Extreme intensity pulses in semiconductor lasers with optical injection or feedback

Cristina Masoller
Cristina.masoller@upc.edu
www.fisica.edu.uy/~cris

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José A. Reinoso (Universidad Nacional de Educación a Distancia, UNED, Spain)

Jordi Zamora Munt (IFISC, Mallorca, Spain)

B. Garbin, M. Feyereisen, S. Barland, M. Giudici (INLN, Nice, France)

Jorge Tredicce (INLN, now at Universite de la Nouvelle Caledonie)

Jose Rios Leite (Universidade Federal de Pernambuco, Recife, Brasil)
UPC Campus Terrassa

Gaia research Building

1. Barcelona
2. Castelldefels
3. Igualada
4. Manresa
5. Mataró
6. Sant Cugat del Vallès
7. Terrassa
8. Vilanova i la Geltrú
Nonlinear optics and laser dynamics research labs
- Introduction to extreme events & optical rogue waves.

- Semiconductor laser with **optical injection**: experimental observations & numerical results.

- Semiconductor laser with **optical feedback**: numerical results.

- Summary and conclusions.
RWs are rare, ultra-high waves that fall outside (and far from) the main part of long-tailed probability distributions.
A RW is usually defined as a wave that is two times the significant wave height of the area. The significant wave height is the average of the highest one-third of waves that occur over a given period.

- Serious problem for the design of off-shore platforms.

Source: National Geographic
Optical RWs: first observation

A recent review of the state-of-the-art

EDITORIAL

Recent progress in investigating optical rogue waves

N Akhmediev\textsuperscript{1}, J M Dudley\textsuperscript{2}, D R Solli\textsuperscript{3,4} and S K Turitsyn\textsuperscript{5}  

The science of rogue waves in optics is now over five years old, and it has emerged as an area of broad interest to researchers across the physical sciences [1]. This area of study was initiated by the pioneering measurement of
We have recently shown experimentally and numerically that continuous-wave optically injected semiconductor lasers can display huge intensity pulses that we identified as deterministic rogue waves.

These pulses can be predicted with a certain anticipation time.

They are generated by an external crisis-like process.

Noise can either enhance or diminish their probability of occurrence.


Deciphering Rogue Waves

Rare pulses with giant intensities—the optical equivalent of rogue ocean waves—have been shown to occur in common laser systems. A team of researchers from Spain, France, and Brazil found a way to generate rogue waves and developed a model for understanding them as a result of a deterministic nonlinear process (Phys. Rev. Lett. 107, 053901). Extremely high waves have been a subject of interest over the past decade in oceanography as well as in other fields (including optics), but we still don’t fully understand what triggers them and how they develop.

Rogue waves on the ocean are typically twice the height of surrounding waves and have steep sides, like “a wall of water.” They have high amplitude, with a fast rise and fast fall. In the laser system demonstrated by the researchers, a rogue wave has an intensity so high that—according to Gaussian statistics—it should be vanishingly improbable. Such waves are unusual, but occur more often than Gaussian statistics can explain.

Rogue waves also can be destructive: paper coauthor Jorge Tredicce at the Université de Nice Sophia Antipolis (France) says, “in mode-locked lasers, those extreme pulses may damage the optics and the crystal ... it is the death of the laser.”

Light from a continuous wave master laser is injected into a stabilized vertical cavity surface-emitting laser (VCSEL) with stabilized pump current and temperature. The VCSEL emitted at 980 nm in a single transverse mode.

Researchers detuned the injection laser from the VCSEL and found that the slave laser output falls into four regions—one of which is stable-locked behavior. As the VCSEL current is increased, the output becomes more and more chaotic. Near the border of the mode-locked region, the researchers found a series of small pulses interrupted by occasional extremely large pulses. Coauthor Cristina Masoller at the Universitat Politècnica de Catalunya (Spain) explains, “we identify two types of optical chaos: one in which rogue waves are rare but they certainly appear and one in which practically they do not exist.” There appear to be areas where rogue waves don’t occur even if the behavior is chaotic.

The experiments were inspired by Tredicce’s theoretical paper that suggested the existence of huge intensity pulses in this laser system. Researchers found that a simple noise-free rate equation model produced results that agree with the experiments. This allowed them to interpret the sporadic high amplitude pulses as the result of a deterministic nonlinear process.

The group now has a simple system that allows them to experiment with optical rogue waves, as well as a model for describing them. Because rogue waves occur in other systems, ranging from ocean surface to acoustic waves to economics, their work could have implications far beyond the realm of optics.

Next, they want to find a mechanism that creates rogue waves in their system, as well as whether they can increase or decrease their likelihood.

—Yvonne Carter-Powell
Optically injected semiconductor lasers

Master Laser

Tunable SCL

Injection ratio

Frequency detuning \( \Delta \nu = \nu_s - \nu_0 \)

Parameters:

- Injection ratio
- Frequency detuning \( \Delta \nu = \nu_s - \nu_0 \)

Dynamical regimes:

- Injection locking (cw output)
- Period-one oscillation
- Period-two oscillation
- Chaos

Detection system (photo detector, oscilloscope, spectrum analyzer)

Adapted from J. Ohtsubo
Labyrinth bifurcations in optically injected diode lasers

V. Kovanis\textsuperscript{1}, A. Gavrielides\textsuperscript{2}, and J.A.C. Gallas\textsuperscript{3,4,5,\textsuperscript{a}}

\textsuperscript{1} Air Force Research Laboratory, 2241 Avionics Circle, Wright-Patterson AFB, Dayton OH 45433, USA
\textsuperscript{2} USAF, Research Laboratory, High Power Solid State Lasers Branch, Kirtland AFB, NM 87117, USA
\textsuperscript{3} TecEdge, Wright Brothers Institute, 5100 Springfield Street, Dayton OH 45431, USA
\textsuperscript{4} Departamento de Física, Universidade Federal da Paraíba, 58051-970 João Pessoa, Brazil
\textsuperscript{5} Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, Brazil

Lyapunov diagram

Bifurcation diagram
Instabilities in lasers with an injected signal


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 \( \nu_s = g(\text{Temp}) = f(I) \)

We varied the slave laser pump current and detected the output of the laser:

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

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, $\Delta \nu = -1.34$ GHz)

C. Bonatto et al, PRL 107, 053901 (2011)
Histograms of pulse amplitude

Border = mean value + 8 $\sigma$

$I = 0.972$ mA

$I = 0.976$ mA
The complex optical field, $E$ (photon number $\propto |E|^2$)

The carrier density, $N$

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

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

Solitary laser parameters: $\alpha$, $\tau_p$, $\tau_N$, $\mu$

$\mu$: normalized pump current parameter

Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns
Deterministic simulations \( (\beta_{sp}=0) \)

- **Lyapunov diagram**
- **Slave laser pump current**
- **Point A: No RWs**
- **Point B: RWs**
Experiments

Simulations
Rogue waves in the parameter space (pump current, frequency detuning)

Lyapunov diagram

Number of RWs
Statistics of the RW waiting time

Experimental data

Deterministic & stochastic simulations ($\beta_{sp} = 10^{-4}$)
Measured intensity time traces (500 RWs)

Simulated time traces

- $\langle H \rangle + 8\sigma$
  - $\beta_{sp} = 0$
  - 459 RWs

- $\langle H \rangle + 8\sigma$
  - $\beta_{sp} = 10^{-2}$
  - 53 RWs

- $\langle H \rangle + 4\sigma$

J. Zamora-Munt et al, PRA 87, 035802 (2013)
Influence of spontaneous emission noise

\[ \beta_{sp} = 0 \]

\[ \beta_{sp} = 10^{-4} \]

\[ \beta_{sp} = 10^{-2} \]
Fixed points in the phase space

What triggers a RW pulse?
A RW is triggered whenever the trajectory closely approaches the unstable manifold of S2.
Experimental data: amplitude of the intensity pulses

Numerical simulations

chaos with RWs and chaos without them
An external crises-like process enables access to the phase space region where the stable manifold of $S_2 (x)$ is.

Why chaos with RWs and chaos without them?
Dynamics with optical feedback from a short external cavity

Typical parameter values:
\[ \alpha = 5, \ T = 1710, \ \theta = 70, \ J = 1.155 \]

\[ \tau = 2L/c \]

Short EC:
\[ f_{\text{ext}} = 1/\tau > f_{\text{ro}} \]

\[ dE/\text{ds} = (1 + i\alpha)NE(s) + \eta e^{-i\omega\theta}E(s - \theta) + \beta\xi, \]
\[ TdN/\text{ds} = J - N - (1 + 2N)|E(s)|^2. \]

\[ s = t/\tau_p, \ \ \ \ \ \ \ \ \ \ \ \theta = \tau / \tau_p \]
\[ T_{\text{RO}} = \pi\sqrt{2T/J} = 171 \]
Regular Pulse Packages (RPPs)

- Experiments

- Simulations

T. Heil et al, PRL 87, 243901 (2001)
Numerical bifurcation diagram

Regular pulse packages

Extreme pulses

Using a high threshold

Using a lower threshold

Predictability
Deterministic intermittency

Increasing $\eta$

(a) Laser Power [arb. units]

(b) Feedback Rate $\eta$ [dimensionless]

(c) Power Extrema [arb. units]

Time (in units of $\Theta$)
Influence of noise

- Transition 1: noise induced EPs
Transition 2: noise advances the switching
- Transition 3: noise advances the switching
Optically injected semiconductor lasers:

- Intensity pulses characterized by long-tailed histograms; giant rare pulses interpreted as Rogue Waves.
- Different types of chaos identified: without and with rogue waves.
- **Origin** of RWs: deterministic. An external crises-like process enables access to the region in phase space where RWs can be triggered.
- **Predictability**: in our system RWs can be predicted with some anticipation.
- **Control**: noise strongly affects their probability of occurrence.

External-cavity lasers:

- Similar results, intermittency is the route to extreme pulses.
THANK YOU FOR YOUR ATTENTION!

<cristina.masoller@upc.edu>
Universitat Politecnica de Catalunya
http://www.fisica.edu.uy/~cris/