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Rogue Waves in the Dynamics of Optically Injected Semiconductor Lasers

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Outline

- Introduction
  - Rogue Waves (Tredicce)
  - Semiconductor Lasers
  - Optical injection phenomena
- Experimental observations
- Numerical results
  - Rate equation model
  - Results of simulations
- Summary

According to fishermen tales from a pub in Ireland…

Waves taller than buildings!
Deadly killer freak waves!

are more or less common in deep waters in the Irish Sea…

RWs are:

- ***rare*** events,
- ***extreme*** events,
- and rather universal …
- have been identified not only in oceanography but also in several other natural systems (acoustics, optics and even financial markets…)

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **83**, 061801(R) (2011)

Optical rogue waves in telecommunication data streams

Sergey Vergeles[1,2] and Sergei K. Turitsyn[3]
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Large broadening of short optical pulses due to fiber dispersion leads to a strong overlap in information data streams resulting in statistical deviations of the local power from its average. We present a theoretical analysis of rare events of high-intensity fluctuations—optical freak waves—that occur in fiber communication links using

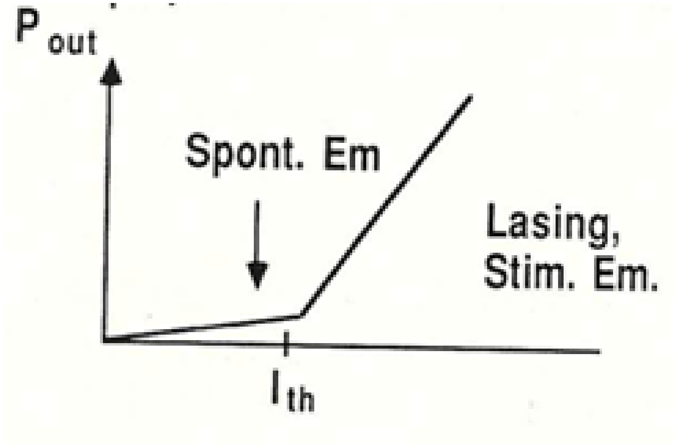
- They are receiving a lot of attention these days!
  - Next: RWs in the nonlinear dynamics of ***semiconductor lasers***

Semiconductor lasers

- Since the invention of the laser in 1960, many types of lasers have been developed, including gas lasers, solid-state lasers and semiconductor lasers (or diode lasers)
- Semiconductor lasers have many advantages: they are compact, fast, reliable and inexpensive.
- They are widely used in
  - Telecommunications
  - Optical Storage (CDs, DVDs)
  - Optical mouse
  - Barcode scanners
  - Laser printers
  - Sensing
  - etc

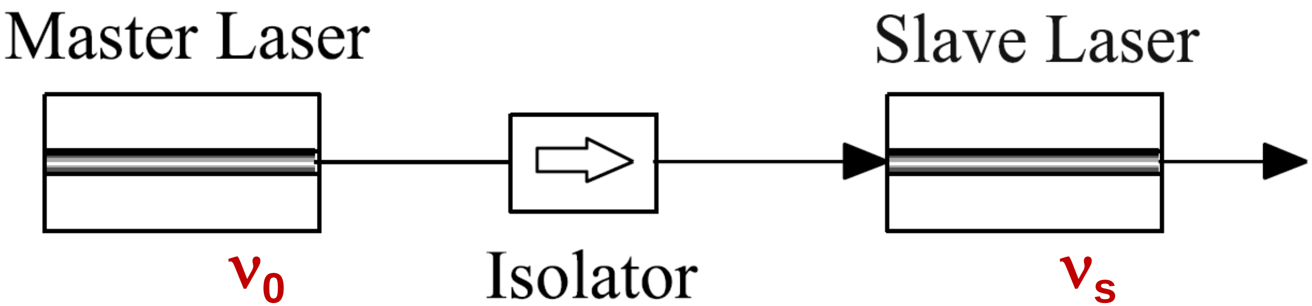
Semiconductor Lasers dynamics

- Semiconductor lasers are nonlinear devices.
- However, ''Solitary'' semiconductor lasers are stable and emit continuous-wave light.
- External perturbations (such as external optical injection, feedback, modulation) can induce a rich variety of nonlinear behaviors.



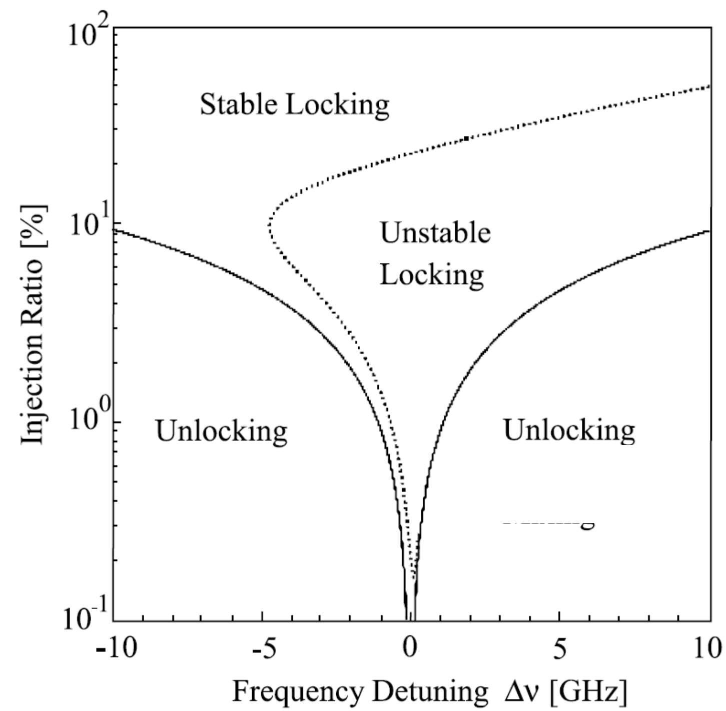
We now focus on the dynamics induced by external optical injection

Optical injection



Detection system (photo detector, oscilloscope, spectrum analyzer)

- Parameters:
  - Injection ratio
  - Frequency detuning $\Delta\nu = \nu_s - \nu_0$
- Dynamical regimes:
  - Injection locking (cw output)
  - Period-one oscillation
  - Period-two oscillation
  - Chaos



Eur. Phys. J. D 58, 181–186 (2010)
DOI: 10.1140/epjd/e2010-00061-4

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Labyrinth bifurcations in optically injected diode lasers

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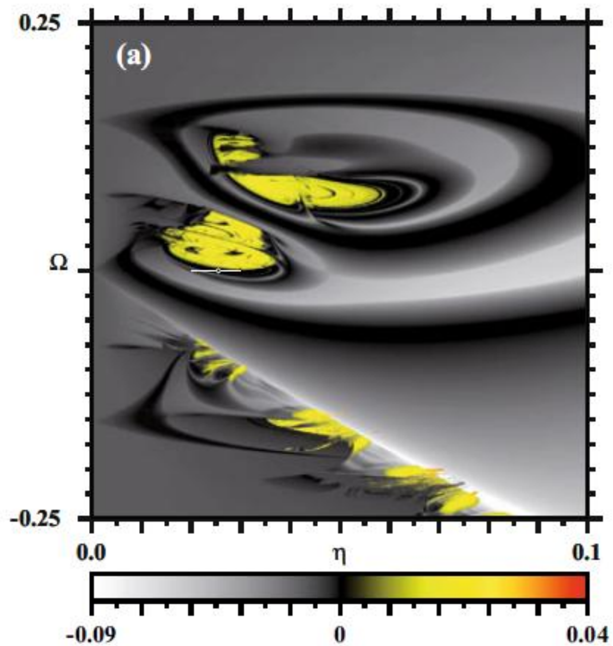
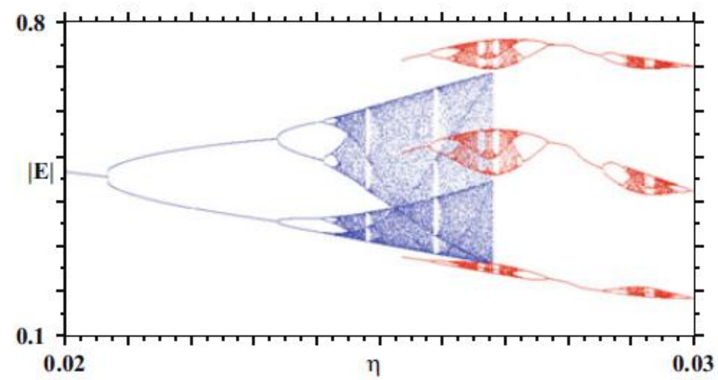
Lyapunov diagram



Bifurcation diagram

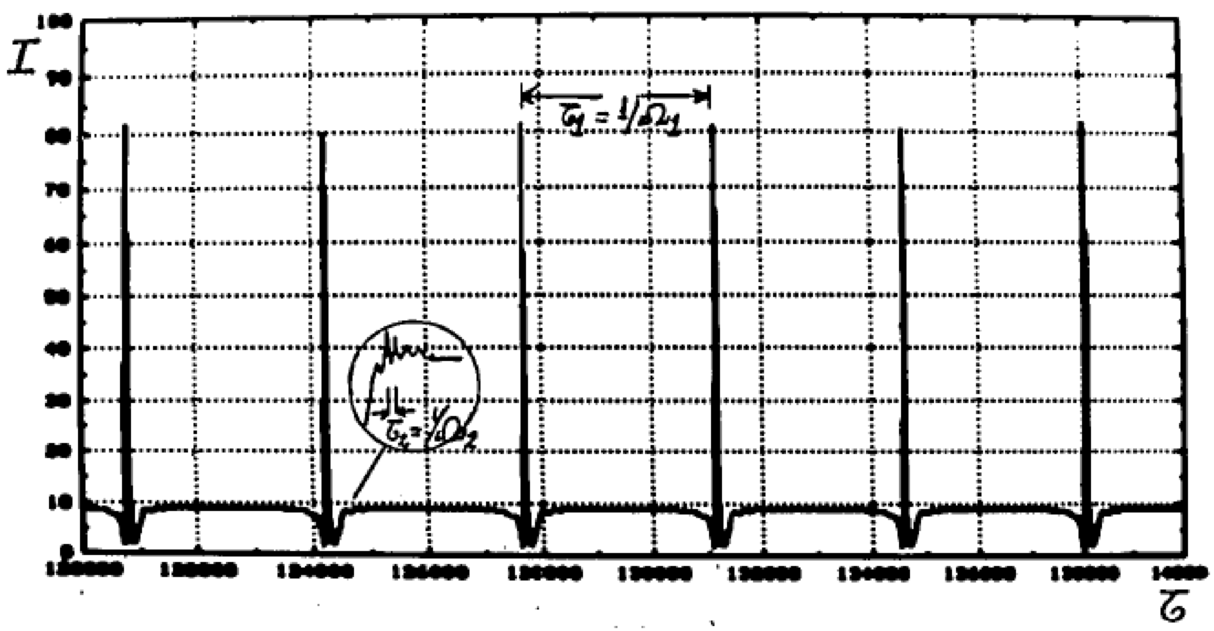


Also Rogue Waves?

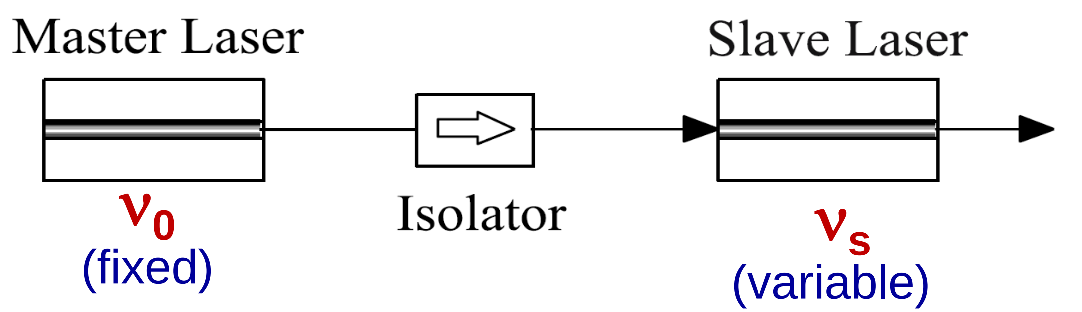
Instabilities in lasers with an injected signal

J. R. Tredicce, F. T. Arecchi, G. L. Lippi, and G. P. Puccioni

178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985



In the Experiments



The frequency detuning between the lasers, $\Delta\nu = \nu_s - \nu_0$, is controlled by the slave laser pump current, **I**

When **I** increases:

→ **Joule heating**

→ **the temperature modifies the cavity refractive index**

→ **decreases the cavity resonance frequency**

$$\nu_s = g(Temp) = f\,(I)$$

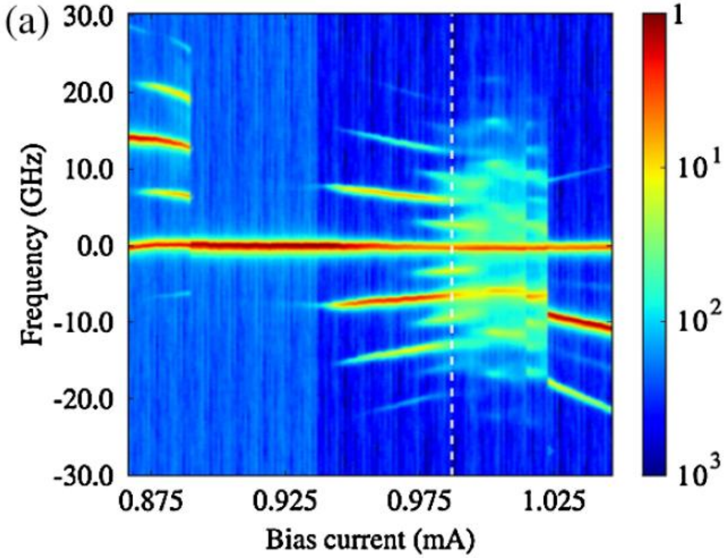
(donde f es una función aproximadamente lineal)

We detected the output of the slave laser:

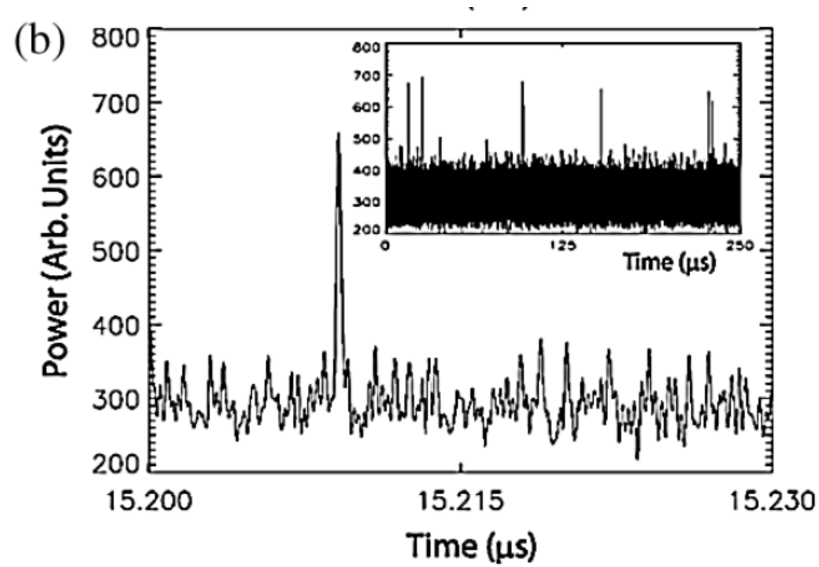
- **Intensity time - series (with a 6 GHz oscilloscope)**
- **Intensity Fourier spectrum (spectrum analyzer)**

Experiments

Fourier spectrum of the laser intensity



Time series of the laser intensity



Five regions as **I** increases:

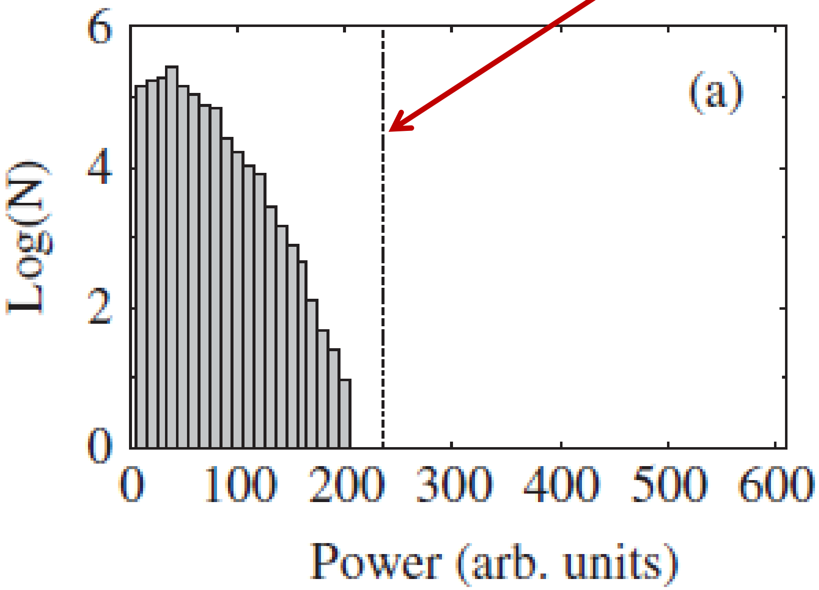
- Beating (independent lasers)
- Period 2 of the beat note
- Stable locking
- Periodic & chaotic oscillations
- Beating (independent lasers again)

(In the chaotic region,
I = 0.976 mA, Δν = -1.34 GHz)

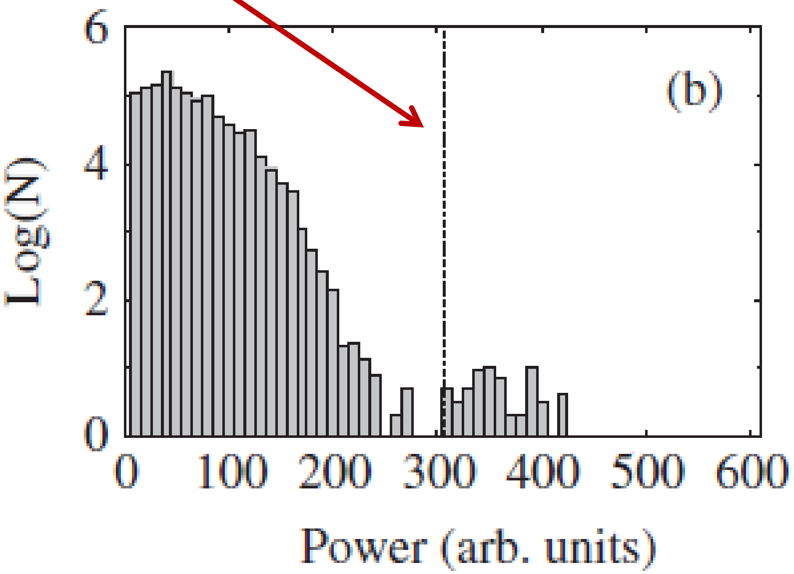
C. Bonatto et al, PRL 107, 053901 (2011)

Histograms of pulse amplitude (log scale)

Border = mean value + 8 σ



I = 0.972 mA



I = 0.976 mA

Model

Two coupled nonlinear rate equations

- The optical field, **E** (photon number $\propto$ **$|E|^2$**)
- The carrier density, **N**

$$\frac{dE}{dt} = \underbrace{\frac{1}{2\tau_p}(1+i\alpha)(N-1)E}_{} + \underbrace{i\Delta\omega + \sqrt{P_{\text{inj}}}}_{} + \underbrace{\sqrt{2\beta_{sp}}\,\xi(t)}_{}$$

$$\underbrace{\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu\text{-}N\text{-}N|E|^2\right)}_{}$$

optical injection
η: injection strength
$\Delta\omega$: frequency detuning

spontaneous emission noise

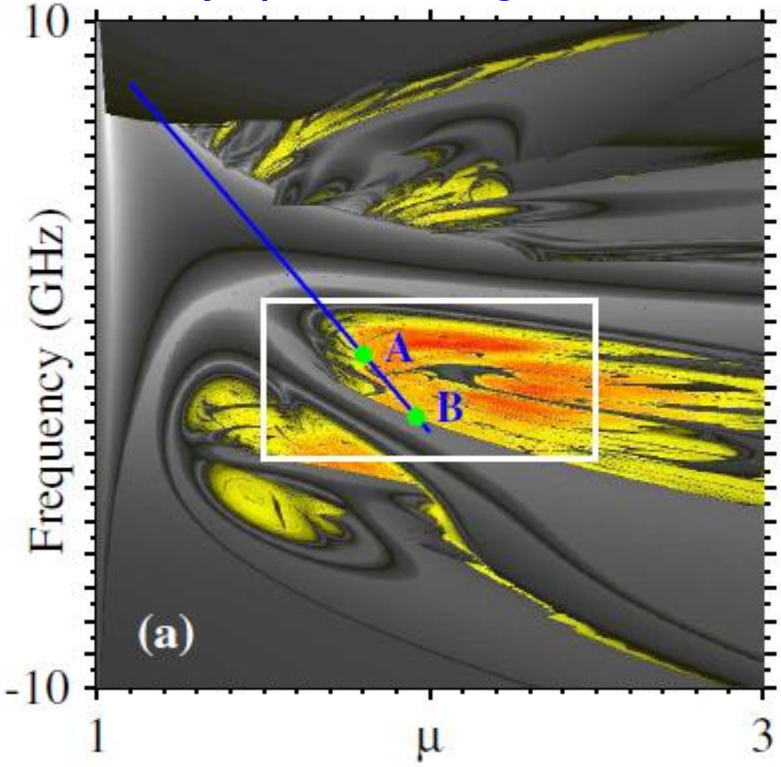
Solitary laser
4 parameters: α τ_p τ_N μ

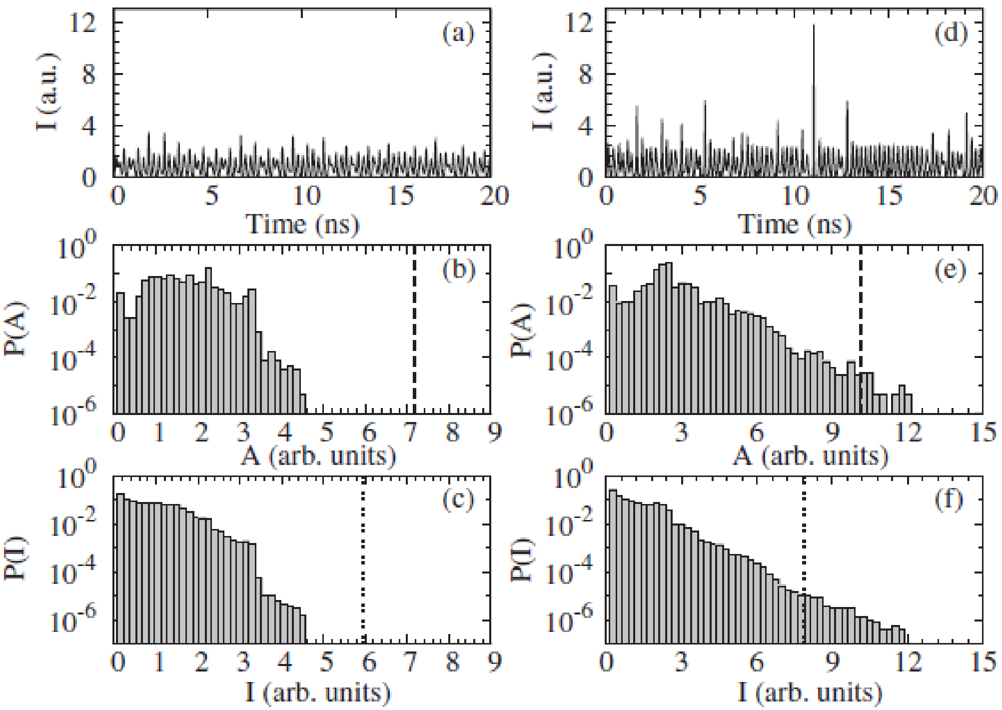
Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

μ: normalized pump current parameter

Results of simulations: deterministic noise-free equations

Lyapunov diagram



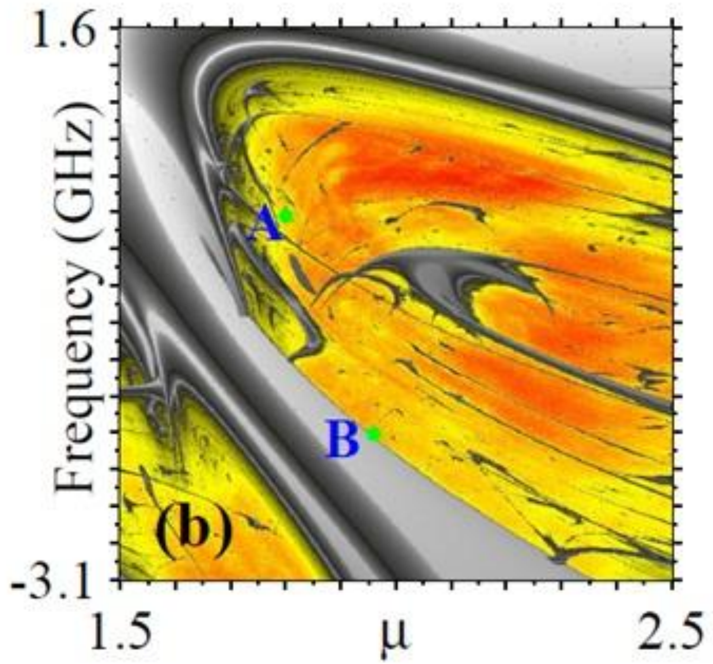


Point A: No RWs

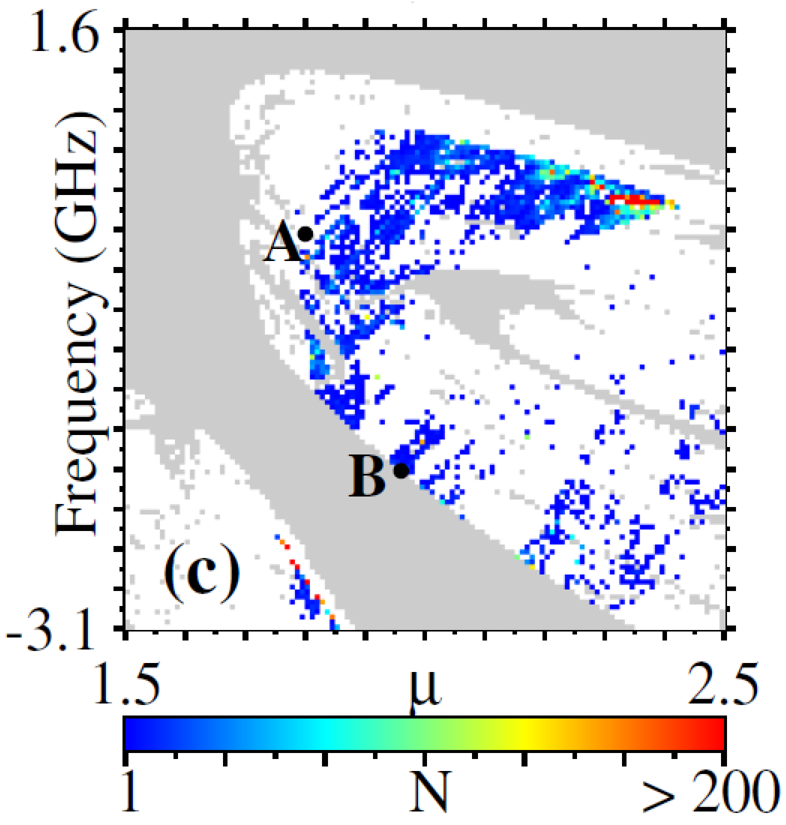
Point B: RWs

Results of simulations: deterministic noise-free equations

Lyapunov diagram

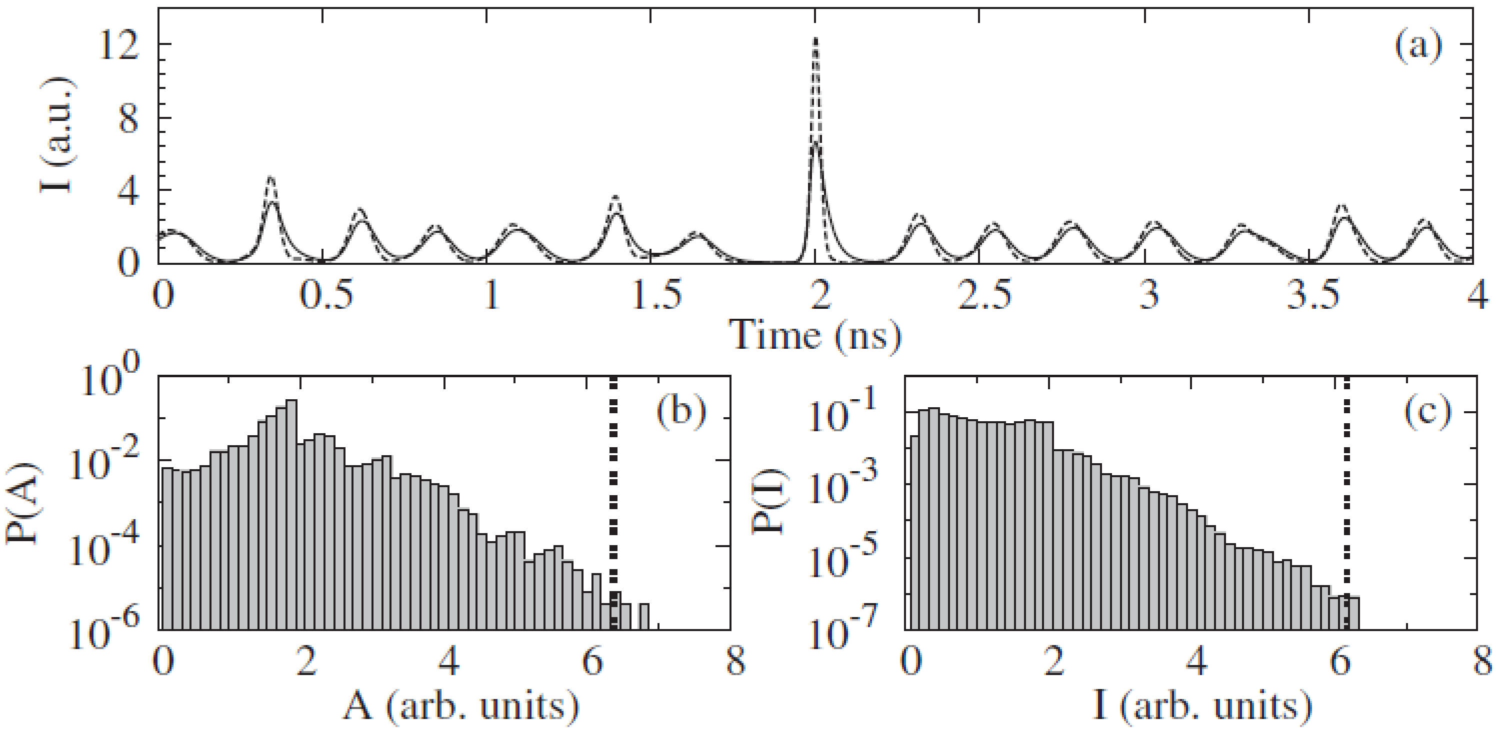


Number of RWs



Influence of noise: simulations of the stochastic rate equations

Solid line: filtered time-series to simulate the finite experimental detection bandwidth



Summary

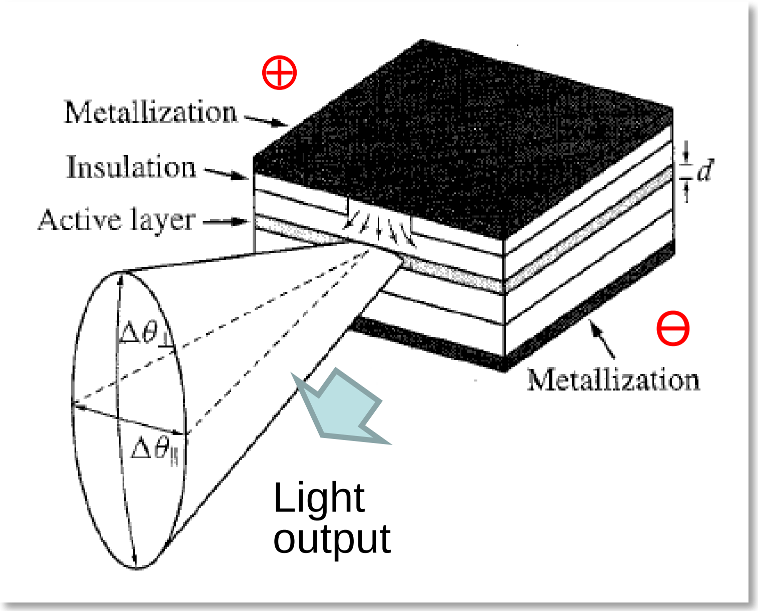
- Giant intensity pulses were interpreted as Rogue Waves
- Different types of chaos: without and with rogue waves
- RWs characterized by Non-gaussian histograms with long tails
- Deterministic nature of these rare and extreme events

THANK YOU FOR YOUR ATTENTION

Semiconductor lasers

Electrically pumped, two types of cavity geometries

Edge-Emitting lasers (EELs)



Pump
current

I (mA)

Vertical-Cavity Surface-Emitting Lasers (VCSELs):