime (s.c.r.).

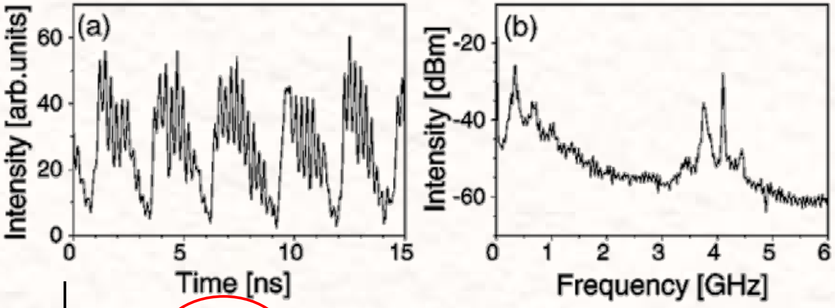


[1] Ohtsubo, J. (2008). Semiconductor Lasers. *Semiconductor Lasers: Stability, Instability and Chaos, Springer Series in Optical Sciences, Volume 111. Springer-Verlag, 2008, 1.*

Evidences of chaotic dynamics (s.c.r.)

Experiments

- (regular)pulse packages [2]

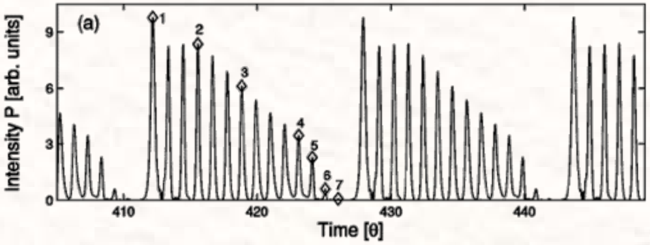


Numerical simulations

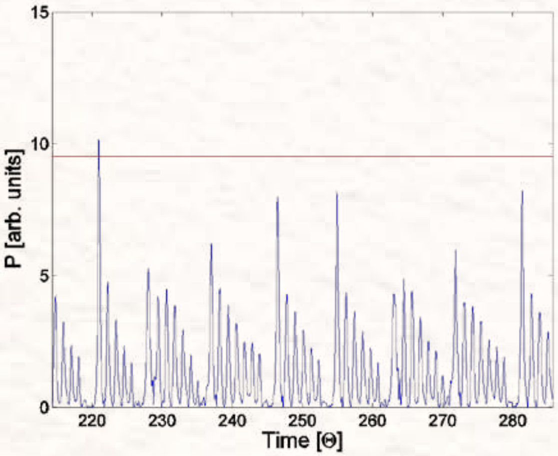
- LK model

RPPs

e.e.



[3]



[4]

[2] Heil, T., Fischer, I., Elsäßer, W., Krauskopf, B., Green, K., & Gavrielides, A. (2003). Delay dynamics of semiconductor lasers with short external cavities: Bifurcation scenarios and mechanisms. *Physical Review E*, *67*(6), 066214.
[3] Tabaka, A., Panajotov, K., Veretennicoff, I., & Sciamanna, M. (2004). Bifurcation study of regular pulse packages in laser diodes subject to optical feedback. *Physical Review E*, *70*(3), 036211.
[4] Reinoso, J. A., Zamora-Munt, J., & Masoller, C. (2013). Extreme intensity pulses in a semiconductor laser with a short external cavity. *Physical Review E*, *87*(6), 062913.

Lang-Kobayashi model

- To explore this phenomenon, we work in the theoretical LK model [5] in the short cavity regime. The rate equations for the complex optical field, E, and the excess carrier number, N, are

$$dE/ds = (1+i\alpha)NE(s) + \underline{\eta e^{-i\omega\theta}E(s-\theta)} + \underline{\beta\xi}$$

$$T\, dN/ds = J - N - (1+2N)|E(s)|^2$$

Solitary laser ($s = t/\tau_p$)
α: line-width enhancement factor
J: pump current
T: carrier life time (τ_n/τ_p)

Optical feedback
η: strength
$\omega\theta$: phase ($\theta = \tau/\tau_p$)

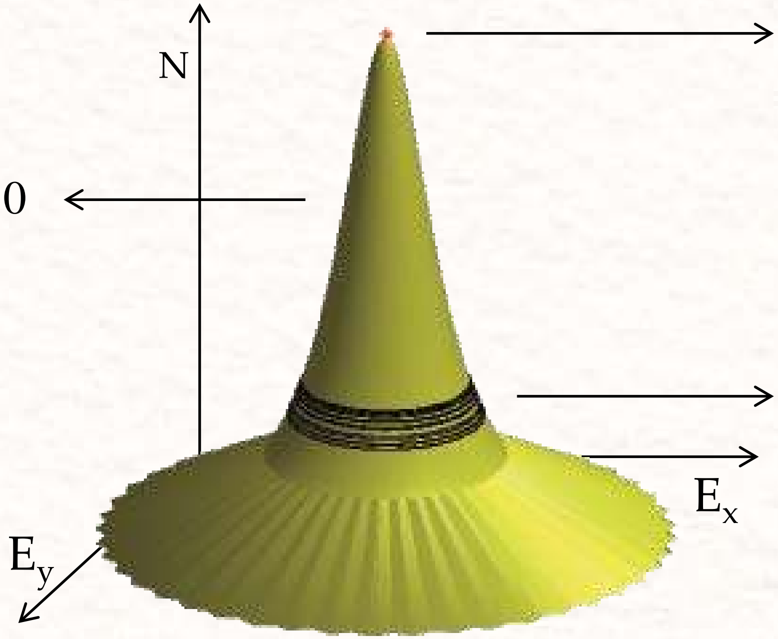
Spontaneous emission noise
β:strength

Normalized to the carrier photon lifetime
$\tau_p \sim 1$ ps

[5] Lang, R., & Kobayashi, K. (1980). External optical feedback effects on semiconductor injection laser properties. *Quantum Electronics, IEEE Journal of*, *16*(3), 347-355.

Stationary solutions

- Random initial conditions evolve towards the external cavity modes (ECMs) (black circles) influenced by the fixed point known as ``laser off´´ (red star).

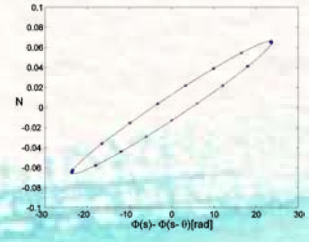


laser off (|E|=0 , N=J)

$$\frac{dN}{ds} = 0$$

ECMs ($E = E_{0s} e^{-i\phi_s}, N = N_s$)

$$\boxed{\begin{aligned} \Delta\phi_s &= -\eta\theta\sqrt{1+\alpha^2}\sin(\Delta\phi_s) \\ E_{0s}^2 &= \frac{J - N_s}{1 + 2N_s} \\ N_s &= -\eta\cos(\Delta\phi_s + \omega\theta) \end{aligned}}$$



Numerical simulations

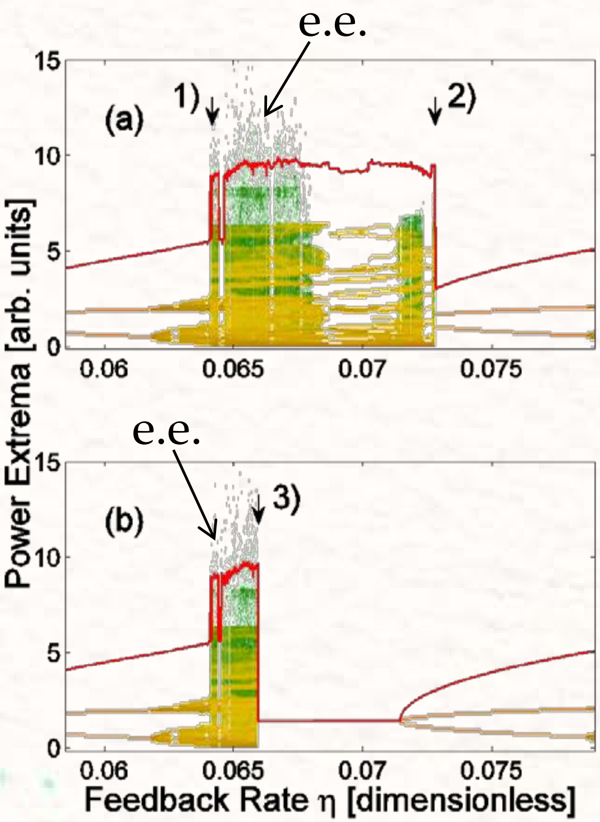
- Parameters are chosen similar to Ref. [3], where high intensity pulses have been first observed in the region known as short cavity regime.
- The feedback strength, η, the feedback phase, ωθ, and the noise strength, β, are taken as control parameters.
- Initial conditions are such that the optical field and carrier number are close to 0.

Parameter	**Value**
T	1710
J	1.155
α	5
θ	70
$\omega\theta$*	$-\arctan(\alpha)$

[3] Tabaka, A., Panajotov, K., Veretennicoff, I., & Sciamanna, M. (2004). Bifurcation study of regular pulse packages in laser diodes subject to optical feedback. *Physical Review E*, *70*(3), 036211.

Dynamics

- When we vary the feedback strength the laser intensity displays a complicated sequence of bifurcations.



(a) Increasing η. For η<0.064, intensity pulses are relatively small (<4). An abrupt change (*transition 1*) occurs at η~0.064, with amplitudes higher than 10, without a clear maximum.

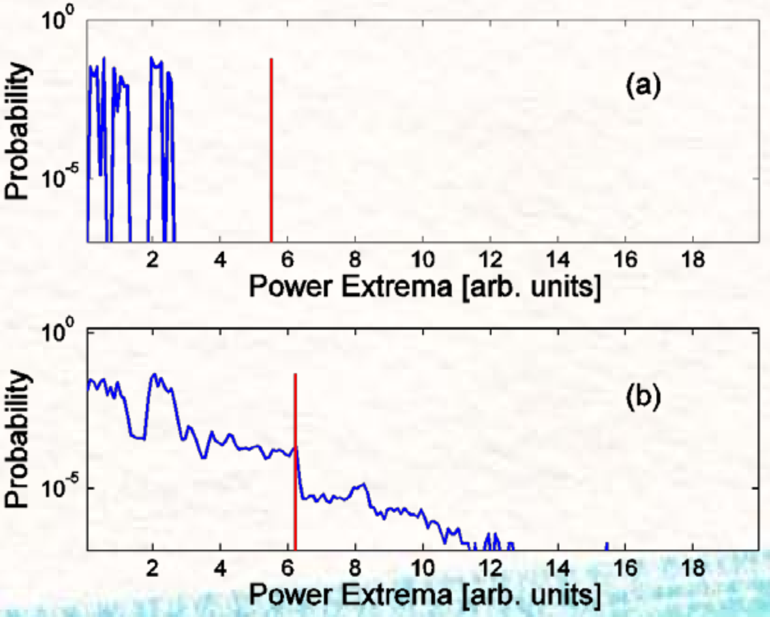
At η~0.073, these dynamics suddenly disappear (*transition 2*) and the intensity becomes oscillatory with constant low amplitude.

(b) Decreasing η the periodic intensity undergoes a Hopf bifurcation and enters in a c.w. regime. It is destabilized at η~0.066 in a saddle-node bifurcation (*transition 3*) , towards the chaotic regime closing a **hysteresis** cycle.

Recognizing extreme pulses

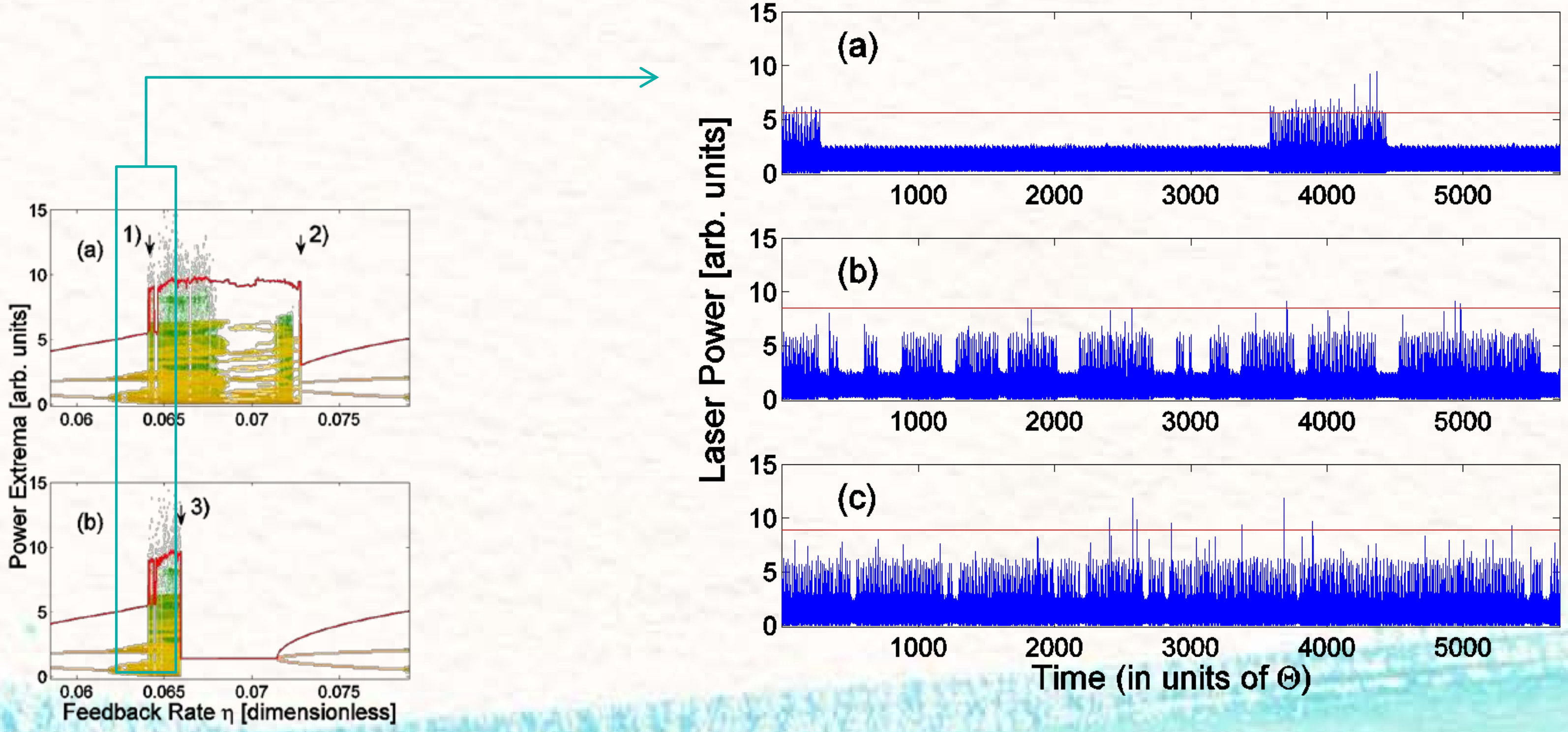
- Before *transition 1,* the distribution of pulse amplitudes presents a well defined cutoff *(a),* in contrast with the long tail after the expansion *(b)* (that reveals the existence of extreme values) (*(a)* η=0,064 , *(b)* η=0,064095).

- Quantitatively extreme values are defined arbitrary as $\bar{x}+5\sigma$, in a compromise between good statistics and extremely long simulations (red line) .



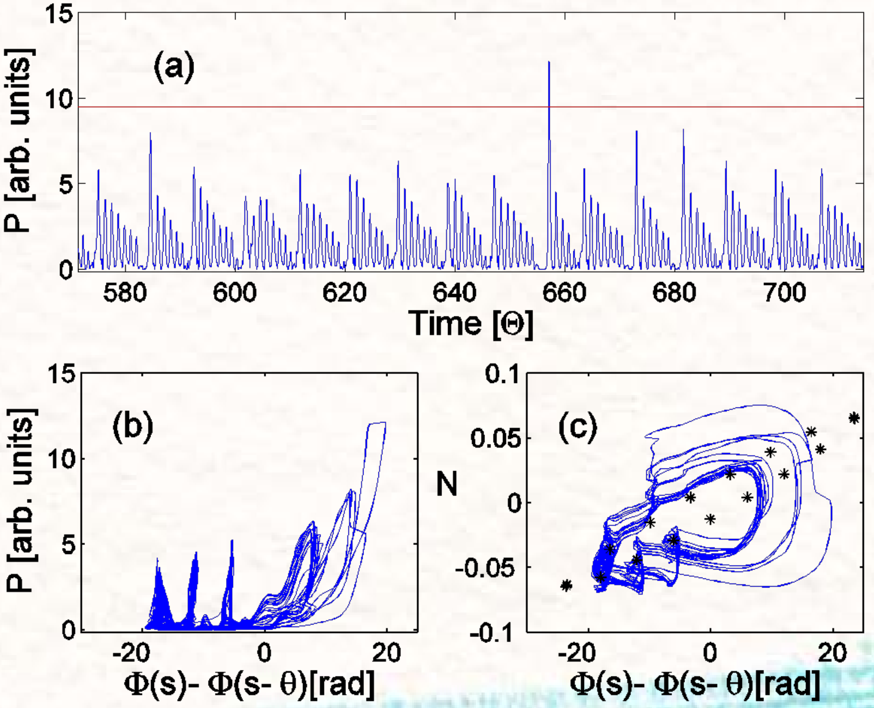
Deterministic intermittency

- In *transition 1* extreme intensity pulses appear through deterministic intermittency, appreciable in temporal series (*(a)* η=0.064095, *(b)* η=0.06412, and *(c)* η=0.0642).



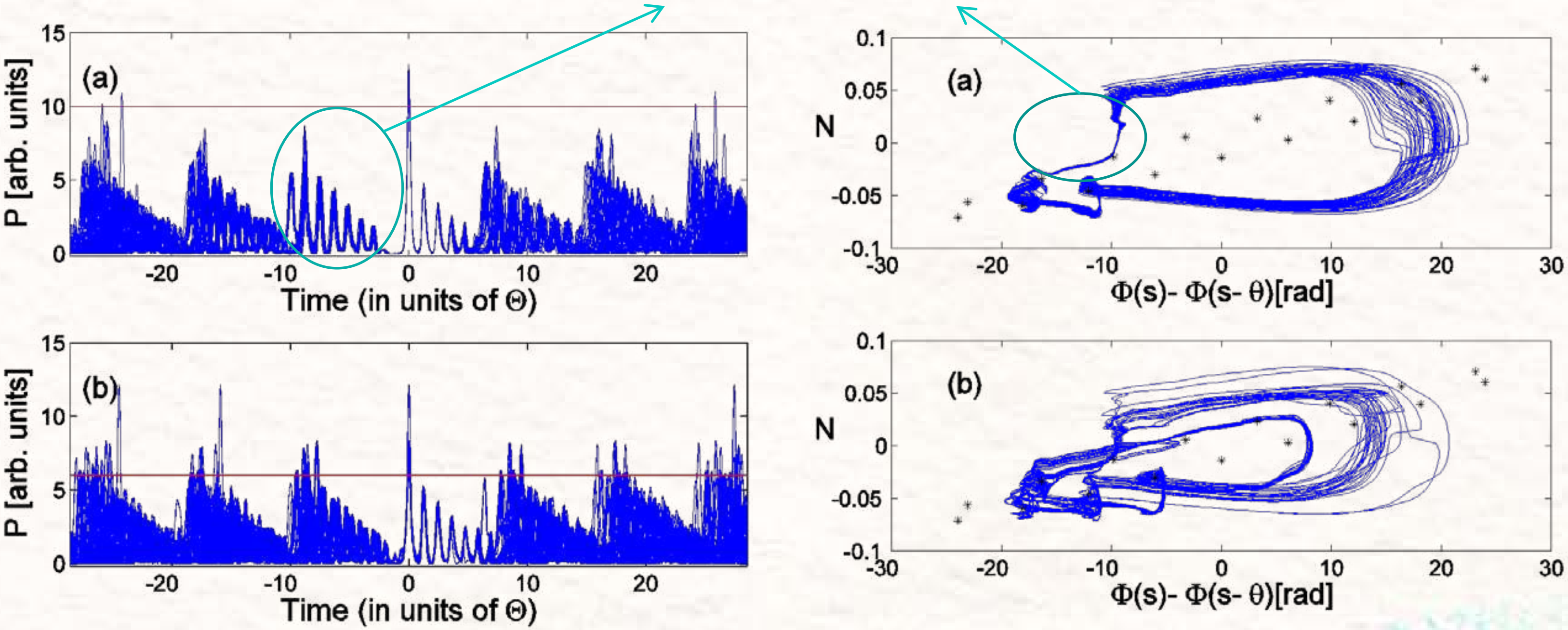
Extreme pulses

- A detail of an extreme pulse is observed in this figure together with the phase portraits [$\Phi(s)-\Phi(s-\theta)$,P] and [$\Phi(s)-\Phi(s-\theta)$,N] ($\eta=0.066$).



Features of extreme pulses

- We select pulses over a certain amplitude threshold ((*a)* 10 and *(b)* 6), and superpose the sections that contain the pulses (η=0.066).

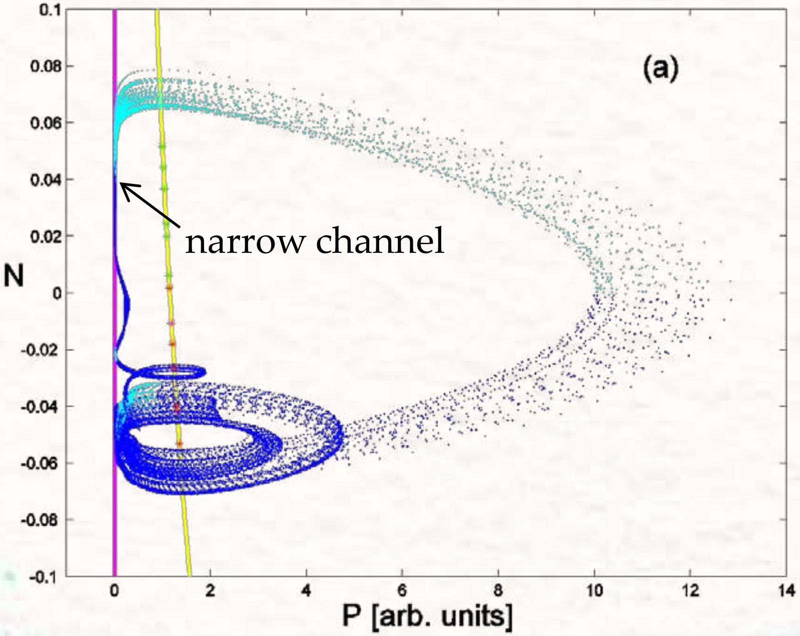


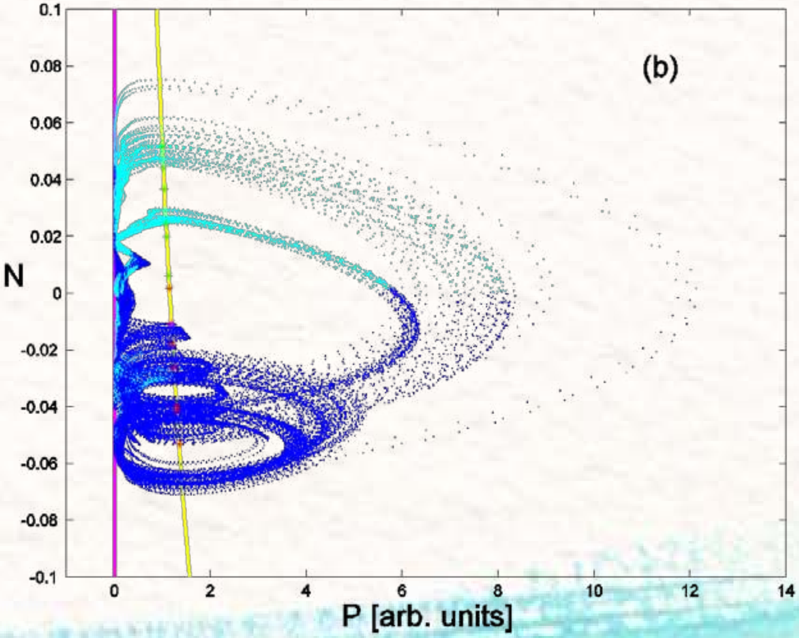
``narrow channel´´

[4] Reinoso, J. A., Zamora-Munt, J., & Masoller, C. (2013). Extreme intensity pulses in a semiconductor laser with a short external cavity. *Physical Review E*, *87*(6), 062913.

Features of extreme pulses

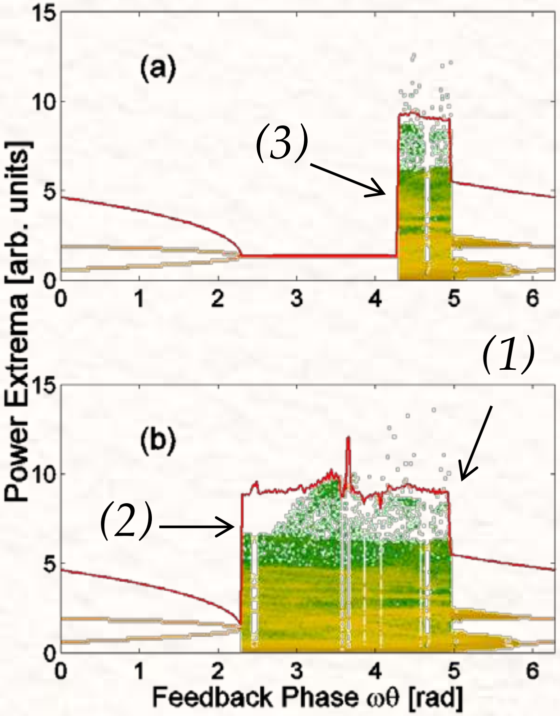
- The rotation of the optical field changes at the onset of every pulse (counterclockwise). It takes higher N for extreme pulses *(a)*.
- As in previous figures, there is a ``narrow channel´´ that defines the trajectory before extreme pulses and is characterized by the rotation of the optical field.





Feedback phase

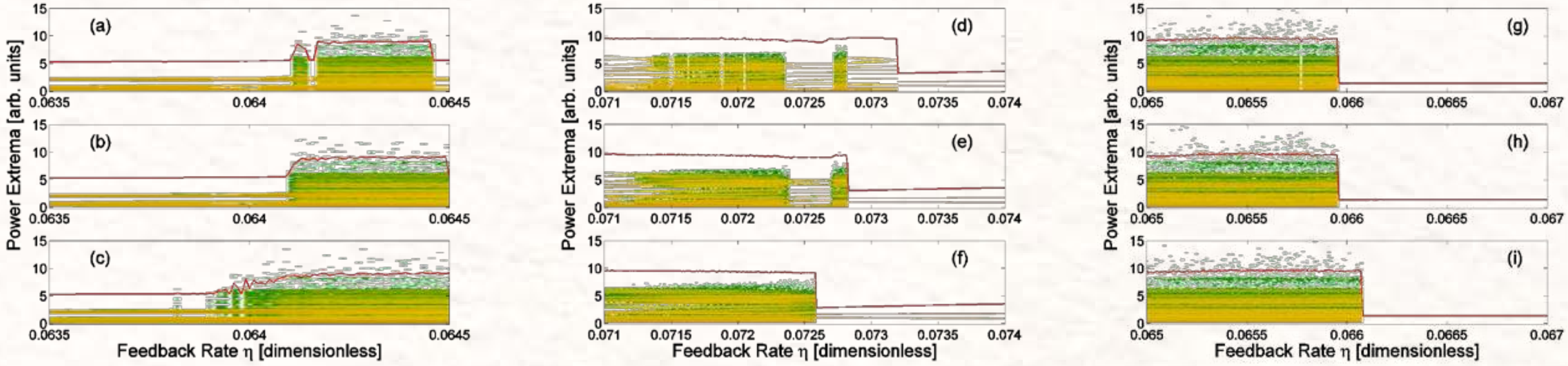
- The bifurcation scenario described for varying feedback strength is also observed when varying the feedback phase.



We observe 3 similar transitions when *(a)* increasing and *(b)* decreasing ωθ.

Noise strength

- One could expect that random fluctuations could induce switchings between coexisting attractors. We show in detail the three transitions.
- The effect of noise observed at *transitions 1 (a-c)*, 2 *(d-f)* and 3 *(g-i)* is the one expected: noise anticipates the transition.
- Before *transition 1* noise leads to occasional extreme intensity pulses *(a-c)*.



The noise strength is β= 0 *(a,d,g)*, 10–4 *(b,e,h)* and 10–3 *(c,f,i)*.

Summary

- We have demonstrated the existence of extreme intensity pulses in a semiconductor laser with optical feedback from a short external cavity.
- We have identified 3 relevant transitions involved in the appearance of extreme pulses, for the feedback strength and the feedback phase.
- Spontaneous emission noise does not modify this scenario but only anticipates the different transitions.
- Both the existence of a ``narrow channel´´ and patterns in the rotation of the optical field are features of the trajectory that characterize extreme pulses and should be considered in future work.

Thank you very much!

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