Nonlinear dynamics and chaos in Optomechanical nanobeams

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Challenges in Cavity Optomechanics

Linear Optomechanics

- Displacement detection
- Optical Spring
- Cooling & Amplification
- Two-tone drive: "Optomechanically induced transparency"
- Ground state cooling
- State transfer, pulsed operation
- Wavelength conversion
- Radiation Pressure Shot Noise
- Squeezing of Light
- Squeezing of Mechanics
- Light-Mechanics Entanglement
- Accelerometers
- Single-quadrature detection, Wigner density
- Optomechanics with an active medium
- Measure gravity or other small forces
- Mechanics-Mechanics entanglement
- Pulsed measurement
- Quantum Feedback
- Rotational Optomechanics

Multimode

- Mechanical information processing
- Bandstructure in arrays
- Synchronization/patterns in arrays
- Transport & pulses in arrays

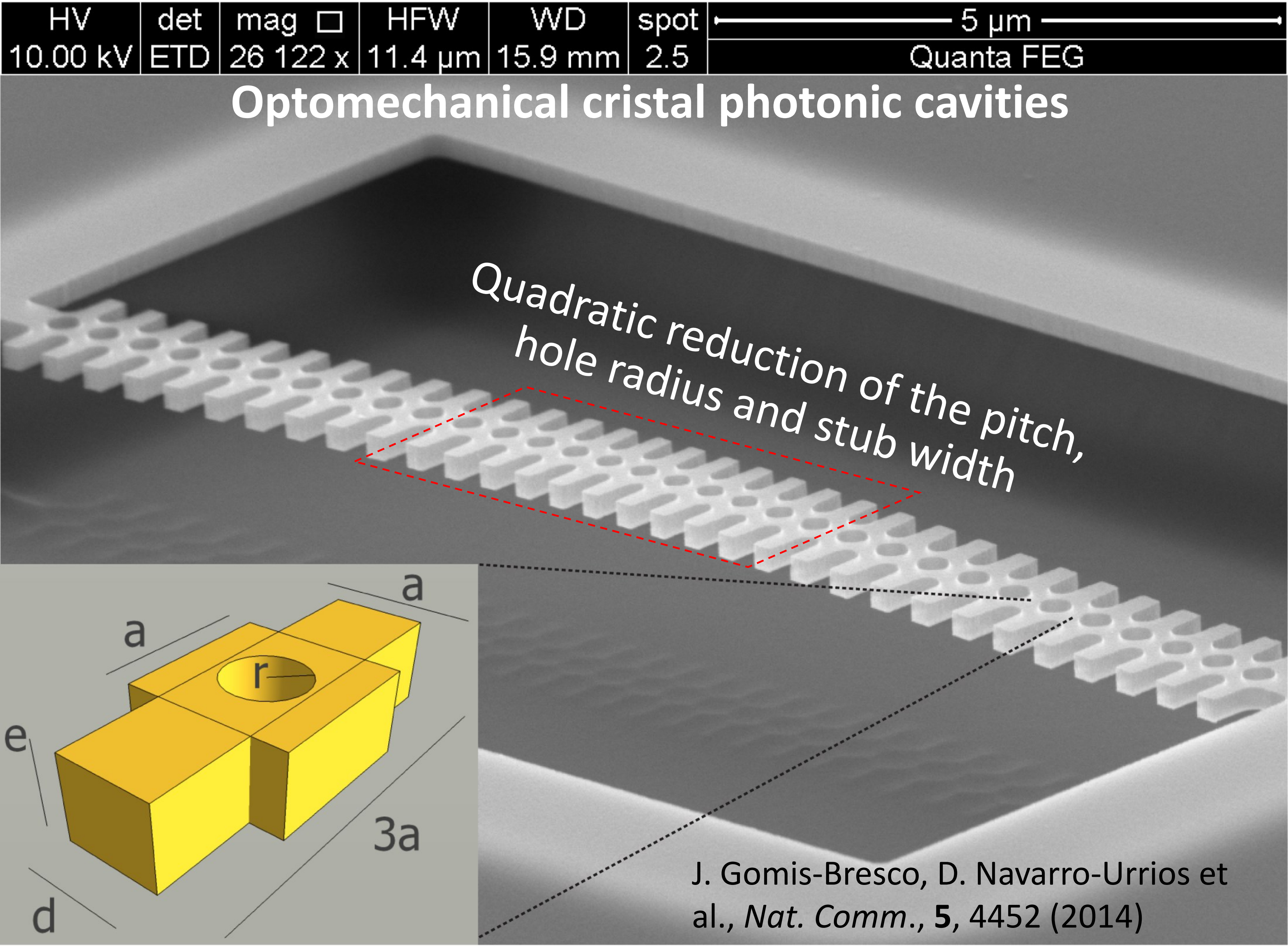
Nonlinear Optomechanics

- Self-induced mechanical oscillations
- Attractor diagram?
- Synchronization of oscillations
- Chaos

OM cavities as versatile building blocks to be used for generating **reference signals**, in **neurocomputational networks**, for **chaos-based secure communications**, etc.

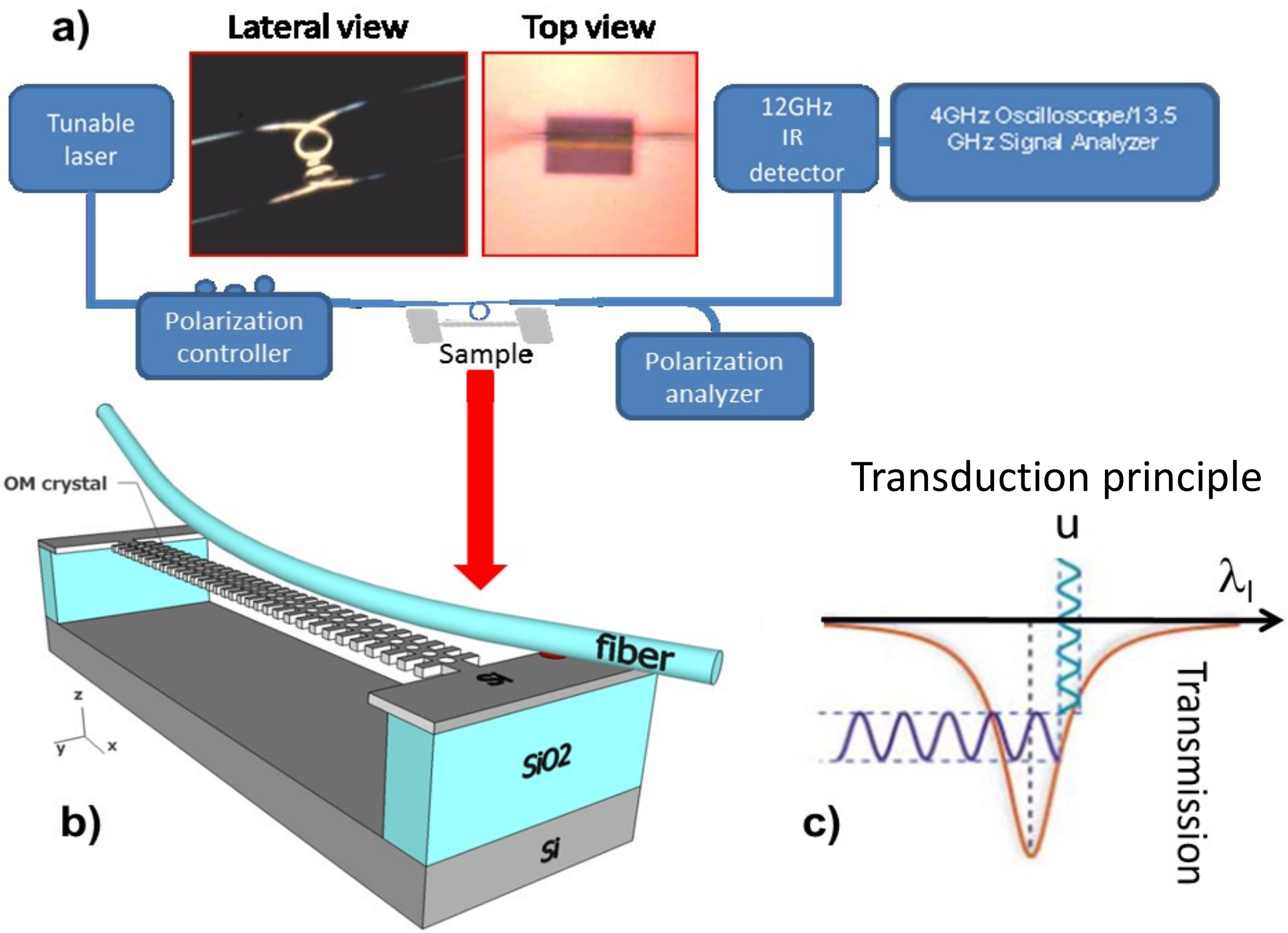
Nonlinear Quantum Optomechanics

- QND Phonon number detection
- Phonon shot noise
- Photon blockade
- Optomechanical "which-way" experiment
- Nonclassical mechanical q. states
- Nonlinear OMIT
- Noncl. via Conditional Detection
- Single-photon sources
- Coupling to other two-level systems
- Optomechanical Matter-Wave Interferometry

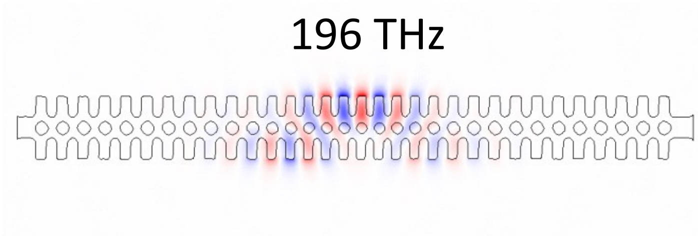

HV
10.00 kV
det
ETD
mag
26 122 x
HFW
11.4 µm
WD
15.9 mm
spot
2.5
5 µm
Quanta FEG
Optomechanical cristal photonic cavities
Quadratic reduction of the pitch, hole radius and stub width
a
a
r
e
3a
d
J. Gomis-Bresco, D. Navarro-Urrios et al., *Nat. Comm.*, **5**, 4452 (2014)

Experimental Setup

- Standard tapered fiber set-up for characterizing optical and mechanical properties of OM devices.
- Mounted on an anti-vibration cage at **atmospheric conditions of air pressure and temperature**

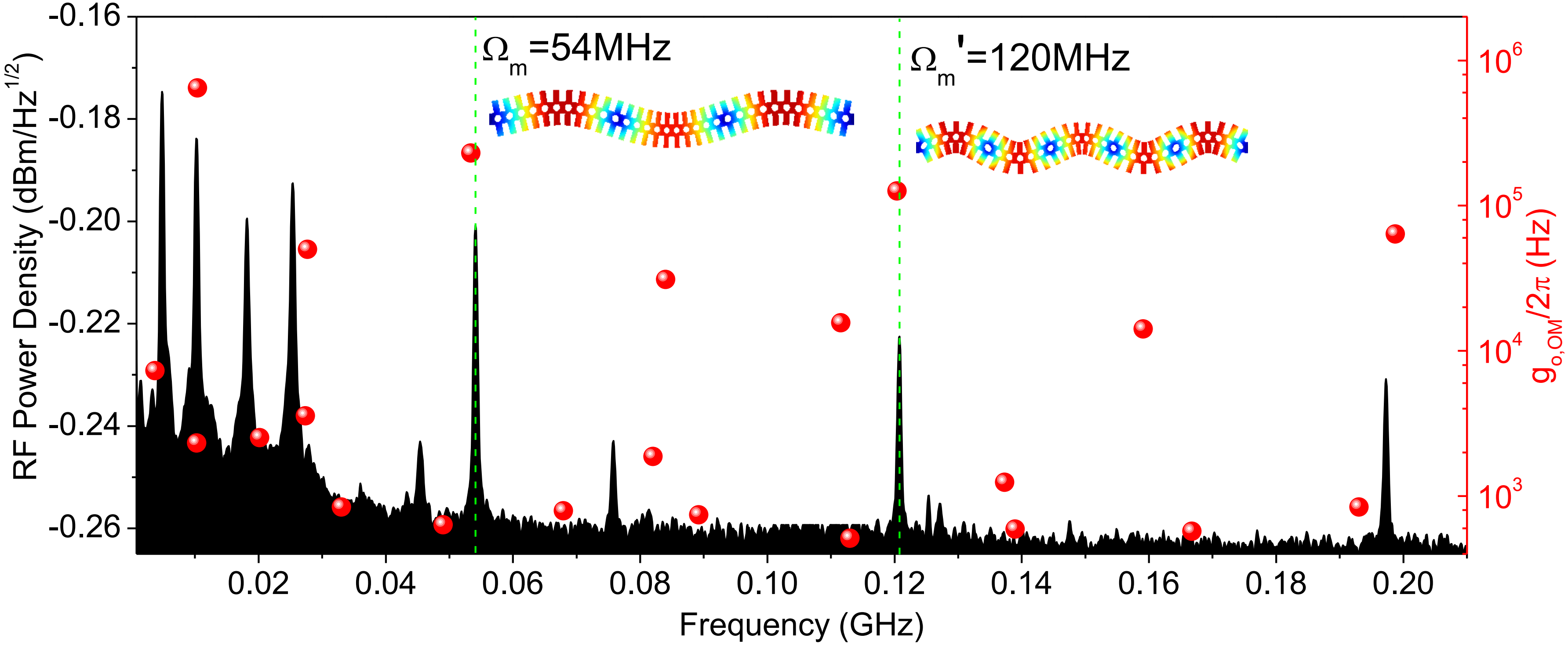


Low frequency mechanical modes



Side-band unresolved: $\frac{\Omega_m}{\kappa} \sim$

In-plane, flexural modes



Thermo-Optic/Free-Carrier-Dispersion self-pulsing

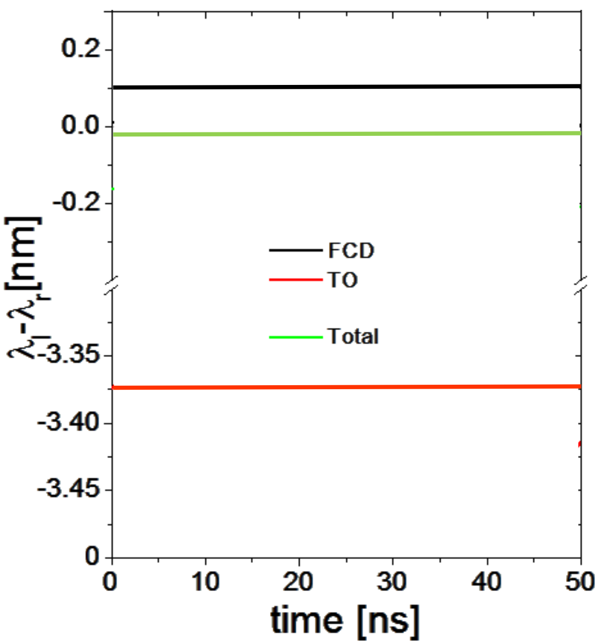
$$\lambda_r \approx \lambda_o + \frac{\partial \lambda_r}{\partial T}\Delta T - \frac{\partial \lambda_r}{\partial N} N$$

TO FCD

λ_r = Resonance wavelength

N=Free carrier density

ΔT= Temperature Increase



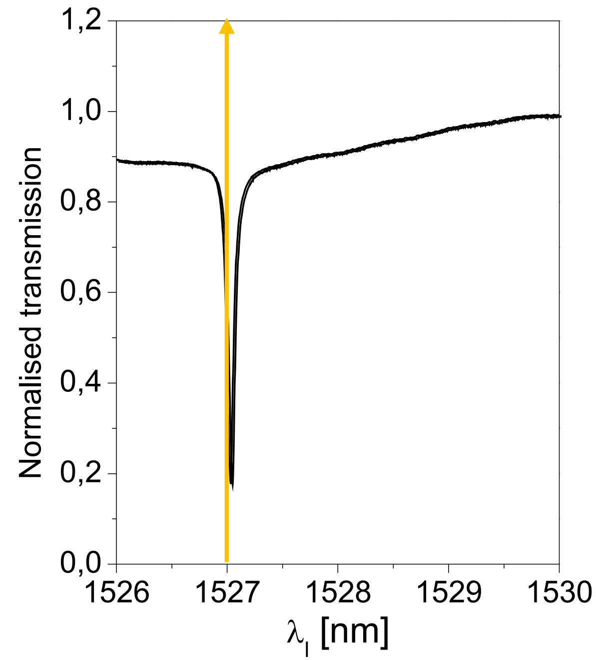
$$\frac{dN}{dt} = -\frac{1}{\tau_{FC}}N + \beta\left(\frac{hc^3}{n^2\lambda_o V_o^2}\right)n_o^2;$$

$$\frac{d\Delta T}{dt} = -\frac{1}{\tau_T}\Delta T + \alpha_{FC} N n_o;$$

Number of intracavity photons

$$n_o = n_{o,max}\left(\frac{\Delta\lambda_o^2}{4(\lambda_l - \lambda_r)^2 + \Delta\lambda_o^2}\right)$$

Knob



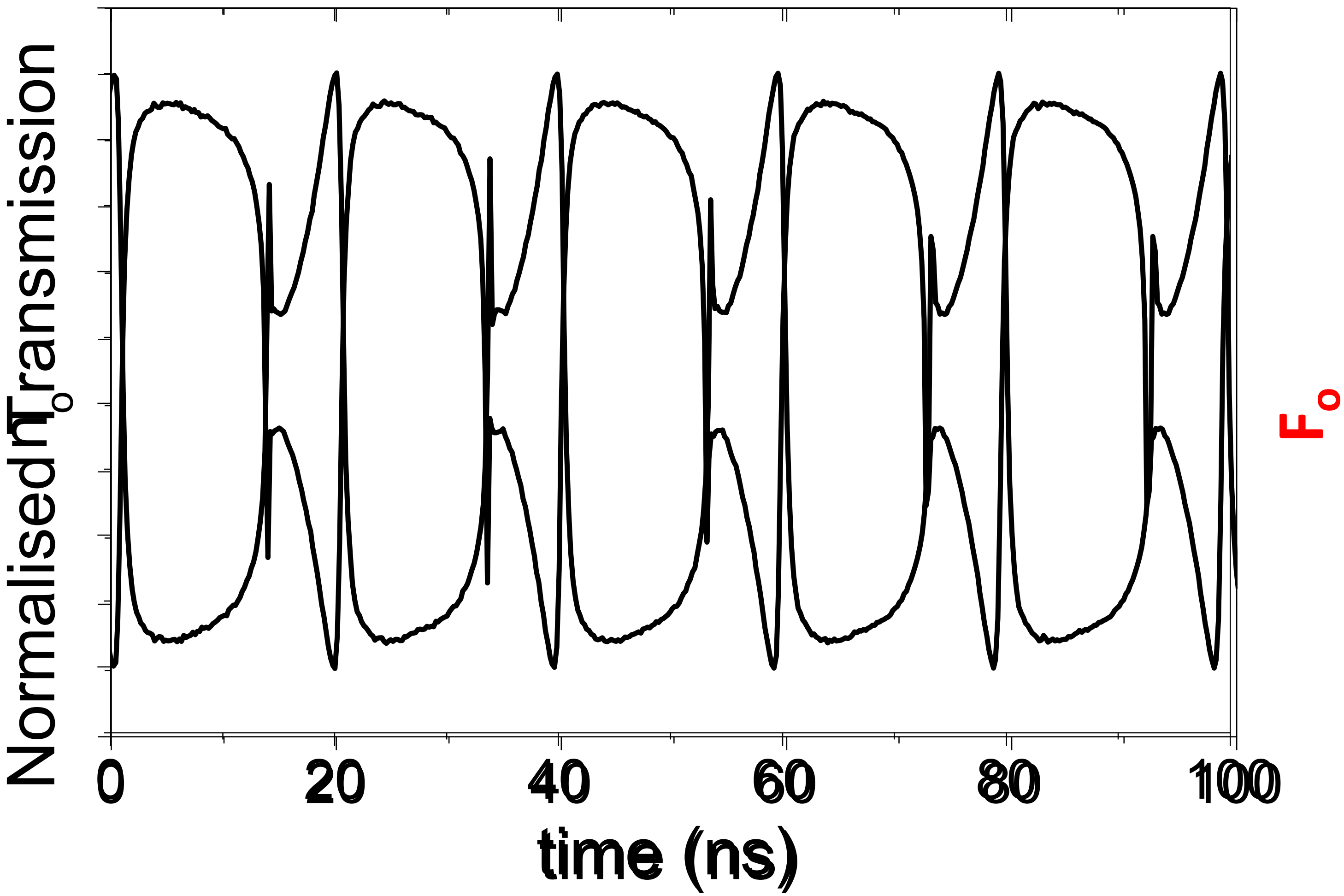
*T. J. Johnson et al., Opt. Express, **14**, 817-831 (2006)*

A stable anharmonic trajectory of the optical resonance is established around the laser wavelength.

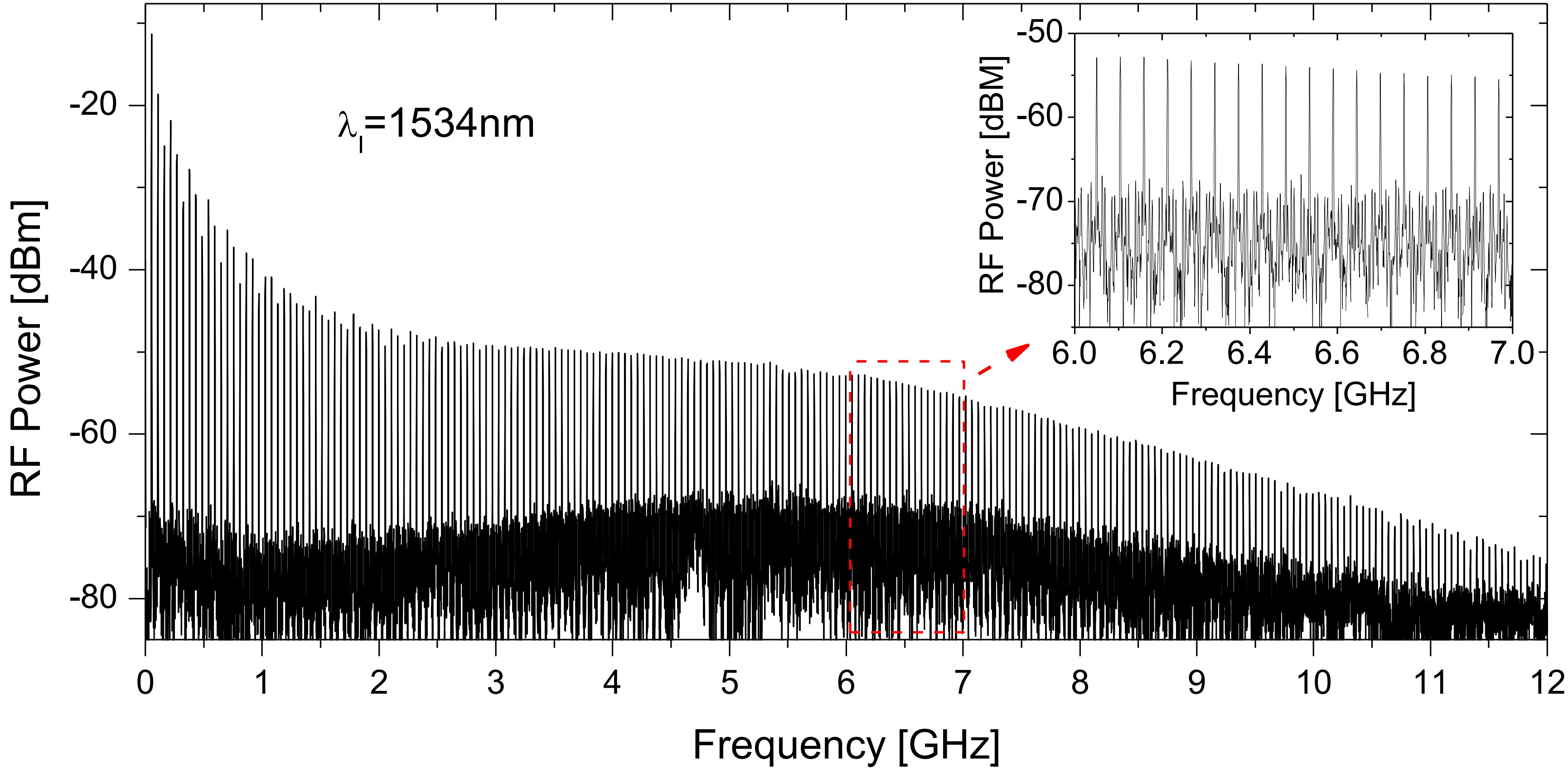
Influence of the self-pulsing on the radiation pressure force

***F_o* = Intracavity radiation pressure force**

$$F_o = \hbar \frac{g_o}{x_{zpf}} n_o$$



RF signal above threshold



“Phonon lasing” by exploiting the self-pulsing

Periodic/anharmonic intracavity radiation pressure force:

$$F_o = F_o(\upsilon_{SP}, 2\upsilon_{SP}, 3\upsilon_{SP}, \ldots, M\upsilon_{SP})$$

$$\nu_{SP} \neq \frac{\Omega_m}{M}$$

Since the structure is an OM crystal

↓

Harmonic oscillator driven by the optical force

m_{eff} … $\Omega_{m,i}$ … $F_o = \frac{\hbar}{x_{zpf}}$ …

$$\frac{dN}{dt} = -\frac{1}{\tau_{FC}} N + \beta \left(\frac{hc^3}{n^2 \lambda_o V_o^2} \right) n_o^2$$

$$\frac{d\Delta T}{dt} = -\frac{1}{\tau_T} \Delta T + \alpha_{FC} N n_o$$

$$n_o = n_{o,max} \left(\frac{\Delta\lambda_o^2}{4(\lambda_l - \lambda_r)^2 + \Delta\lambda_o^2} \right)$$

OM

$$\lambda_r \approx \lambda_o - \frac{\partial \lambda_r}{\partial N} N + \frac{\partial \lambda_r}{\partial T} \Delta T + \frac{\lambda_o^2 g_o}{2\pi c x_{zpf}} u$$

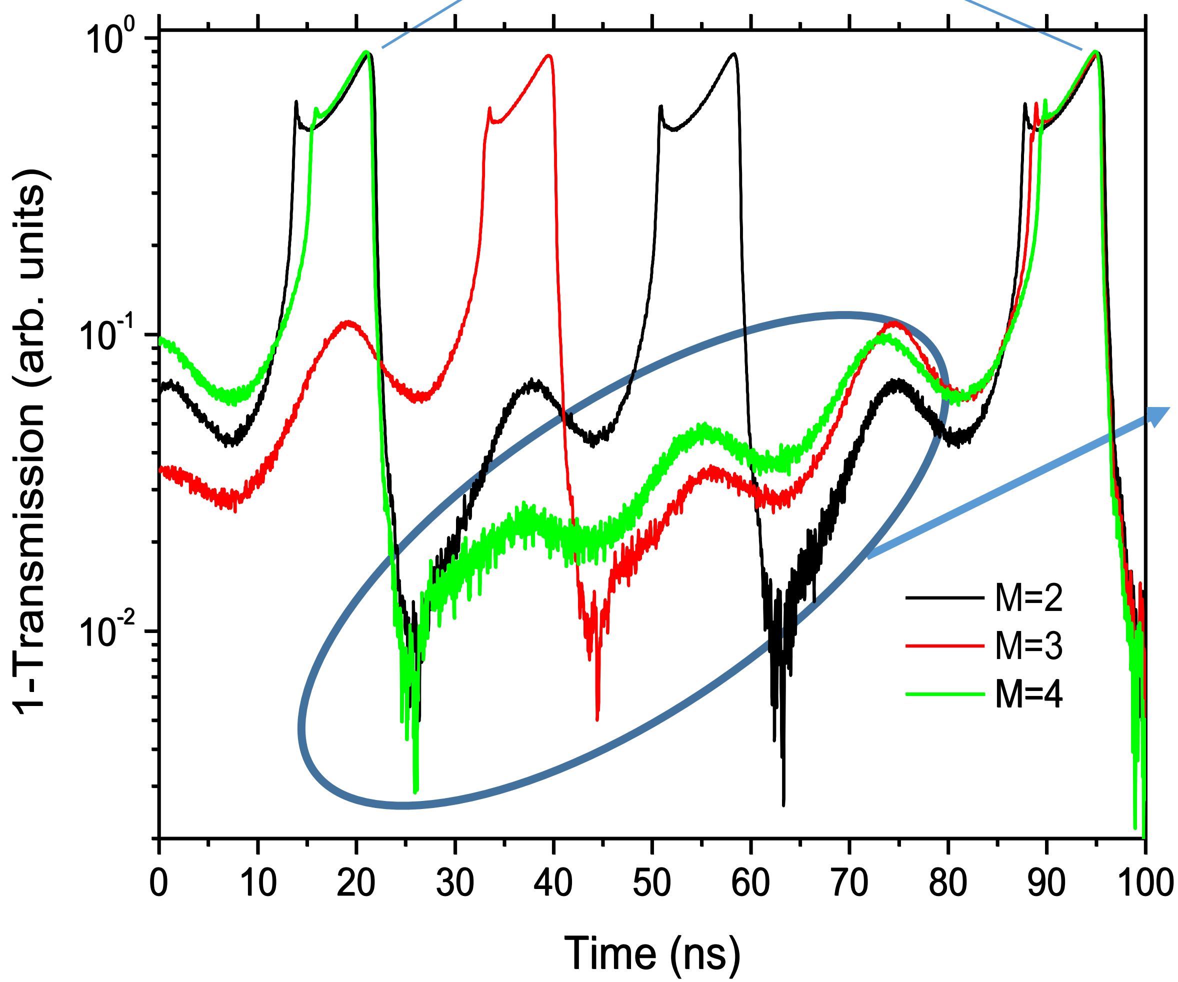
Transmitted signal in the oscilloscope

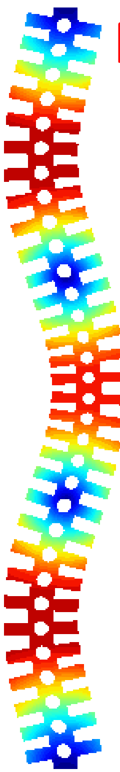
If:

$$\nu_{SP} = \frac{\Omega_m}{M}$$

SP+OM signature

D. Navarro-Urrios et al., Scientific Reports 5, 15733 (2015).





Phonon lasing

OM signature

Ω_m = 54MHz

Amplitude approx: 1nm

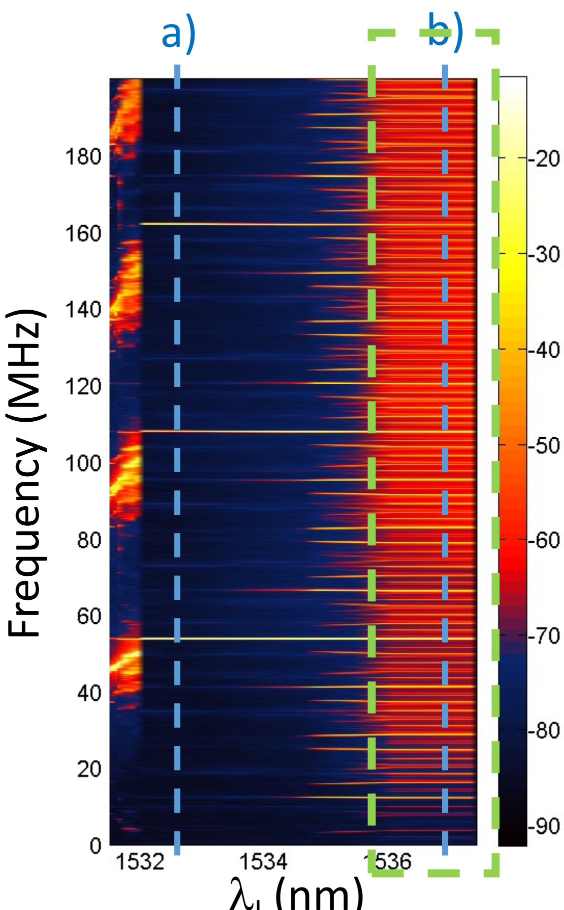
Chaotic regime in the self-pulsing when coupled to the mechanics

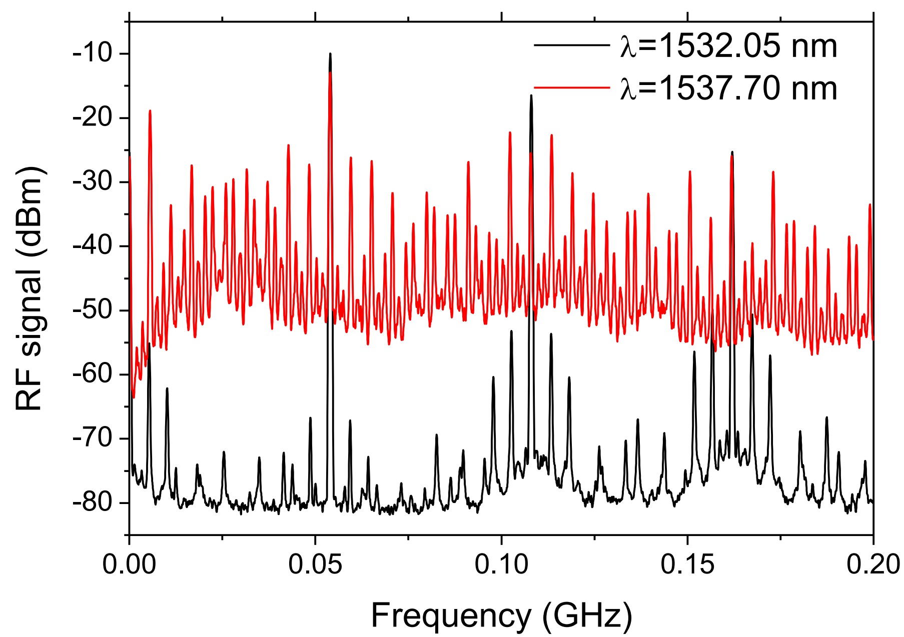
Poincarè-Bendixson theorem: No chaos in 2-dimensional, 1st order non-linear systems.
-> Isolated self-pulsing cannot support chaotic trajectories.

$$\frac{dN}{dt} = -\frac{1}{\tau_{FC}} N + \beta\left(\frac{hc^3}{n^2 \lambda_o V_o^2}\right) n_o^2;$$

$$\frac{d\Delta T}{dt} = -\frac{1}{\tau_T}\Delta T + \alpha_{FC} N n_o;$$

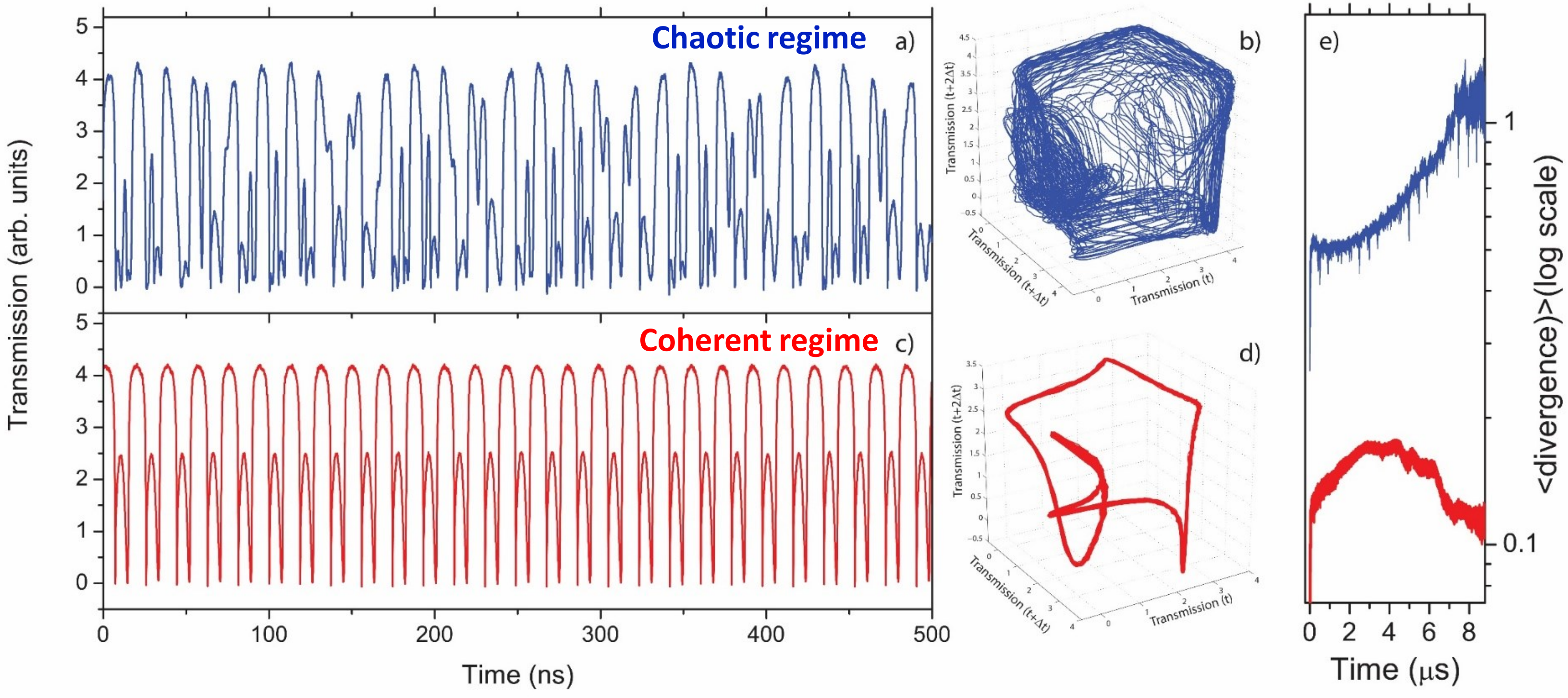
m_{eff} … $Q_{m,i}$ … $= \hbar$ … x_{zpf}





Chaotic regime in the time domain

Time series (experimental) before and after the bifurcation leading to chaos

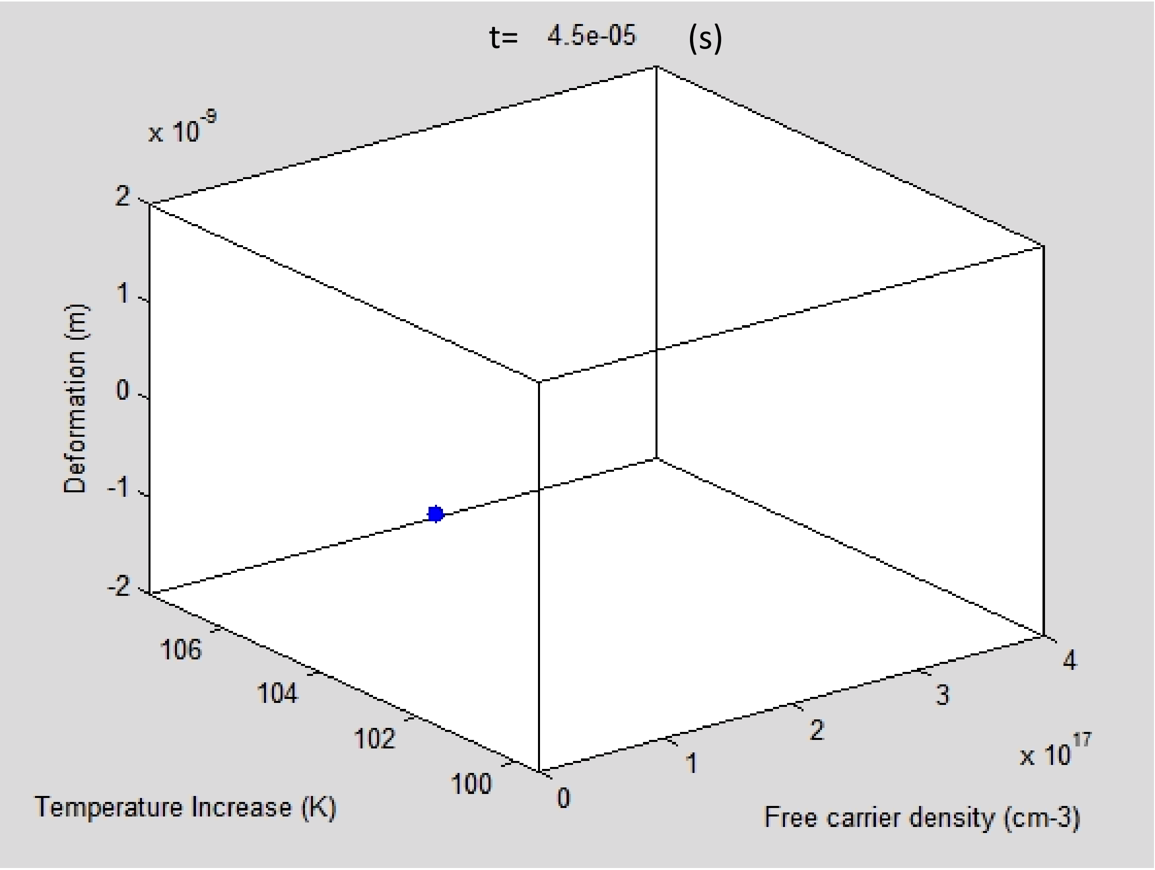


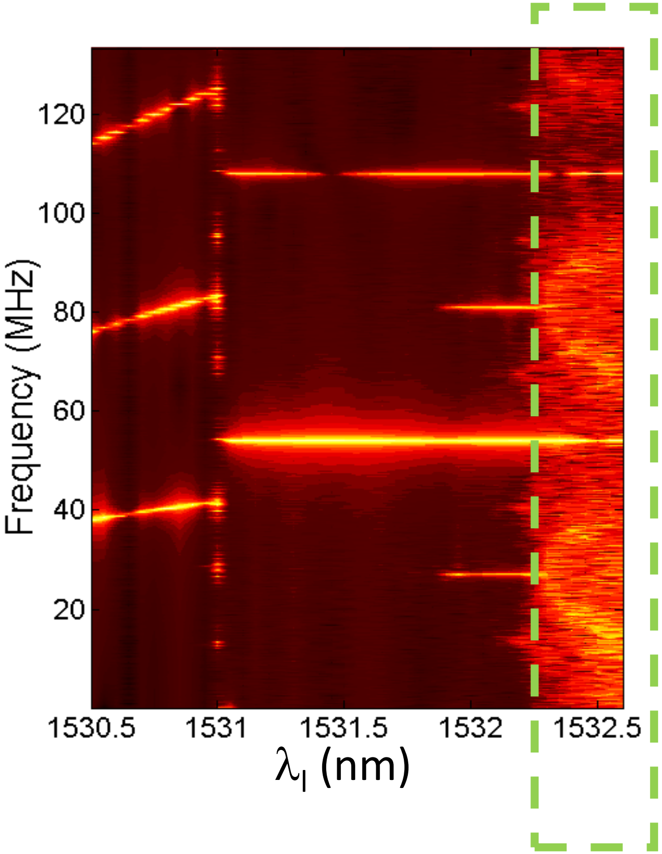
Largest Lyapunov Exponents greater than 1

D. Navarro-Urrios et al., Nature Communications 8, 14965, (2017).

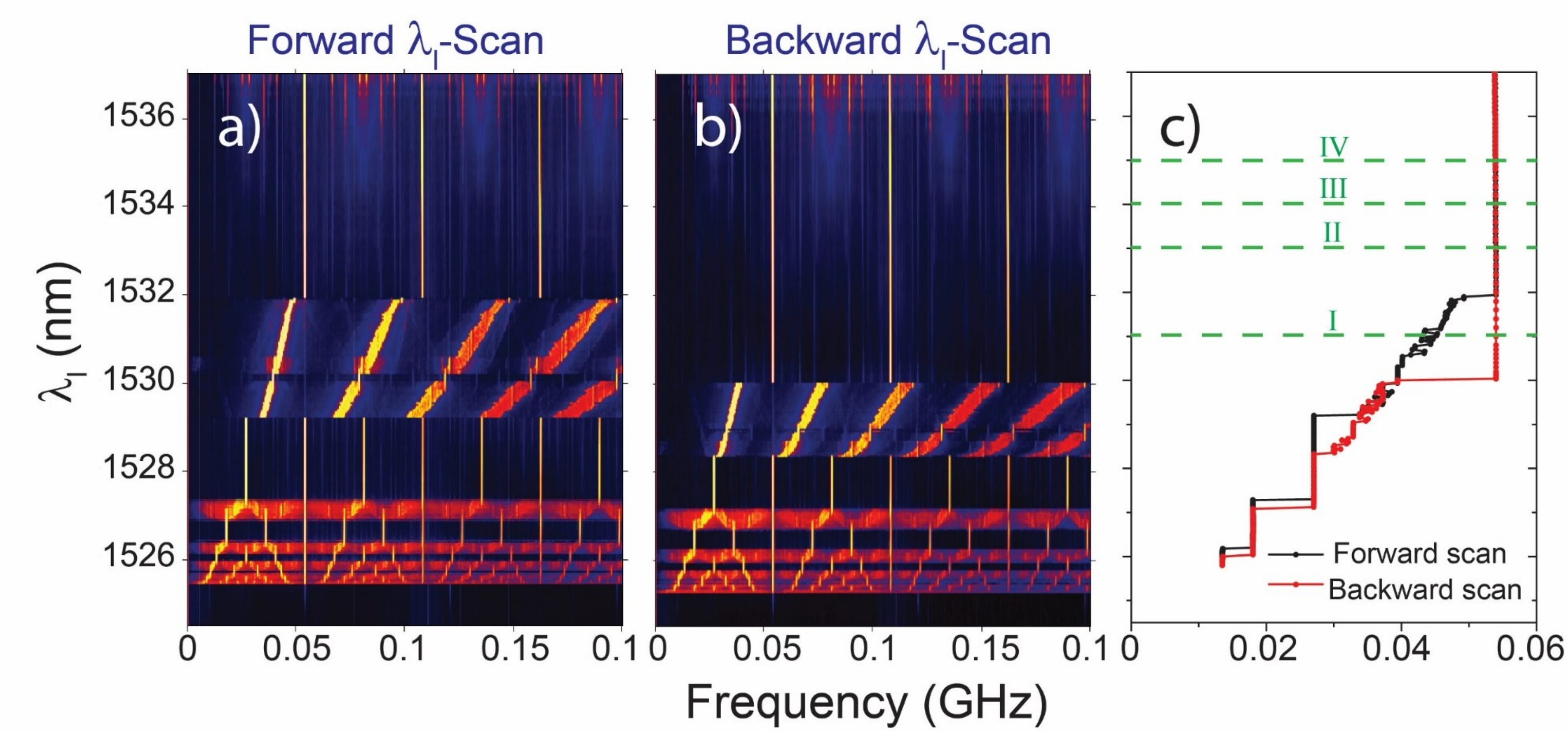
Chaotic regime

Numerical simulations ($g_o/2\pi$=100KHz)



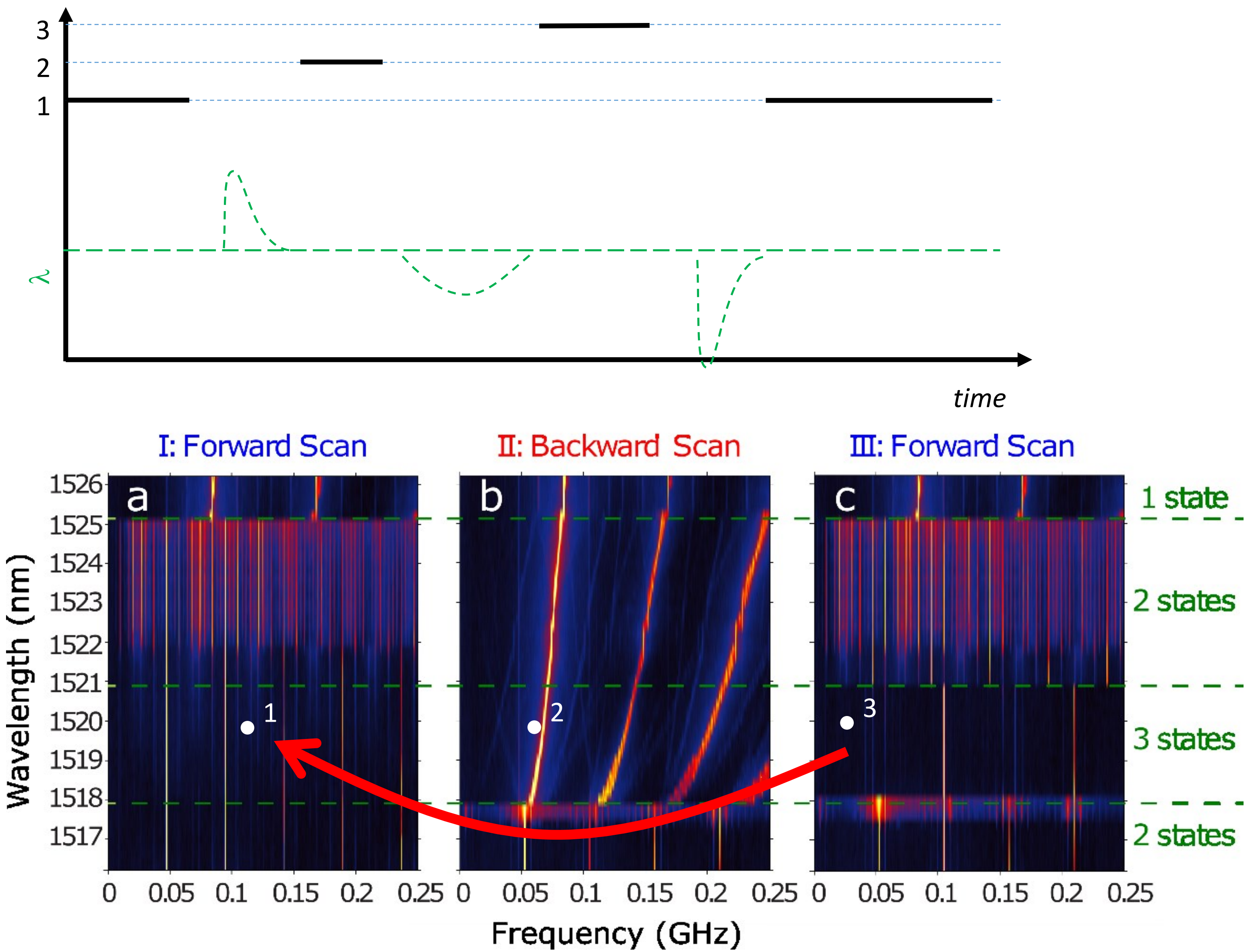


Bistability (Experiment)

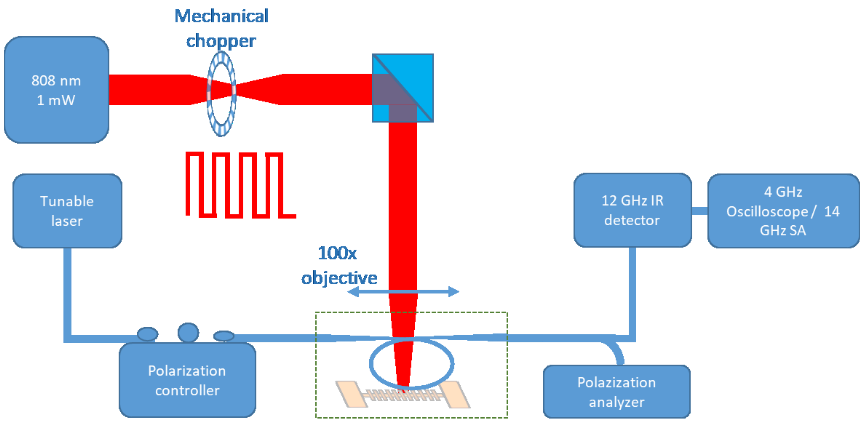


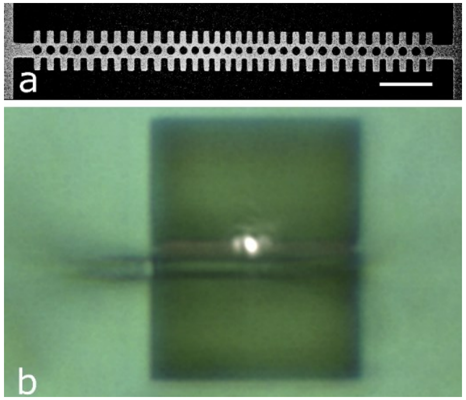
Backwards path: mechanical coherent oscillation is active and the feedback is strong enough to force self-pulsing frequency

Multistability



Switching between different dynamical states using an external source.

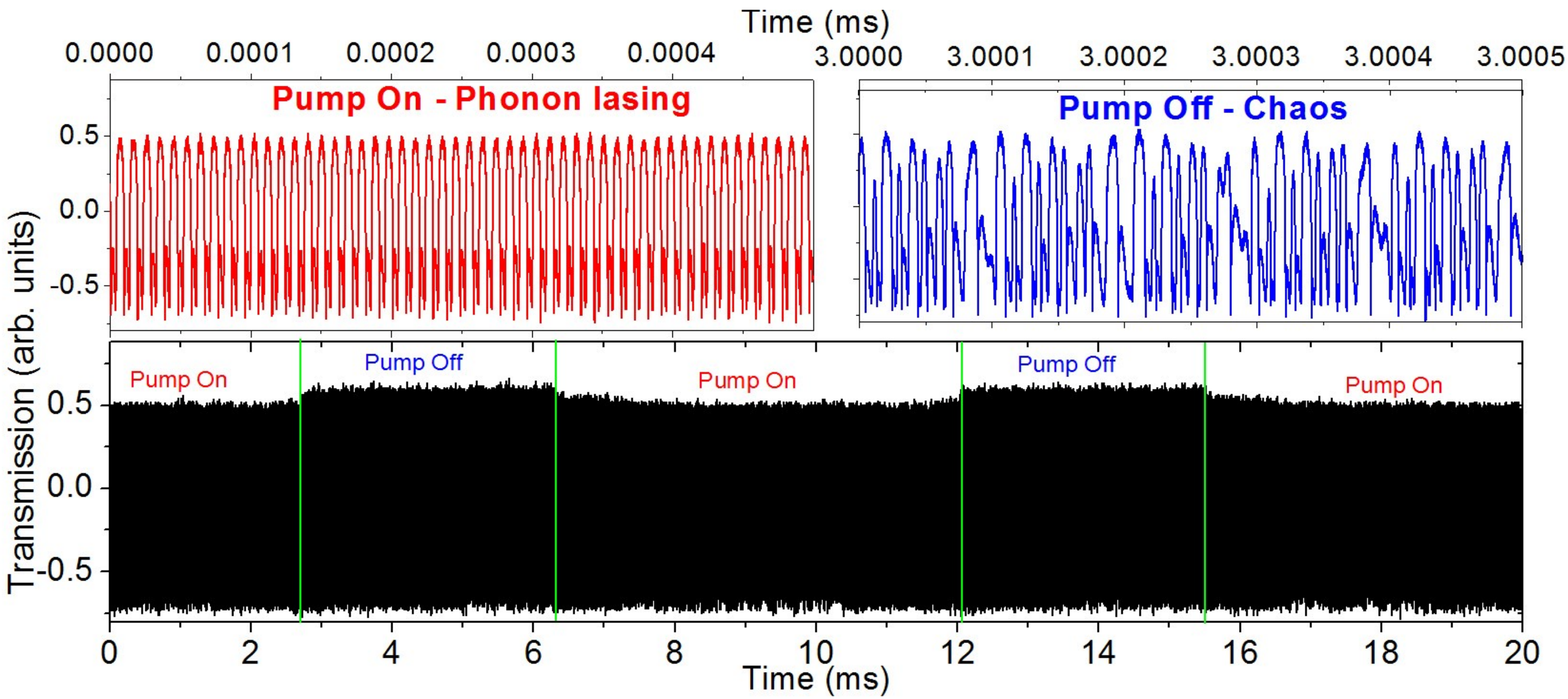




Optical image showing the OM crystal with the fiber below and the pump laser spot. The length of the nanobeam is 16.5 µm .

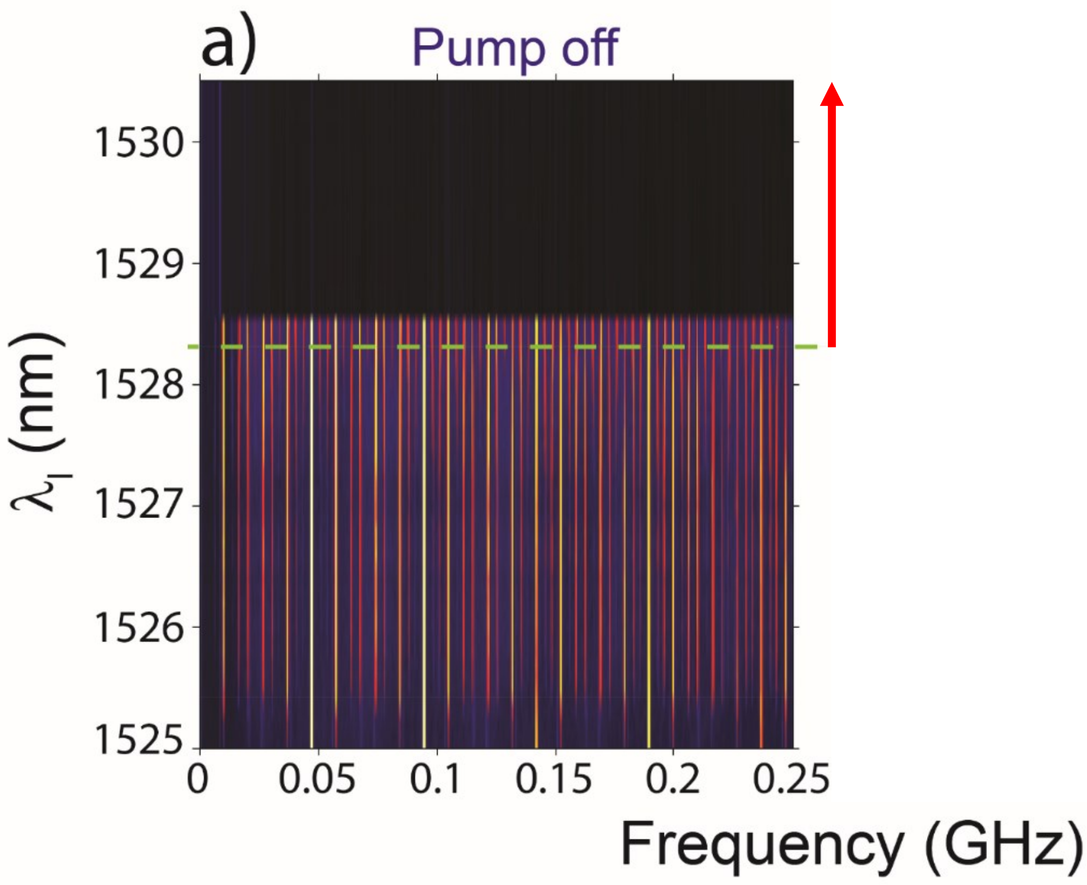
J. Maire, D. Navarro-Urrios, under review.

Switching between different dynamical states using an external source.



Switching mechanism

RF spectra with pump off and on (green line indicates the conditions of the measurements shown in the next slide).

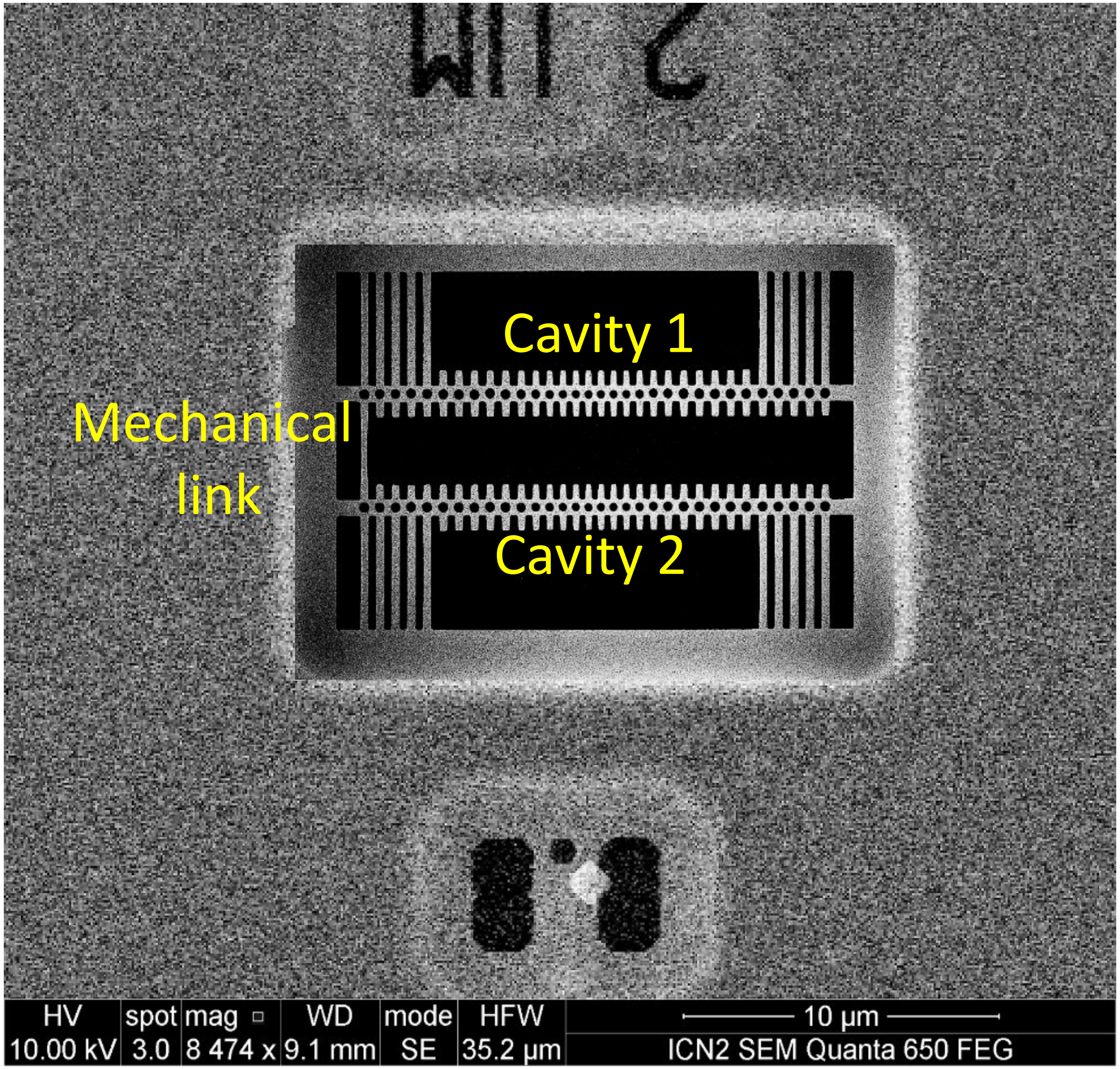


The top laser heats the OM cristal, inducing a spectral shift towards longer wavelengths

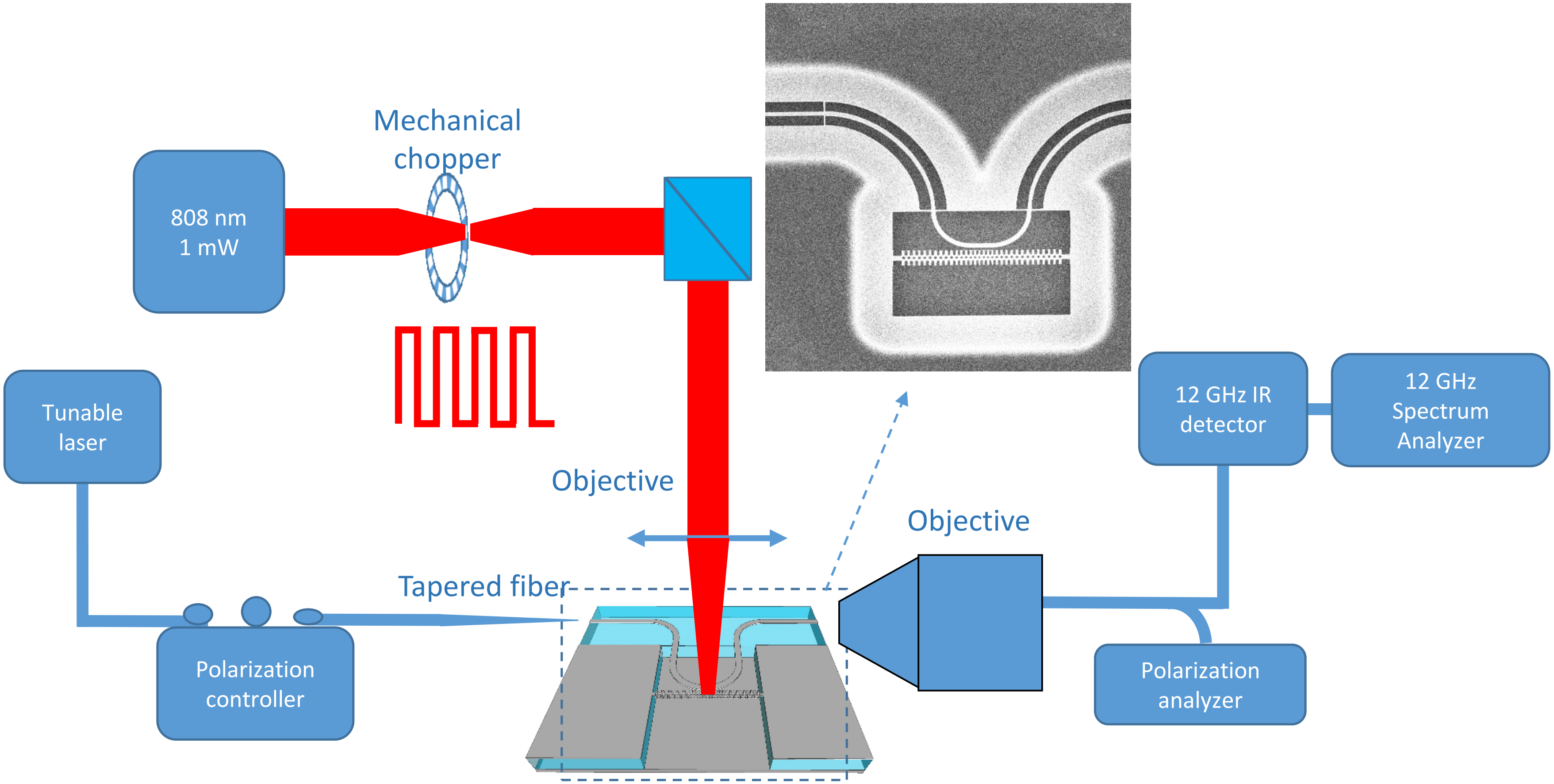
Conclusions

- Rich set of **complex dynamical solutions, including chaos,** experimentally observed in a single and compact Si-based OM nanobeam, optically pumped with a continuous-wave, low-power laser source.
- **Hysteresis, bistability and tristability** of different kinds involving self-pulsing, phonon “lasing” and chaos.
- **Switching between different dynamic solutions** using an external heating source

Outlook: Coupled cavities



Outlook: Towards integration



Thank you!

Ramón y Cajal: RYC-2014-15392

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