Neuromimetic Dynamics in a Micropillar Laser with Saturable Absorber

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Neuromimetic systems

Systems that mimic biological neurons or biological architecture for processing and/or computing

→ artificial neural networks
→ probabilistic computing
→ reservoir computing
→ ...

Potential advantages:

→ energy efficient (brain 20W !)
→ noise tolerant

Computing with Neural Circuits: A Model
John J. Hopfield, David W. Tank
Science, New Series, Vol. 233, No. 4764 (Aug. 8, 1986), 625-633,
Excitable Response = all-or-none response

Action potential

Leaky integrate and fire neuron
Neuromimetic systems

Electronic/Nanoelectronic

Excitable electronic circuit

Memristor

STDP : synaptic time dependent plasticity
Neuromimetic systems

Excitable Semiconductor Optical Systems

Coherent optical injection or feedback

**Macroscopic:**

Excitability:
- slow/fast thermo-optical
  - "slow" (>10 ns)
- in injected active/passive cavity
  - Time << ns
  - Very sensitive to detuning

**Micro/nano:**

- Wünsche et al, PRL 88, 239011 (2001)

**VCSEL with SA**

Slow/fast systems, carriers nonlinearity
- fast < 1 ns (carriers)
- Compact
- Incoherent pumping

Giudici et al, PRE 55, 6414 (1997)

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**Notes:**

- AR coating
- temperature control
- cleaved
Neural photonic networks

Processing information with optical spikes:
Fast and energy efficient
→ Logic, memories, pattern recognition, ...

A Leaky Integrate-and-Fire Laser Neuron for Ultrafast Cognitive Computing,
What is Excitability?

Phenomenological definition:
- An excitable system possesses one stable state.
- If perturbed above a given threshold, it produces pulse-like response with a characteristic shape and turns back to its stable state.
- Property: lethargic/refractory time.
- In neurons, excitable pulses → information encoding and transport.

Need dynamical system that can make a transition from rest state to self-pulsation.
Excitability in semiconductor-based optical systems

Class 1 neural excitability

Saddle-node on invariant circle (SNIC)
Laser with optical feedback/injection

Giudici et al, PRE 55, 6414 (1997)
Mashall et al, Phys. Lett. A 374, 739 (2010)...

Homoclinic-loop bifurcation
Laser with SA


Class 2 neural excitability

FitzHugh-Nagumo
Laser with optical injection
(slow-fast, thermo-optical)

Yacomotti et al, PRL 97 143904 (2006)...

Dubeldam, Krauskopf, Lenstra PRE 69, 6580 (1999)
VCSEL structure with integrated SA

Emission @ 980nm

Pump beam ~800nm

T. Elsass et al, EPJ D 59, 91 (2010)
Excitability in a planar VCSEL-SA

80ps pulse perturbation @ ~800nm

Laser response @ 980nm

<i>R</i> : mean amplitude of the response

σ : standard deviation of the response

Yamada model with noise and sp. emission terms

\[
\begin{align*}
\dot{G} &= -\gamma_g \left[ A + \Lambda_0 \delta(t) - G(1 + I) \right] \\
\dot{Q} &= -\gamma_{sa} \left[ B - Q(1 + sI) \right] \\
\dot{I} &= (G - Q - 1)I + \beta_{sp}(Q + \eta_g)^2 + F_I(t)
\end{align*}
\]

Langevin force

\[
F_I(t) = (N_g + \eta_g) \sqrt{2R_{sp}}I \xi(t) \\
\langle \xi(t)\xi(t') \rangle = \delta(t - t')
\]


Micropillar laser with intracavity SA

Coated and half buried single micropillar structure

LPN-CNRS
From excitable regime to gain switching regime

**Experiment**

**Bias Pump**
- Excitable threshold increases with decreasing pump
  \[ \propto 1 + B - A \]
  *Pump - non sat. loss - cav. loss*

- Excitable response amplitude decreases with decreasing pump bias

- Low bias pump has **inhibitory** effect
From excitable regime to gain switching regime

**Experiment**

- Excitable threshold increases with decreasing pump
- Excitable response amplitude decreases with decreasing pump bias

**Yamada model**

- Low bias pump has **inhibitory** effect

Equation: $\propto 1 + B - A$

*Pump - non sat. loss - cav. loss*
Relative refractory period


& Physics Synopsis: Semiconductor Lasers Get Nervy
Relative refractory period

**Responses**

Perturbations

Delay 194ps 298ps 508ps


& Physics Synopsis: Semiconductor Lasers Get Nervy

& Physics Synopsis: Semiconductor Lasers Get Nervy
Relative refractory period


& Physics Synopsis: Semiconductor Lasers Get Nervy
Relative refractory period and excitable behaviour

First perturbation above excitable threshold
2nd perturbation with fixed delay and varying amplitude

Smaller delays → more difficult to trigger 2nd excitable pulse
Dynamic inhibition

Below threshold perturbation:

\[
R(t) = G(t) - Q(t) - 1
\]

Negative net gain: Pulse not triggered

Above threshold perturbation:

Positive net gain: Pulse triggered
$b_1 = 0.001, b_2 = 0.002$

$\mu_2 = 2, \ s = 10, \ \eta_1 = 1.6, \ \beta_{sp} = 10^{-5}$

Comparison with model
Timing aspects

$b_1 = 0.001, \ b_2 = 0.001$

$b_1 = 0.001, \ b_2 = 0.002$

$b_1 = 0.0001, \ b_2 = 0.002$

net gain
Relative and absolute refractory periods in neurons

**Absolute refractory period**

**Relative refractory period**

→ increase of the excitable threshold  
→ reduced response

Excitable threshold is not fixed:  
depends on the history of the system  
→ The system has memory
Timing aspects
Delay decreases with perturbation amplitude. For a given perturbation amplitude, delay increases with decreasing bias pump.

\[
t_d = \frac{2}{\sqrt{\left(1 - \frac{I^\text{th}}{I_0}\right) \left[2 \gamma (aB - A) I_0 \right]}} \arctan \left( \frac{1}{\sqrt{1 - \frac{I^\text{th}}{I_0}}} \right)
\]


**Delay with varying bias pump as a function of perturbation**

- \(A = -40\)
- \(A = 2.6\)
- \(B = 2, \gamma = 0.001, a = 10, I_0^\text{th} = 2.8\)

**Fits of delay**
Debate:
Information encoded in spike rate or individual spike timing?

Here we can encode input perturbation amplitude in spike delay.
Temporal summation

(a) Subthreshold, no summation

(b) Temporal summation

Threshold of axon of postsynaptic neuron
Resting potential

Membrane potential (mV)

0

-70

-55
Temporal summation @ resonance

1st Input Pulses

Output Pulses
Temporal summation @ resonance

2\textsuperscript{nd} Input Pulses

- 250ps
- 350ps
- 450ps
- 550ps
- 650ps

Output Pulses

Time (s)
Temporal summation @ resonance

Input Perturbations

- 250ps
- 350ps
- 450ps
- 550ps
- 650ps

Output Pulses

Time (ns)

Intensity (arb. u.)
Temporal summation @ resonance

1\textsuperscript{st} pulse

2\textsuperscript{nd} pulse

45/55
50/50
55/45
Coincidence detector:
→ response only if input spikes arrive with small delay
→ auditory system of the barn owl
Coincidence detector:

→ response only if input spikes arrive with small delay
→ auditory system of the barn owl
Micropillar laser with SA can mimic some of the properties of neuron but is 1 million times faster than biological neuron!

- Absolute and Relative refractory periods
- Temporal summation
- Promising architecture for `neuromimetic computing by coupling several single units
Fast response and absolute refractory time

Double pulse perturbation

(a)

(b)

(a')

(b')

Intensity (arb. u.)

Time (arb. u.)

Delay = 700ps

Delay = 260ps

Perturbation pulse: ~80ps duration

Response pulse as short as 190ps