Observation of Highly Regular Oscillations in the Intensity of a Semiconductor Laser Near Threshold with Optical Feedback and Small-Amplitude Direct Current Modulation

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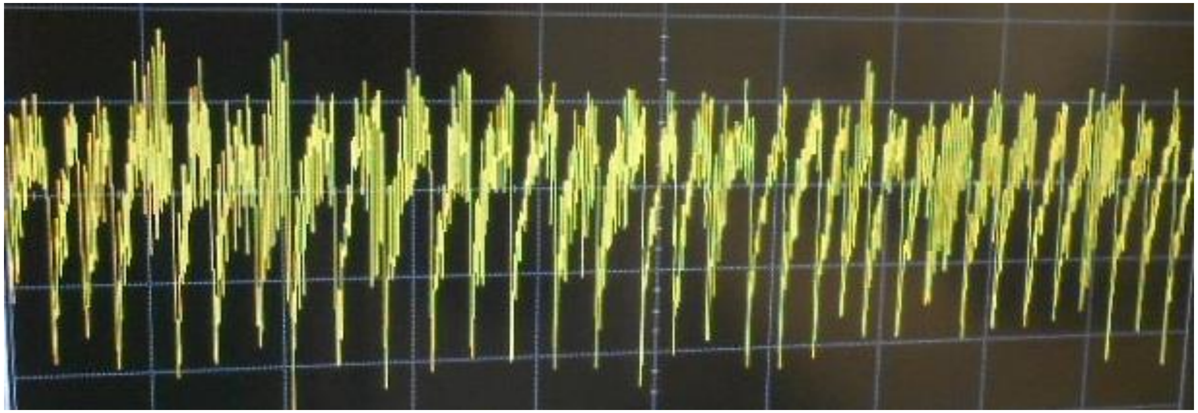
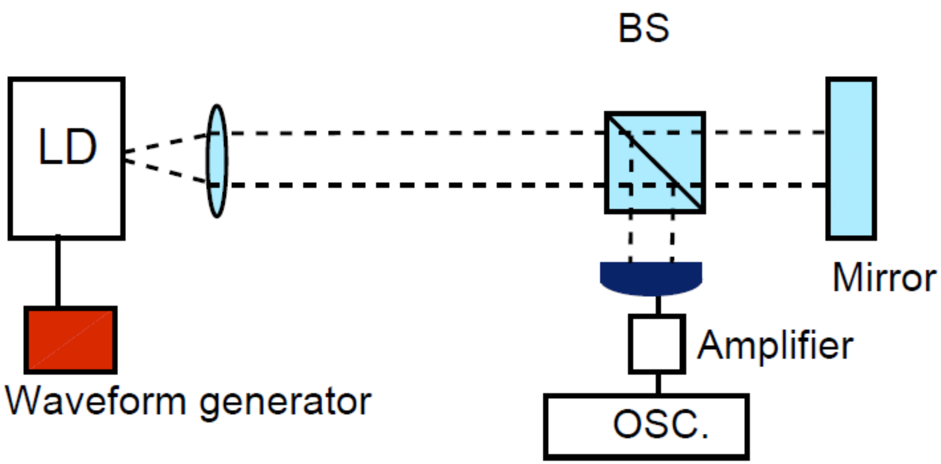
International Workshop on Nonlinear Dynamics in Semiconductor Lasers
NDSL 2021

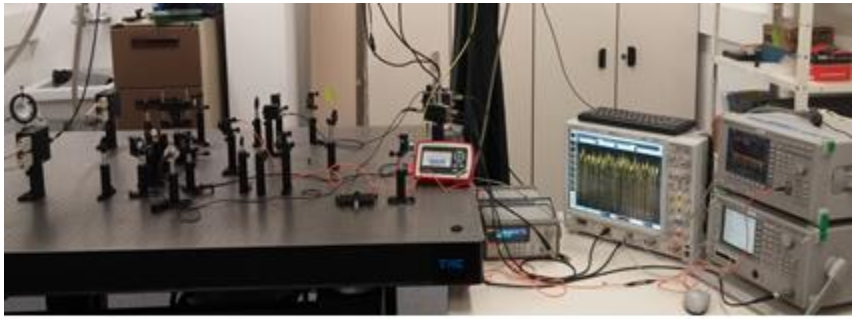
Outline

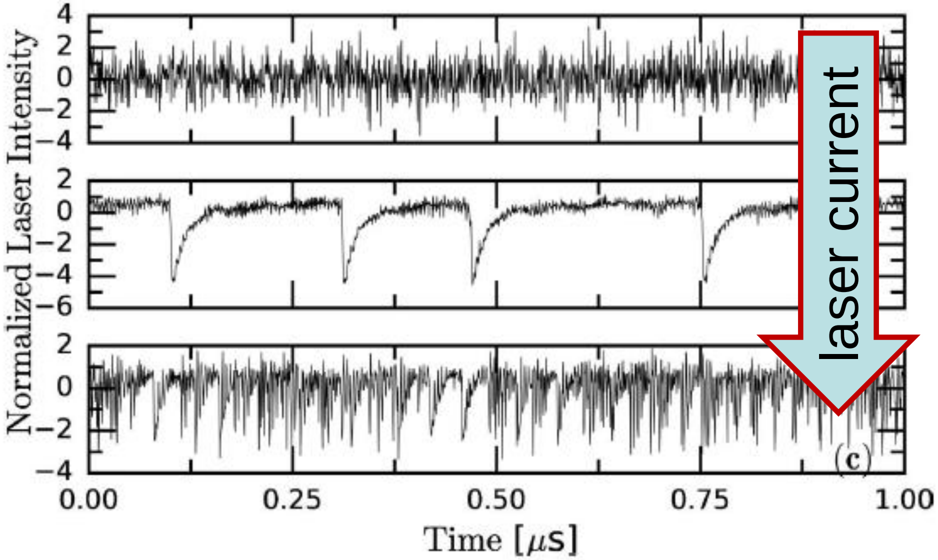


- Overview of the dynamics of external cavity diode lasers (EELs) with direct pump current modulation
  - Near threshold: low frequency fluctuations
  - Role of sinusoidal current modulation
- Model simulations
- Conclusions and open questions

Dynamics of a semiconductor laser with optical feedback



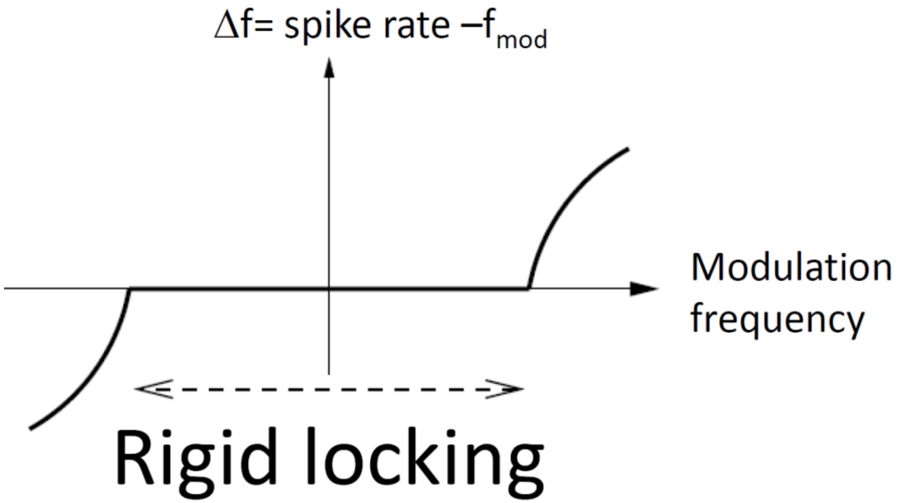


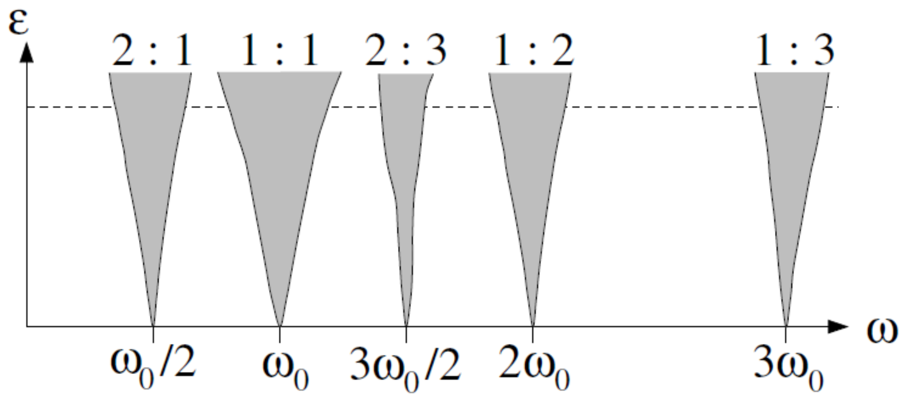


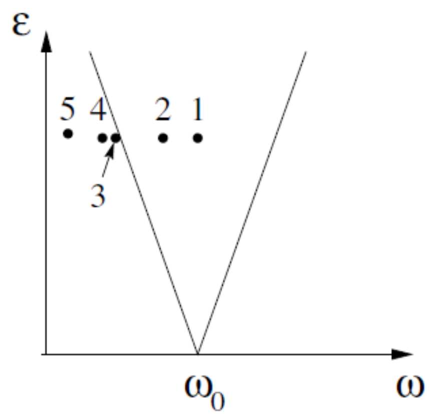
Question:

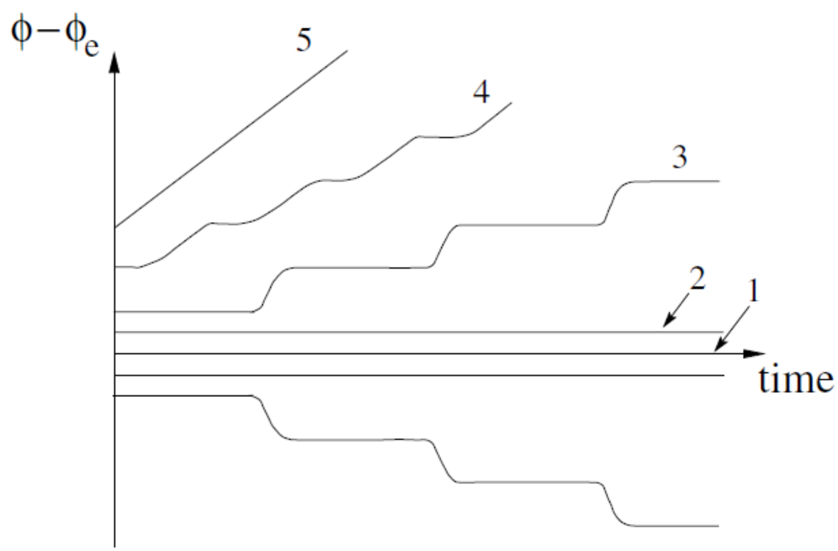
Can we “lock” the optical spikes (“low frequency fluctuations”) to a **small-amplitude** sinusoidal signal that modulates the laser current?

Locking an oscillator to an external periodic signal









Pikovsky, Rosenblum and Kurths: Synchronization (Cambridge University Press)

Small-amplitude sinusoidal current modulation: the distribution of the intervals between spikes (inter-spike-intervals) shows noisy locking

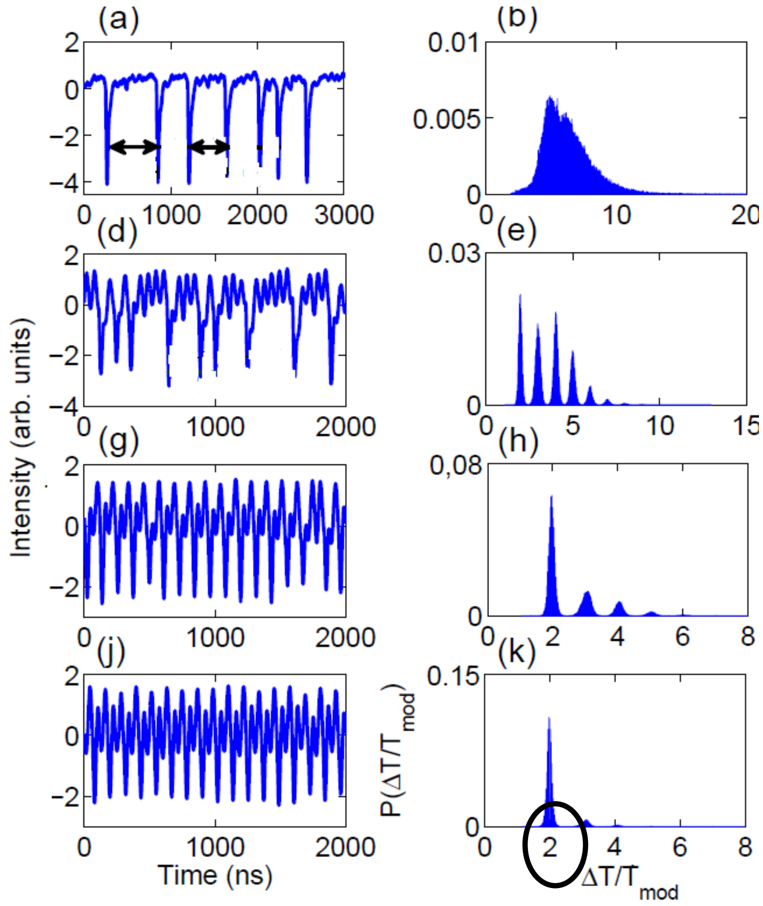
No modulation

I_{dc} = 39 mA
f_{mod} = 17 MHz

1.2%

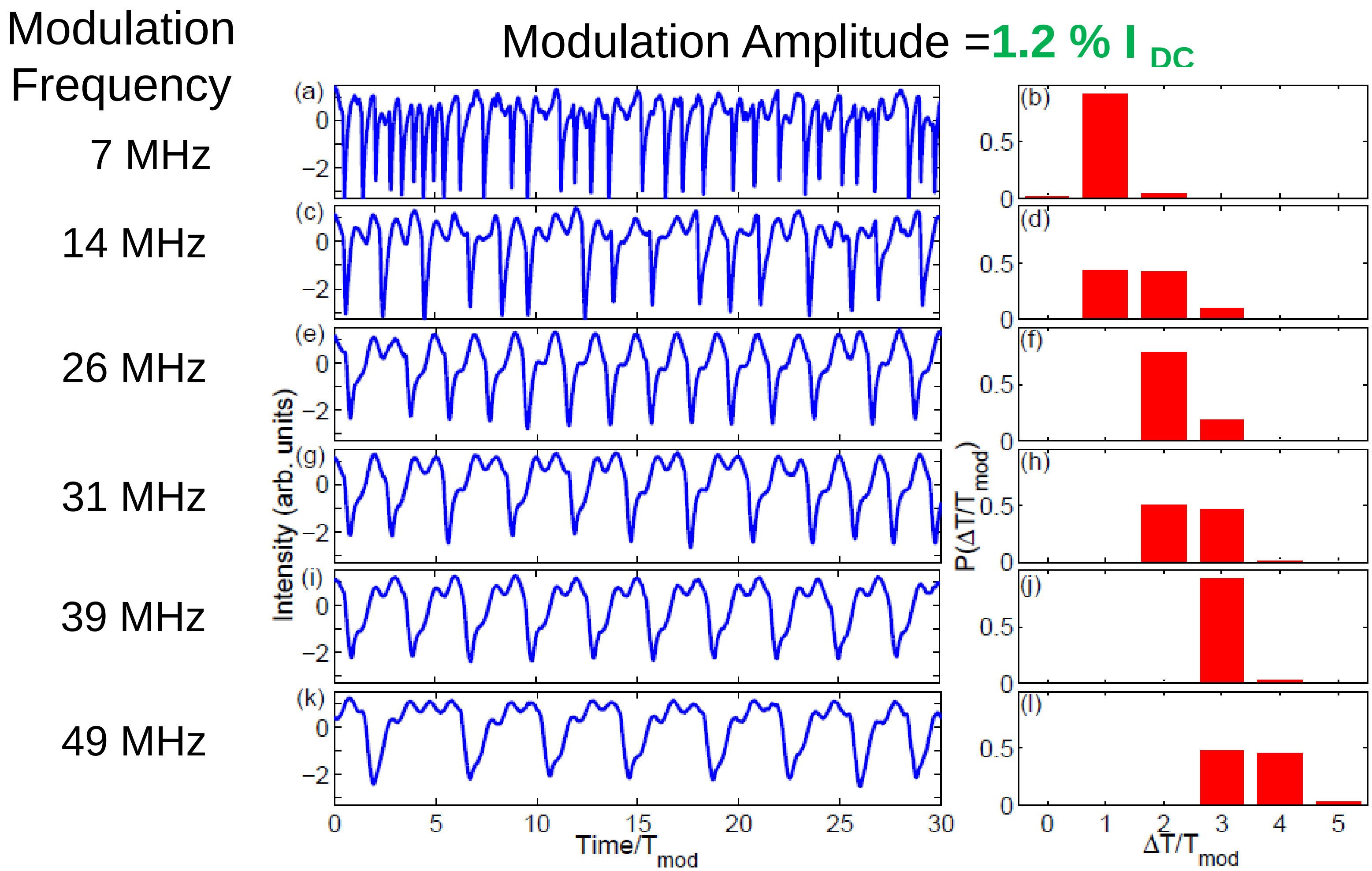
1.6%

2%



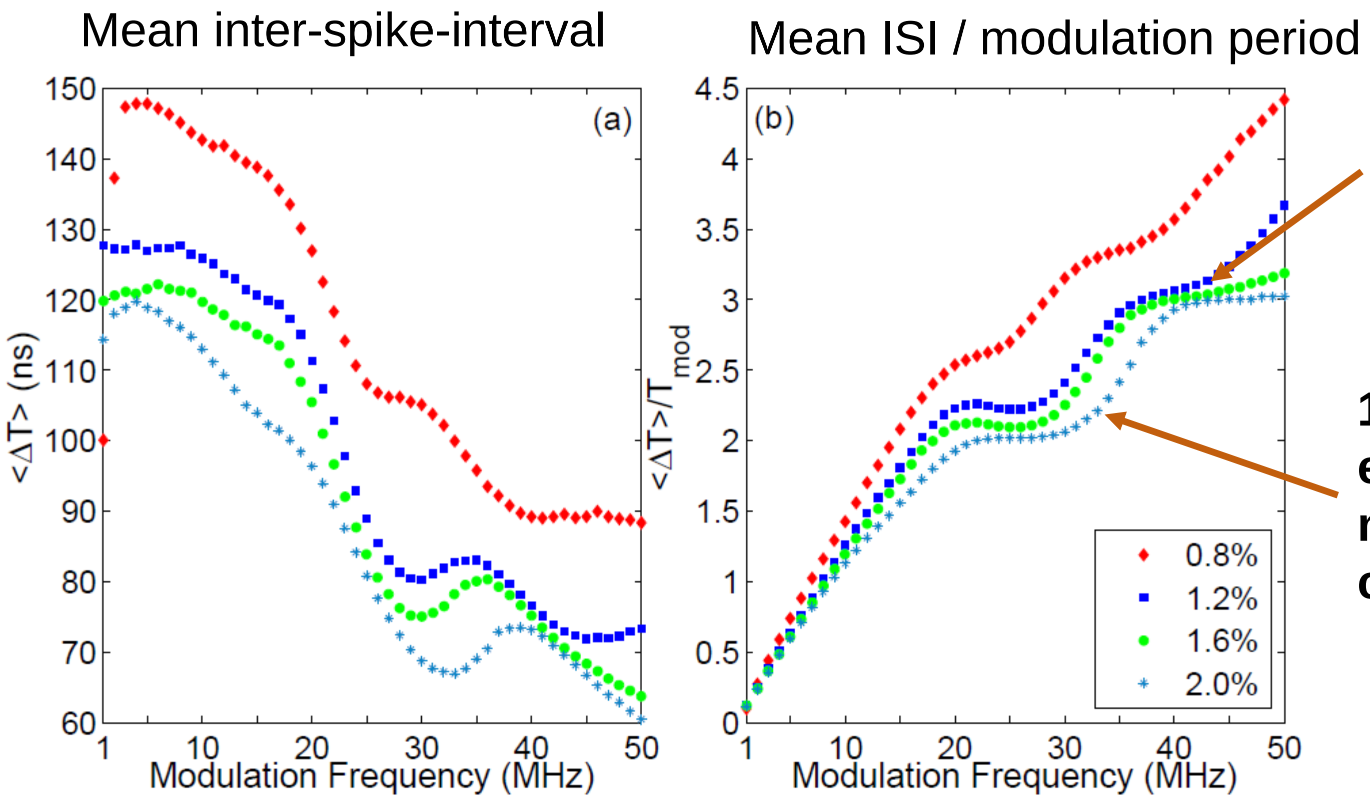
A. Aragoneses, T. Sorrentino, S. Perrone, D. J. Gauthier, M. C. Torrent, C. Masoller, "*Experimental and numerical study of the symbolic dynamics of a modulated external-cavity semiconductor laser*", Optics Express **22**, 4705 (2014).

Small-amplitude sinusoidal current modulation: the distribution of the intervals between spikes (inter-spike-intervals) shows noisy locking



T. Sorrentino, C. Quintero-Quiroz, A. Aragoneses, M. C. Torrent, C. Masoller, "*Effects of periodic forcing on the temporally correlated spikes of a semiconductor laser with feedback*", Optics Express **23**, 5571 (2015).

Locking “plateaus”



1 spike every 3 modulation cycles

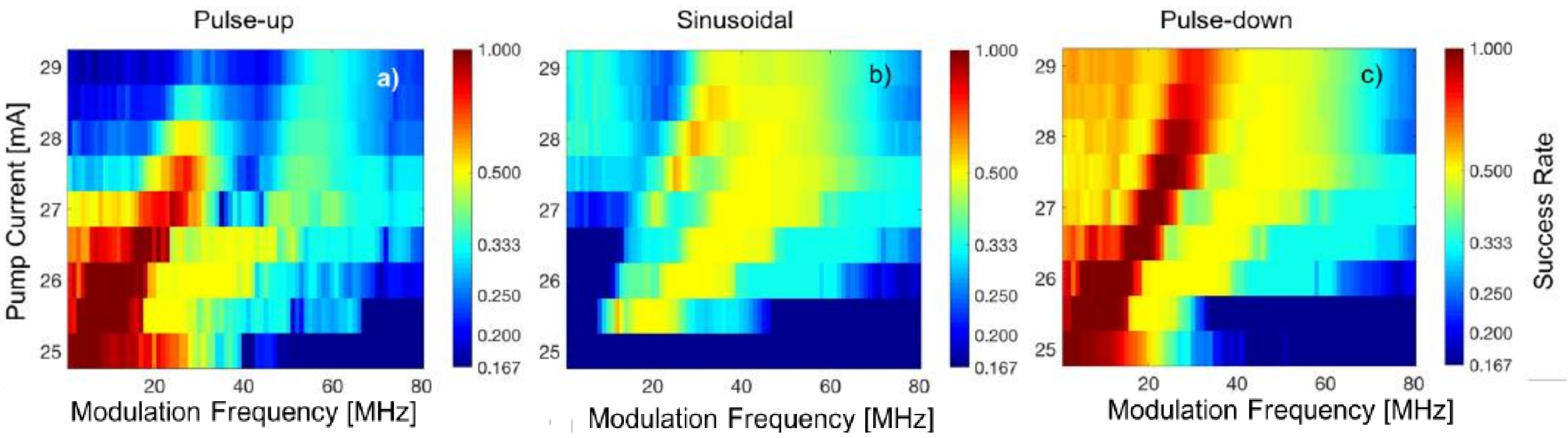
1 spike every 2 modulation cycles

Why no 1:1 locking plateau?

T. Sorrentino et al., Optics Express **23**, 5571 (2015).

Success rate: number of spikes per modulation cycle.
Experiments done with different modulation waveforms

Modulation Amplitude =**2.5 - 2.2 % I** $_{DC}$



Why no 1:1 locking plateau?

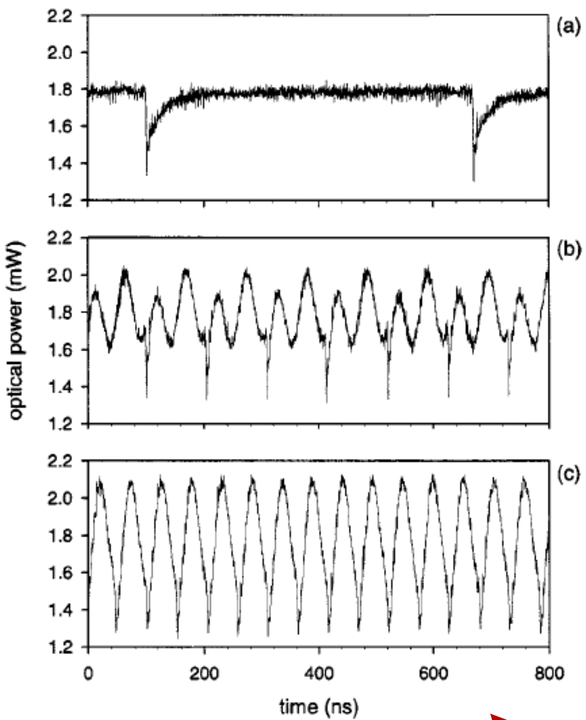
J. Tiana-Alsina et al., Opt. Express 26, 9298 (2018)

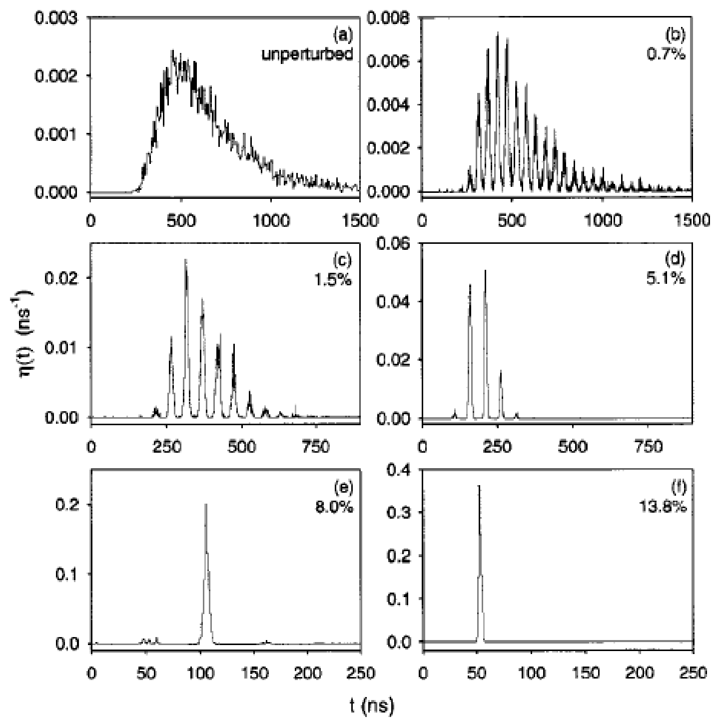
Earlier work

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 36, NO. 2, FEBRUARY 2000

David W. Sukow and Daniel J. Gauthier

Entraining Power-Dropout Events in an External-Cavity Semiconductor Laser Using Weak Modulation of the Injection Current





modulation amplitude: **13.8 %** of the dc level of the laser current.

Simulations to try to understand the lack of 1:1 regular locking generated by small-amplitude modulation

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Lang-Kobayashi model

$$\dot{E} = k(1+i\alpha)(G-1)E + \eta E(t-\tau)e^{-i\omega_0\tau} + \sqrt{D}\xi,$$
$$\dot{N} = \gamma_N(\mu_{dc} + a_{mod}\sin(2\pi f_{mod}t) - N - G|E|^2).$$

$$G = N/(1+\epsilon|E|^2)$$

Simplifications:

- Single-mode emission
- One reflection in the external cavity
- No spatial inhomogeneities

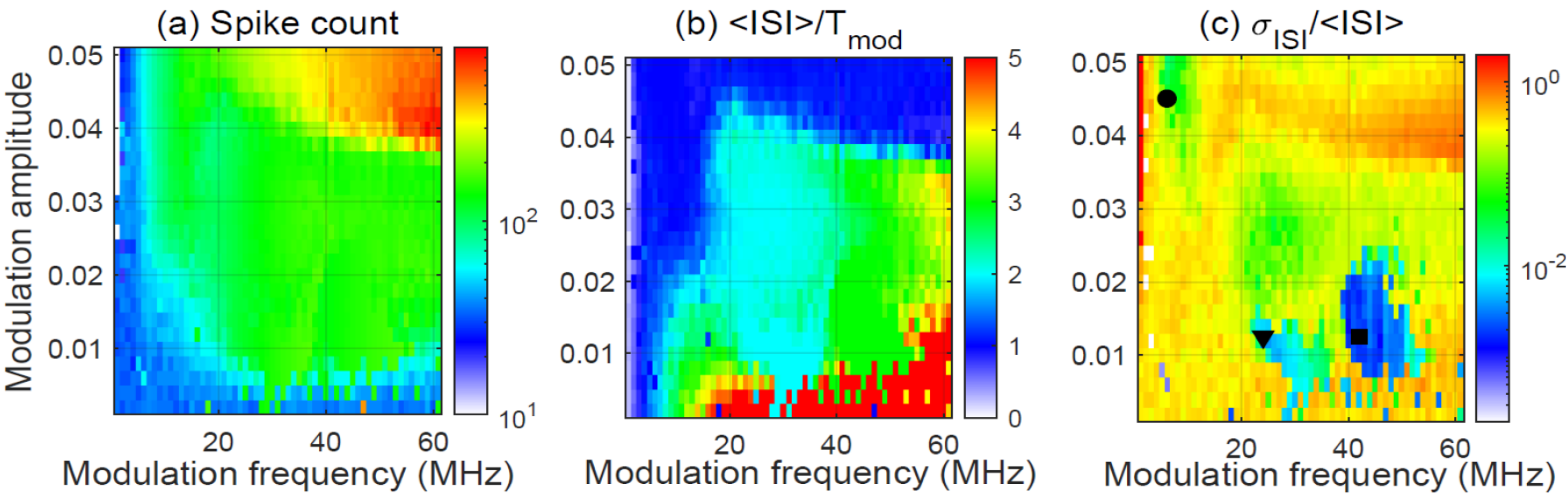
Notice:

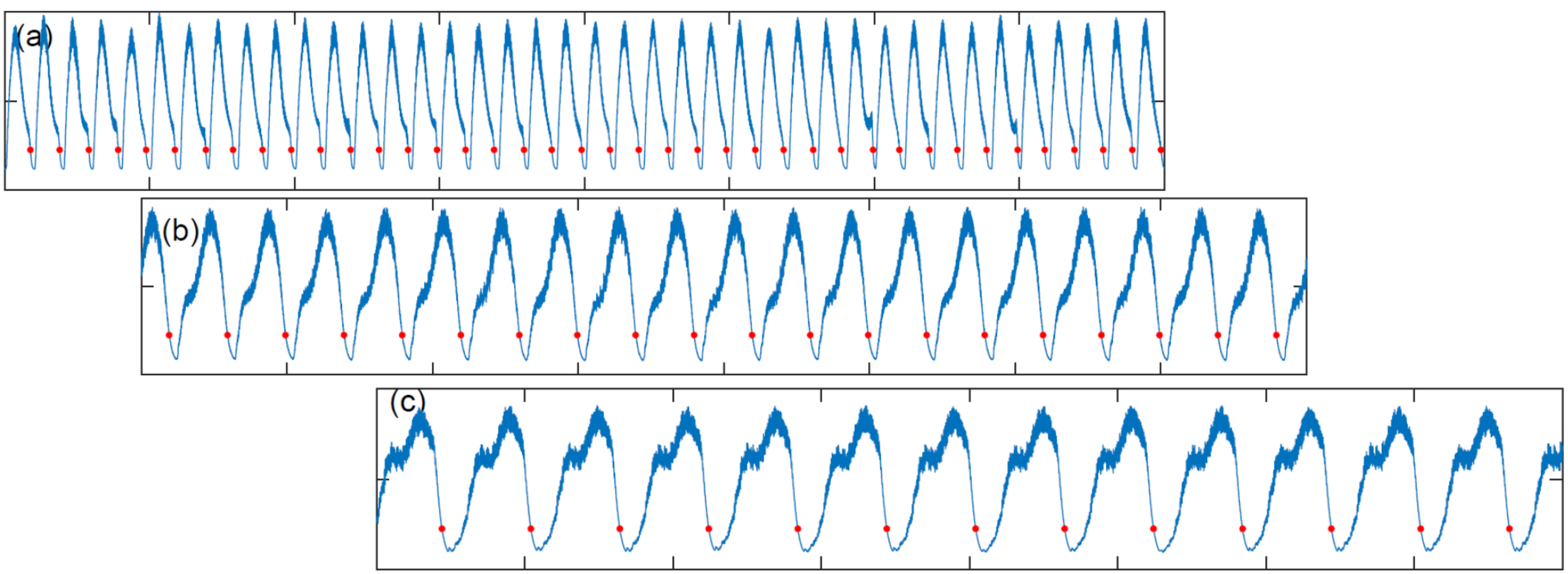
The steady-state solutions (“external cavity modes”) with sinusoidal modulation become limit cycles.

Parameters:

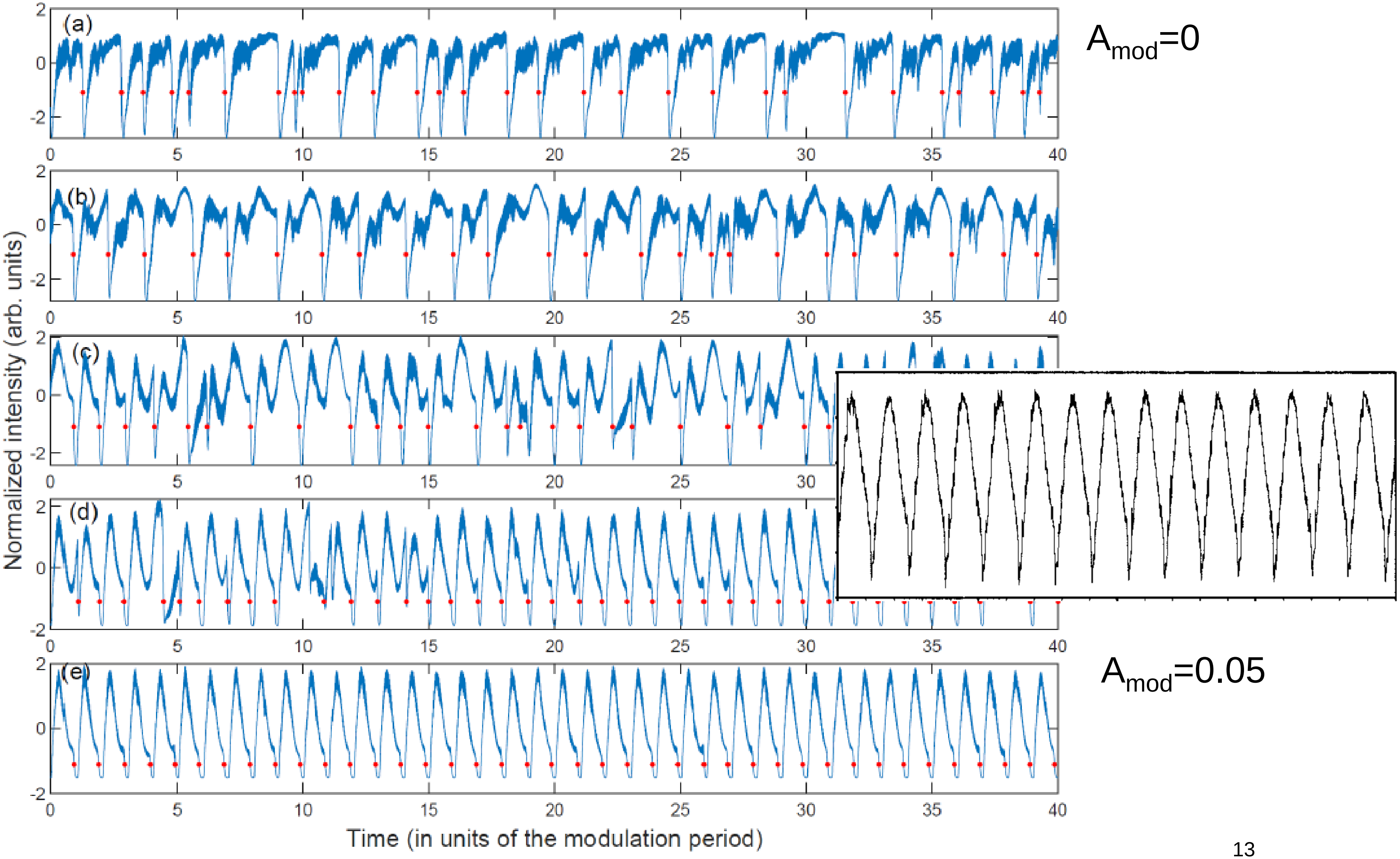
$$k = 300\ \text{ns}^{-1},\ \gamma_N = 1\ \text{ns}^{-1},\ \alpha = 4,\ \epsilon = 0.01$$
$$\eta\text{=}30\ \text{ns}^{-1},\ \tau = 5\ \text{ns},\ \mu_{dc} = 0.99\ \text{and}\ D = 10^{-5}\ \text{ns}^{-2}$$

Results

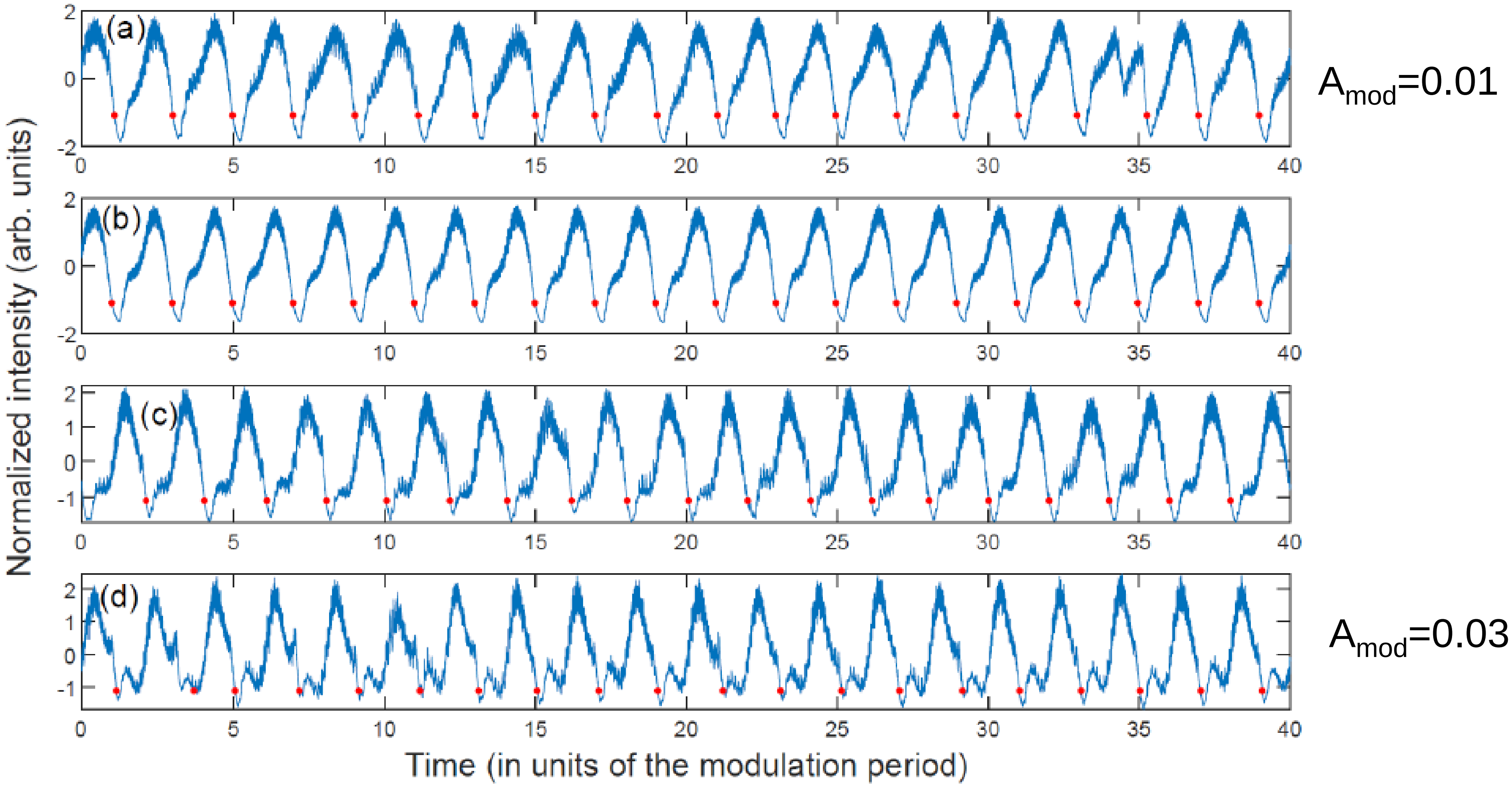

(a) Spike count
Modulation amplitude
0.05
0.04
0.03
0.02
0.01
20
40
60
Modulation frequency (MHz)
10^2
10^1
(b) <ISI>/T_{mod}
5
4
3
2
1
0
(c) σ_{ISI}/<ISI>
10^0
10^{-2}


(a)
(b)
(c)

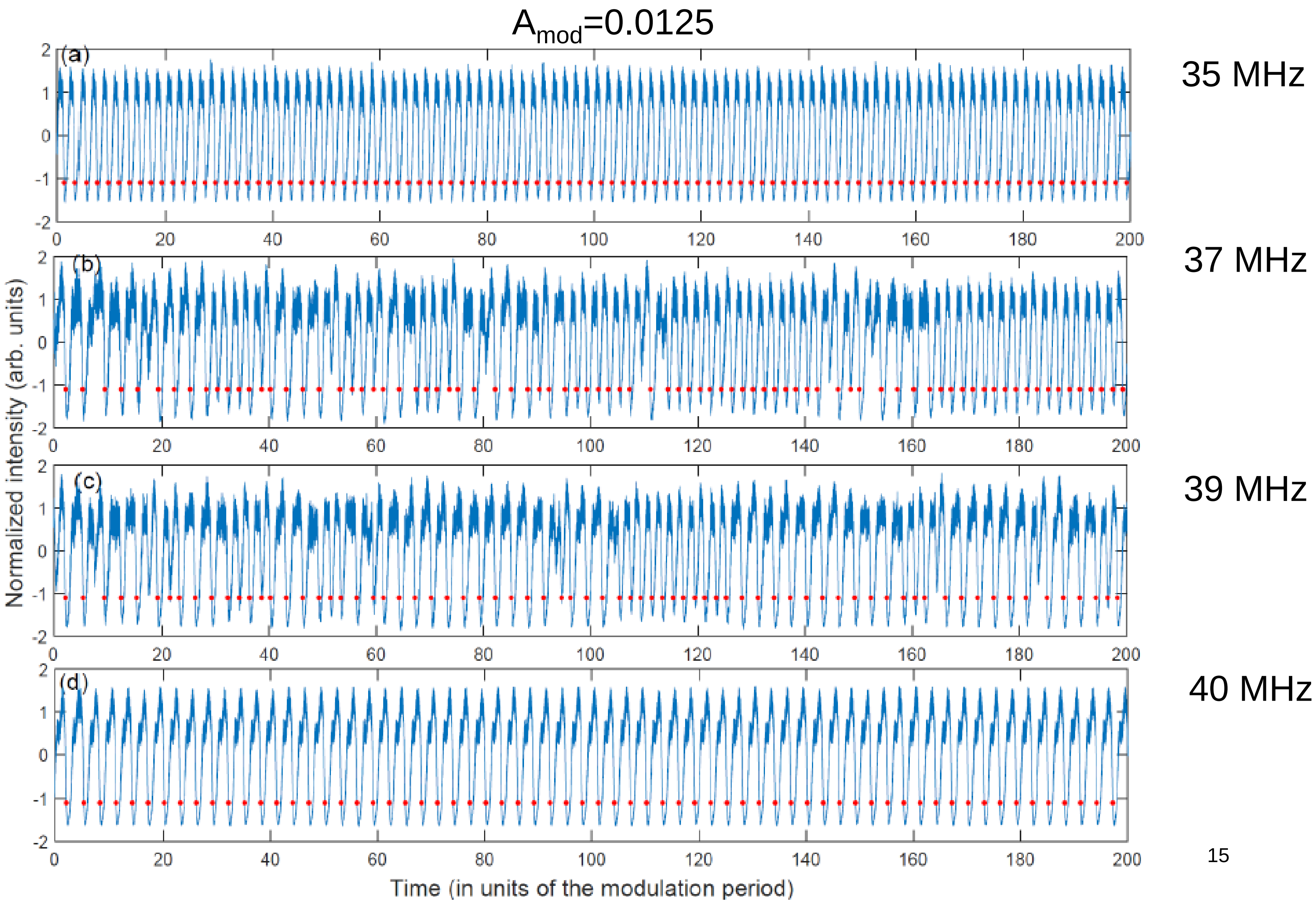
High modulation amplitude is needed to generate 1:1 locked spikes



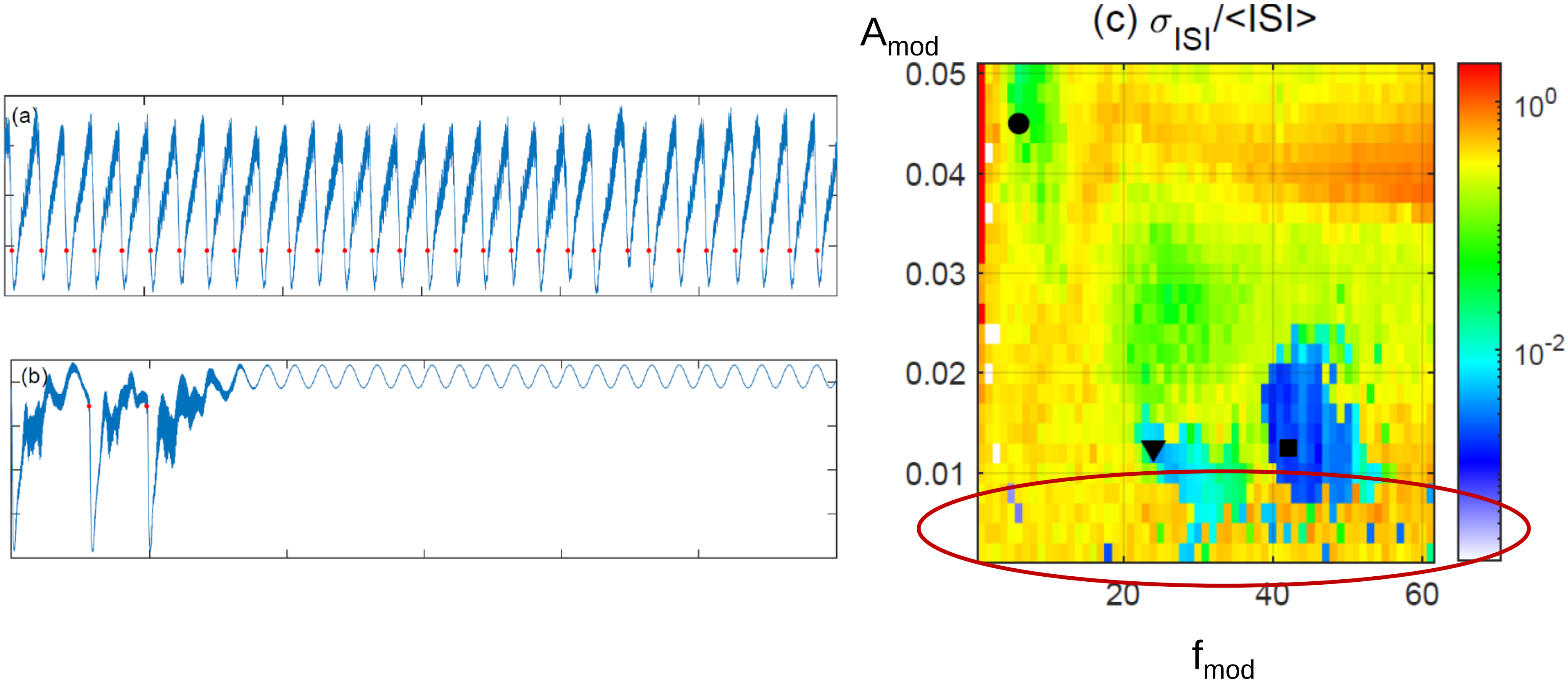
Subharmonic locking (2:1, 3:1) is obtained in a limited range of modulation amplitudes



Transition between 2:1 and 3:1 locking: intermittency



For some modulation conditions, after transient spikes there are sinusoidal oscillations



Conclusion and open question

- Consistent with experimental observations, in the simulations, with small amplitude sinusoidal current modulation, no 1:1 locking was found.
- In the experiments, in the locking regions, the regularity of the spike timing is much higher than in the simulations. Why?

Thank you for your attention!
Cristina.masoller@upc.edu

J. Tiana-Alsina et al., Opt. Express 26, 9298 (2018)
J. Tiana-Alsina et al., Phys. Rev. E 99, 022207 (2019)