Locating lasing threshold in a thresholdless laser

SAND2014-16486PE

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Motivation

Setup

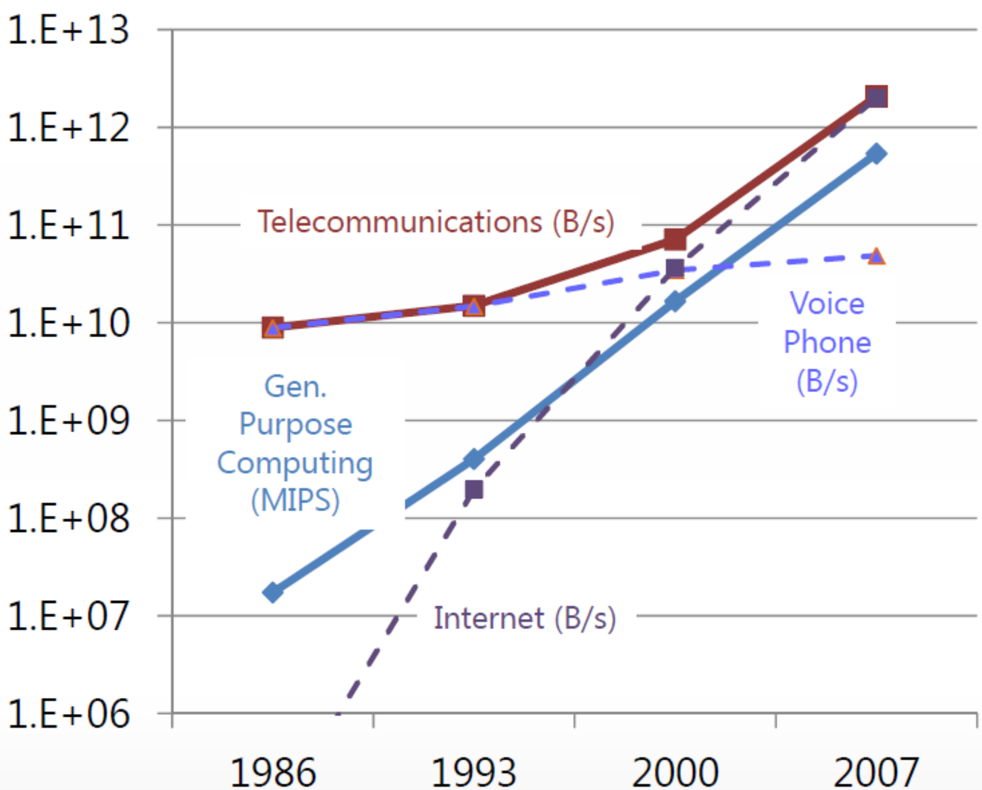
Examples: a) Thresholdless lasing
b) Single-photon source

Thanks to:
Sandia's LDRD program, funded by U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why fund nanolaser development?

Attojoule optoelectronics – why and how

David Miller IEEE Photonics Summer Topicals, 2013



M. Hilbert and P. Lopez, "The World's Technological Capacity to Store, Communicate, and Compute Information," Science 332, 60 (2011)

MIPS – million instructions per second
~ 3 - 6 instructions = 1 floating point operation (FLOP)

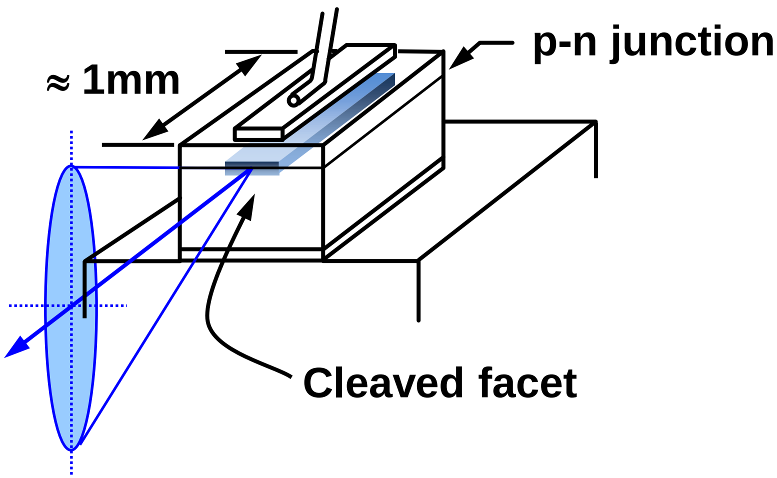
Both
- Internet traffic
- General purpose computing hardware

growing ~ 60 % per year
- ~ X 100 in 10 years

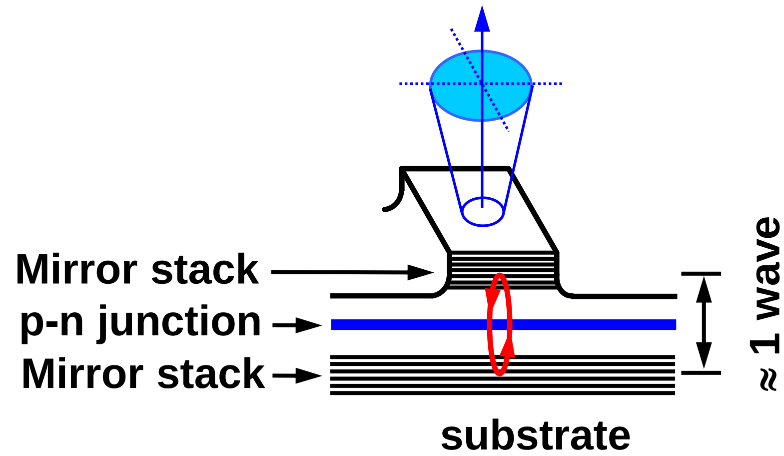
Massive challenge for hardware scaling of
- Energy
  - Energy per bit has to reduce
    - Energy scaling not environmentally sustainable
      - Information technology already (2006) consumed ~ 1.5% of US electricity
- Communication density inside systems
  - already at limits for electrical approaches

Towards smaller and smaller lasers

Edge - Emitting Laser

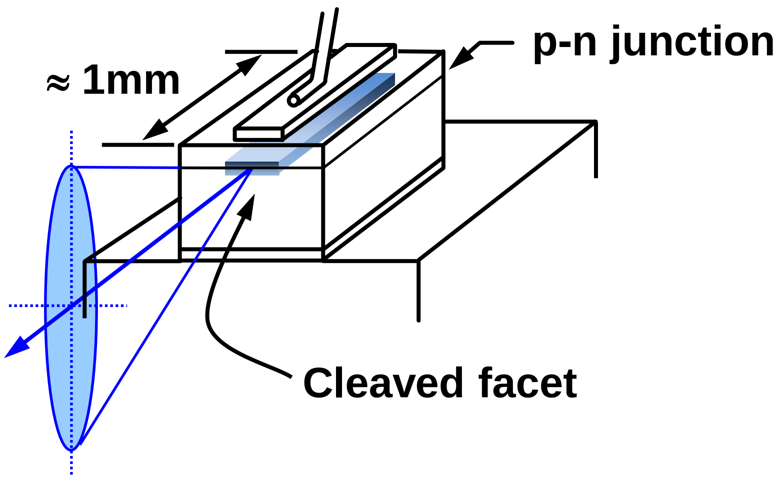


Vertical-Cavity Surface-Emitting Laser (VCSEL)



Towards smaller and smaller lasers

Edge - Emitting Laser



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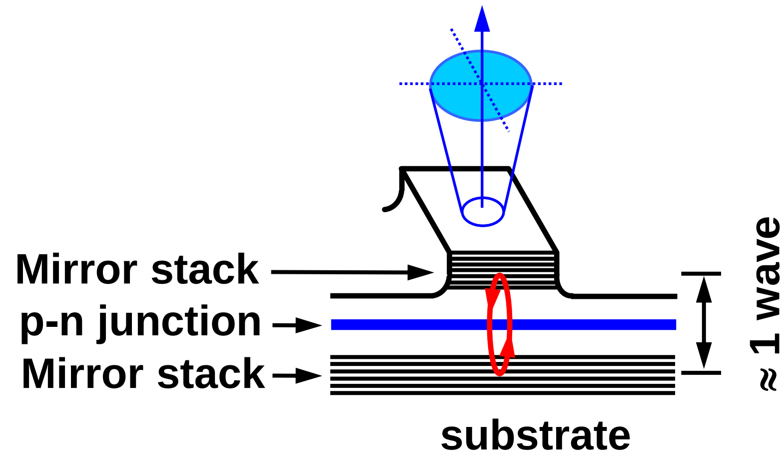


Nanolasers

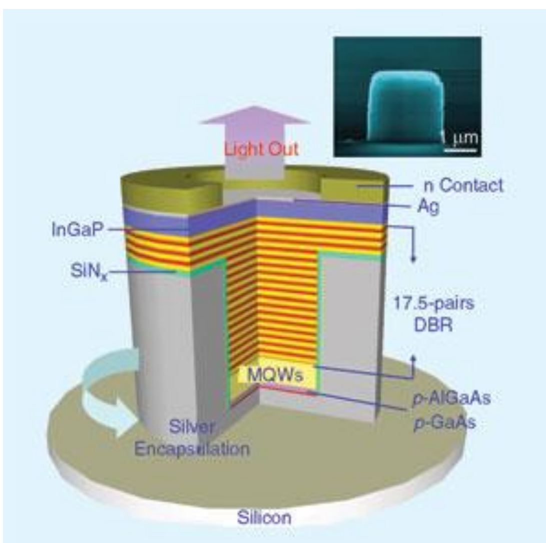
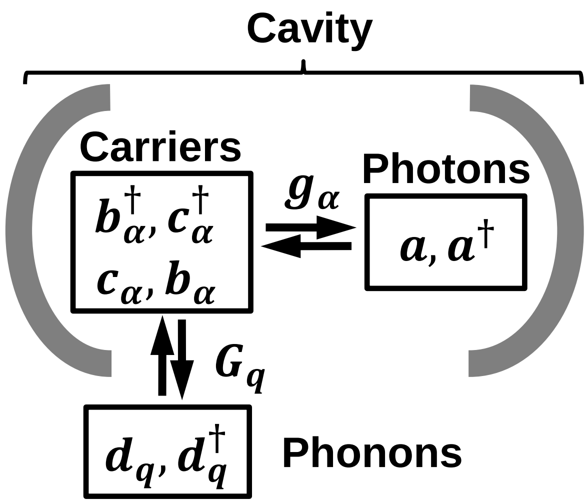


Figure 6. Combining semiconductors and metals enables nanolasers having a footprint roughly a factor <u>100 smaller</u> than that of a classical VCSEL. Adapted from a figure originally created by C. Y. Lu et al., UIUC.

Taken from D. Bimberg, IEEE Photonics Society Research Highlights

How we used to study semiconductor lasers



$$H = H_0$$ *Single-particle energies*

$$-\hbar\sum_{\alpha}\left(g_\alpha b_\alpha^\dagger c_\alpha^\dagger a - g_\alpha^* a^\dagger c_\alpha b_\alpha\right)$$ *Light-carrier*

$$+\hbar\sum_{\alpha\beta q} G_q\left(c_\alpha^\dagger c_\beta + b_\alpha^\dagger b_\beta\right)\left(d_q + d_q^\dagger\right)$$ *Carrier-phonon*

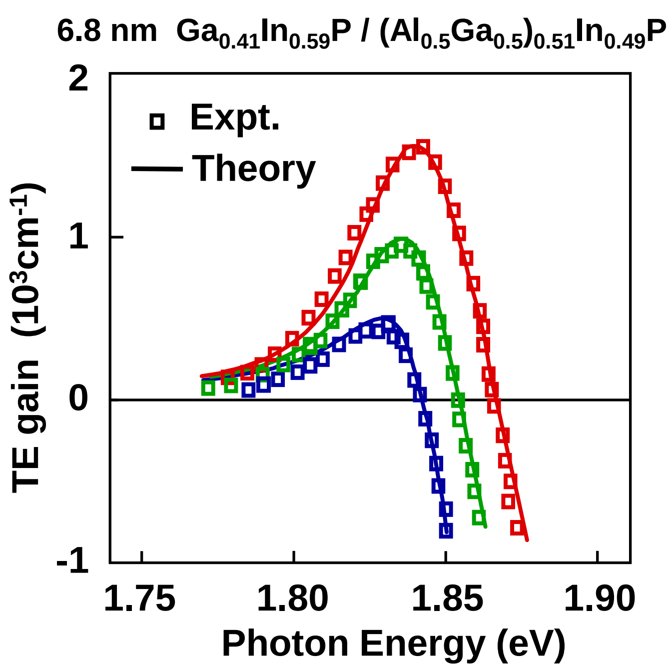
Carrier-carrier

$$+\frac{1}{2}\sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, c_\alpha^\dagger c_\beta^\dagger c_\eta c_\sigma + \frac{1}{2}\sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger b_\beta^\dagger b_\eta b_\sigma$$

$$-\sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger c_\beta^\dagger c_\eta b_\sigma$$

Matrix element of

$$\frac{e^2}{4\pi\varepsilon_b|r - r'|}$$



Chow, Smowton, Blood, Girdnt, Jahnke, Koch, APL.71, 157 (1997)

$$\langle c_\alpha^\dagger c_\alpha\rangle, \langle b_\alpha^\dagger b_\alpha\rangle, \langle a^\dagger a\rangle, \langle c_\alpha^\dagger b_\alpha^\dagger a\rangle$$

$$\left\langle c_\alpha^\dagger c_\beta^\dagger\, c_\eta\, c_\sigma\right\rangle, \left\langle c_\alpha^\dagger c_\beta^\dagger\, (d_q^\dagger)^n (d_q)^m\right\rangle$$

What we do differently with nanolasers

Injection current

QW: $n_{e,k}^{QW}\,,\; n_{h,k}^{QW}$

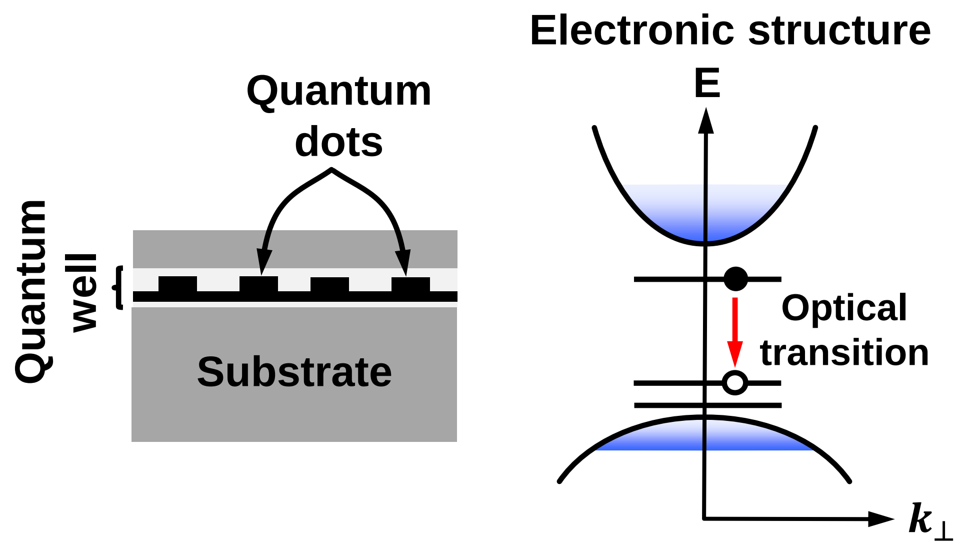
$\gamma_{c-c}\,,\,\gamma_{c-p}$

QDs: $\langle c_n^\dagger c_n \rangle$, $\langle b_n^\dagger b_n \rangle$, $\langle c_n^\dagger b_n^\dagger a \rangle$ — ω_n

$$g \leftarrow \wp \sqrt{\frac{\nu}{\hbar \epsilon_b V}}\, W(R_{QD}) \sum_n C(R_n)\, V(R_n)$$

Photons: $\langle a^\dagger a \rangle$, $\langle a^\dagger a(\tau) \rangle$ ← Coherence time

$\langle a^\dagger a^\dagger a\, a \rangle$, $\langle a^\dagger a^\dagger a\, b_n c_n \rangle$, $\langle a^\dagger a\, c_n^\dagger c_n \rangle$, $\langle a^\dagger a\, b_n^\dagger b_n \rangle$ } $g^{(2)}(0)$

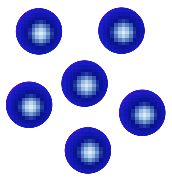
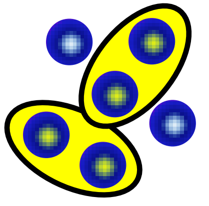
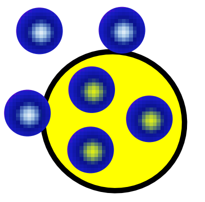


Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

Similarities and difference with AMO

Cluster expansion

Single particles | Correlated pairs | Correlated 3-particle clusters

$\langle \hat{N} \rangle =$  $+$  $+$  $+ \ldots$

$\langle c_\alpha^\dagger c_\alpha \rangle, \langle b_\alpha^\dagger b_\alpha \rangle, \langle c_\alpha^\dagger b_\alpha^\dagger a \rangle, \langle a^\dagger a \rangle$

Example $\langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle = \langle c_\alpha^\dagger c_\alpha \rangle \langle a^\dagger a \rangle + \delta \langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle$ $\left(c_\alpha c_\beta - c_\beta c_\alpha = 0 \right)$

Normal ordered: $\frac{d}{dt} c_\alpha^\dagger c_\alpha a^\dagger a = -g_\alpha b_\alpha^\dagger c_\alpha^\dagger a^\dagger a a + \sum_\beta g_\beta b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a + h.a.$

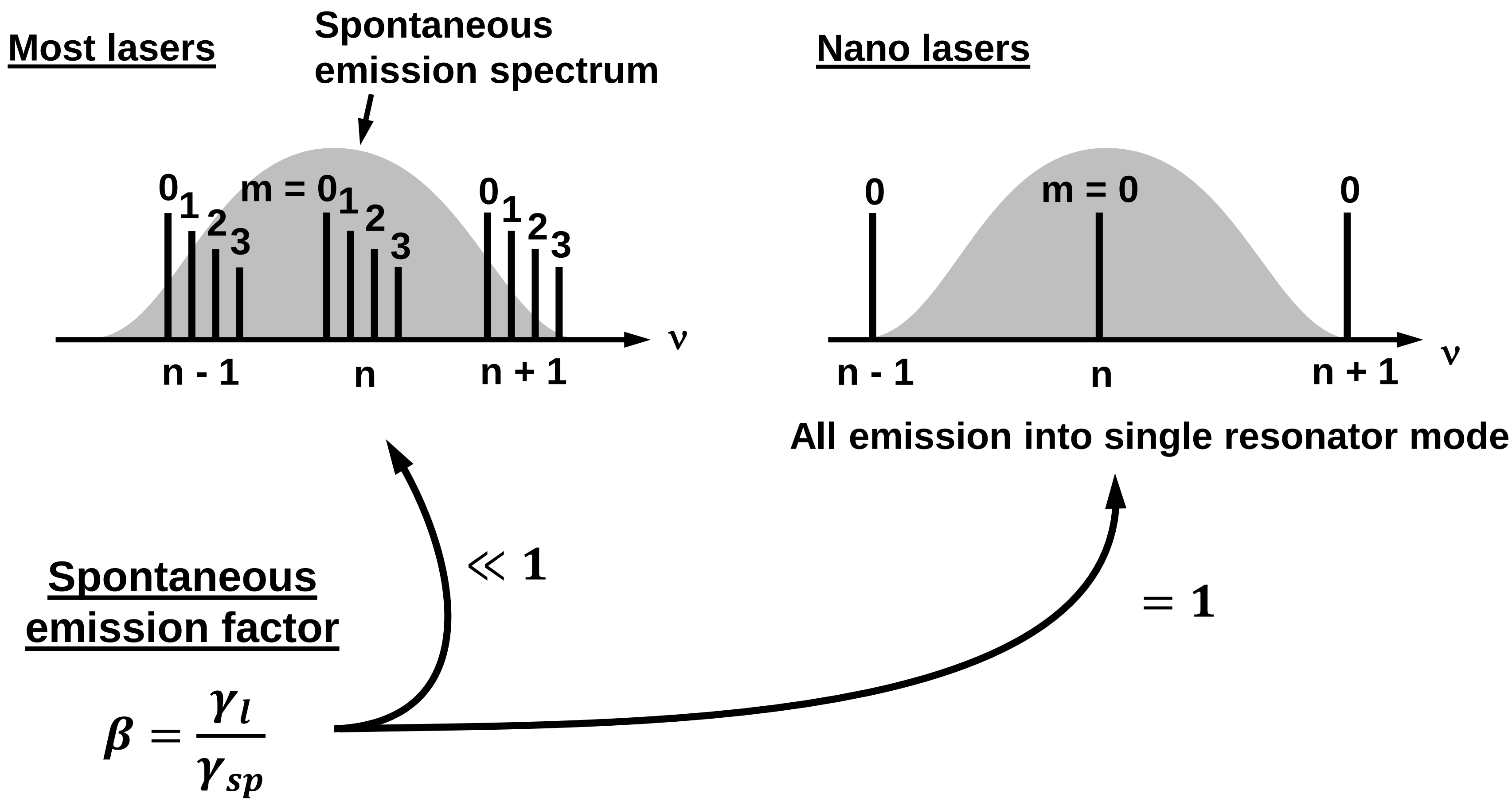
Factorization: $\left\langle b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a \right\rangle = (1 - \delta_{\alpha\beta}) p_\beta n_e^\alpha + \delta \left\langle b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a \right\rangle$

⋮

$$\frac{d}{dt} \delta \langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle = \frac{d}{dt} \langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle - \frac{d n_e^\alpha n_p}{dt}$$

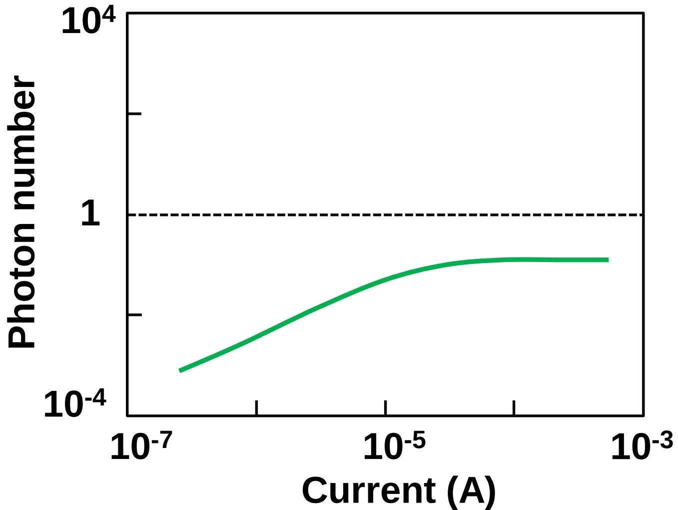
$$= -g_\alpha p_\alpha (n_e^\alpha + n_p) - g_\alpha \delta \langle b_\alpha^\dagger c_\alpha^\dagger a^\dagger a a \rangle + \sum_\beta \delta \left\langle b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a \right\rangle + c.c.$$

Why work on nanolasers?

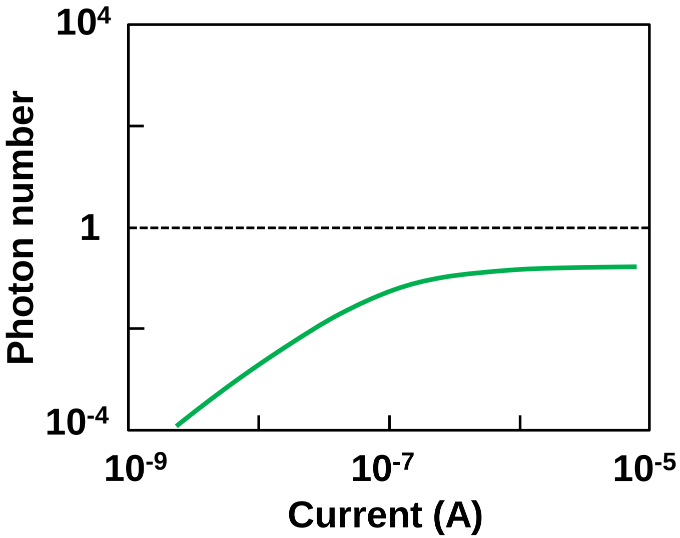


N_{QD} = 50, Δ_{inh} = 20meV, γ_c = 10^{10}, 5 x 10^{10}, 10^{11}, 5 x $10^{11}$$s^{-1}$

β = 0.01



β = 1



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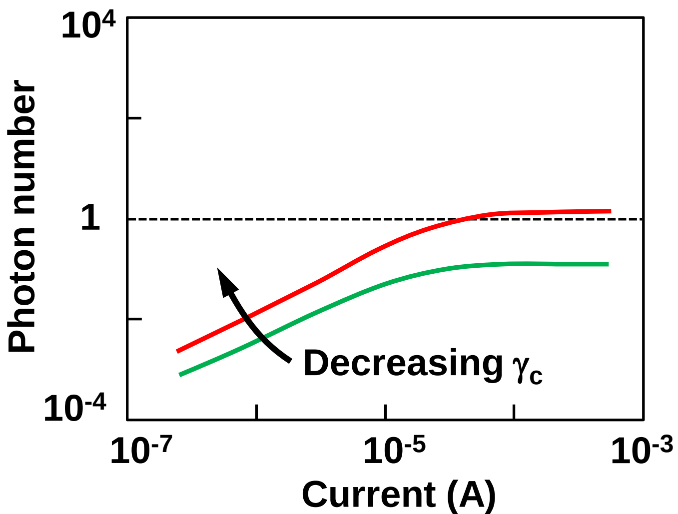

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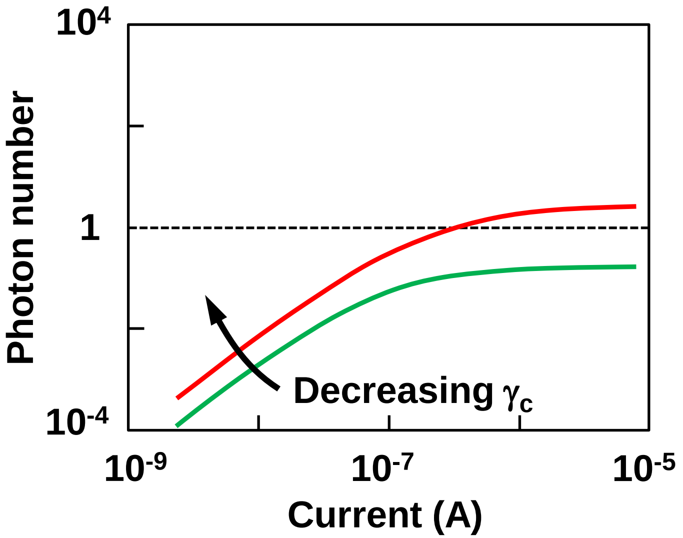

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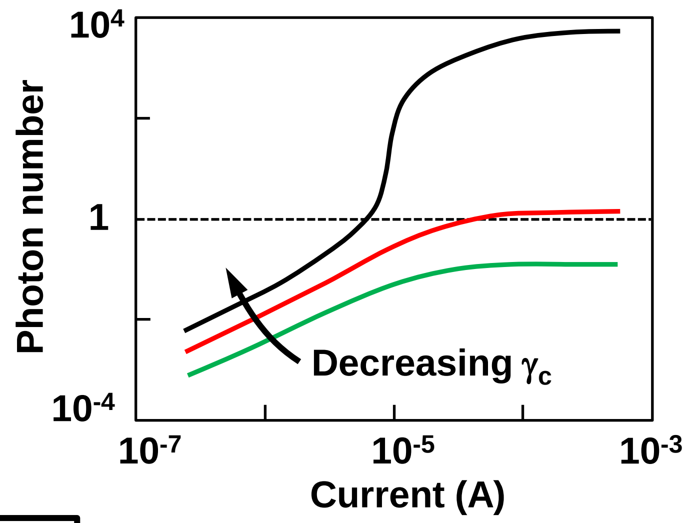

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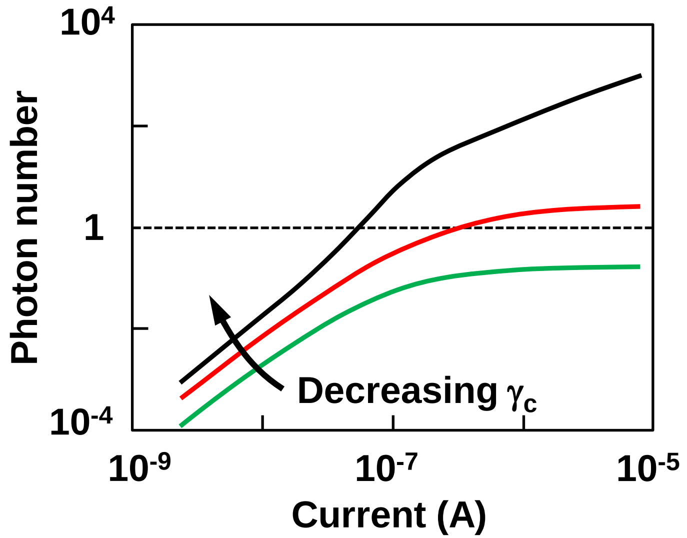

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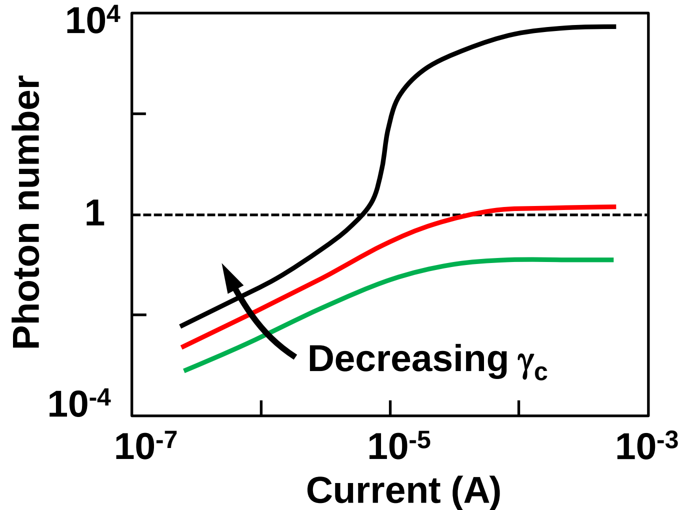
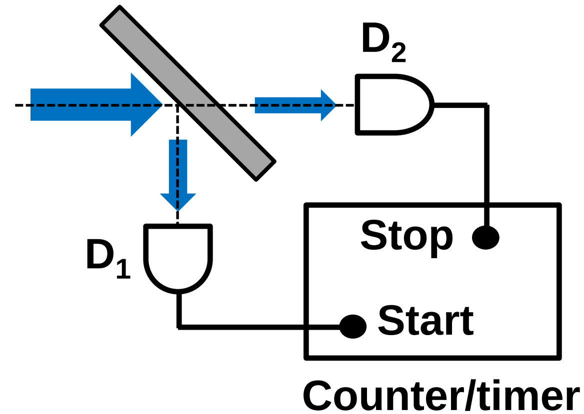


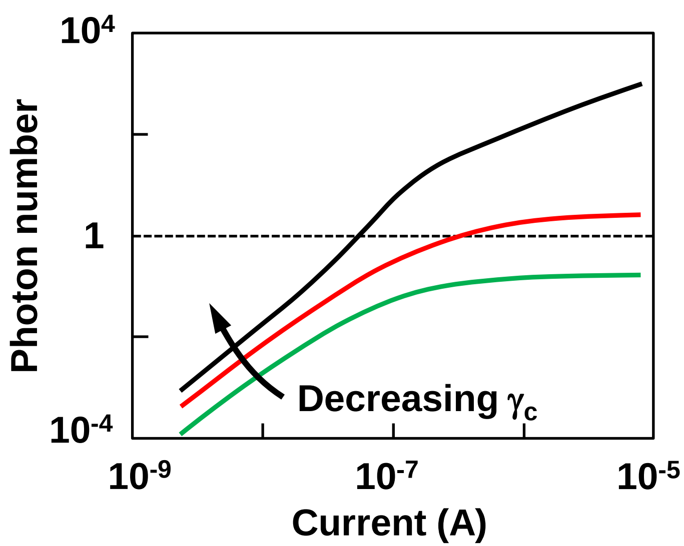
Hanbury-Brown-Twiss experiment

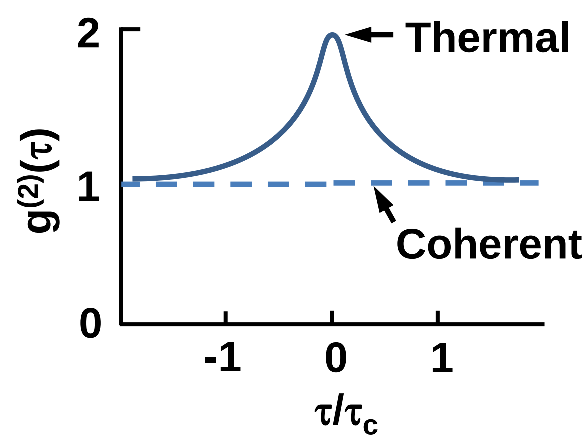


Second-order correlation function

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

β = 1





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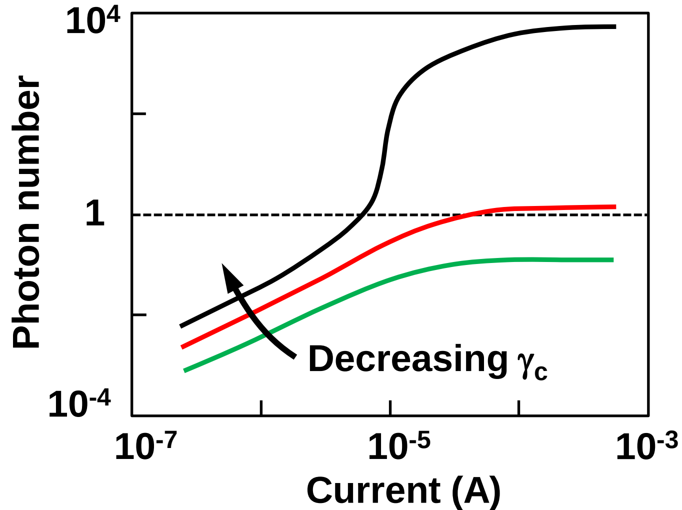
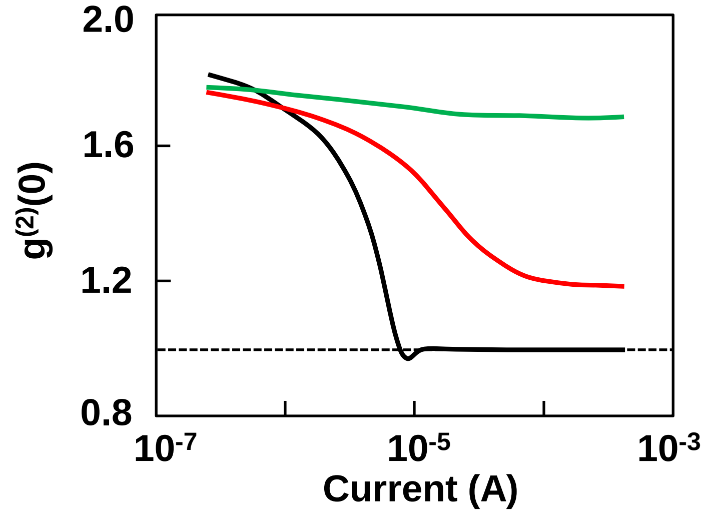
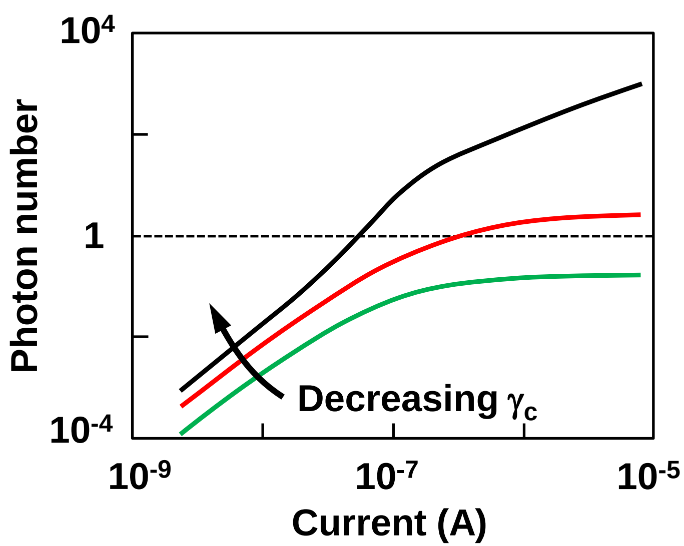
β = 0.01





β = 1



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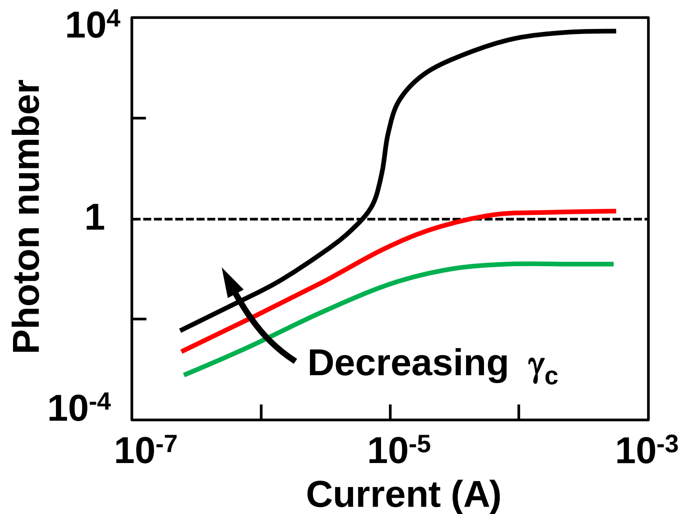
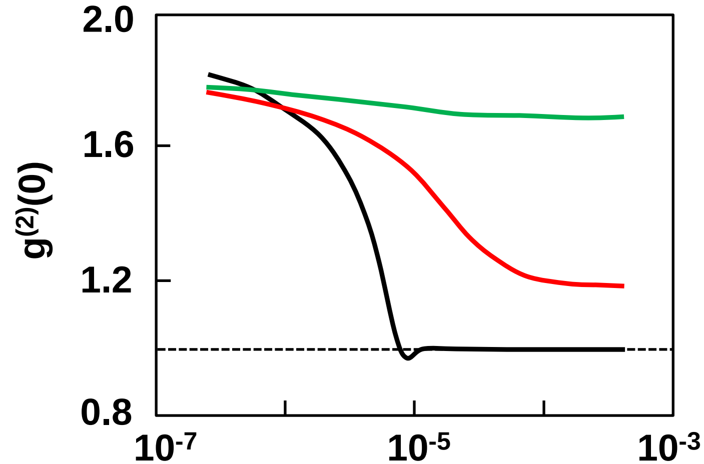
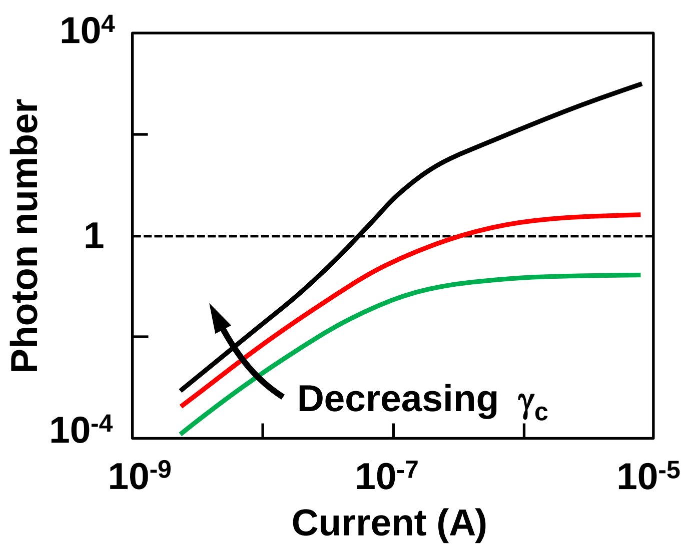
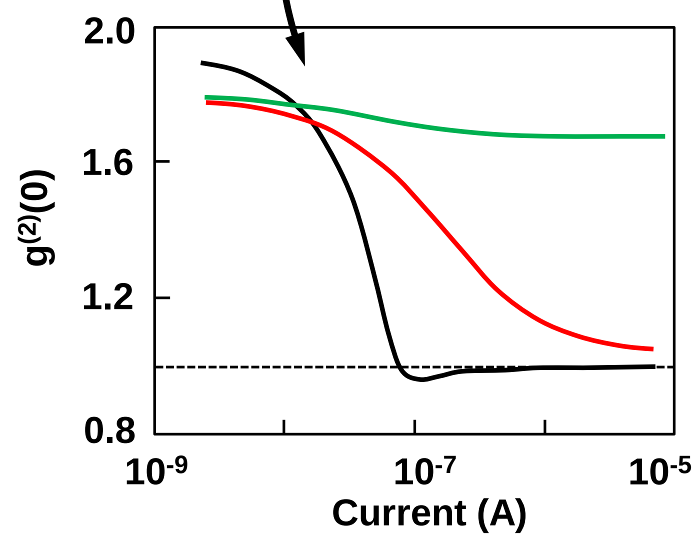




β = 1

No such thing as thresholdless lasing?

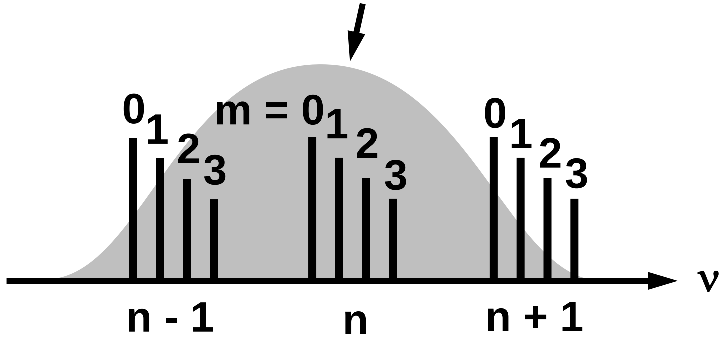




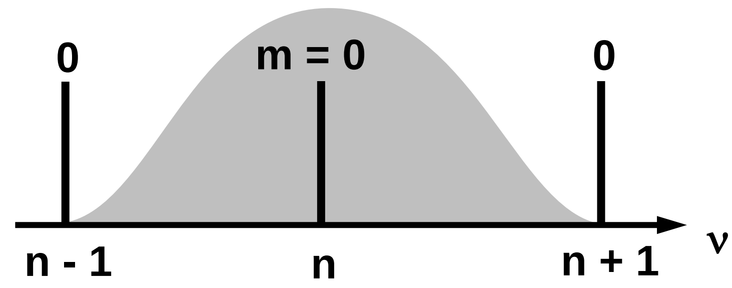
Why work on nanolasers?

Most lasers

Spontaneous emission spectrum

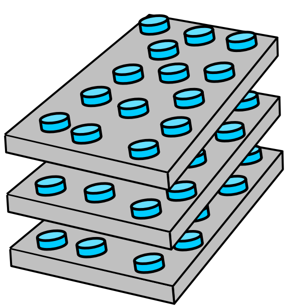


Nanolasers

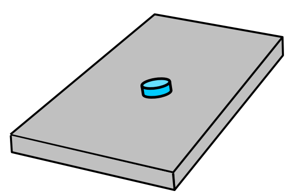


All emission into single resonator mode

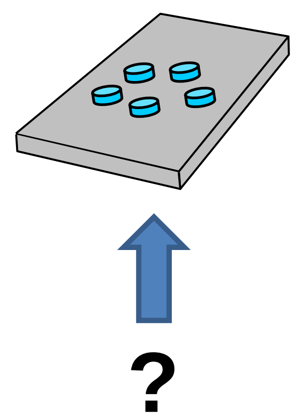
Typical QD-laser active region



Single-photon source active region

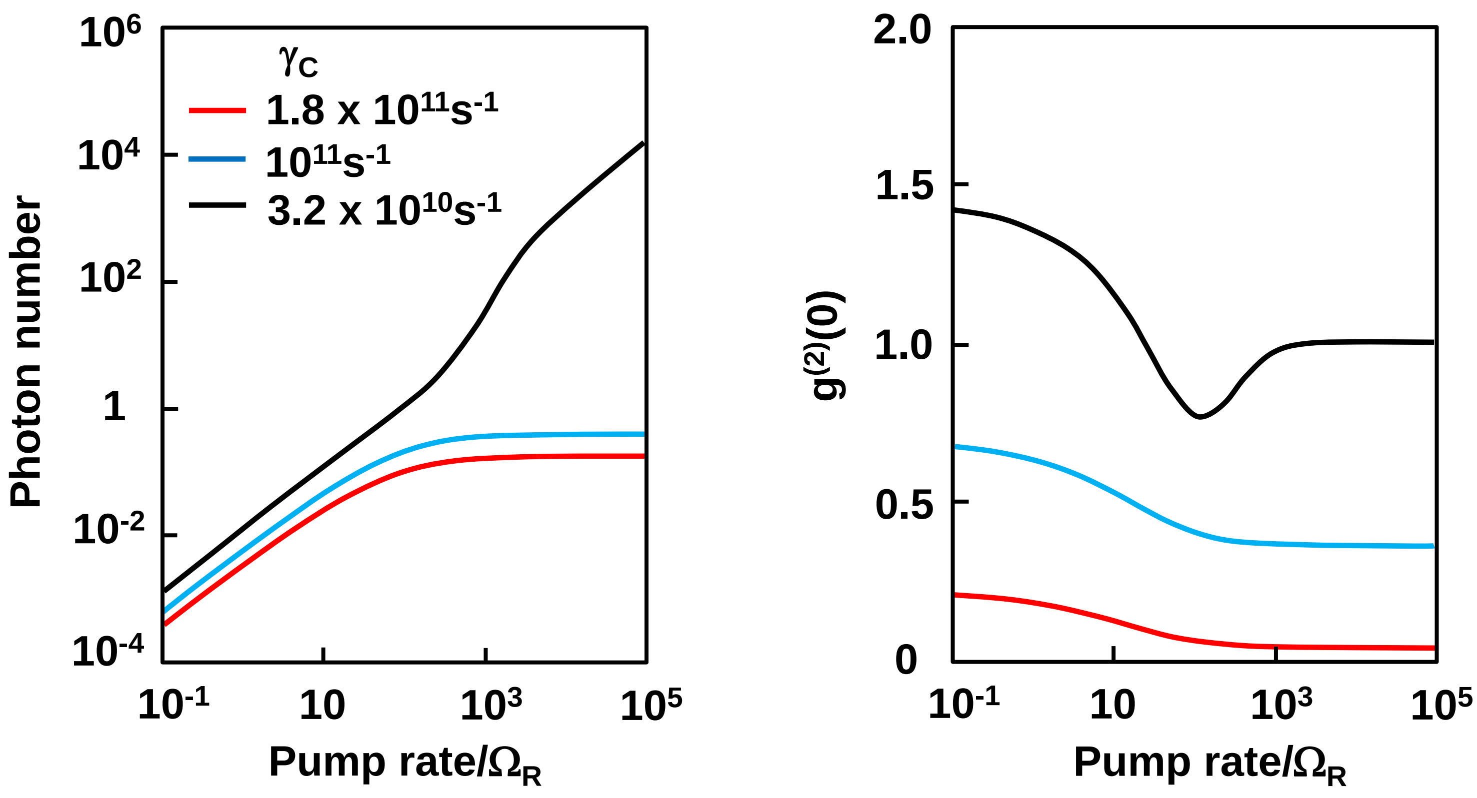


Few-QD active region



Single-quantum-dot active region

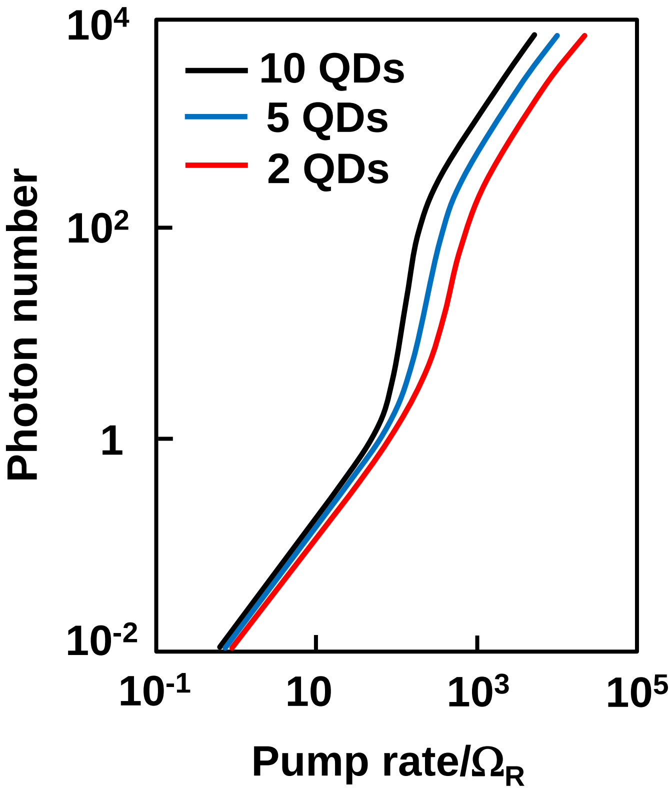
Single-photon source ➡ Nonclassical-light source ➡ Laser

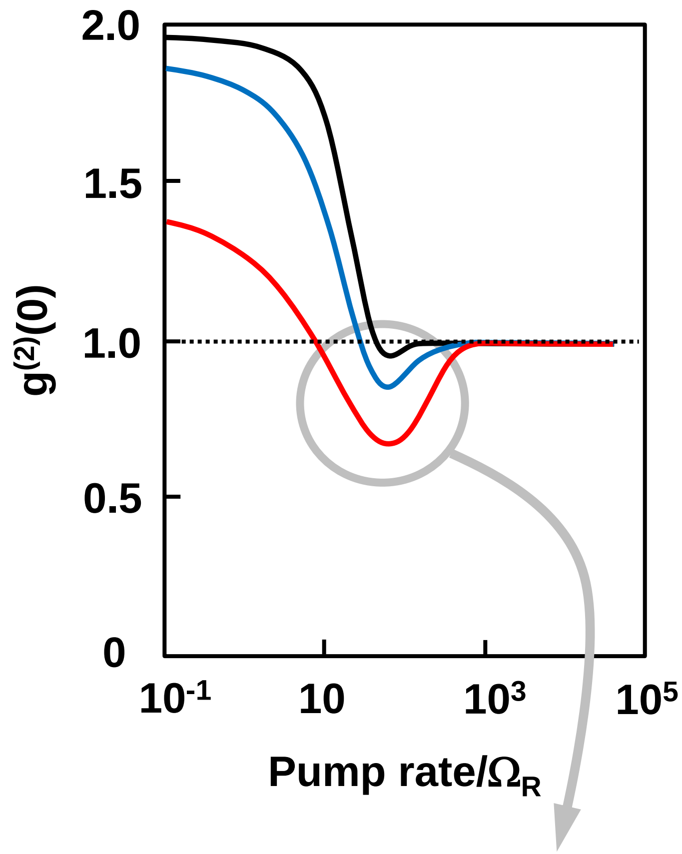


Vacuum Rabi frequency: $\Omega_R = 2.7 \times 10^{11} s^{-1}$

Few-quantum-dot active region

Question: Can we increase single-photon production rate?

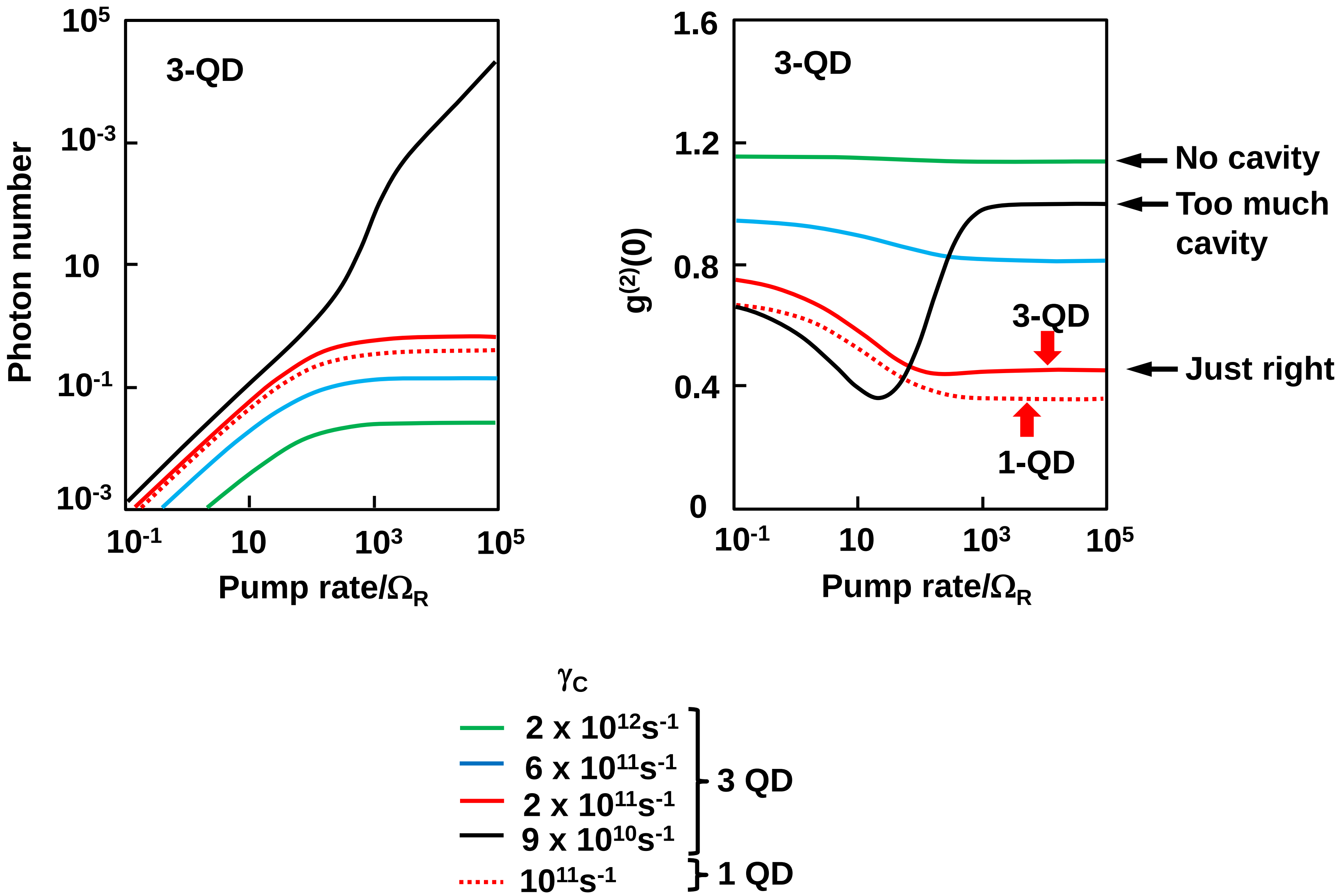




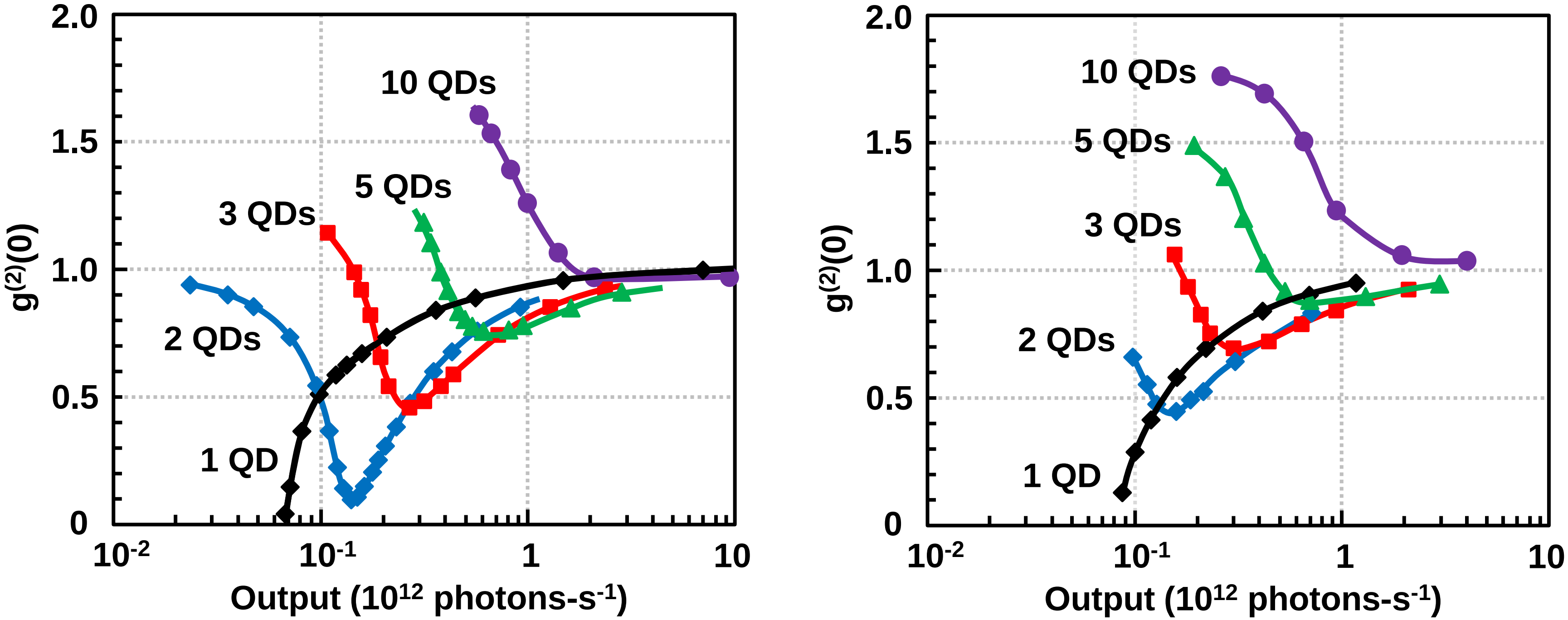
QD	γ_C
10	$2 \times 10^{11} s^{-1}$
5	$10^{11} s^{-1}$
2	$6 \times 10^{10} s^{-1}$

Light-carrier correlation
Leading terms:
$\delta\langle c^\dagger c a^\dagger a\rangle, \delta\langle b^\dagger b a^\dagger a\rangle,$
$\delta\langle b^\dagger c^\dagger a^\dagger a a\rangle$

Single-photon source with few-emitter active region?

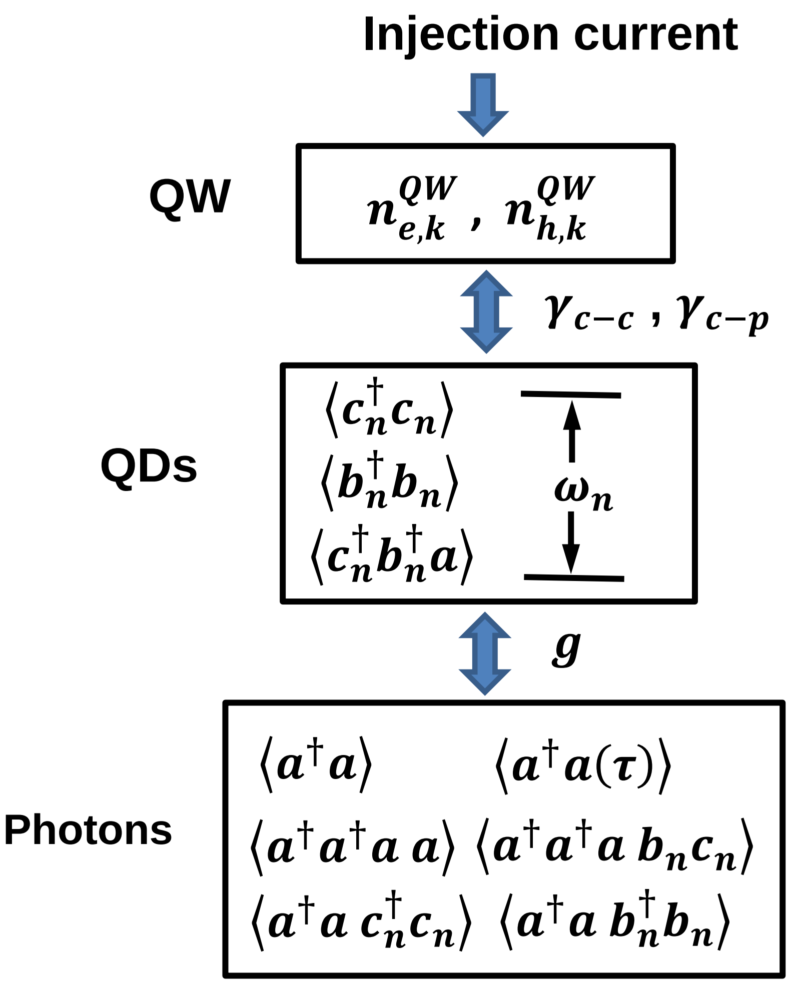


Increasing single-photon production rate with few-emitter active region



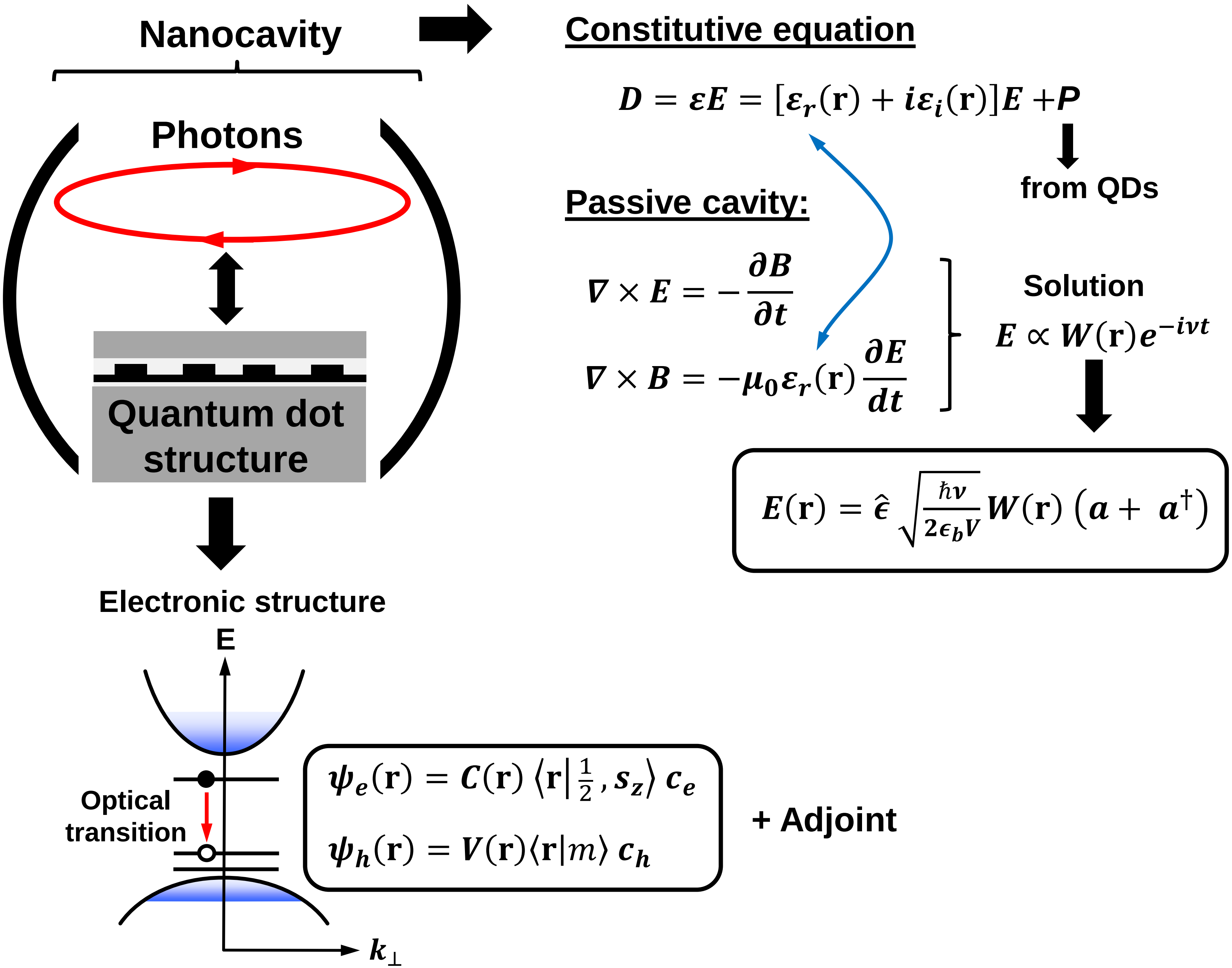
Concerns and next refinements

Present model



More rigorous treatment of excitation necessary for few-QD situations

Beyond doublet



Nanocavity
Photons
Quantum dot structure
Electronic structure
E
Optical transition
$k_\perp$
Constitutive equation
$D = \varepsilon E = [\varepsilon_r(\mathbf{r}) + i\varepsilon_i(\mathbf{r})]E + P$
from QDs
Passive cavity:
$\nabla \times E = -\frac{\partial B}{\partial t}$
$\nabla \times B = -\mu_0 \varepsilon_r(\mathbf{r}) \frac{\partial E}{dt}$
Solution
$E \propto W(\mathbf{r}) e^{-i\nu t}$
$E(\mathbf{r}) = \hat{\epsilon} \sqrt{\frac{\hbar\nu}{2\epsilon_b V}} W(\mathbf{r}) \left(a + a^\dagger\right)$
$\psi_e(\mathbf{r}) = C(\mathbf{r}) \left\langle \mathbf{r} \middle| \frac{1}{2}, s_z \right\rangle c_e$
$\psi_h(\mathbf{r}) = V(\mathbf{r}) \langle \mathbf{r} | m \rangle c_h$
+ Adjoint

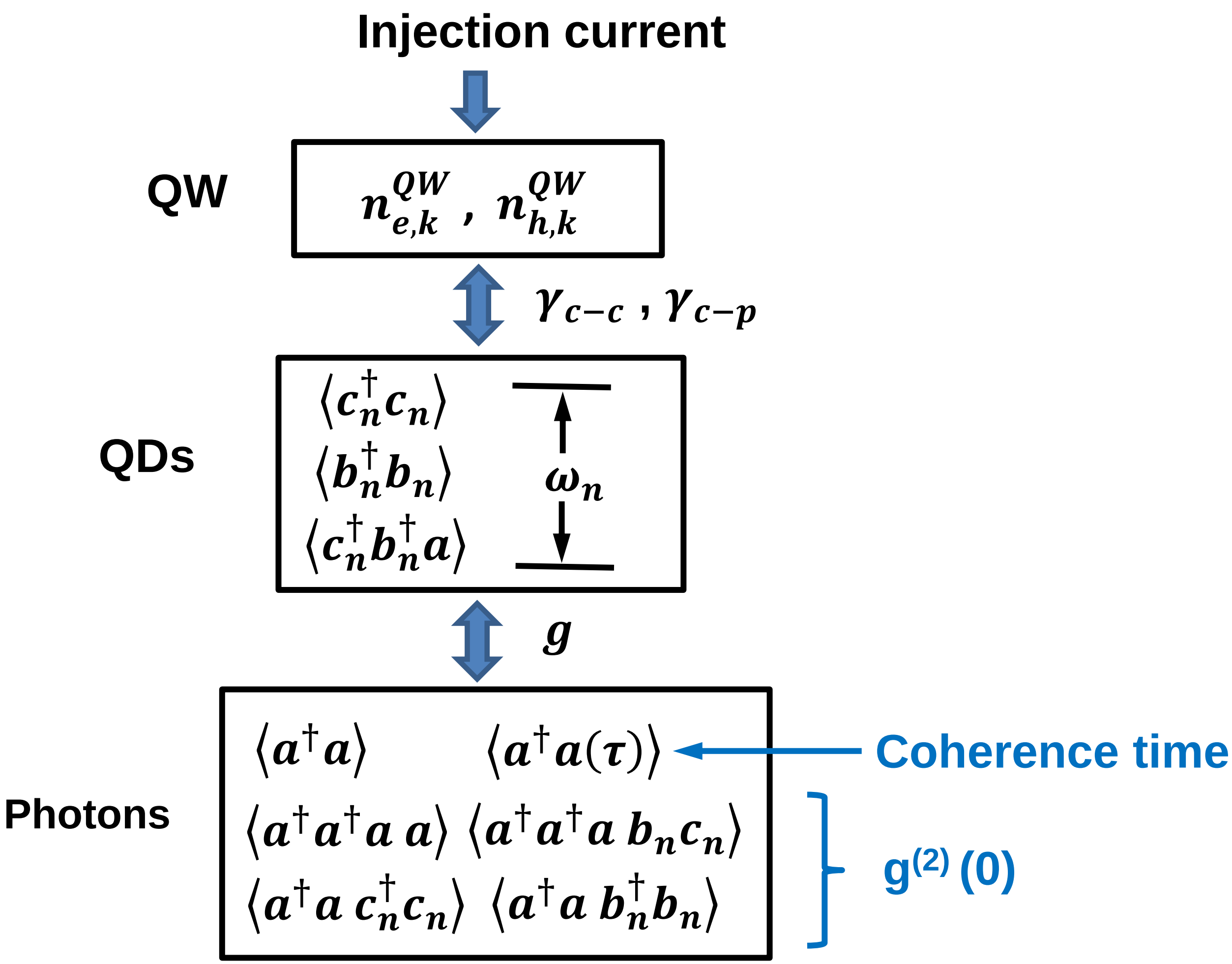
Hamiltonian

$$\mathrm{H} = \hbar\nu\left(a^{\dagger}a + \frac{1}{2}\right) + \sum_{\alpha}\left[\varepsilon_{e,\alpha}^{QD}\, c_{\alpha}^{\dagger}c_{\alpha} + \varepsilon_{h,\alpha}^{QD}\, b_{\alpha}^{\dagger}b_{\alpha} - \hbar g\left(c_{\alpha}^{\dagger}b_{\alpha}^{\dagger}a - a^{\dagger}b_{\alpha}c_{\alpha}\right)\right]$$

Inhomogeneous broadening

$$\wp\sqrt{\frac{\nu}{\hbar\epsilon_b V}}\, W(R_{QD}) \sum_{n} C(R_n)\, V(R_n)$$

Present model



LED ⟶ Laser ⟶ Thresholdless laser