Noise Influence on Nanolaser Large Signal Modulation

T. Wang, J. Zhou, G.P. Puccioni, W. Zhao, X. Lin, H. Chen, G. Wang, G.L. Lippi

Noise Influence on Nanolaser Large Signal Modulation

T. Wang[1,2], J. Zhou[3], G.P. Puccioni[4], W. Zhao[1,2], X. Lin[5], H. Chen[5], G. Wang[1,2], and G. L. Lippi[6]

[1] Engineering Research Center of Smart Microsensors and Microsystems of MOE
[2] School of Electronics and Information
[3] School of Communication Engineering
Hangzhou Dianzi University, Hangzhou 310018, China

[4] Istituto dei Sistemi Complessi, **CNR**, 50019 Sesto Fiorentino, Italy
[5] Interdisciplinary Center for Quantum Information, College of Information Science and Electronic Engineering, **Zhejiang University**, Hangzhou 310027, China
[6] **Université Côte d'Azur, CNRS**, UMR 7010, Institut de Physique de Nice, France

Objective: Increasing the modulation speed, minimizing thermal footprint, minimizing size and efficiency optimization

Issue: Nanolasers have strong fluctuations due to low photon numbers

$$\frac{\langle \Delta S\rangle}{\langle S\rangle} \propto \frac{1}{\sqrt{\langle S\rangle}}$$

Questions:
A. Is a nanolaser better suited for data transmission?
B. How can we estimate it?
C. What is the maximum transmission speed to be expected?

Rate Equations model for dielectric devices [1]

$$\dot{S} = -\Gamma_c S + \beta\gamma N(S+1) + F_S(t)\,,$$
$$\dot{N} = P - \beta\gamma N S - \gamma N + F_N(t)\,,$$

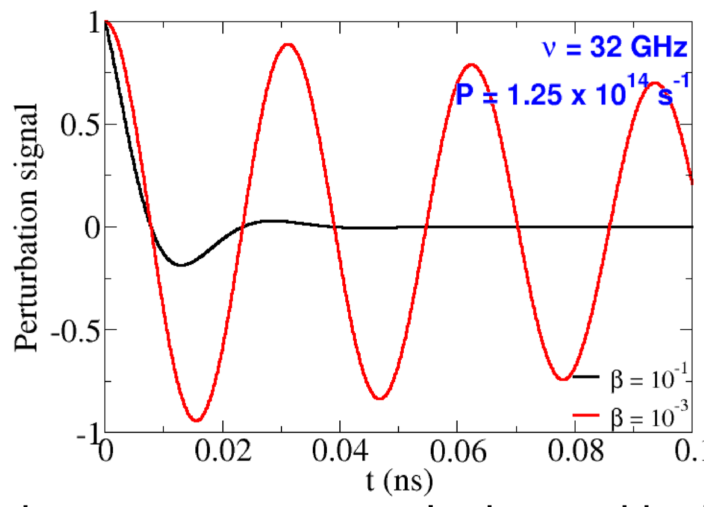
Langevin noise [2]

$$\langle F_i(t) F_j(t')\rangle = 2F_{ij}\delta(t-t')$$

Number of	Relax. rate	Parameters
Photons: S	Γ_c: Cavity	β: % spont. em. in laser
Carriers: N	γ: Carrier	P: Pump rate

A. Nanolasers have more noise but stronger damping

Comparison of simulated perturbation at frequency ν and same pump (i.e., same photon flux)



Perturbations are more strongly damped in the nanolaser!

Topological properties

Steady states

$$\overline{S} = \beta^{-1}\left\{\left(\frac{C-1}{2}\right) + \sqrt{\left(\frac{C-1}{2}\right)^2 + \beta C}\right\}$$

$$\overline{N} = \frac{\Gamma_c}{\beta\gamma}\frac{C}{1+\beta\overline{S}} \qquad C = \frac{P}{P_{th}} \qquad P_{th} = \frac{\Gamma_c}{\beta}$$

Eigenvalues

$$\begin{aligned}\lambda_\pm &= \frac{((\overline{S}-\overline{N})\beta+1)\gamma+\Gamma_c}{2}\\ &\pm \frac{1}{2}\left\{\left[(\overline{S}^2 - 2\overline{N}\overline{S} + \overline{N}^2 - 4\overline{N})\beta^2 + 2(\overline{S}+\overline{N})\beta + 1\right]\gamma^2\right.\\ &\left.+(-2\Gamma_c(\overline{S}+\overline{N})\beta - 2\Gamma_c)\gamma + \Gamma_c^2\right\}^{\frac{1}{2}}\\ &= \alpha \pm i\omega_r\end{aligned}$$

Linear stability

Perturbation decay

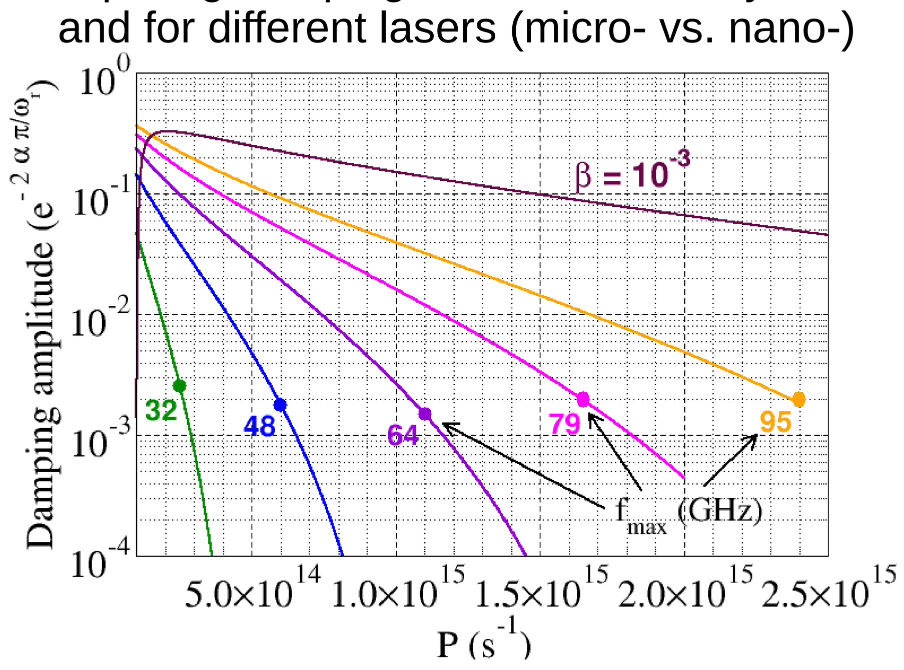
$$\begin{aligned} x(t) &= x_0 + \xi e^{\lambda t}\\ &= x_0 + \xi e^{\pm i\omega_r t} e^{\alpha t}\end{aligned}$$

α

ω_r

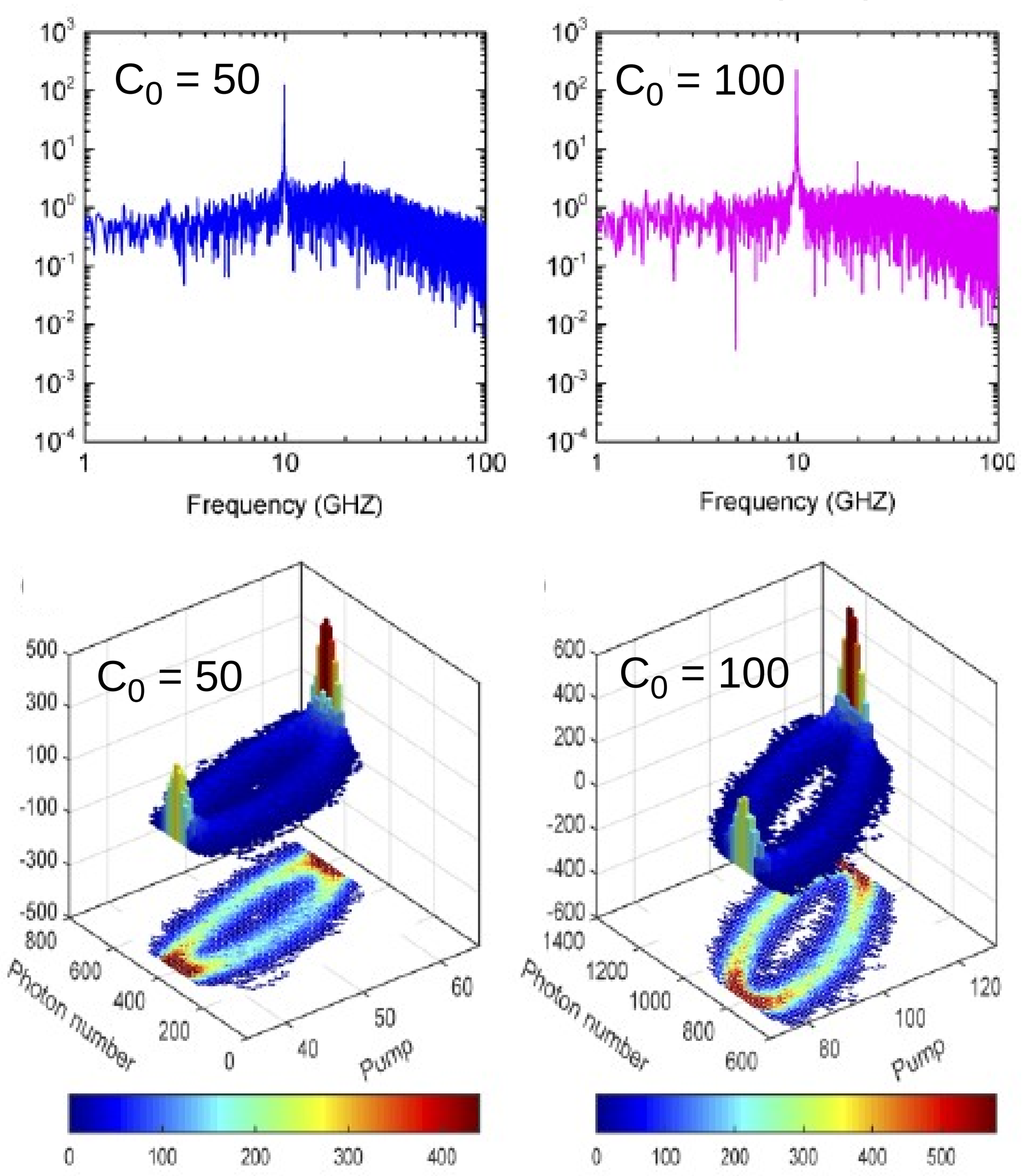
B. Quantitative (relative) damping analysis

Comparing damping for different cavity losses and for different lasers (micro- vs. nano-)



Direct simulation

Nanolaser (β = 0.1) response to sinusoidal modulation at ν = 10 GHz for different normalized pump values



$$C(t) = C_0 + C_m\cos(2\pi\nu t)\ , \qquad C_m = \frac{C_0}{4}$$

Numerical integration: Euler-Maruyama method [3]

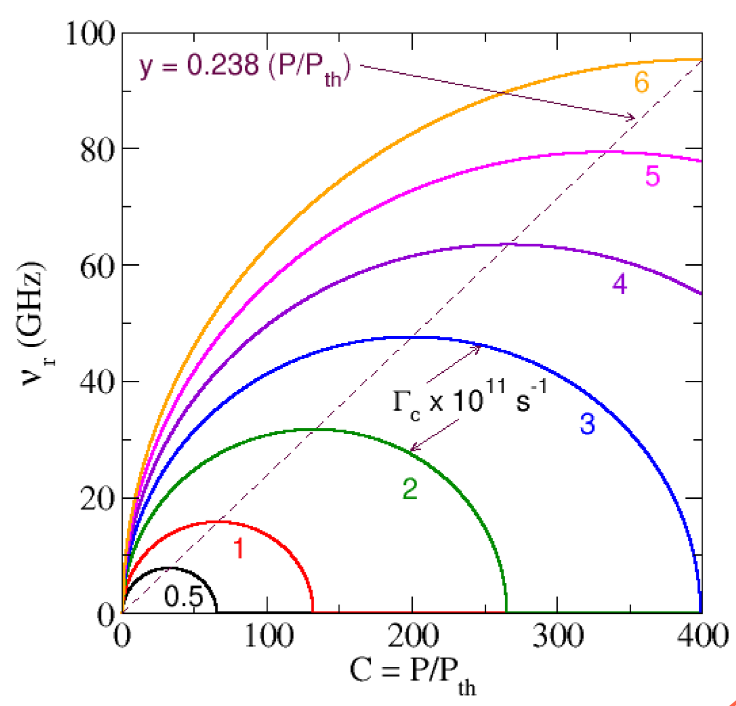
$\nu_r > \nu$

$\Gamma_c = 1 \times 10^{11}$

Larger C_0 smaller noise

C. Maximum transmission speed

- The temporal response depends on the internal time constant T
- Depending on C, the maximum response speed changes, so does noise damping
- The response is a function of cavity losses
- Increasing the maximum speed (bandwidth) is very costly in terms of necessary pump (slope < 0.25)



Conclusions:

The topological analysis permits an a priori assessment of the potential for communication speed both in terms of maximum attainable values and of expected noise influence. The debate [4,5] on actual transmission speed attainable can be supported by these arguments.
Nanolasers hold promise for better performance (for same photon flux) as long as technological issues relative to current densities can be solved[6].

References

[1] T. Wang *et al.*, *Methodological investigation into the noise influence on nanolasers' large signal modulation*, Opt. Express **29**(4), 5081-5097 (2021).
[2] L. A. Coldren and S. W. Corzine, *Diode lasers and photonic integrated circuits* (Wiley, 1995).
[3] G.L. Lippi, J. Mørk, and G.P. Puccioni, *Numerical solutions to the Laser Rate Equations with noise: Technical issues, implementation and pitfalls,* Nanophotonics VII, 106722B (2018); (SPIE, Bellingham, WA, USA).
[4] K. Ding *et al.*, *Modulation bandwidth and energy efficiency of metallic cavity semiconductor nanolasers with inclusion of noise effects*, Laser Photonics Rev. **9**(5), 488-497 (2015).
[5] B. Romeira and A. Fiore, "Physical limits of nanoLEDs and nanolasers for optical communications," Proc. IEEE **108**(5), 735-748 (2020).
[6] J. B. Khurgin and G. Sun, *Comparative analysis of spasers, vertical-cavity surface-emitting lasers and surface-plasmon-emitting diodes*, Nat. Photonics **8**(6), 468-473 (2014).