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Transitions of determinism and stochasticity in time-delayed complex systems with modulation

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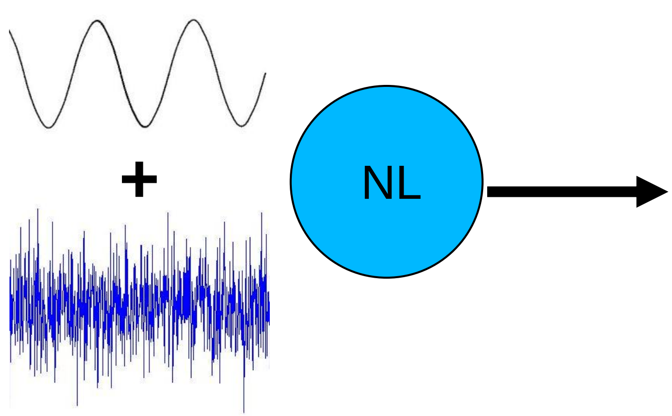
Introduction: Nonlinear oscillator with external periodic forcing

Stochastic resonance (periodic, aperiodic)

Ghost resonance (missing fundamental illusion)

Entrainment, synchronization, …



Laser dynamics

Detection of complex signals

Sensors improvement

Neuronal networks dynamics

Human brain

Animal senses

[A. Neiman, X. Pei, W.Wojtenek, L. Wilkens, F. Moss, H. A. Braun, M. T. Huber and K. Voigt, Phys Rev. Lett., **82**, (1999)]
[L. Gammaitoni, P. Hänggi, P. Jung and F. Marchesoni, Rev. Mod. Phys., **70**, 223 (1998)]
[D. R. Chialvo, Chaos, **13**, (2003)]
[J. Cartwright, D.L. González, O. Piro, Phys. Rev. Lett., **82**, 5389 (1999)]

Goal of the work

GOAL:

- Characterize the delayed-feedback induced complex dynamics under the influence of an external periodic forcing, at an event-level description.
- Verify an existing model for this type of systems at this level of description.

USING:

- Symbolic time series analysis.

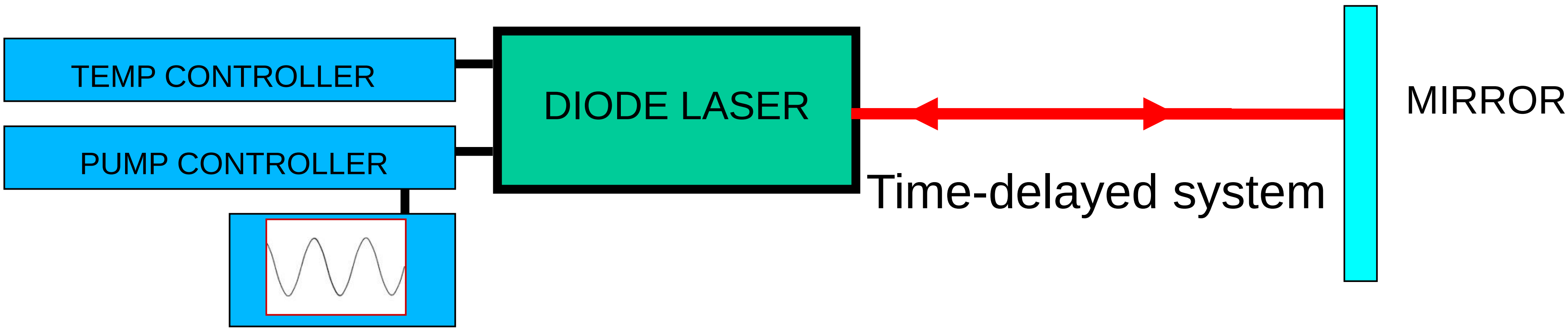
Introduction: Semiconductor lasers

• Aplications: fiber optics telecomunications, optical data storage, life science, material processing, sensing, ...

• Non-linear devices easily perturbed by optical feedback.

• Feedback & noise (spontaneous emission) induce complex stochastic dynamics.

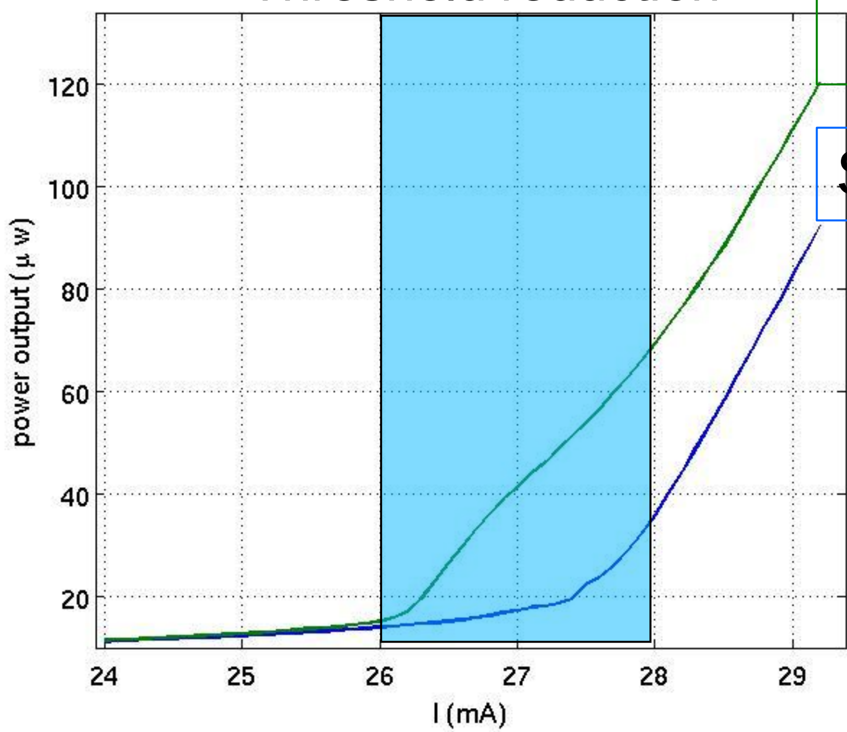
•Stochastic resonance, ghost resonance, entrainment, synchronization, …



[D. W. Sukow & D. J. Gauthier, IEEE Jour. Quan. Elec., **36**, 175 (2000)]
[J. M. Buldú, J. García-Ojalvo, C.R. Mirasso and M. C. Torrent, Phys. Rev. E, **66**, 021106 (2002)]
[C. González, J. M. Buldú, M. C. Torrent and J. García-Ojalvo, Phys. Rev. A, **76**, 05824 (2007)]
[M. Ciszak, O. Calvo, C. Masoller, C.R. Mirasso, R. Toral, Phys. Rev. Lett., **90**, 204102 (2003)]

Introduction: Semiconductor lasers

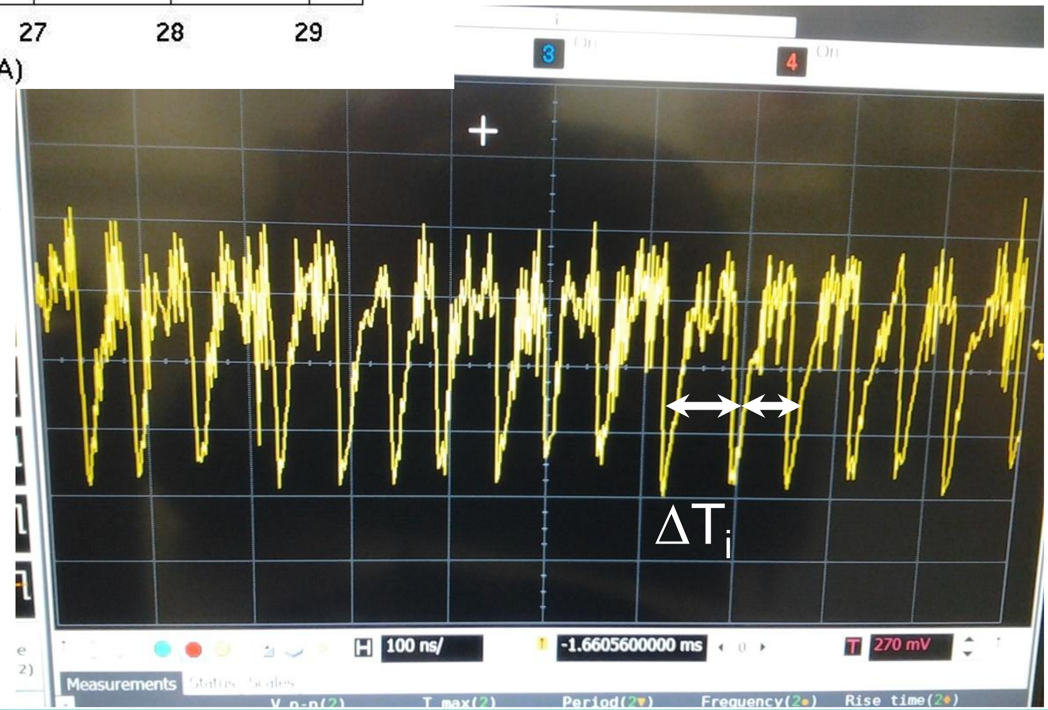
Threshold reduction



Laser with feedback

Solitary laser

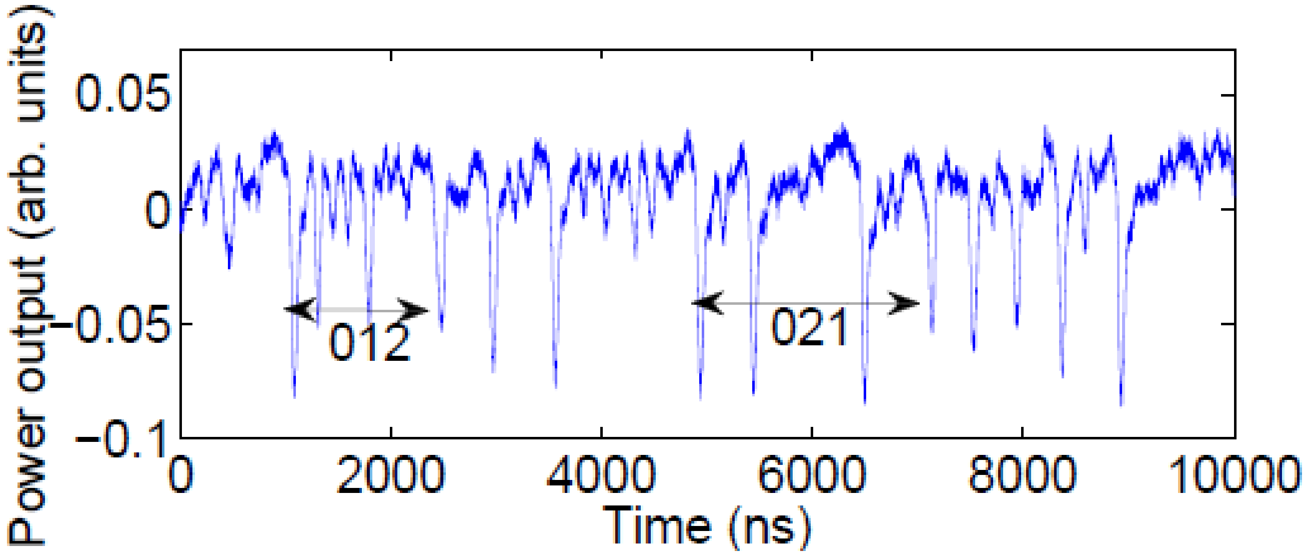
Laser output with feedback



Inter Dropout Interval = ΔT_i

Time delay ~ 5ns
<IDI> ~ 200 ns
1GHz oscilloscope

Time series analysis: Ordinal patterns



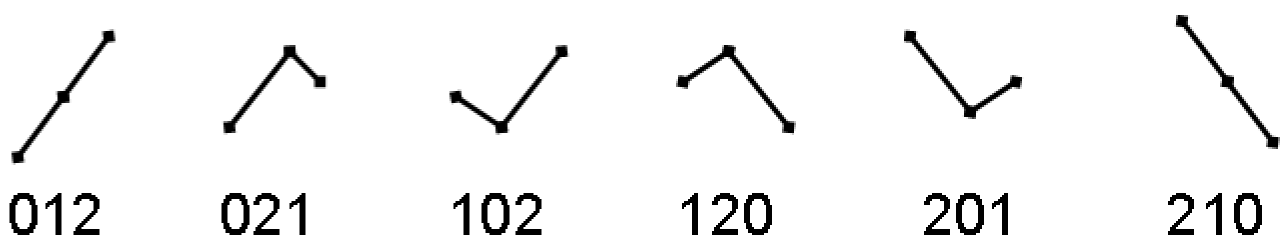
D = 3
D! = 6

Experimental time trace showing the sudden dropouts.

IDI = Inter Dropout Interval (ΔT_i).

Transformation of IDIs into ordinal patterns.

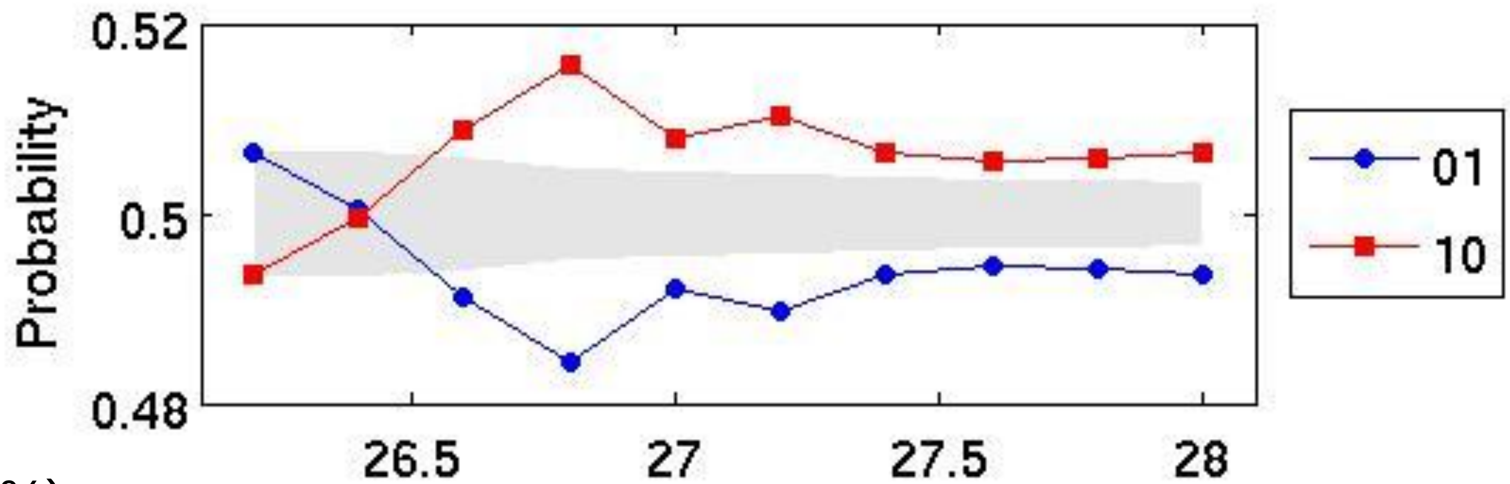
Heart beats, epilepsy, economy, climatology, ...



[C. Bandt & B. Pompe PRL, **88**, 174101 (2002)]

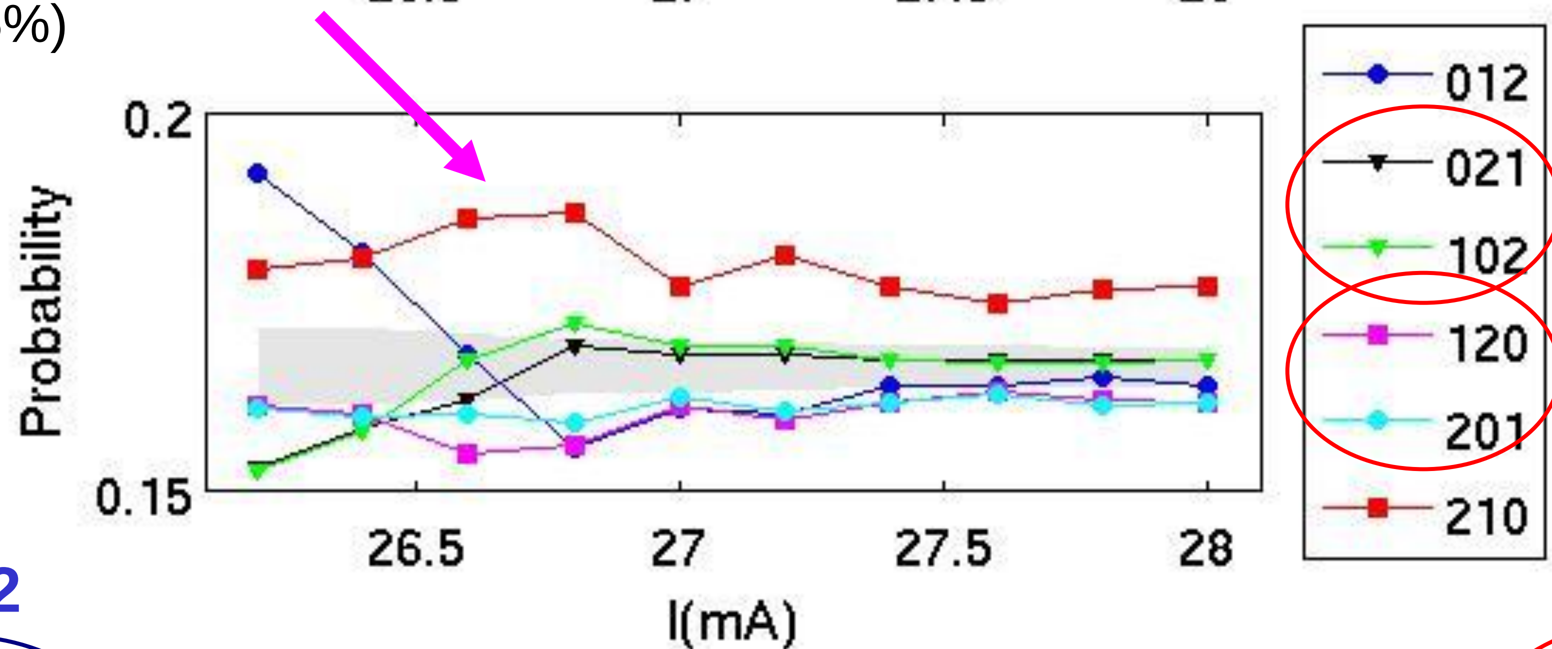
[N. Rubido, J. Tana-Alsina, M. C. Torrent J. García-Ojalvo & C. Masoller, Phys. Rev. E, **84**, 026202 (2011)]

Time series analysis: Ordinal patterns



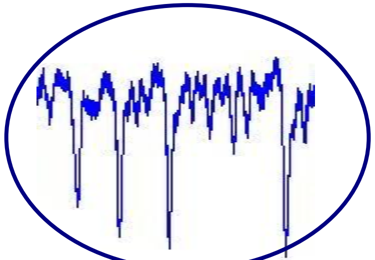
D=2

(3σ ➔ 95%)

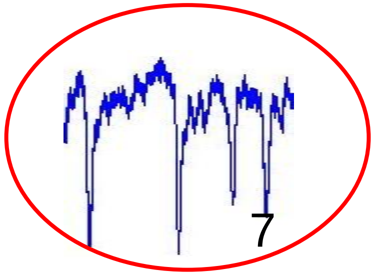


D=3

012

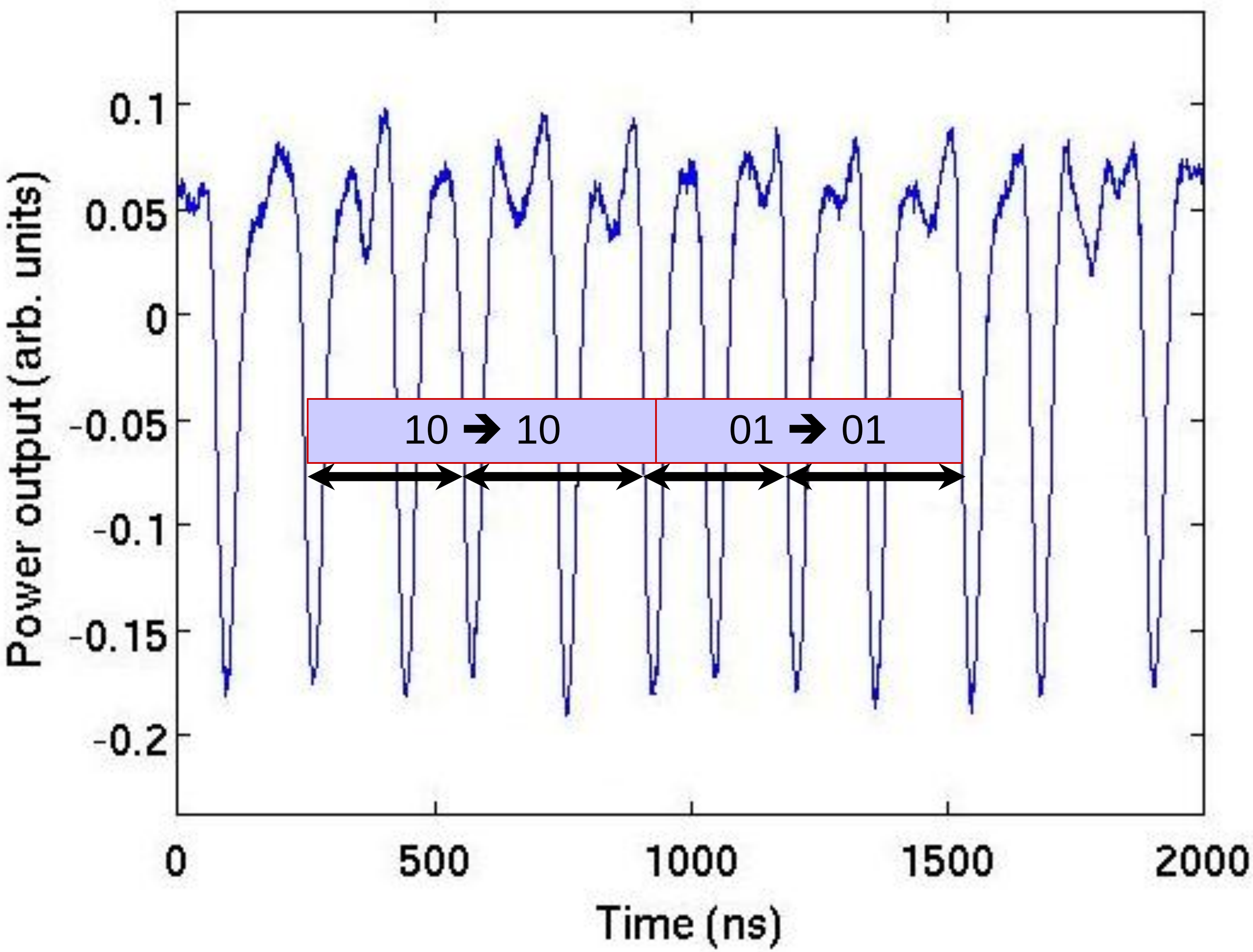


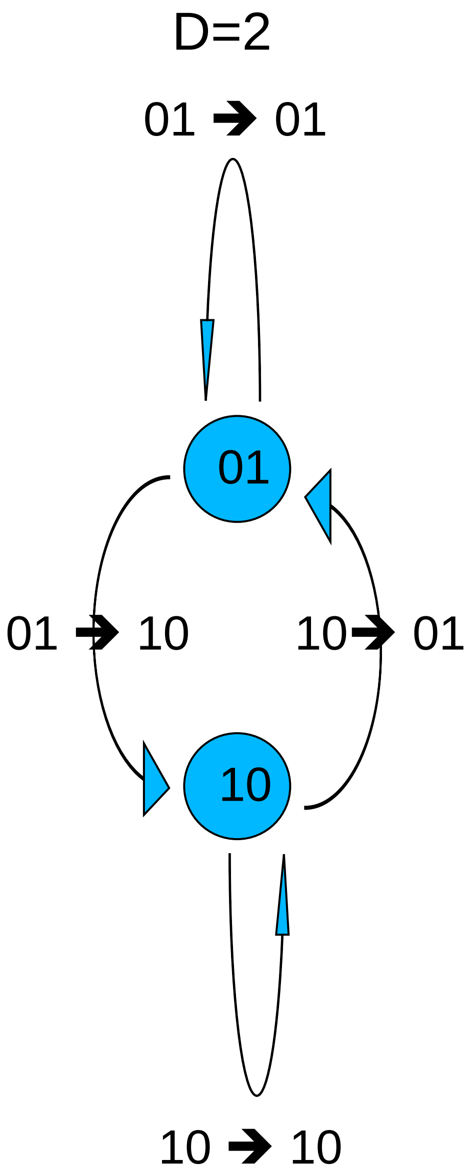
210



[A. Aragoneses, N. Rubido, J. Tiana-Alsina, M. C. Torrent & C. Masoller, *Sci. Rep.*, **3**, 1778 (2013)]

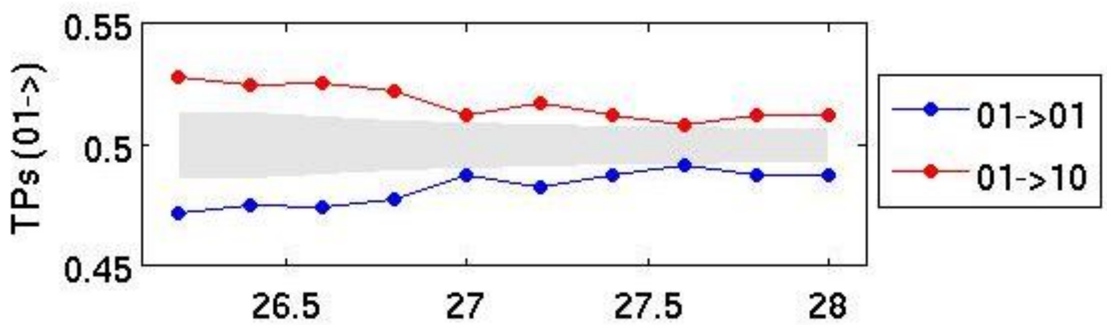
Time series analysis: Transition probabilities



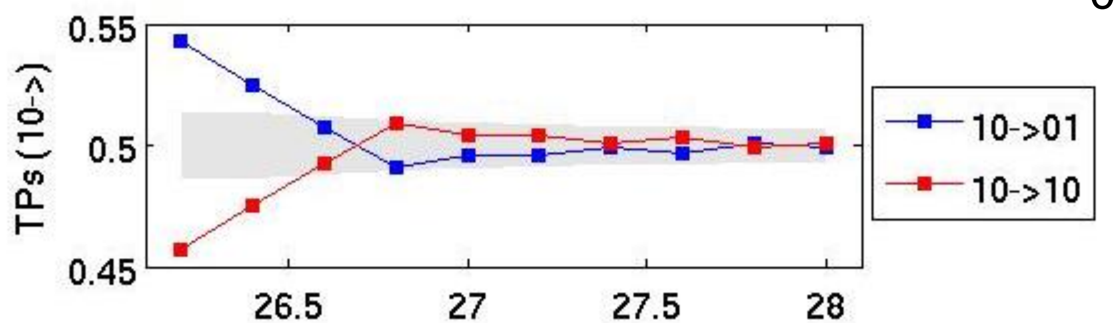


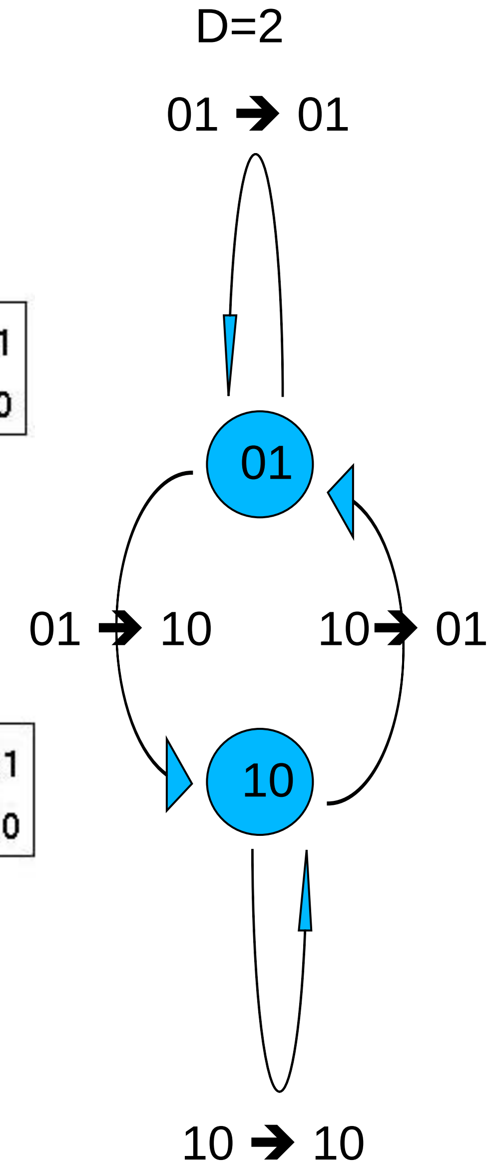
Time series analysis: Transition probabilities

$$T_{01\to 01} + T_{01\to 10} = 1$$

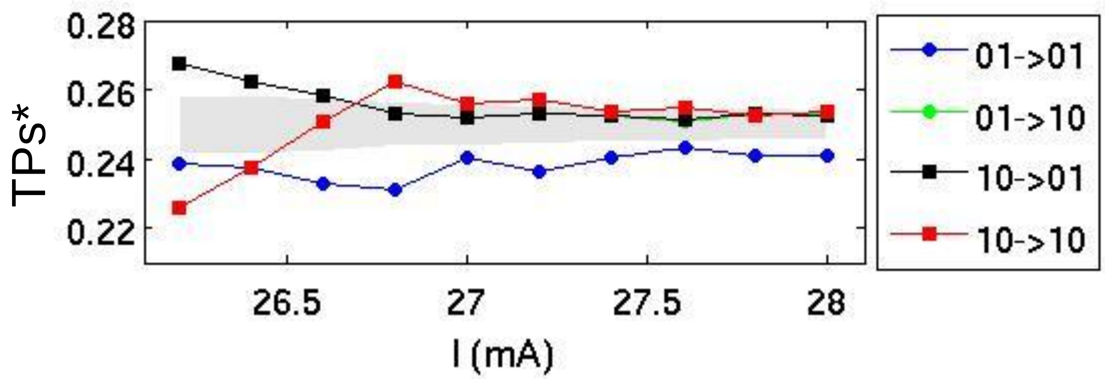


$$T_{10\to 01} + T_{10\to 10} = 1$$

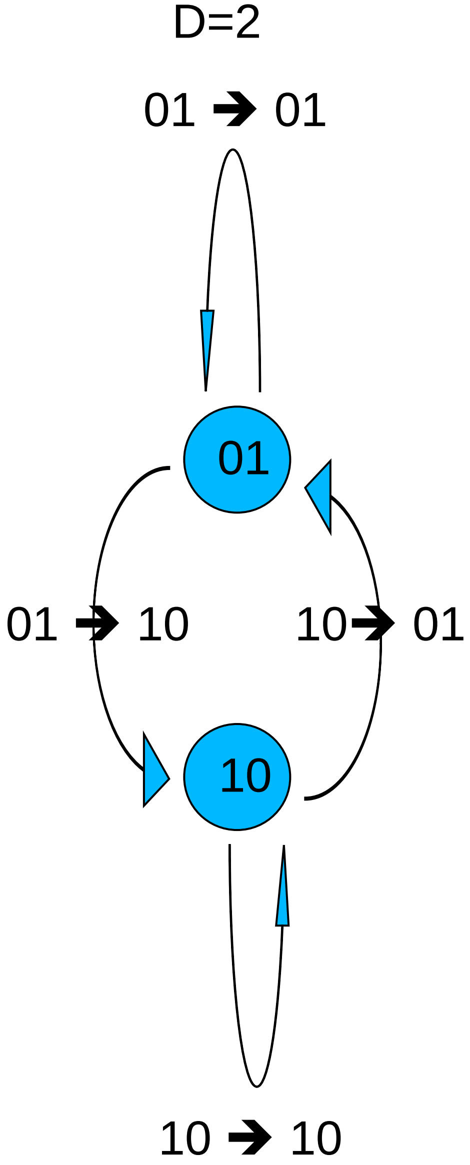




Time series analysis: Transition probabilities



$$T^{*}_{01\rightarrow01}+T^{*}_{01\rightarrow10}+T^{*}_{10\rightarrow01}+T^{*}_{10\rightarrow10}=1$$



- Ordinal patterns analysis is a useful tool to dintinguish signatures of determinism and stochasticity in spiking complex systems.

- Transition probabilities of D=2 show that the system has memory of up to 4 consecutive events.

The Lang-Kobayashi model

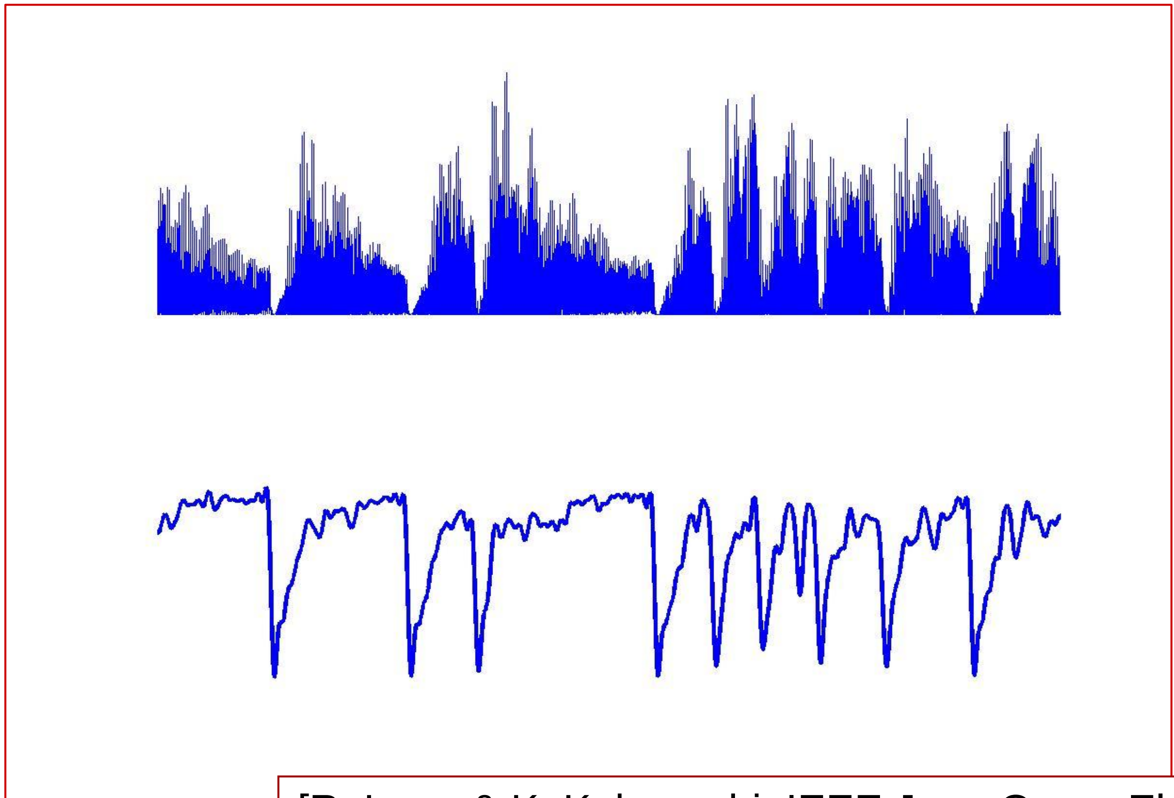
$$\dot{E}(t) = k(1+i\alpha)\left[g(N,|E|^2)-1\right]E(t) + \eta e^{-i\omega_0\tau}E(t-\tau) + \sqrt{\beta_{sp}}\,\xi(t)$$

$$\dot{N}(t) = \gamma_N\left(\mu - N - g|E|^2\right)$$

$$\mu = a_0 + b_0\sin(\omega t)$$

Feedback term **Noise term**

External periodic forcing



$\alpha = 4$

$\varepsilon = 0.01$

$\eta = [10:10:60]ns^{-1}$

$k = 300ns^{-1}$

$\tau = 5ns$

$\omega_0\tau = 1.11\pi$

$a_0 = 0.98:0.01:1.1$

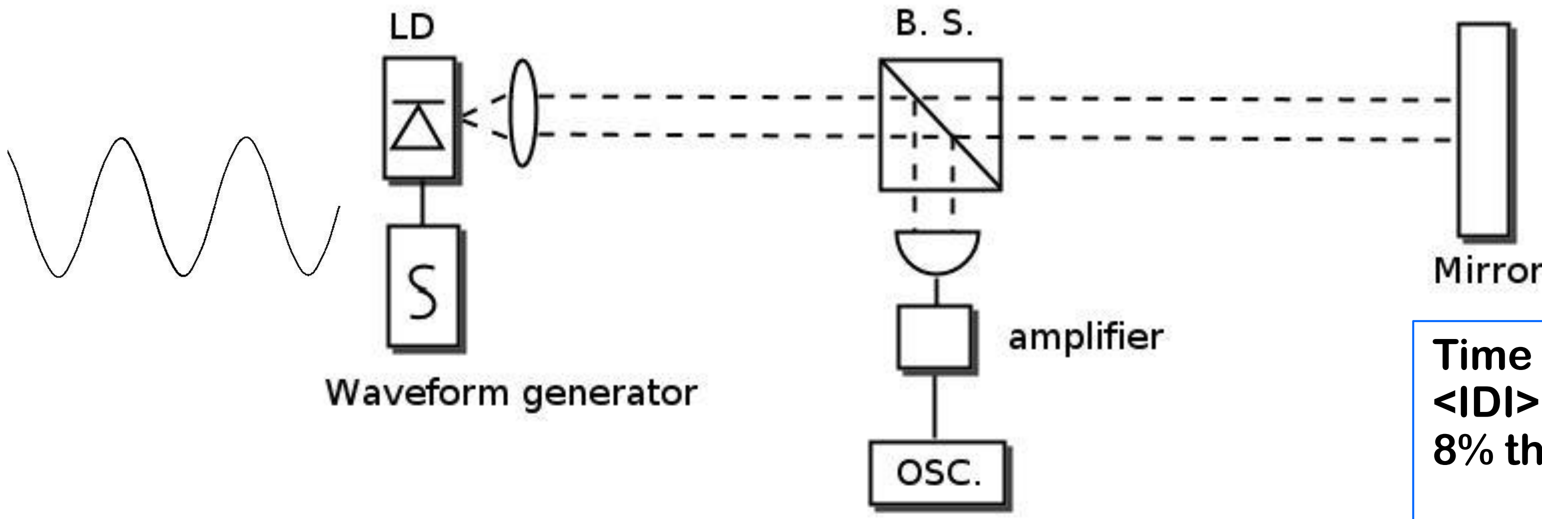
$b_0 = a_0\cdot(0.01:0.01:0.1)$

$\gamma_N = 1ns^{-1}$

$\beta_{sp} = 10^{-4}ns^{-1}$

[R. Lang & K. Kobayashi, IEEE Jour. Quan. Elec., **3**, 347 (1980)]

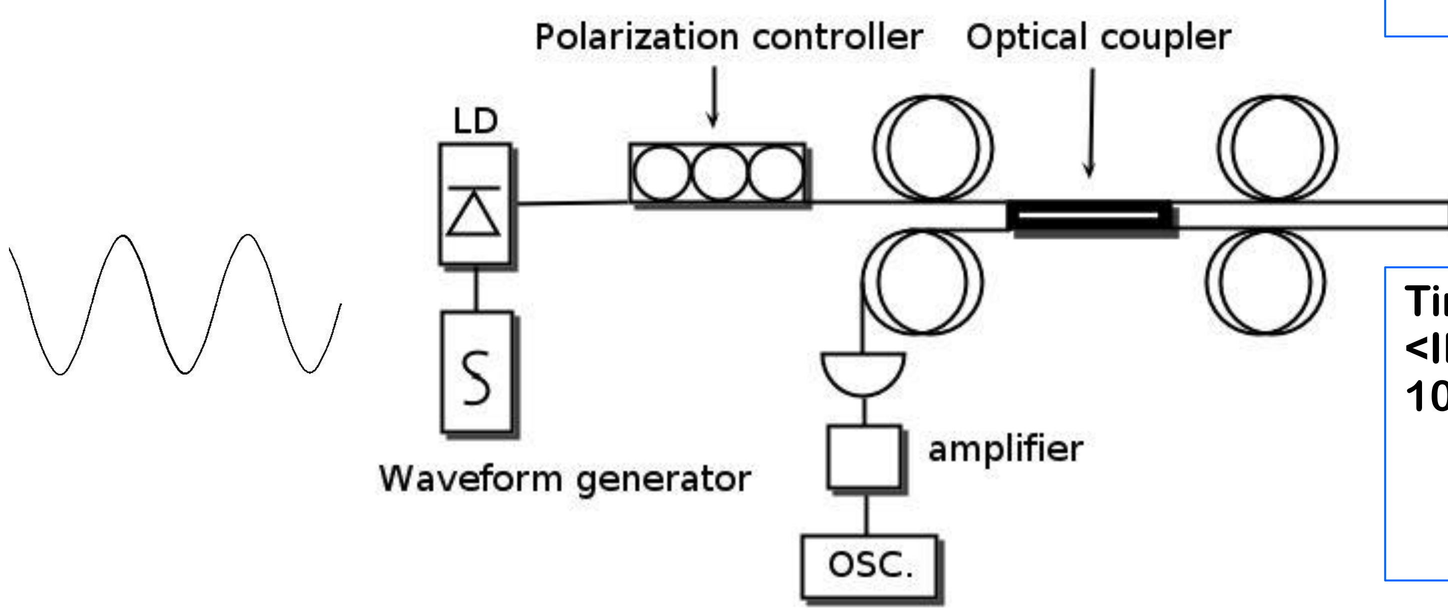
Experimental setup



Time delay ~ 5ns
<IDI> ~ 200 ns
8% threshold reduction

$$I = 1.03 \cdot I_{th}$$

$$\lambda = 660nm$$

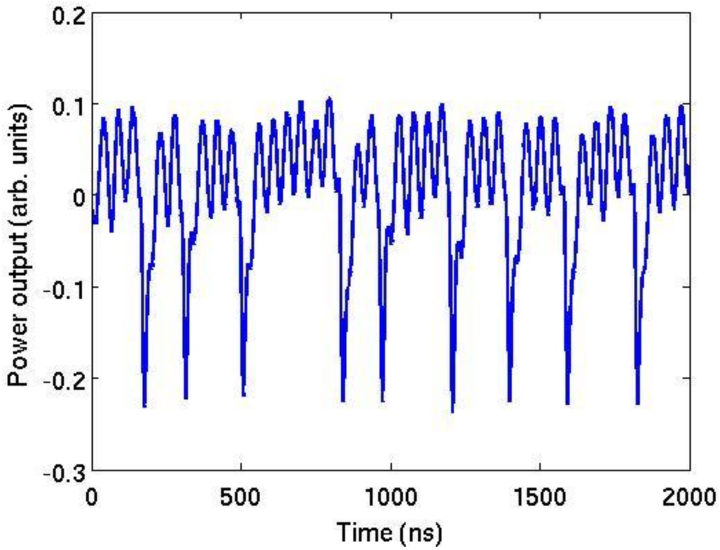


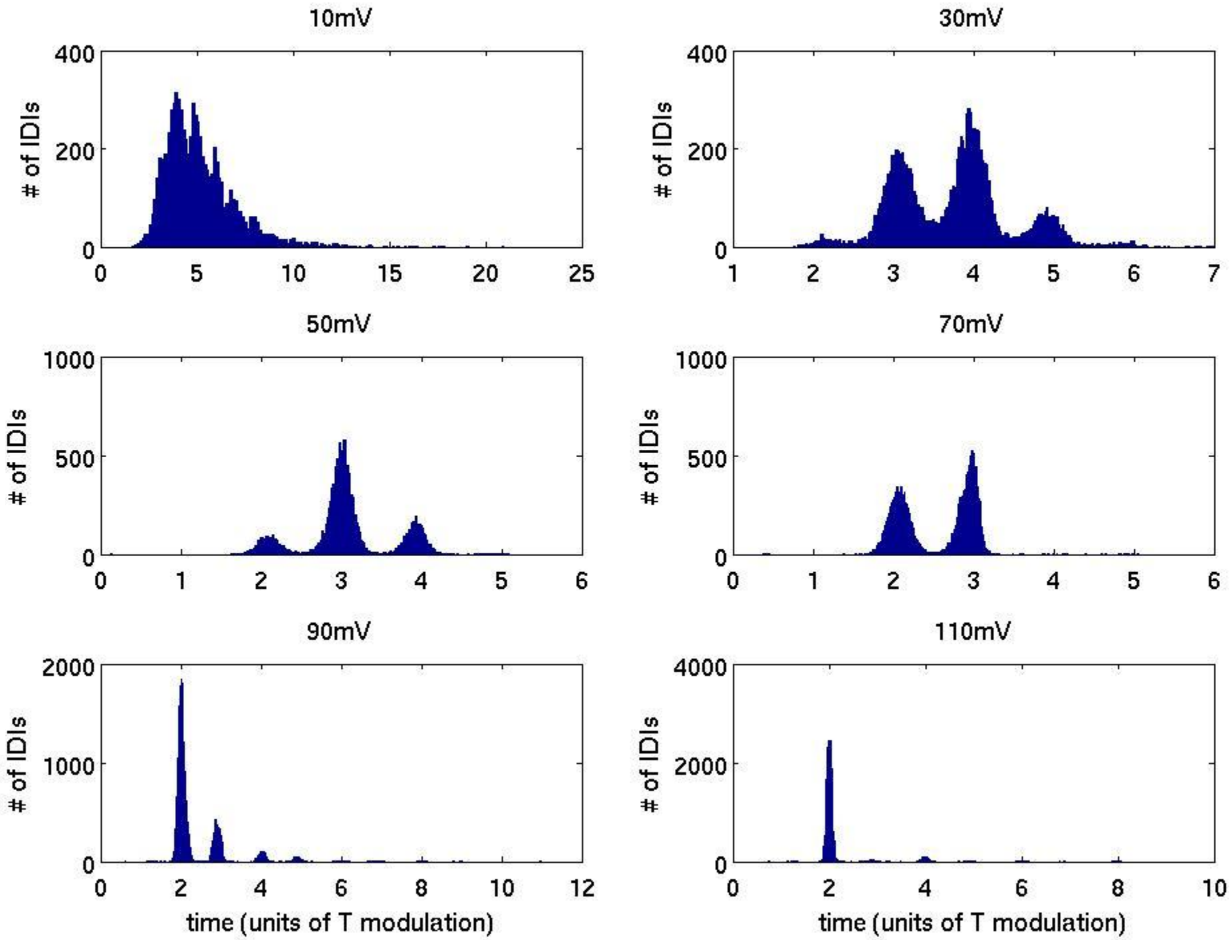
Time delay ~ 25ns
<IDI> ~ 2000 ns
10% threshold reduction

$$I = 1.12 \cdot I_{th}$$

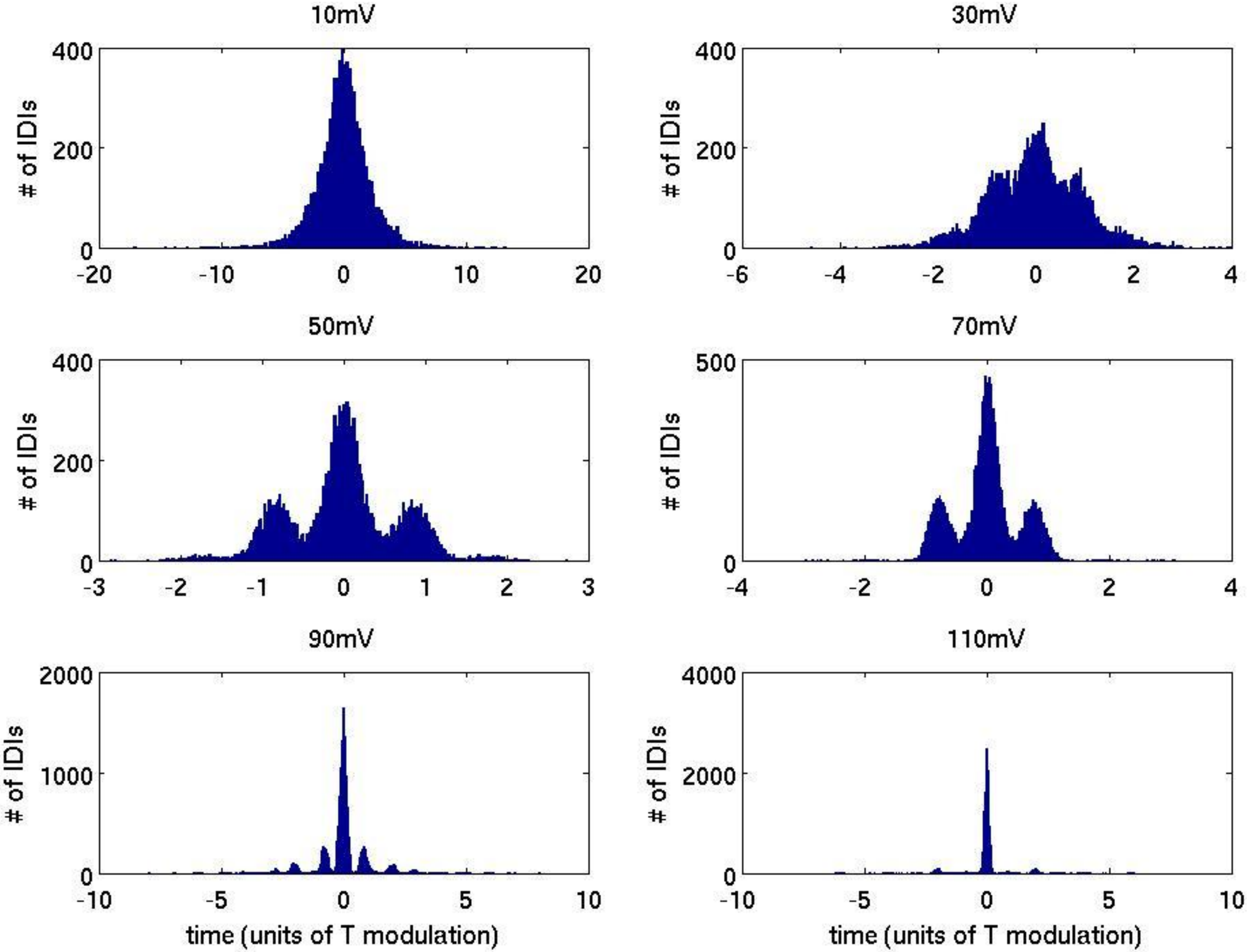
$$\lambda = 1550nm$$

Events histograms

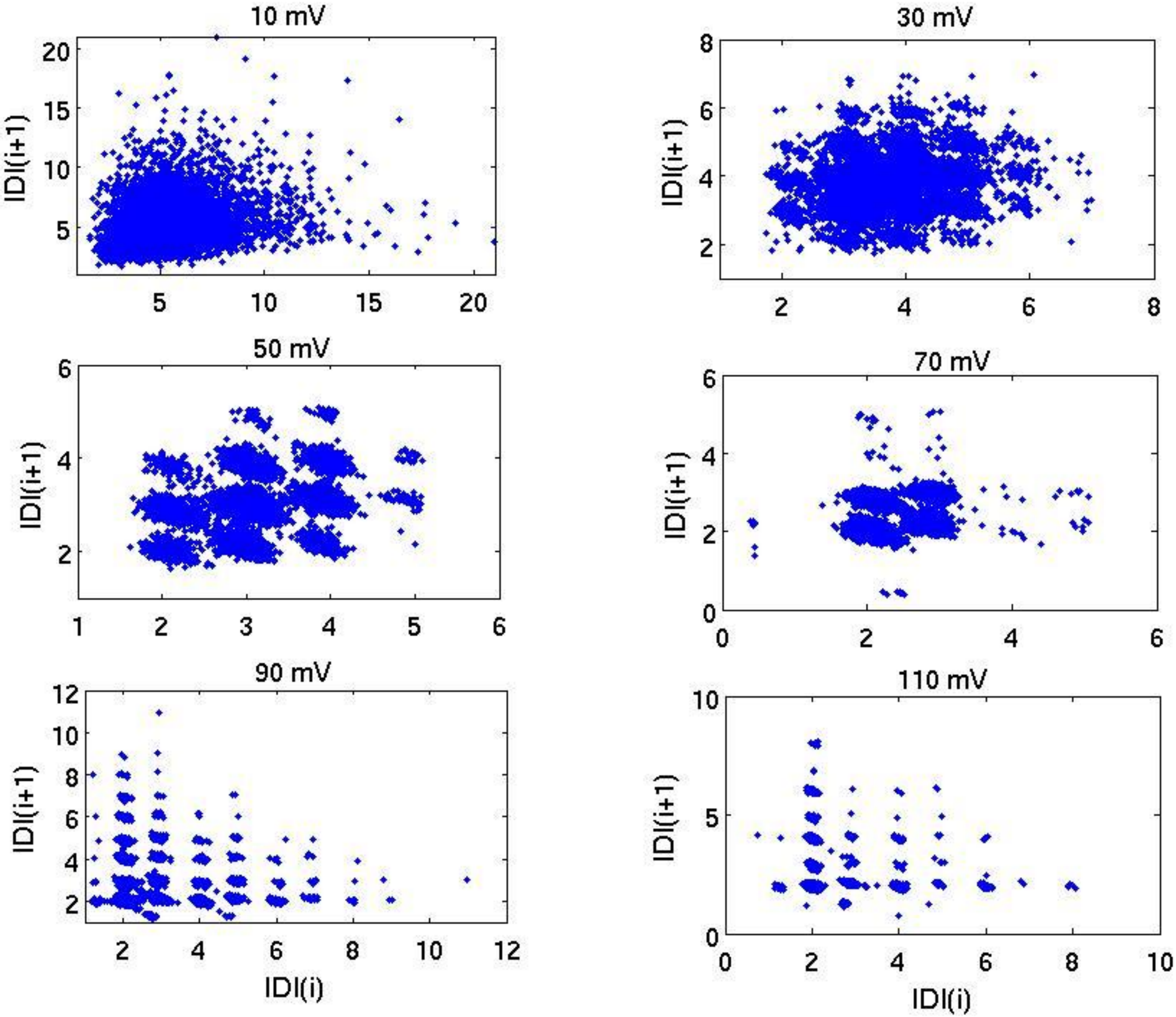




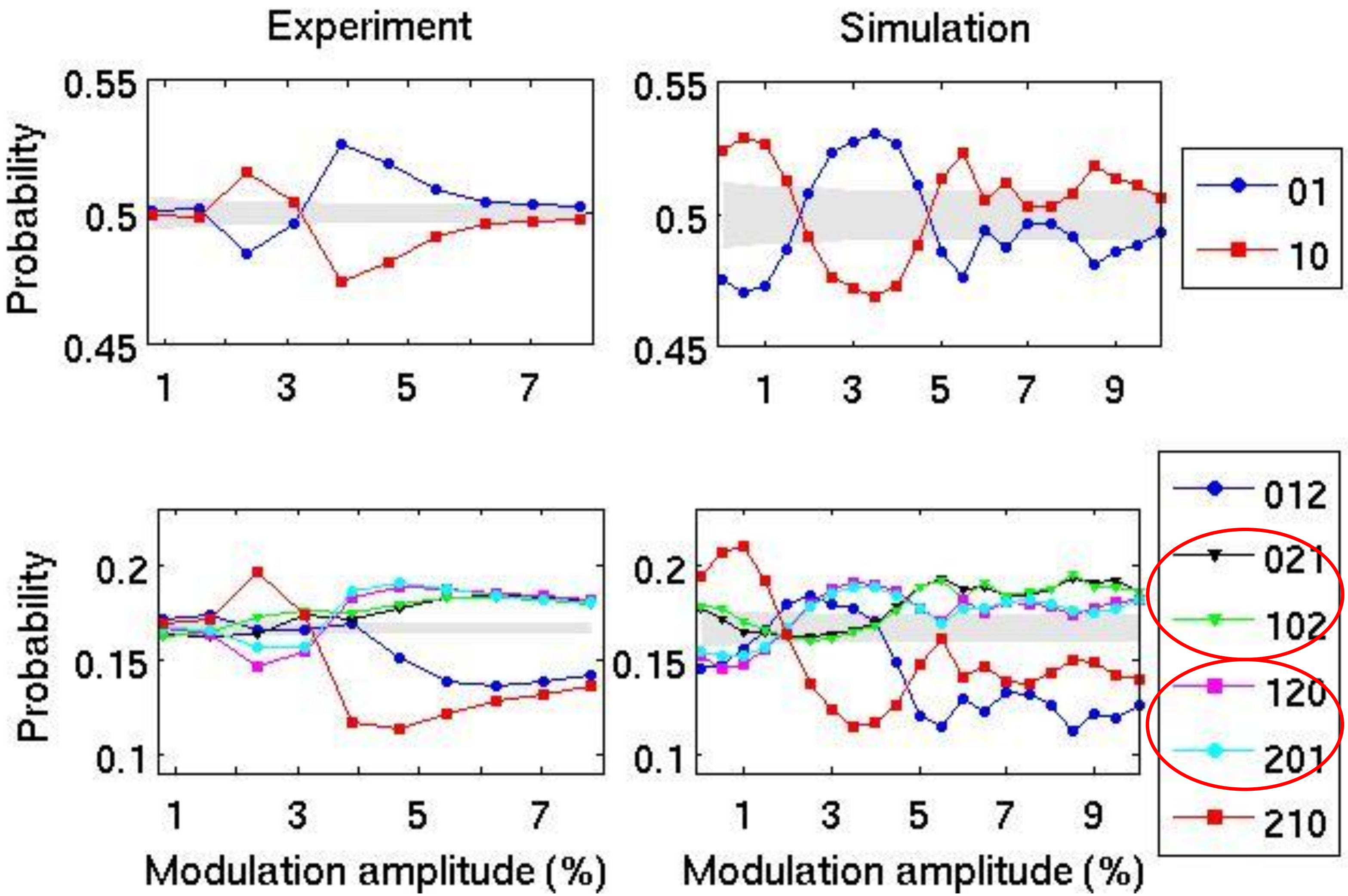
Histograms of [event(i+1)-event(i)]



Return maps



Results: Ordinal patterns (experiments and simulations)



D=2

D=3

$f = 17MHz$

$I = 1.03 \cdot I_{th}$

$I_{th} = 38mA$

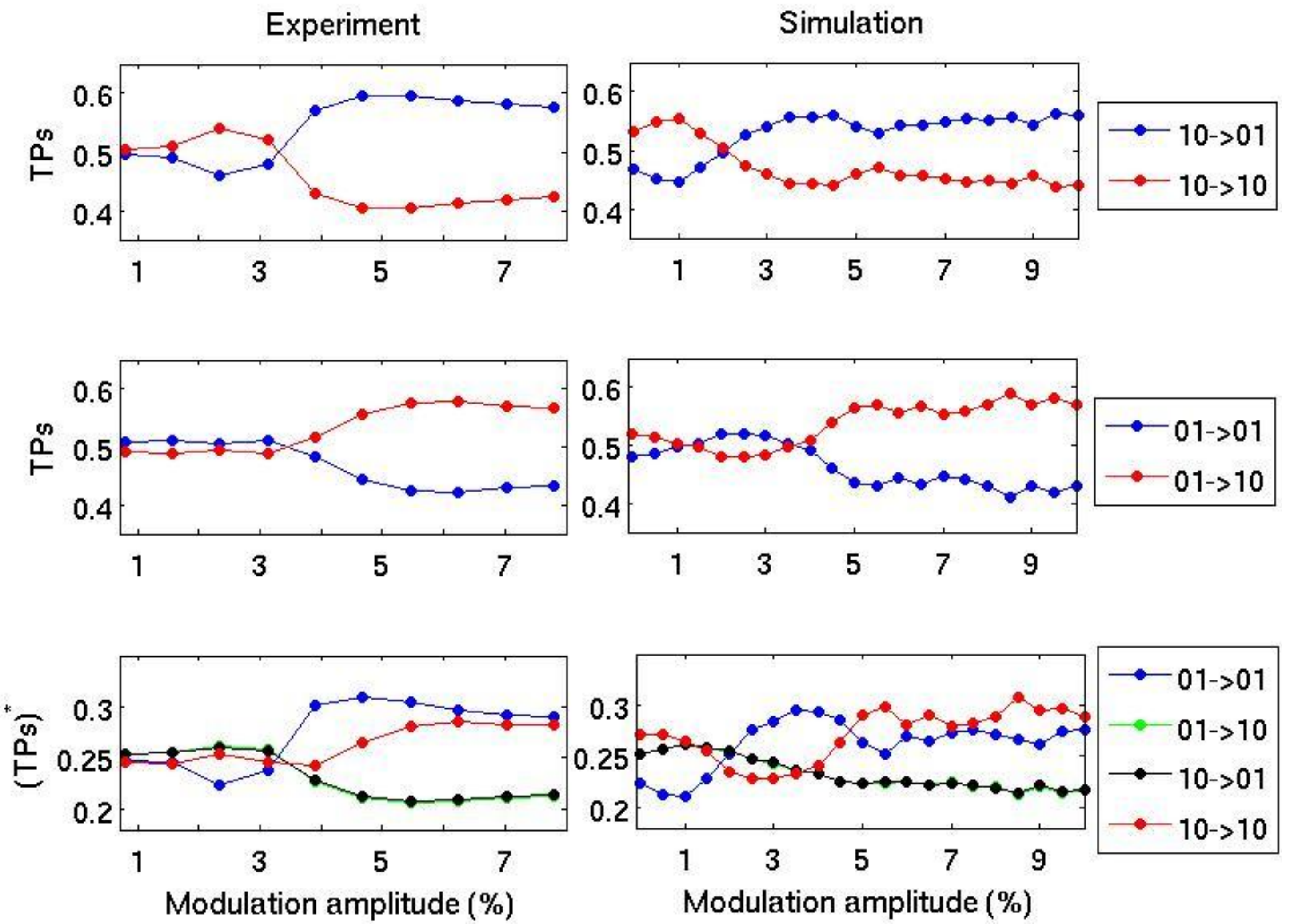
8% *threshold reduction*

$f = 15MHz$

$\mu = 1.01$

$\eta = 10ns^{-1}$

Results: Transition probabilities (experiments & simulations)



$f = 17 MHz$

$I = 1.03 \cdot I_{th}$

$I_{th} = 38 mA$

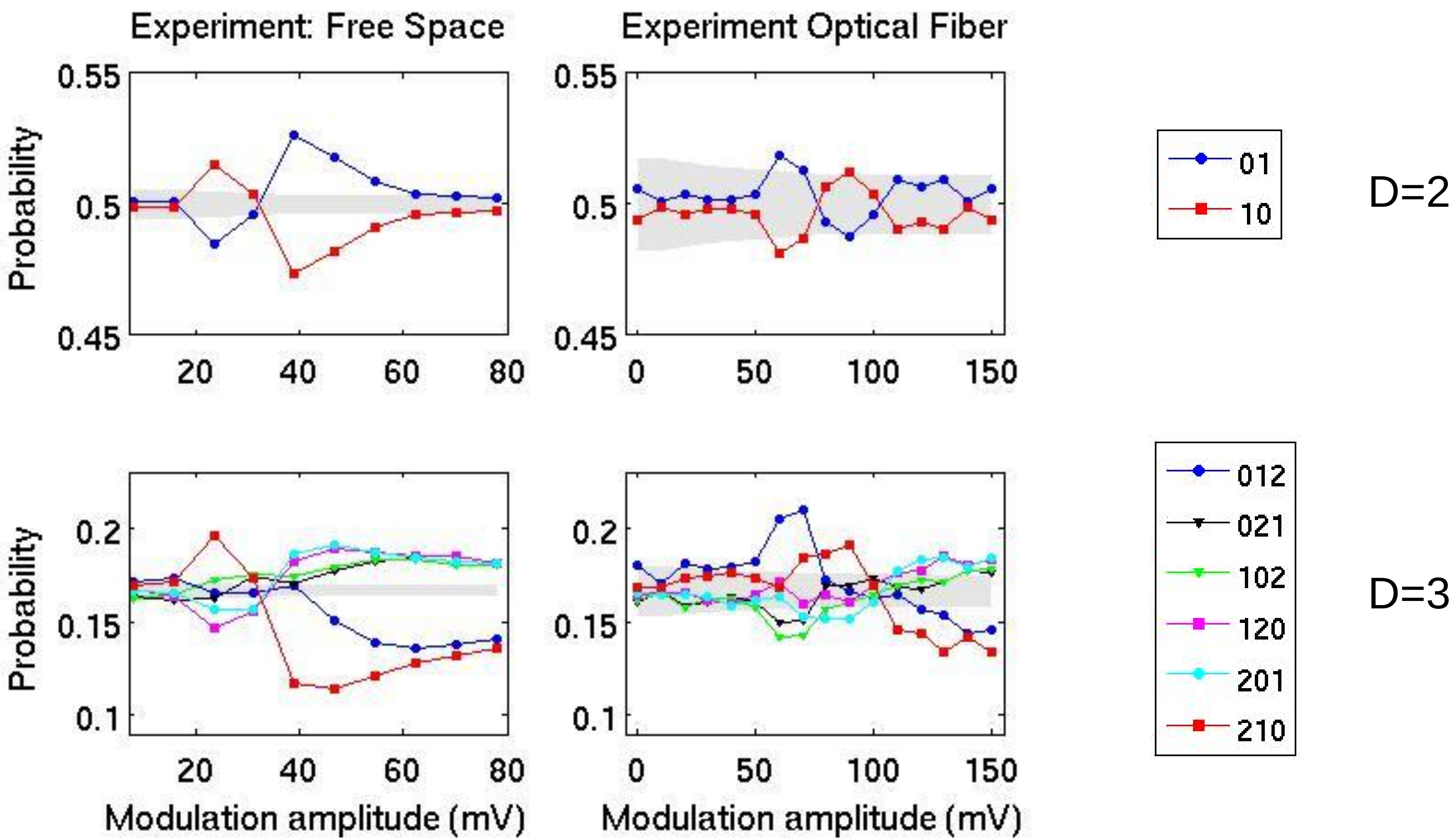
8% *threshold reduction*

$f = 15 MHz$

$\mu = 1.01$

$\eta = 10 ns^{-1}$

Results: Free space laser vesus optical fiber laser



$f = 17 MHz$

$I = 1.03 \cdot I_{th}$

$I_{th} = 38 mA$

8% *threshold reduction*

74,000-207,000 IDIs

$f = 2 MHz$

$I = 1.12 \cdot I_{th}$

$I_{th} = 12.2 mA$

10% *threshold reduction*

8,000-19,000 IDIs

Conclusions

- Lang & Kobayashi model describes sucessfully the dynamics found in experiments at the event level of description of the LFFs.

- A structure in the OPs and TPs is found for up to 4 consecutive events.

- A clustering of the ordinal patterns is found for a wide range of conditions and both, for experiments and simulations.

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Thank you for your attention

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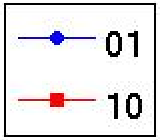
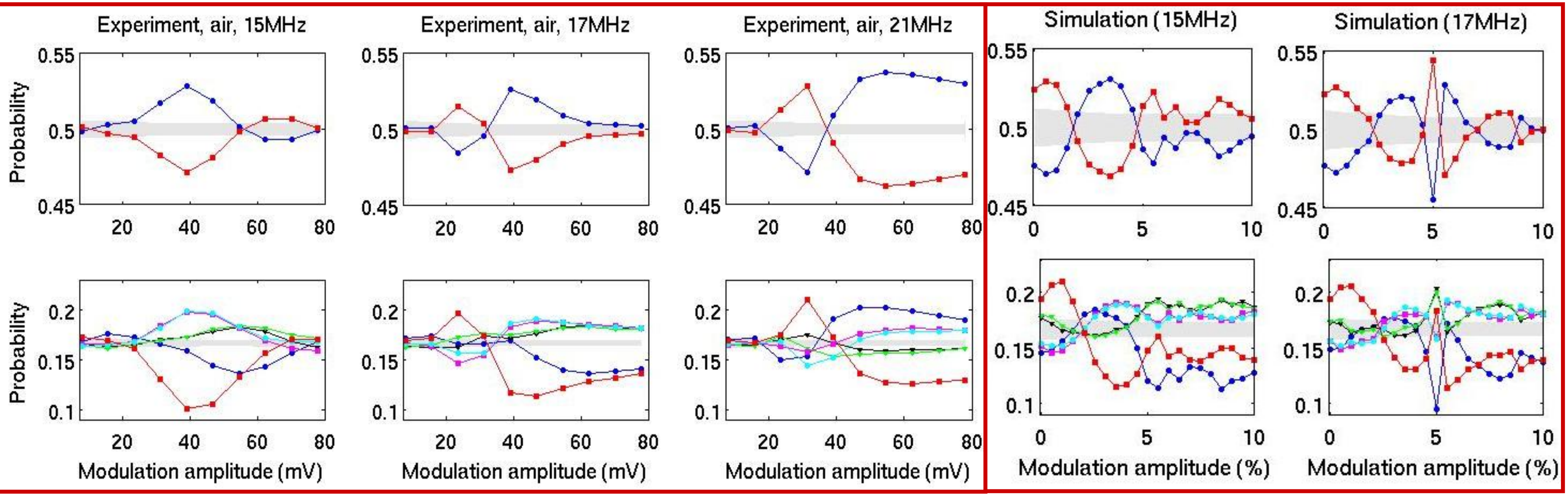
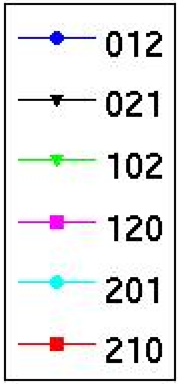
Results: Effect of frequency (Ordinal patterns)

D=2





D=3



$f = 17MHz$

$I = 1.03 \cdot I_{th}$

$I_{th} = 38mA$

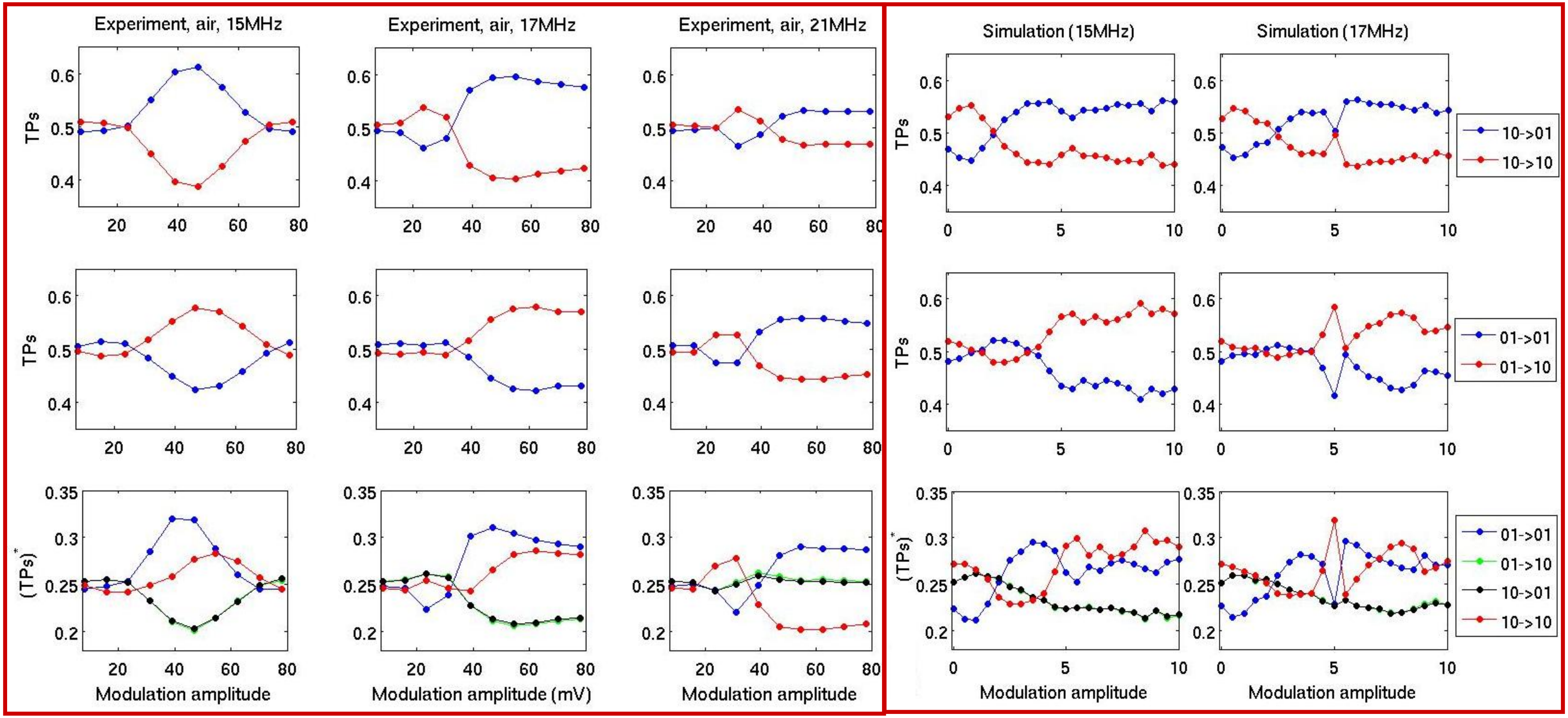
8% *threshold reduction*

$f = 15MHz$

$\mu = 1.01$

$\eta = 10ns^{-1}$

Results: Effect of frequency (transition probabilities)



$$I = 1.03 I_{th}$$

8% *threshold reduction*

$$\lambda = 660nm$$

$$\mu = 1.01$$

$$\eta = 10ns^{-1}$$

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Introduction: Semiconductor lasers