Quantum Behavior in Mesoscale Lasers

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4.00pm Monday June 17, 2019, Session 1P14 FocusSession.SC3: Nanophotonics 2, Room 24 - 2nd Floor

Outline

The macroscopic semiconductor laser diode

- Second-order non-equilibrium phase transition with optical field as the order parameter
- Fluctuations enhance lasing emission below laser threshold and contribute to temperature dependence of semiconductor laser diode threshold current

Semiclassical master equations to describe mesolasers

- Comparison between mean-field and probabilistic picture
- Semiclassical system trajectories and photon blinking modelled by the Monte Carlo method

A quantum mechanical meso-laser model

- Steady-state properties as a function of pump and number of emitters
- Photon Fano-factor, excitation pinning, emission linewidth
- Symmetry-protected long-lived emitter states in meso-lasers

Future challenges

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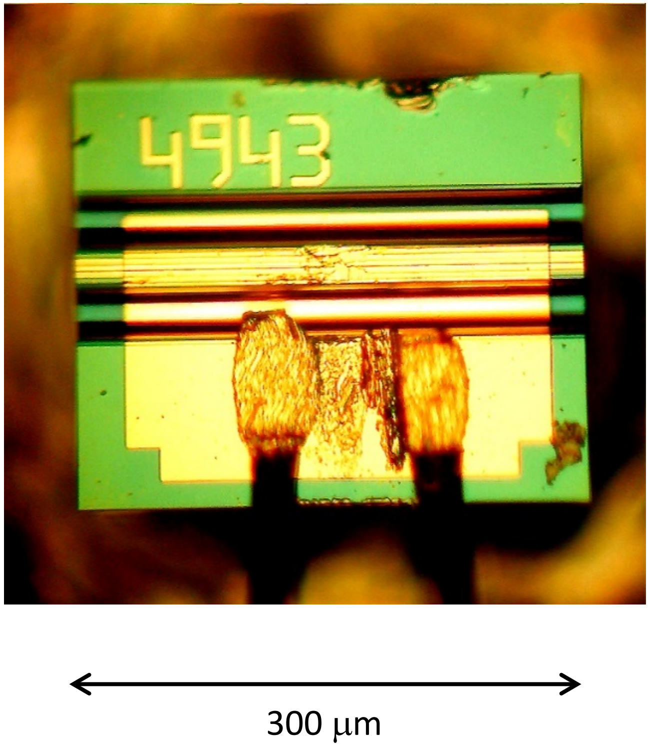
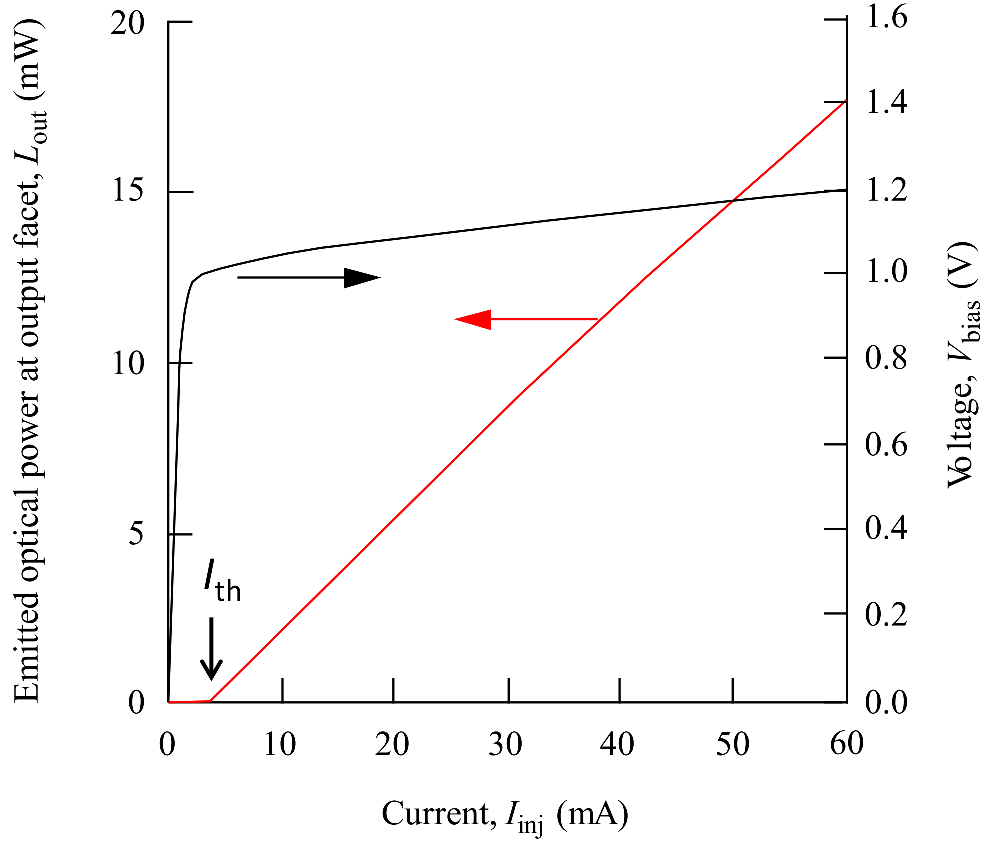
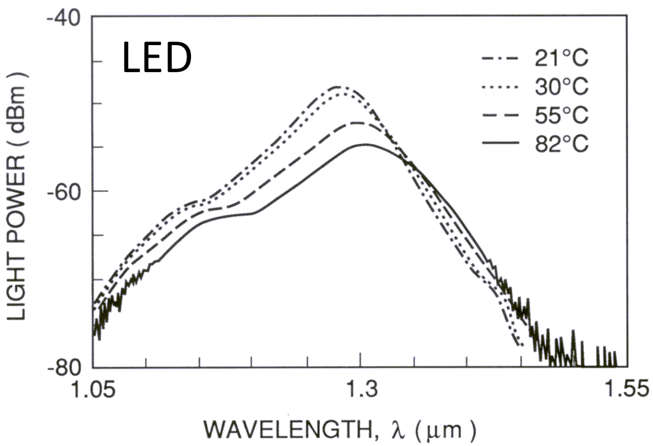
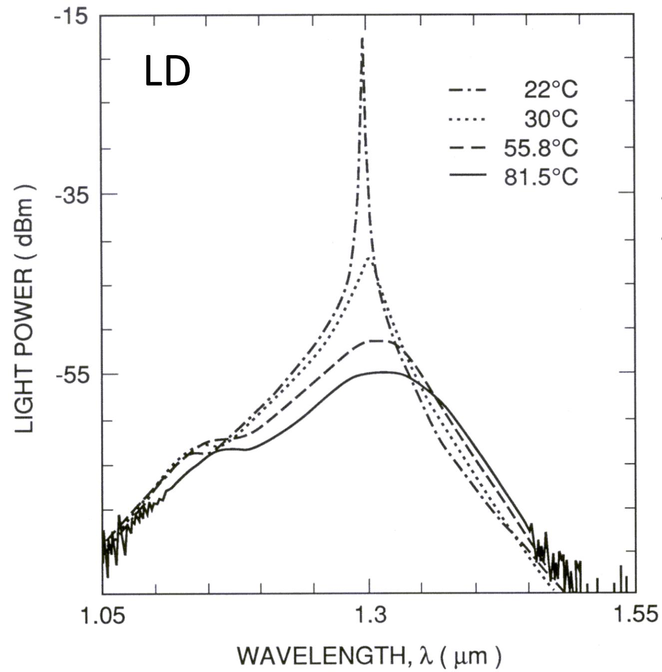


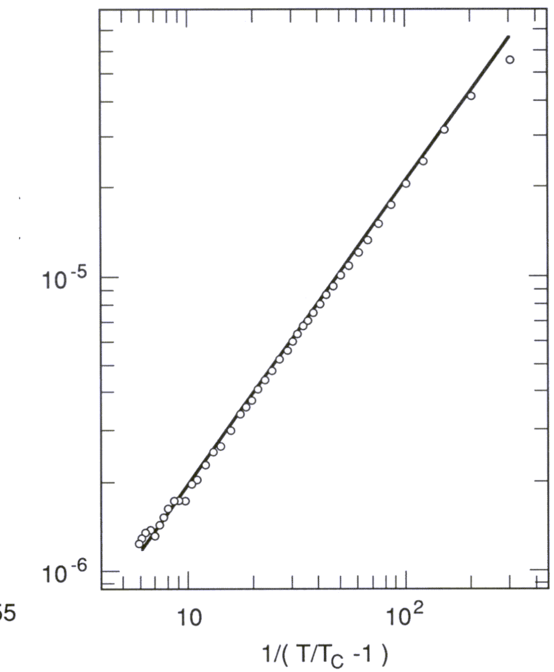


- Photons experience non-linear threshold behavior transitioning from disordered light (spontaneous emission) to ordered light (stimulated emission) with increasing pump current
  - Active volume V = 300 x 0.14 x 0.8 μm^3 = 34 x 10^{-12} cm^{-3} = 34 μm^3
  - I_{th} = 3 mA, <n> = 2 x 10^7, <s> = 10^5, β = 10^{-4}, 7 ps photon cavity round-trip
- Existing mean-field theories (rate equations and Gaussian noise - Langevin) applies to these large systems

Fluctuations enhance light output below I_{th}

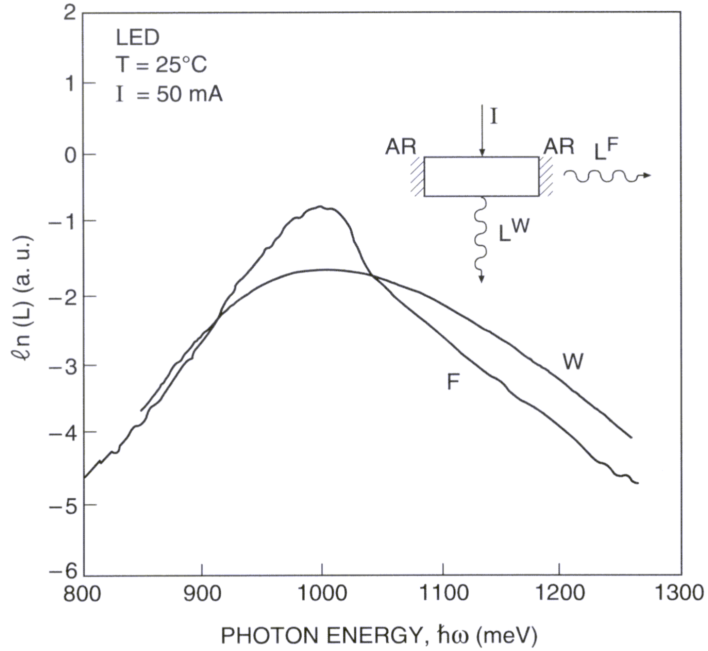


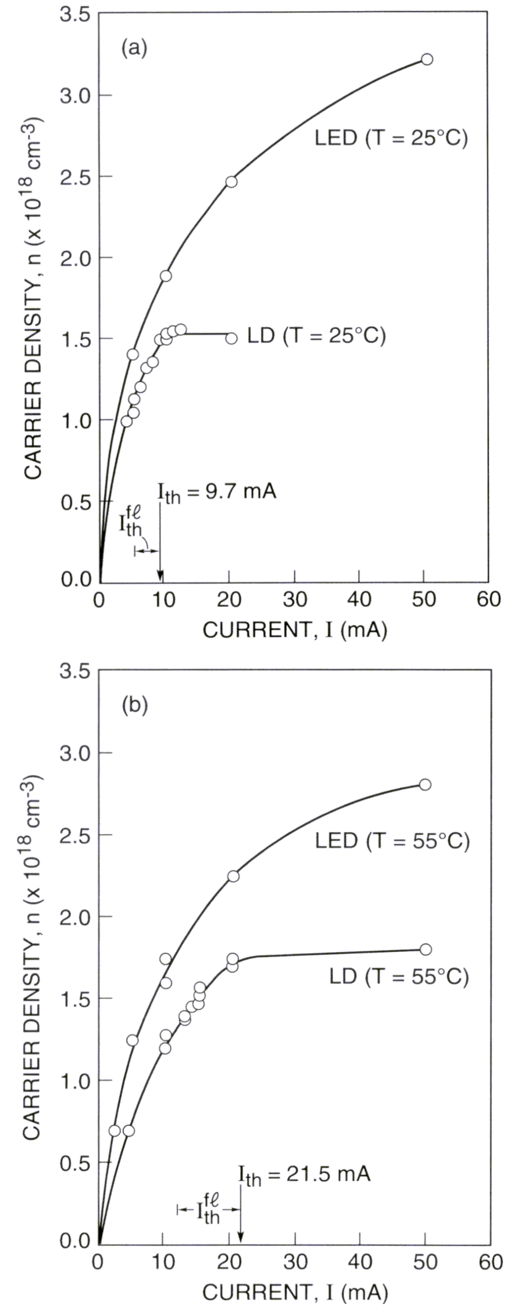




- Experimentally compare LED and LD using *same* geometry and active region
  - AR coat LD to make LED
- Landau-Ginzburg phase transition analogy for macroscopic semiconductor laser with below-threshold fluctuations into the lasing state
  - Intensity fluctuations scale as $1/(T/T_C - 1)^\gamma$
  - Experimentally γ=1.04, T_C = 301.4 K

Fluctuations and carrier pinning



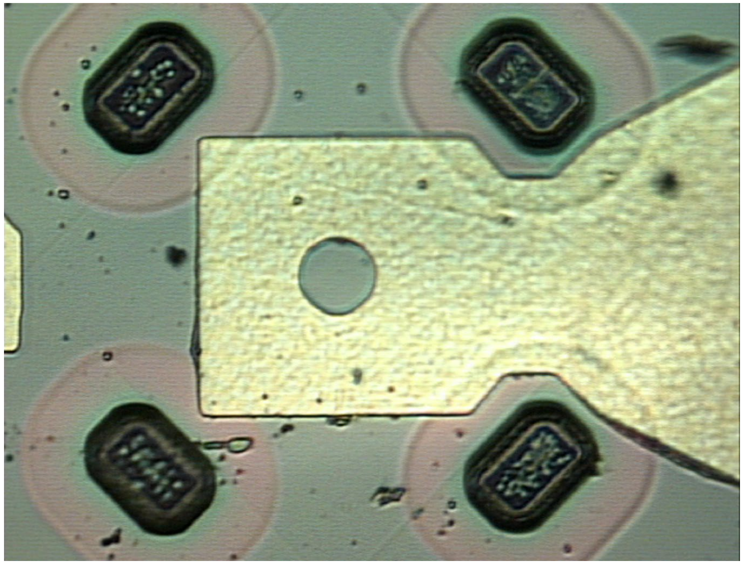


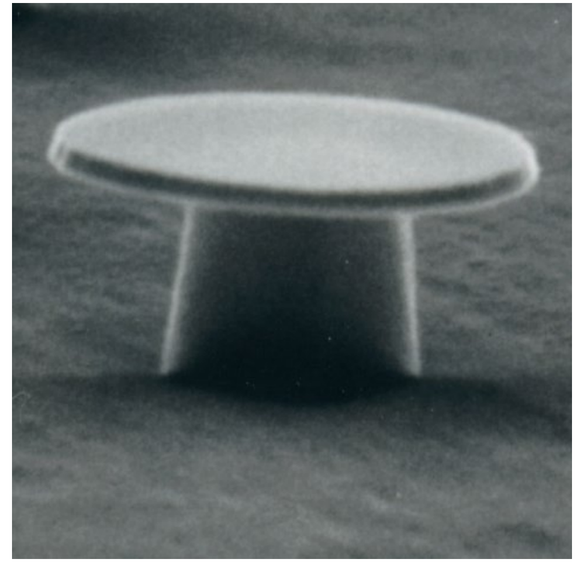
- Carrier number n from L_W (spontaneous emission)
  - Carrier pinning above threshold current
- Fluctuations in photons s remove carriers below threshold and contribute to the temperature dependence of laser diode threshold current, I_{th}
  - There is a contribution, I_{fl}, to the threshold current I_{th}
- Continuum mean-field rate equations set $\langle ns \rangle = \langle n \rangle \langle s \rangle$ and

$$d\langle n \rangle/dt = I - B\langle n^2 \rangle - a\Gamma\langle n-n_0 \rangle\langle s \rangle/V$$

$$d\langle s \rangle/dt = \beta B\langle n^2 \rangle + a\Gamma\langle n-n_0 \rangle\langle s \rangle/V - \kappa\langle s \rangle$$

Semiclassical master equations to describe mesolasers





100 μm

2 μm

- Fraction of spontaneous emission into lasing mode increases with decreasing optical cavity size
  - Phenomenological parameter β can increase from ~10^{-5} to ≤ 1
  - Role of fluctuations is of increasing importance in mesolasers
  - *Control* of photon number and excitation number fluctuations is an outstanding challenge
- Capture physics of particle number quantization using master equations (a set of differential equations in continuous probability functions, P_{ns}) to describe quantized particle number states in the system

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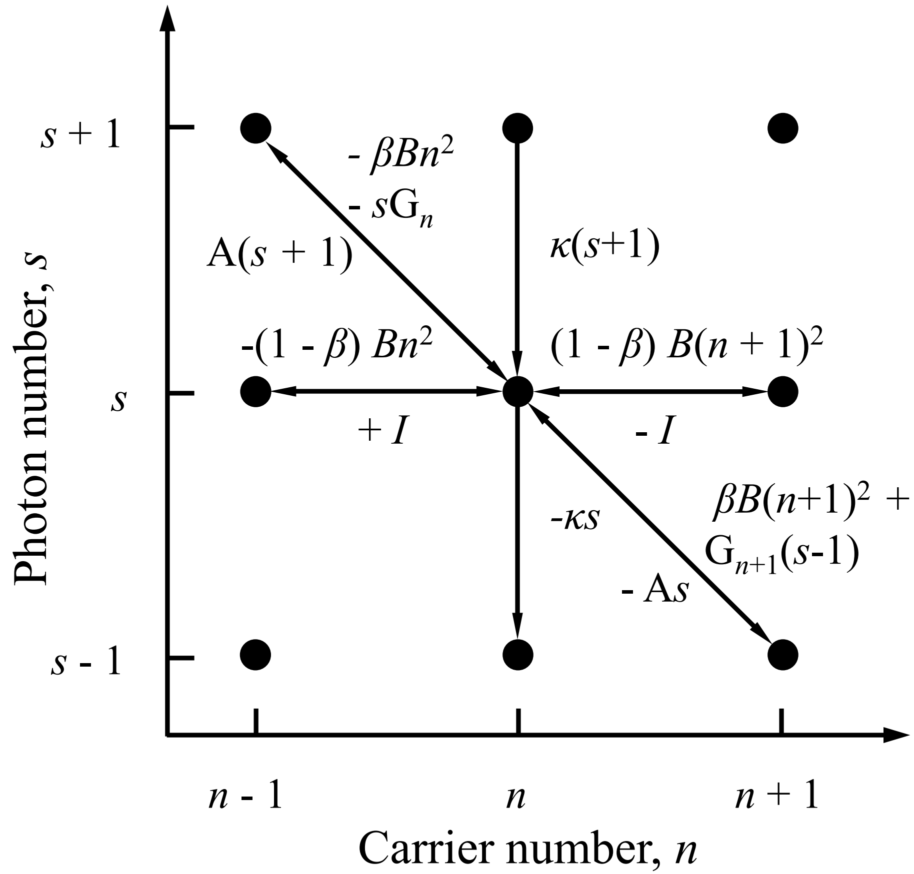
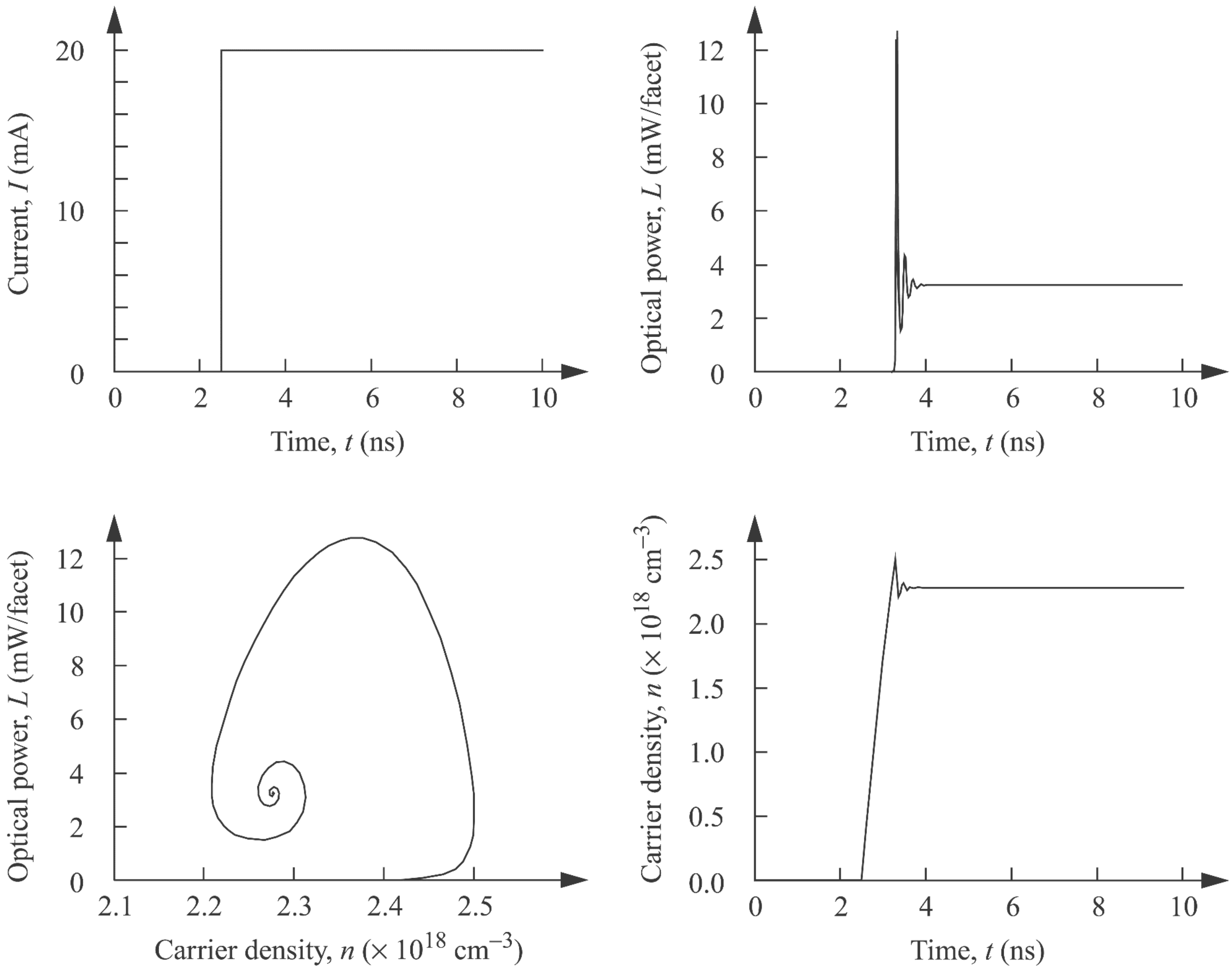


$$\frac{dP_{n,s}}{dt} = -\kappa(sP_{n,s} - (s+1)P_{n,s+1}) - (sG_n P_{n,s} - (s-1)G_{n+1}P_{n+1,s-1}) - (sAP_{n,s} - (s+1)AP_{n-1,s+1})$$
$$-\beta B(n^2 P_{n,s} - (n+1)^2 P_{n+1,s-1}) - (1-\beta)B(n^2 P_{n,s} - (n+1)^2 P_{n+1,s}) - I(P_{n,s} - P_{n-1,s})$$

- Capture physics of particle number quantization
  - Quantize photon number *s* and excited emitter electron particle number *n,* correlations $\langle ns\rangle \neq \langle n\rangle\langle s\rangle$, photon energy $\hbar\omega_0$

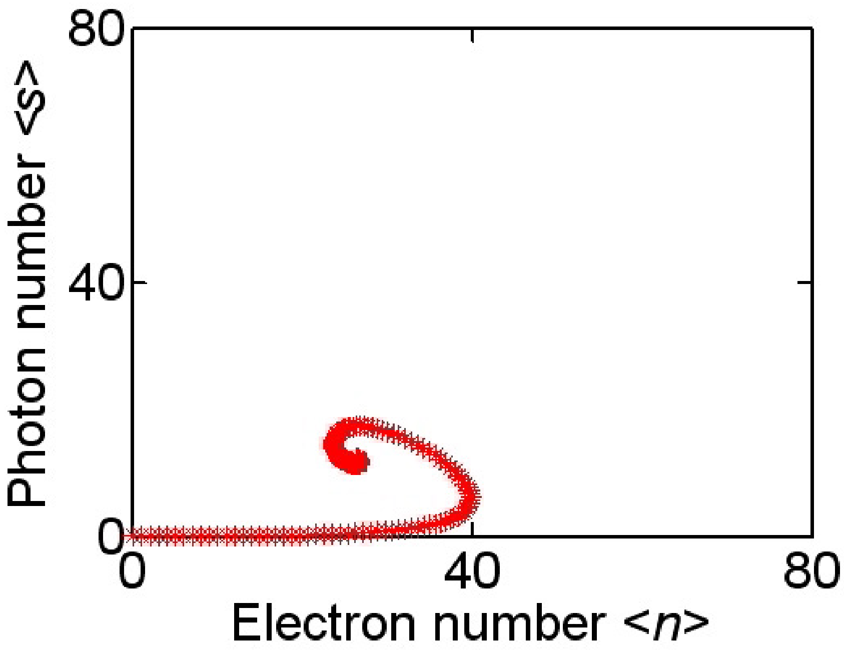
Continuum mean-field rate equation prediction

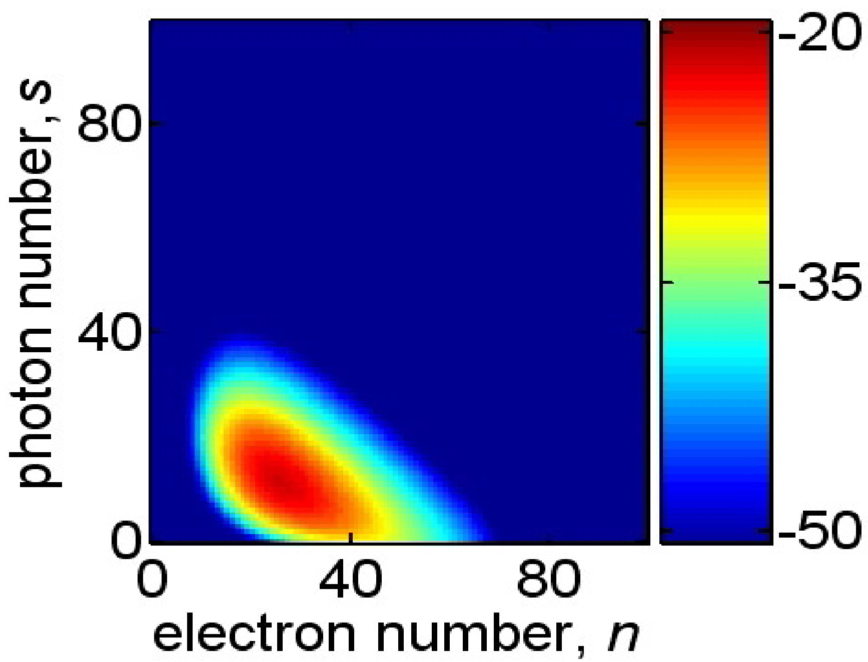


Comparison between mean-field and probabilistic picture

Continuum mean-field rate equation prediction

Modeling discrete quantum system using continuum probability functions, $P_{n,s}$

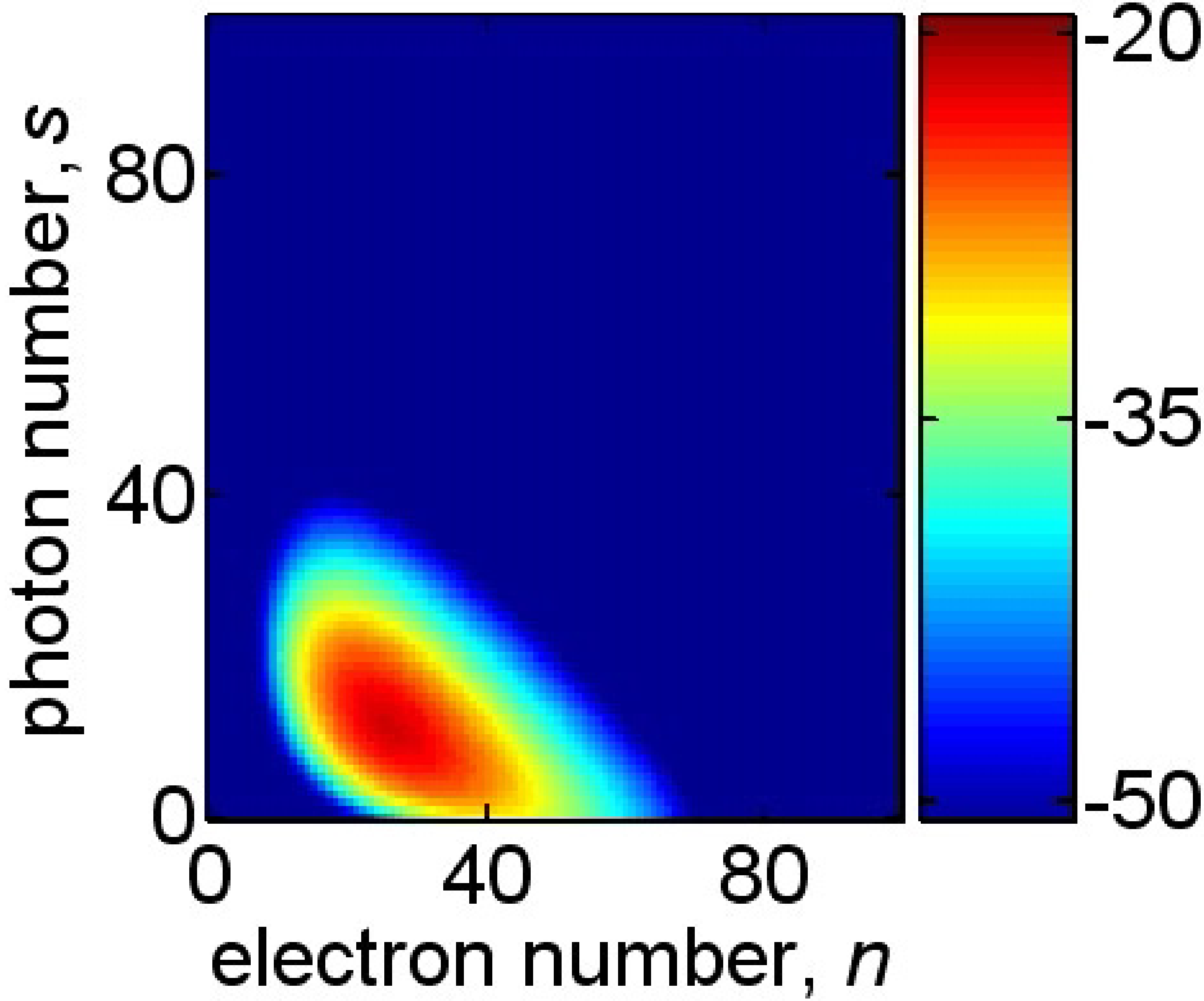




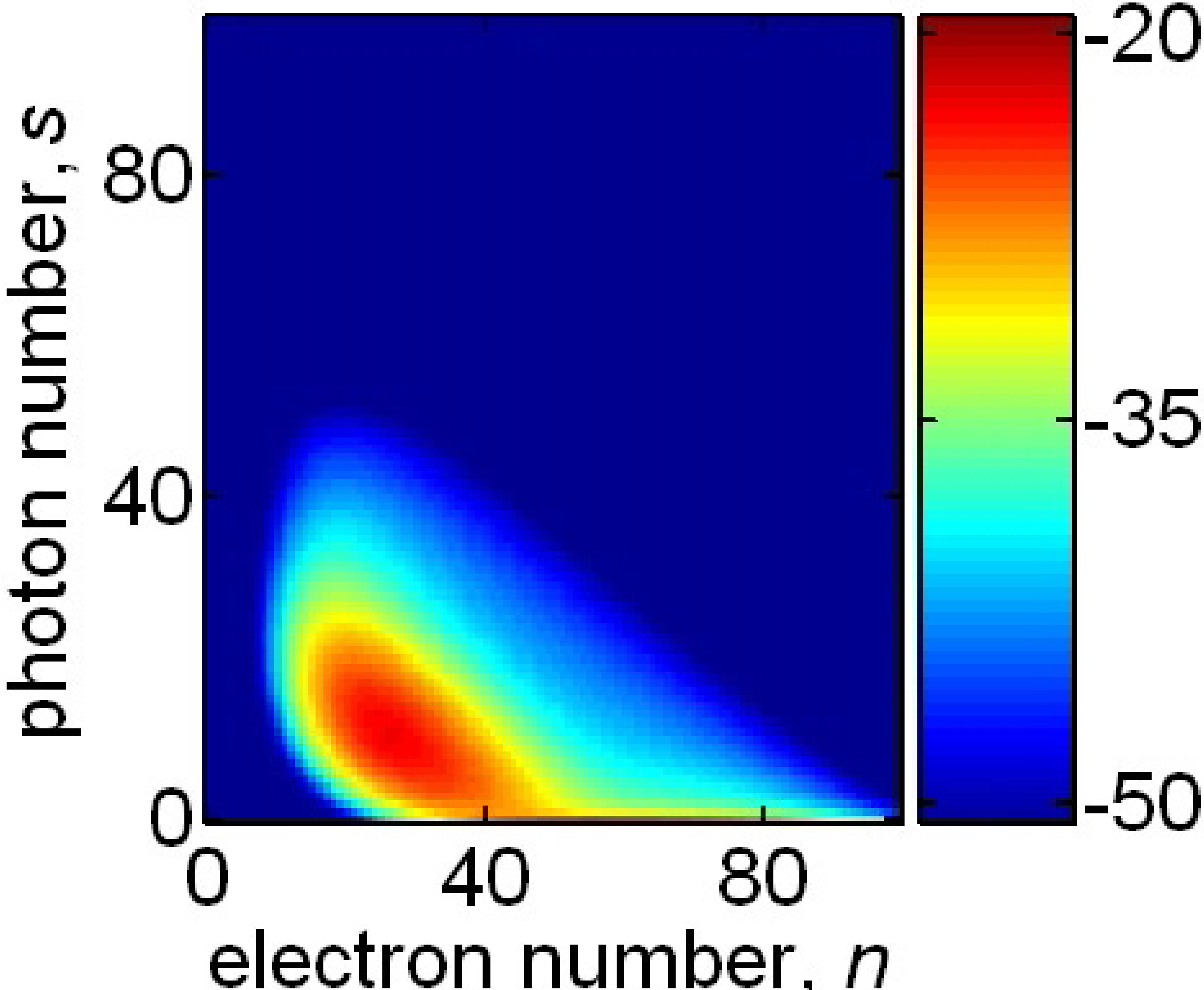
Approximate first moment (<n>, <s>) continuum mean–field model

Probabilistic semiclassical master equation picture, $P_{n,s}$ for n electron excitations and s photons in the cavity

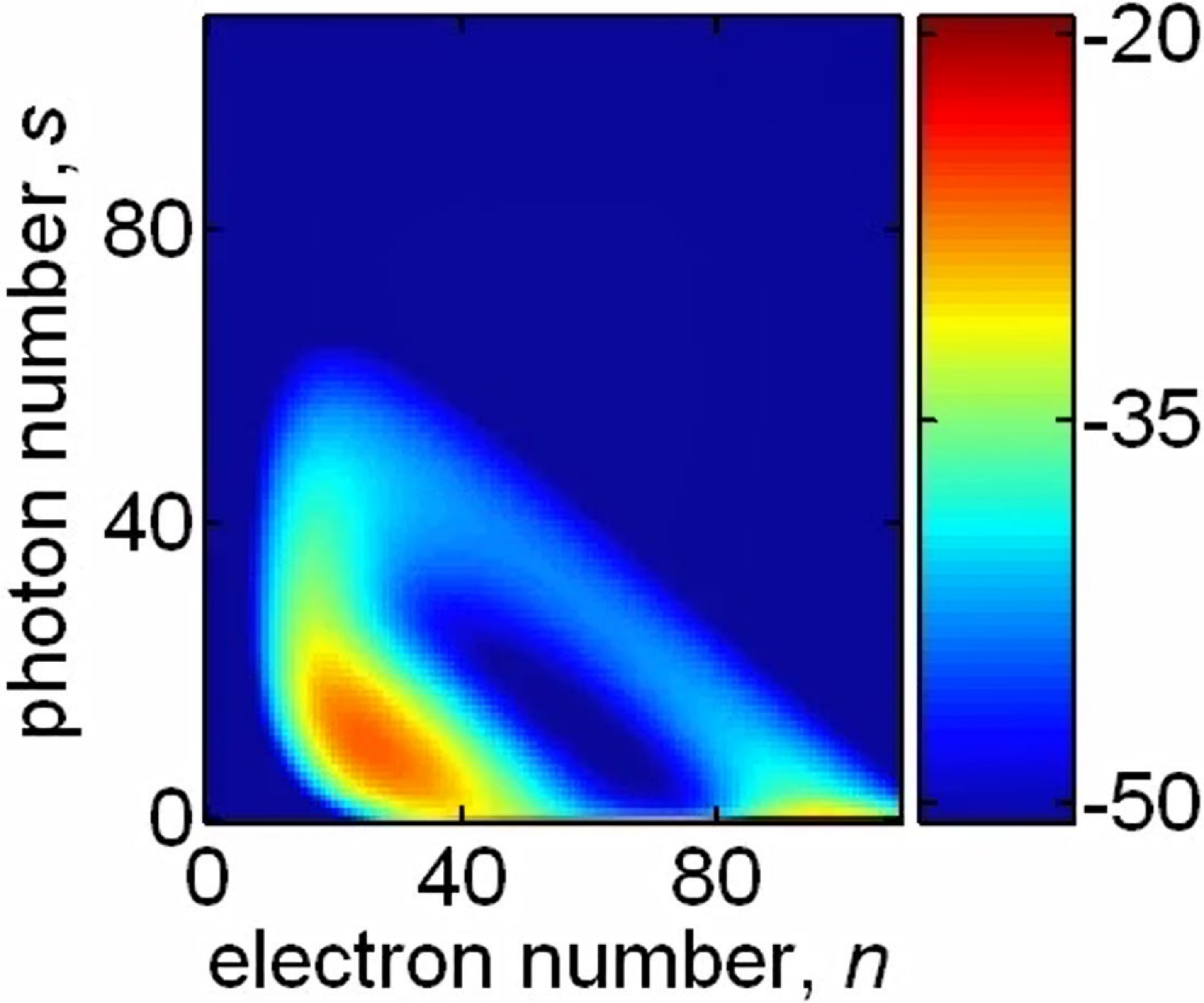
Time evolution of $10\log_{10}(P_{ns})$ for β=1



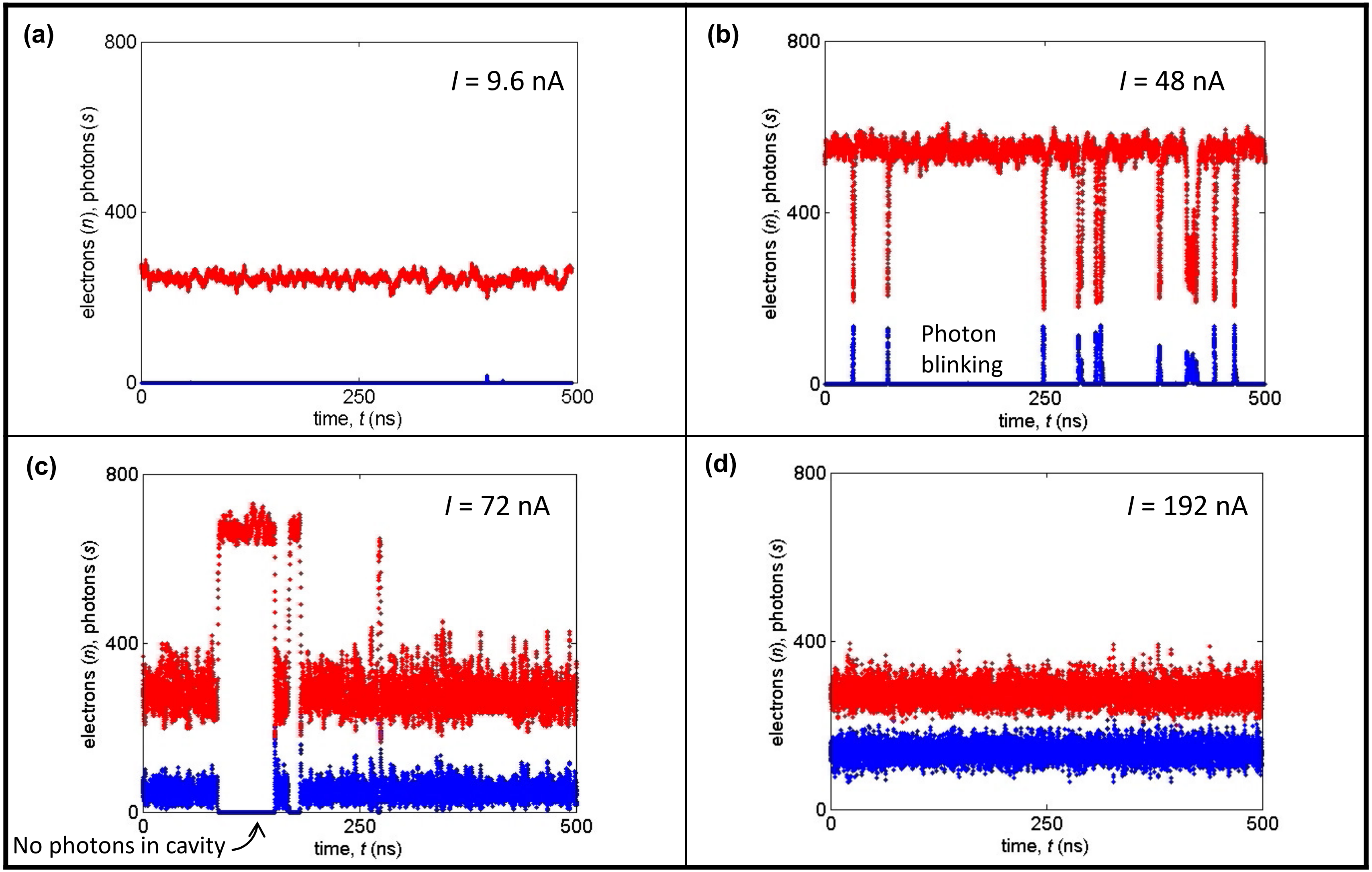
Time evolution of $10\log_{10}(P_{ns})$ for β=0.1



Time evolution of $10\log_{10}(P_{ns})$ for β=0.01



Semiclassical system trajectories by the Monte Carlo method



(a) I = 9.6 nA. (b) I = 48 nA. Note, photon blinking. (c) I = 72 nA. (d) I = 192 nA. Electrons (red), photons (blue).
Parameters : Volume = 0.1μm x 0.1μm x 10nm, Γ = 0.25, $a = 2.5 \times 10^{-18}$ cm^2 s^{-1}, $B = 10^{-10}$ cm^3 s^{-1}, $\beta = 10^{-4}$, $n_0 = 10^{18}$ cm^{-3}, α_i = 1 cm^{-1}, n_r = 4, $r = 1 - 10^{-6}$.

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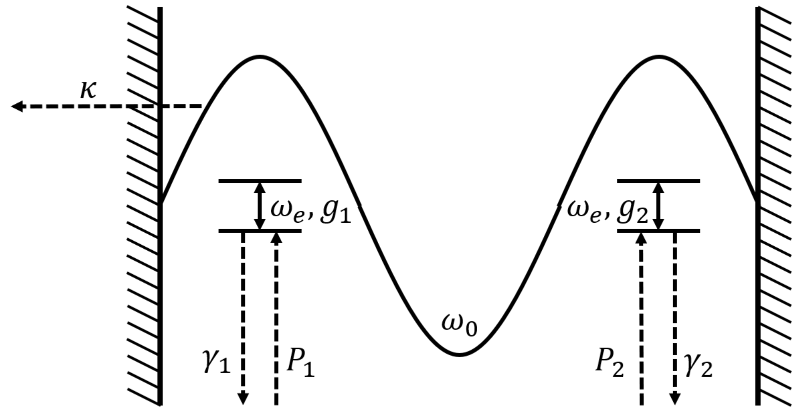
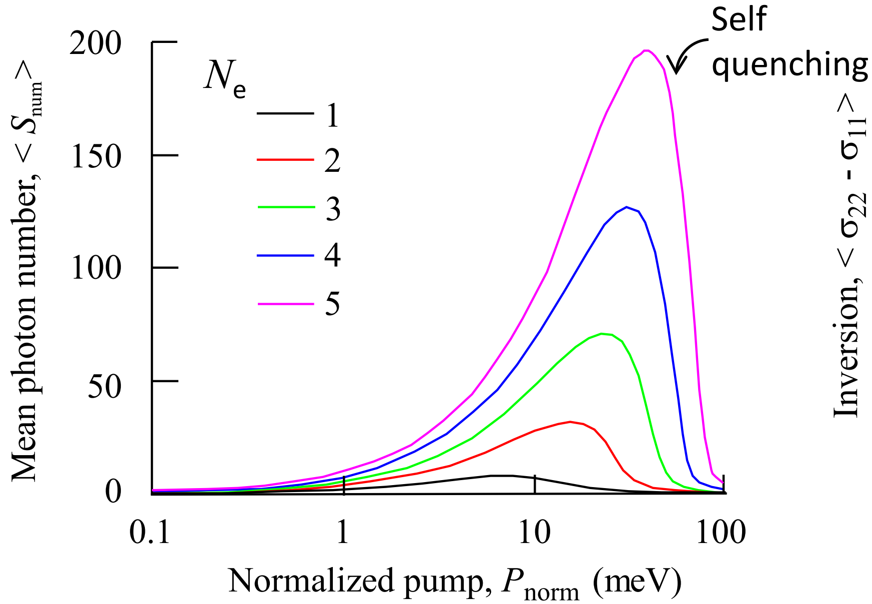


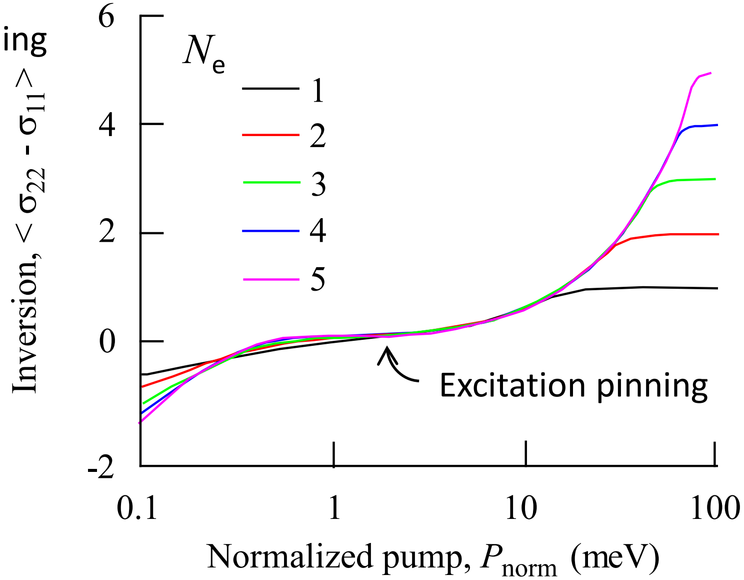
Solve open system with Linblad master equation:
(e.g. K. Roy-Choudhury and A. F. J. Levi, Phys. Rev. A **83**, 043827 (1-9) (2011))

$$\frac{\mathrm{d}\hat{\rho}}{\mathrm{dt}} = \frac{i}{\hbar}\left[\hat{\rho}, H_\mathrm{S}\right] + \frac{\kappa}{2}\left(2\hat{b}\hat{\rho}\hat{b}^\dagger - \hat{b}^\dagger\hat{b}\hat{\rho} - \hat{\rho}\hat{b}^\dagger\hat{b}\right)$$
$$+\sum_{n=1}^{N_e}\frac{\gamma_n}{2}\left(2\hat{\sigma}_n\hat{\rho}\hat{\sigma}_n^\dagger - \hat{\sigma}_n^\dagger\hat{\sigma}_n\hat{\rho} - \hat{\rho}\hat{\sigma}_n^\dagger\hat{\sigma}_n\right)$$
$$+\sum_{n=1}^{N_e}\frac{P_n}{2}\left(2\hat{\sigma}_n^\dagger\hat{\rho}\hat{\sigma}_n - \hat{\sigma}_n\hat{\sigma}_n^\dagger\hat{\rho} - \hat{\rho}\hat{\sigma}_n\hat{\sigma}_n^\dagger\right)$$

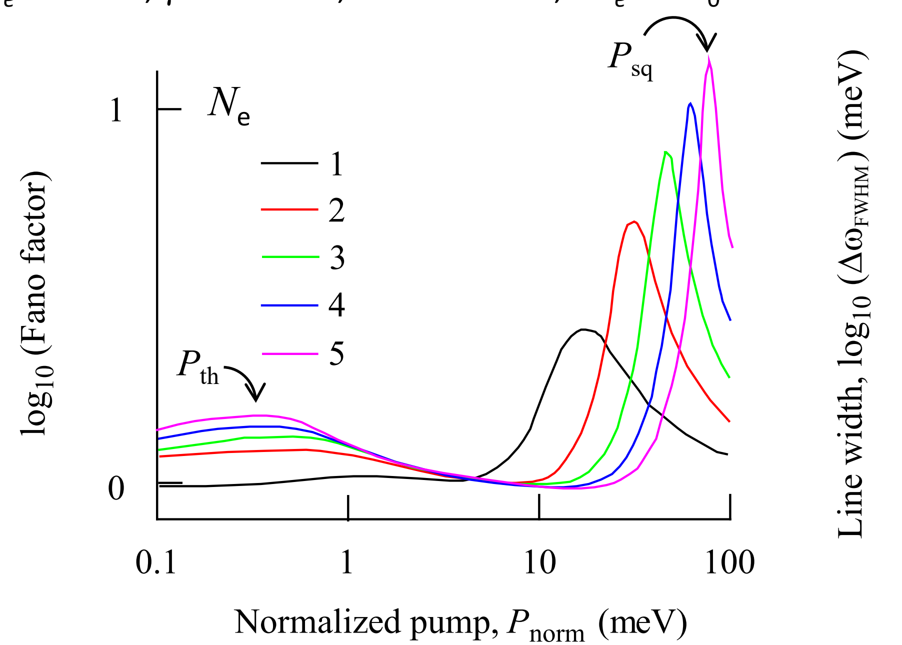
$$H_\mathrm{S} = \hbar\omega_0\hat{b}^\dagger\hat{b} + \sum_{n=1}^{N_e}\hbar\omega_e\hat{\sigma}_n^\dagger\hat{\sigma}_n + \sum_{n=1}^{N_e}\hbar g_e\left(\hat{b}\hat{\sigma}_n^\dagger + \hat{b}^\dagger\hat{\sigma}_n\right)$$

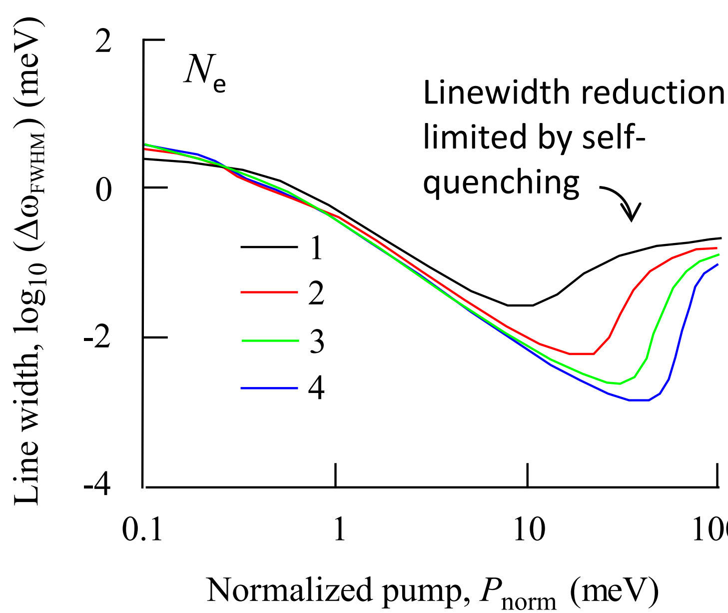
Steady-state properties as a function of pump and number of emitters





g_e = 1 meV, γ = 0.1 meV, κ = 0.25 meV, $\hbar\omega_e = \hbar\omega_0$ = 1000 meV





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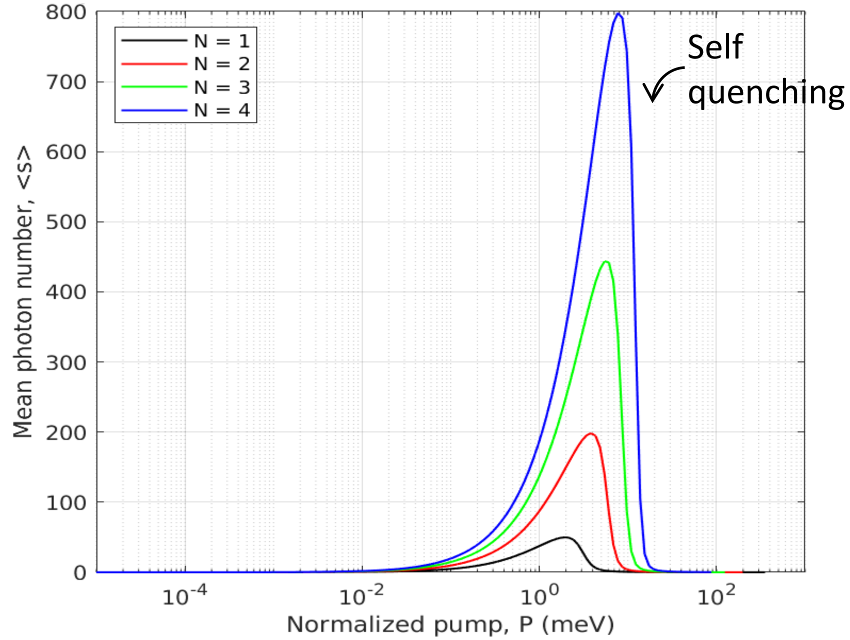
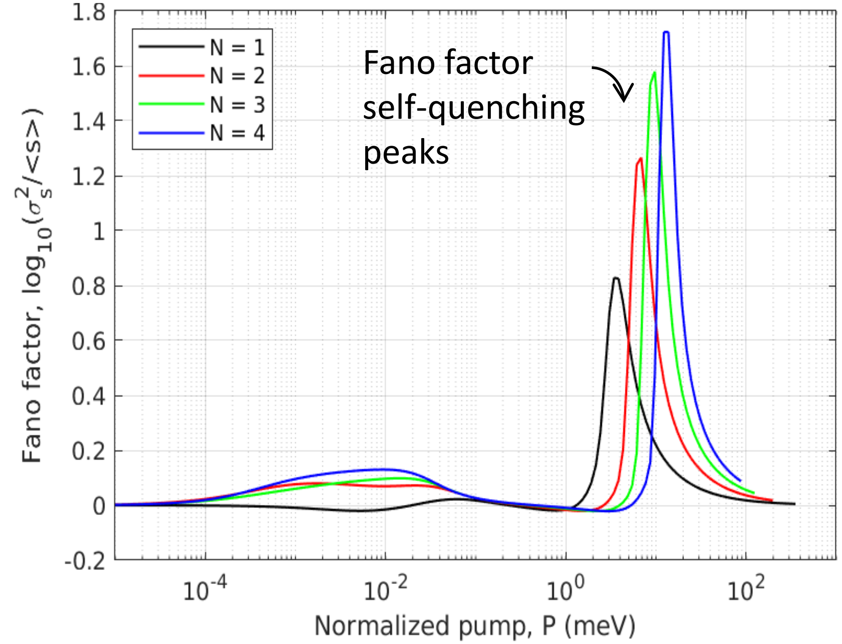
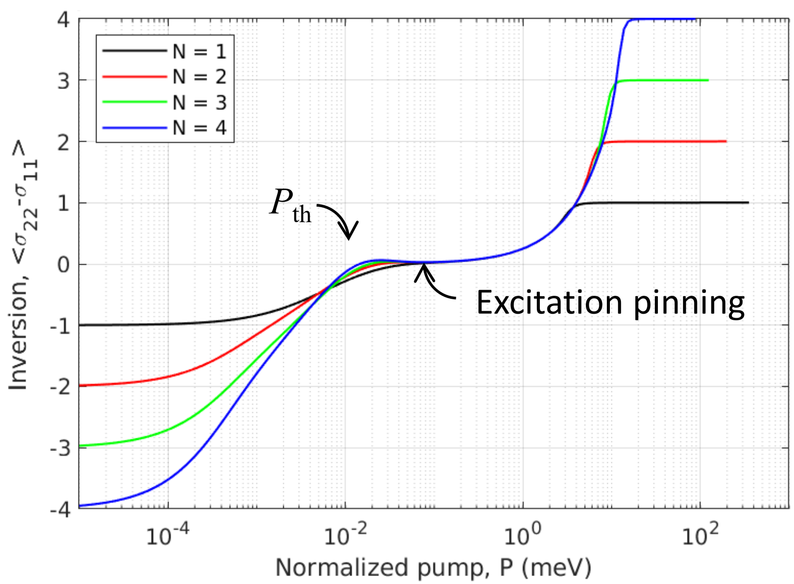
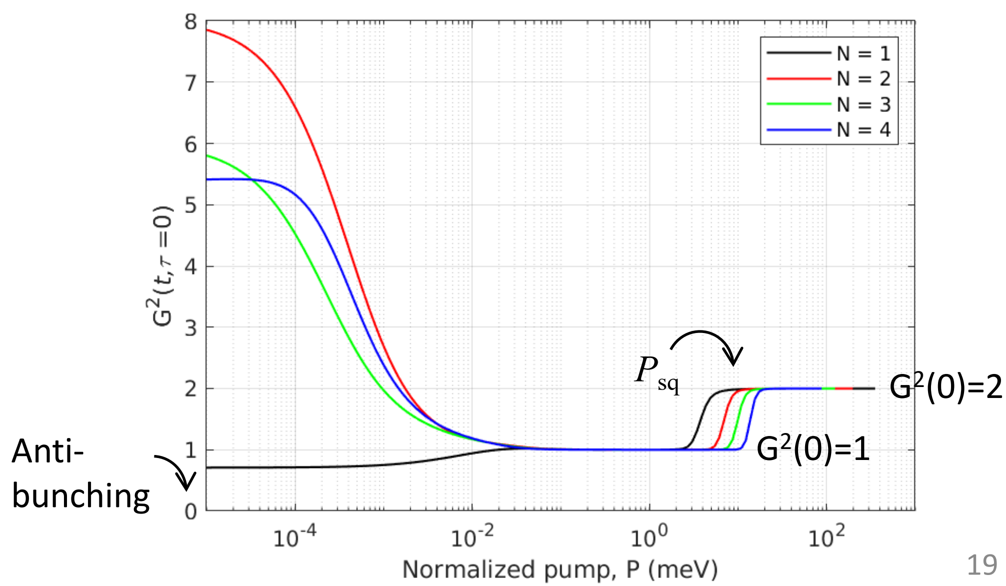


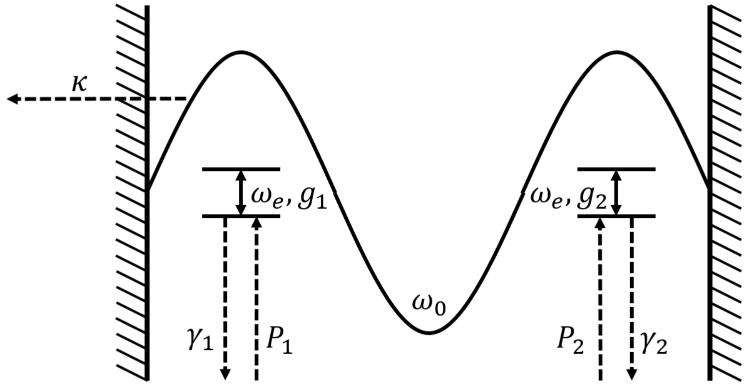


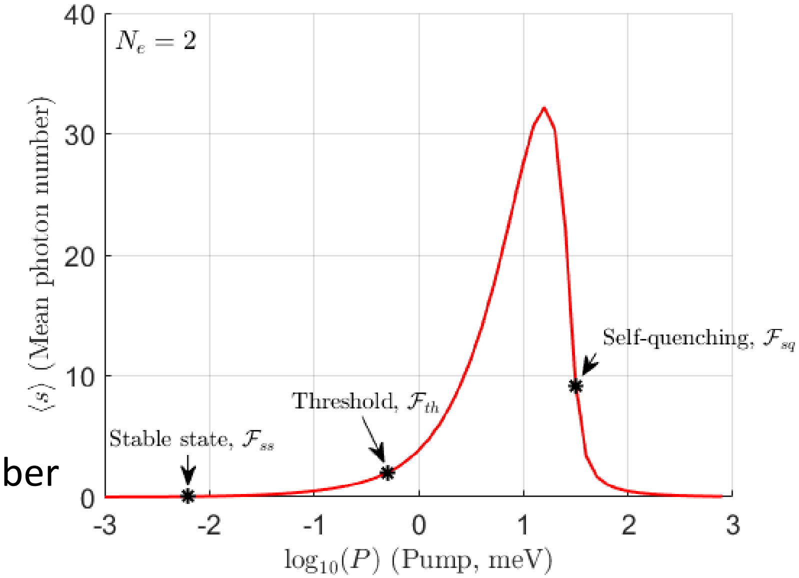
g_e = 0.1 meV, γ = 0.001 meV, κ = 0.01 meV, $\hbar\omega_e = \hbar\omega_0$ = 1000 meV





Symmetry-protected long-lived emitter states in meso-lasers





Photon Fano factor measures spread in photon number distribution normalized to mean photon number

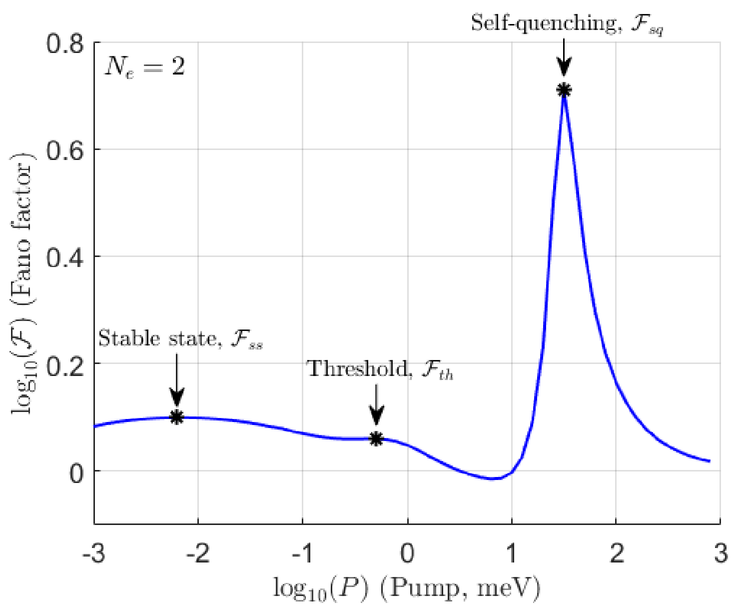
$$\mathcal{F}(\hat{\rho}) = \frac{\sigma_s^2}{\langle s \rangle} = \frac{Tr(\hat{\rho}\hat{s}^2) - Tr(\hat{\rho}\hat{s})^2}{Tr(\hat{\rho}\hat{s})}$$

$N_e = 2$ symmetry-protected long-lived emitter state

$$|\psi_-\rangle_e = \frac{1}{\sqrt{2}}\left(|10\rangle_e - |01\rangle_e\right)$$

$N_e = 2$ short-lived emitter state coupling to cavity mode

$$|\psi_+\rangle_e = \frac{1}{\sqrt{2}}\left(|10\rangle_e + |01\rangle_e\right)$$

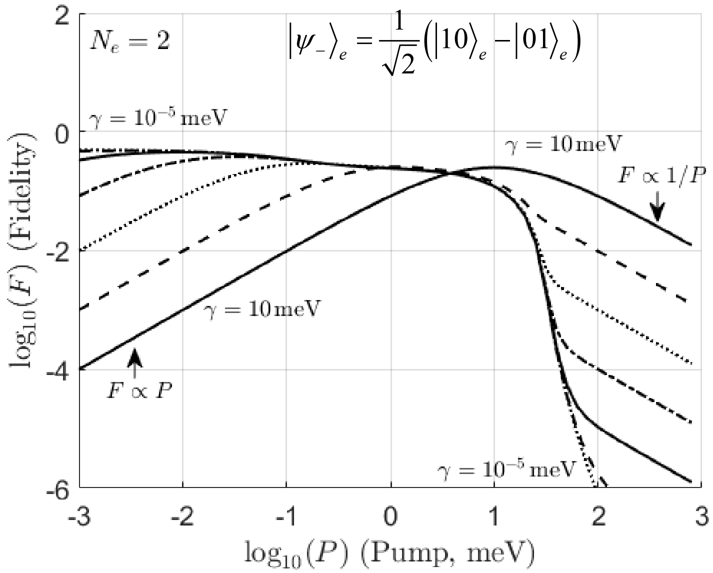


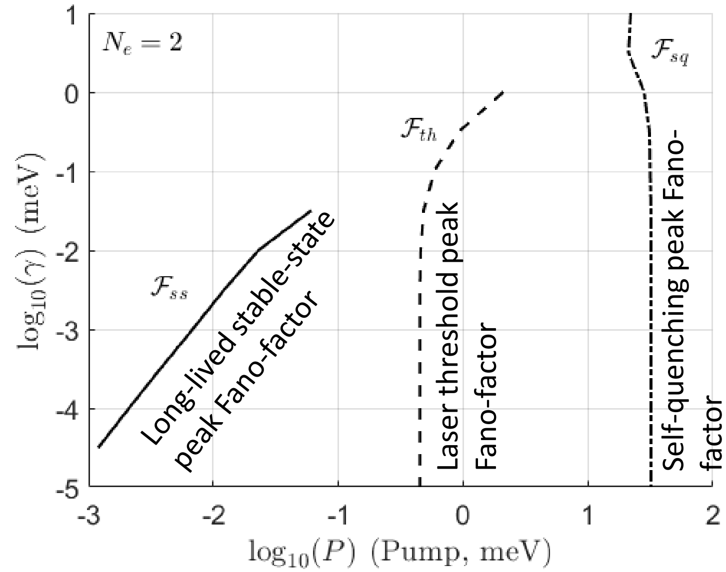
Fidelity measures similarity between two density matrices

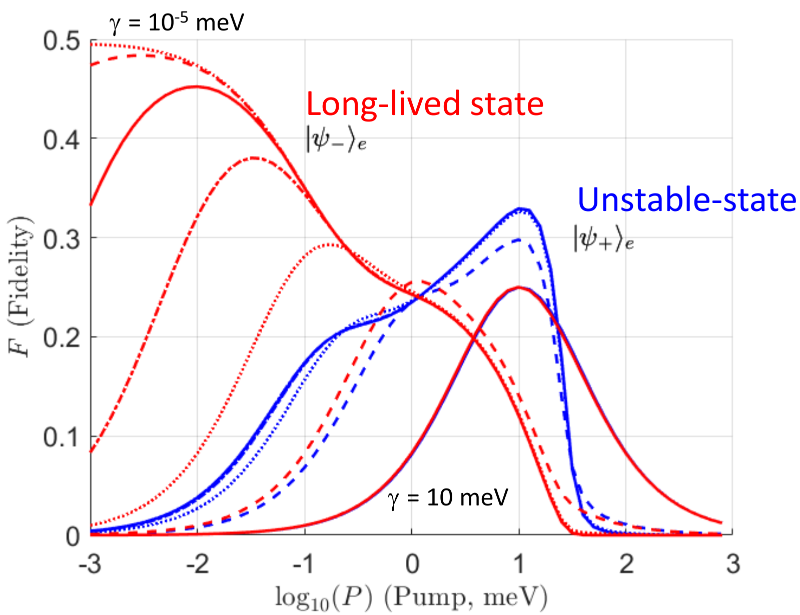
$$F(\hat{\rho}_1, \hat{\rho}_2) = Tr\left[\sqrt{\sqrt{\hat{\rho}_1}\hat{\rho}_2\sqrt{\hat{\rho}_1}}\right]^2$$

$g_1 = g_2 = g_e = 1$ meV, $\gamma_1 = \gamma_2 = \gamma = 10^{-3}$ meV, $\kappa = 0.25$ meV
$P_1 = P_2$ and normalized to number of emitters

Behavioral regimes for long-lived emitter states in meso-lasers







g = 1 meV, $\gamma = 10^{-5}$ - 10 meV, and κ = 0.25 meV

Values of pump, P, at which the Fano factor peaks for a given value of γ (loss into non-lasing modes) indicating transitions between regimes of different dynamic behavior

N_e = 2, g = 1 meV, and κ = 0.25 meV.

In phase transition analogy, Fano factor peaks *separate* different characteristic behavior

Lifetime τ_- of symmetry-protected long-lived state determined by γ and P, so can have τ_- > 1ns

Lifetime τ_+ of short-lived state determined by fastest process coupling to the cavity mode, in this case via g, so τ_- ~ 1 ps

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- Photon and excitation fluctuations in both classical macroscopic and mesoscale lasers play an important role in determining device performance
  - While mesoscale lasers might exhibit quantum behavior, there is no agreed *measure* of how much quantumness (wave-particle duality, identical indistinguishable particles, linear superposition of particle states, non-local entanglement of particles, …)
- Fluctuations peak around transitions between characteristic behavioral modes of operation
  - Laser threshold: analogous to a second-order non-equilibrium phase transition with the optical field as the order-parameter
  - Self-quenching: excitation saturation
  - Symmetry-protected long-lived states
- Control of fluctuations and associated dissipation (n.b. the fluctuation-dissipation theorem) can result in useful device behavior
  - For example, a macroscopic laser diode operating close to the thermodynamic limit can have a lasing mode emission linewidth and photon Fano-factor that decreases with increasing injection current $I_{inj} > I_{th}$.
  - In contrast, the reduction in linewidth and reduction in photon Fano-factor in a mesolaser as pump is increased to values greater than P_{th} is limited by the existence of self-quenching as pump values approach P_{sq}
- Overcoming practical limitations associated with control of mesoscale laser behavior presents an interesting challenge whose successful solution might be demonstrated by suppression of fluctuations that occurs near laser threshold, self-quenching, or dissipation in symmetry-protected quantum states

Acknowledgements

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Walter Unglaub

K. Roy-Choudhury and A. F. J. Levi, “Quantum fluctuations and saturable absorption in mesoscale lasers” Phys. Rev. A **83**, 043827 (1-9) (2011))

Amine Abouzaid, Walater Unglaub, and A. F. J. Levi, “Behavioral regimes and long-lived emitter states in mesolasers” J. Phys. B **52**, 245401 (2019)

END