Nanolasers as solution to efficiency droop in solid-state lighting

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Efficiency droop

Nanolasers

Laser solution to droop

Thanks to:

Sandia's Laboratory Directed Research & Development (LDRD) Program

LED efficiency droop

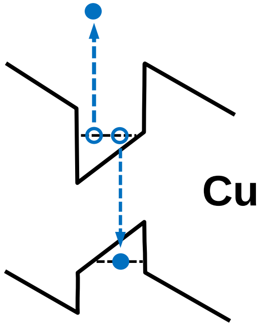
Carrier density rate equation

$$\frac{dN}{dt} = \frac{\overset{\text{Injection efficiency}}{\overset{\downarrow}{\eta_{inj}}}J}{ed} - \underset{\underset{\text{Defects}}{\uparrow}}{AN} - \underset{\underset{\text{Spontaneous emission}}{\uparrow}}{BN^2} - \underset{\underset{\text{Auger}}{\uparrow}}{CN^3}$$

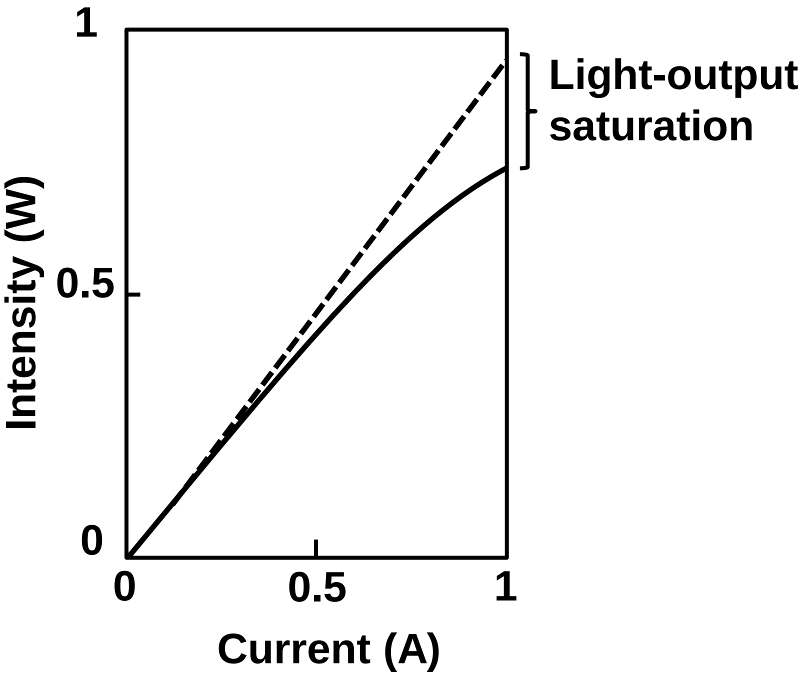
Internal quantum efficiency

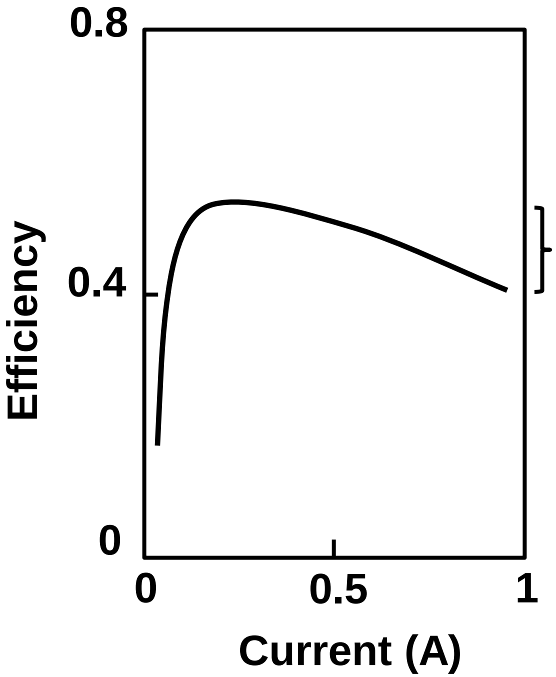
$$IQE = \frac{BN^2}{J/_{ed}} = \frac{\eta_{inj}BN^2}{AN + BN^2 + CN^3}$$

Auger scattering



Culprit





Droop

Laser

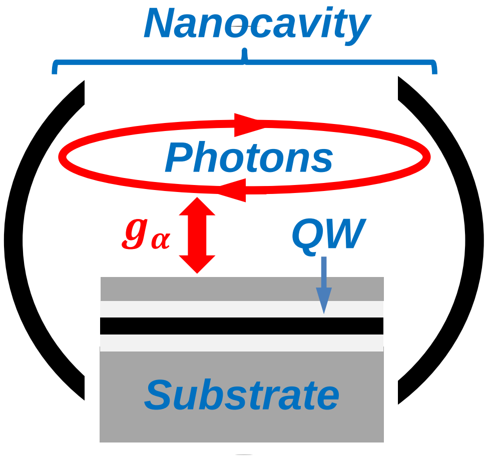
Carrier density rate equation

$$\frac{dN}{dt} = \frac{\eta_{inj}J}{ed} - AN - BN^2 - CN^3 - \overbrace{\frac{2gI}{\hbar\nu}}^{\text{Stimulated emission}}$$

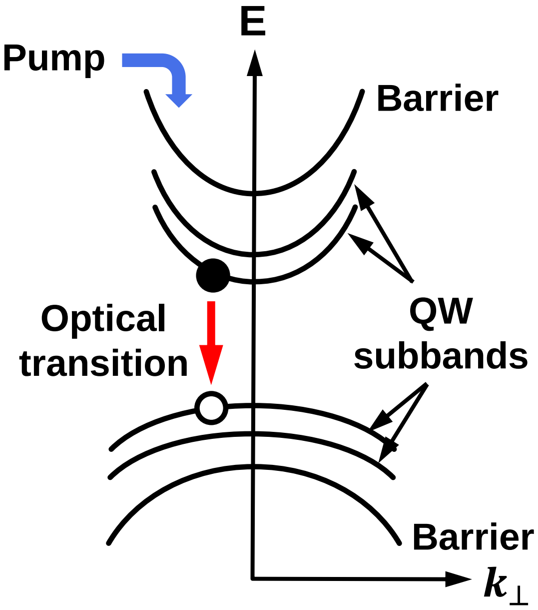
Laser intensity

$$I = \frac{\hbar\nu}{2g_{th}}\left[\frac{\eta_{inj}J}{ed} - \left(AN_{th} + BN_{th}^2 + CN_{th}^3\right)\right]$$

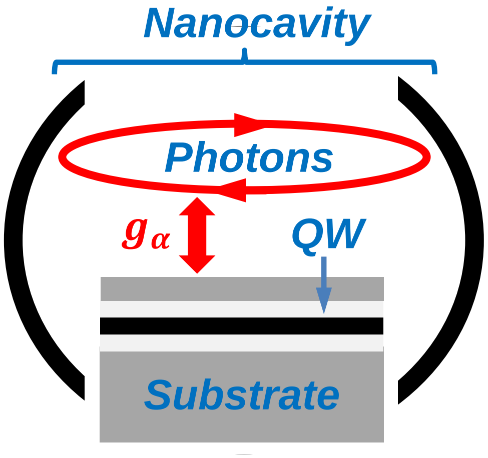
Model setup



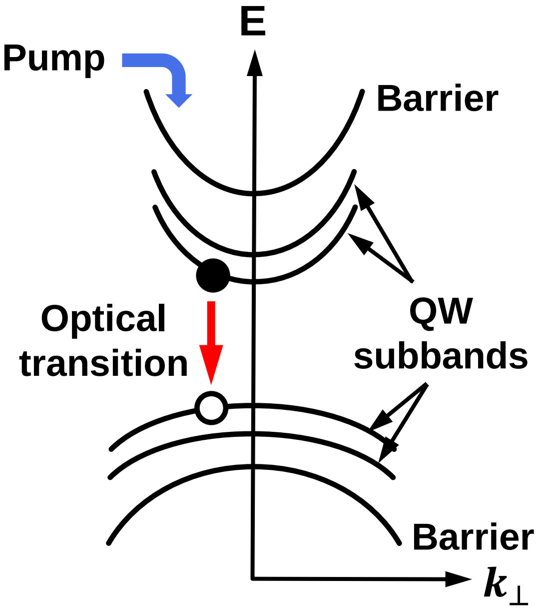
Electronic structure



Model setup: Hamiltonian



Electronic structure



$$H = \sum_{\alpha} \varepsilon^{e}_{\alpha}\, c^{\dagger}_{\alpha} c_{\alpha} + \sum_{\beta} \varepsilon^{h}_{\beta}\, b^{\dagger}_{\beta} b_{\beta} \;+ \hbar\omega\left(a^{\dagger} a + \frac{1}{2}\right)$$

Single-particle

$$+\frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, c^{\dagger}_{\alpha} c^{\dagger}_{\beta} c_{\eta} c_{\sigma} + \frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^{\dagger}_{\alpha} b^{\dagger}_{\beta} b_{\eta} b_{\sigma}$$

$$-\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^{\dagger}_{\alpha} c^{\dagger}_{\beta} c_{\eta} b_{\sigma}$$

Matrix element of $\frac{e^{2}}{4\pi\varepsilon_{b}|r - r'|}$

Carrier-carrier

$$+\hbar\sum_{\alpha\beta q} G_{q}\left(c^{\dagger}_{\alpha} c_{\beta} + b^{\dagger}_{\alpha} b_{\beta}\right)\left(d_{q} + d^{\dagger}_{q}\right)$$

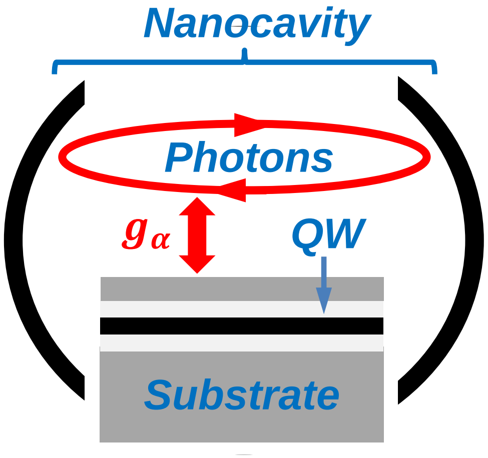
Carrier-phonon

$$-\hbar\sum_{\alpha}\left(g_{\alpha} b^{\dagger}_{\alpha} c^{\dagger}_{\alpha} a - g^{*}_{\alpha} a^{\dagger} c_{\alpha} b_{\alpha}\right)$$

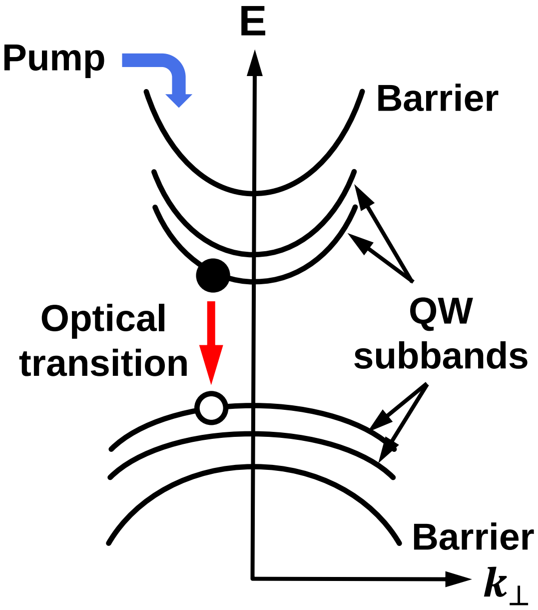
Light-carrier

$$\wp\sqrt{\frac{\nu}{\hbar\epsilon_{b} V}}\; W\left(Z_{QW}\right)\sum_{n} C_{\alpha}(Z_{n})\, V_{\alpha}(Z_{n})$$

Model setup: Hamiltonian



Electronic structure



$$H = \sum_\alpha \varepsilon^e_\alpha c^\dagger_\alpha c_\alpha + \sum_\beta \varepsilon^h_\beta b^\dagger_\beta b_\beta + \hbar\omega\left(a^\dagger a + \frac{1}{2}\right)$$

Single-particle

$$+\frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, c^\dagger_\alpha c^\dagger_\beta c_\eta c_\sigma + \frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^\dagger_\alpha b^\dagger_\beta b_\eta b_\sigma$$

$$-\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^\dagger_\alpha c^\dagger_\beta c_\eta b_\sigma$$

Matrix element of $\dfrac{e^2}{4\pi\varepsilon_b|r-r'|}$

Carrier-carrier

$$+\hbar\sum_{\alpha\beta q} G_q\left(c^\dagger_\alpha c_\beta + b^\dagger_\alpha b_\beta\right)\left(d_q + d^\dagger_q\right)$$

Carrier-phonon

$$-\hbar\sum_\alpha\left(g_\alpha b^\dagger_\alpha c^\dagger_\alpha a - g^*_\alpha a^\dagger c_\alpha b_\alpha\right)$$

Light-carrier

$$\wp\sqrt{\frac{\nu}{\hbar\epsilon_b V}}\,W(Z_{QW})\sum_n C_\alpha(Z_n)\,V_\alpha(Z_n)$$

Model: population dynamics and correlations

Heisenberg Picture

$$\frac{\partial}{\partial t}A = -\frac{i}{\hbar}\,[A,H]$$

$$\langle c^{\dagger}_{\alpha}c_{\alpha}\rangle, \langle b^{\dagger}_{\alpha}b_{\alpha}\rangle, \overbrace{\langle c^{\dagger}_{\alpha}b^{\dagger}_{\alpha}a\rangle}, \langle a^{\dagger}a\rangle$$

$$\langle a^{\dagger}a^{\dagger}aa\rangle, \langle c^{\dagger}_{\alpha}c^{\dagger}_{\sigma}c_{\sigma}c_{\alpha}\rangle, \langle c^{\dagger}_{\alpha}c_{\alpha}a^{\dagger}a\rangle$$

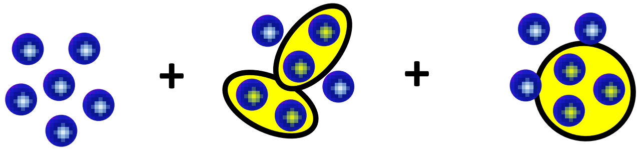
populations
polarizations
correlations

Cluster expansion

Single particles

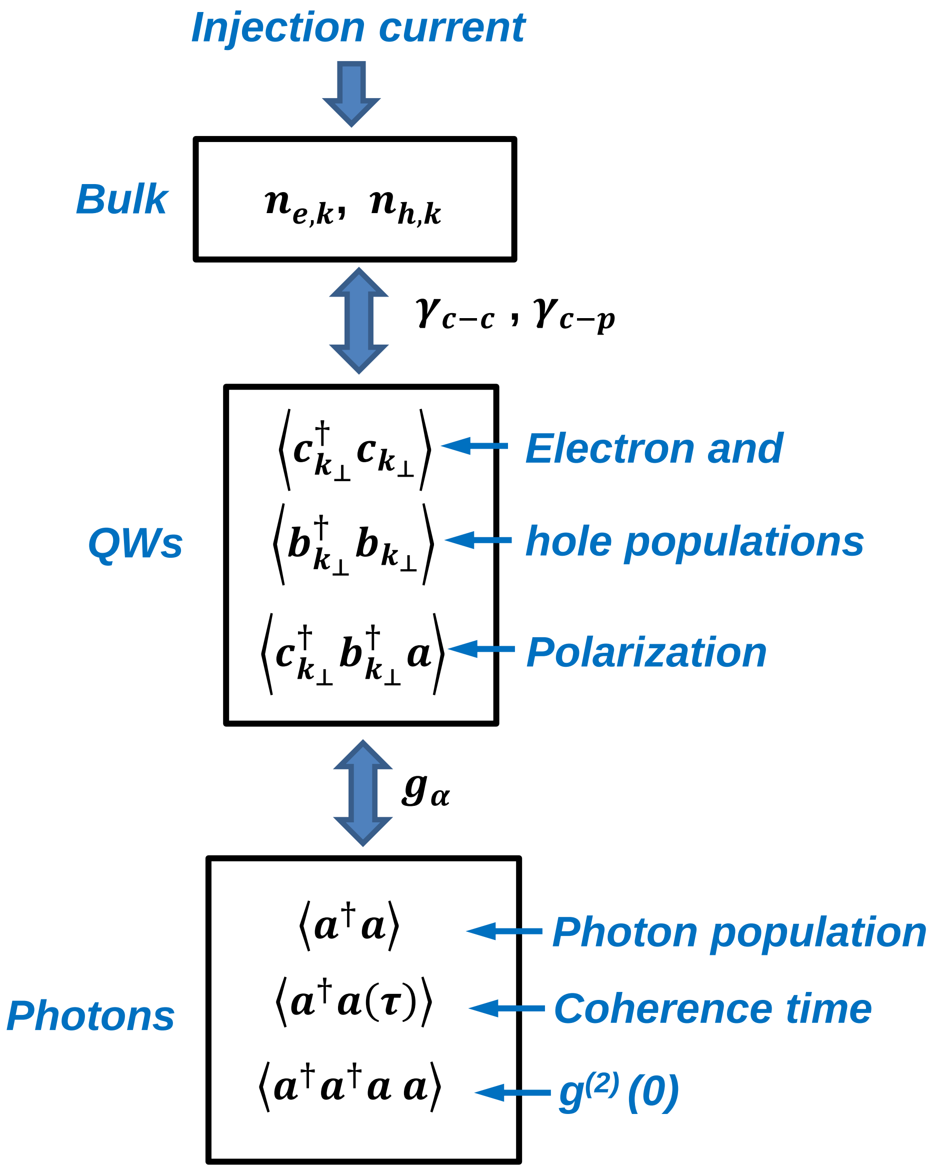
Correlated 3-particle clusters

$\langle N\rangle$ =



Correlated pairs

+ …



Injection current

Bulk $n_{e,k},\ n_{h,k}$

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

QWs

$\langle c^{\dagger}_{k_{\perp}}c_{k_{\perp}}\rangle$ *Electron and*

$\langle b^{\dagger}_{k_{\perp}}b_{k_{\perp}}\rangle$ *hole populations*

$\langle c^{\dagger}_{k_{\perp}}b^{\dagger}_{k_{\perp}}a\rangle$ *Polarization*

g_{α}

Photons

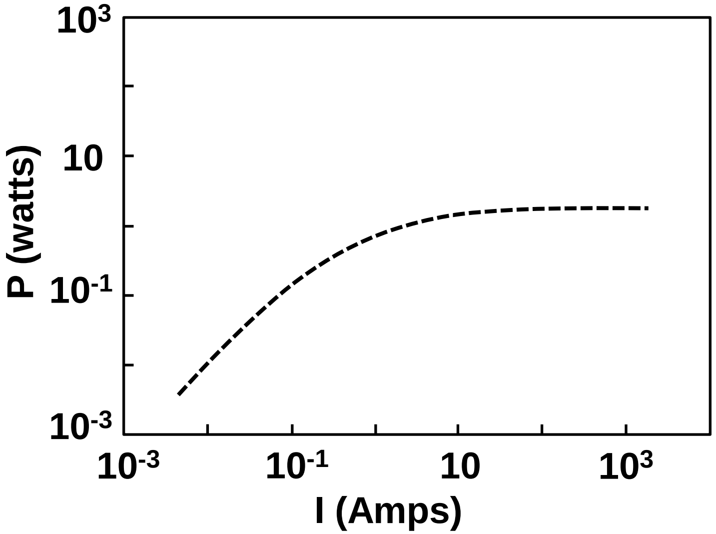
$\langle a^{\dagger}a\rangle$ *Photon population*

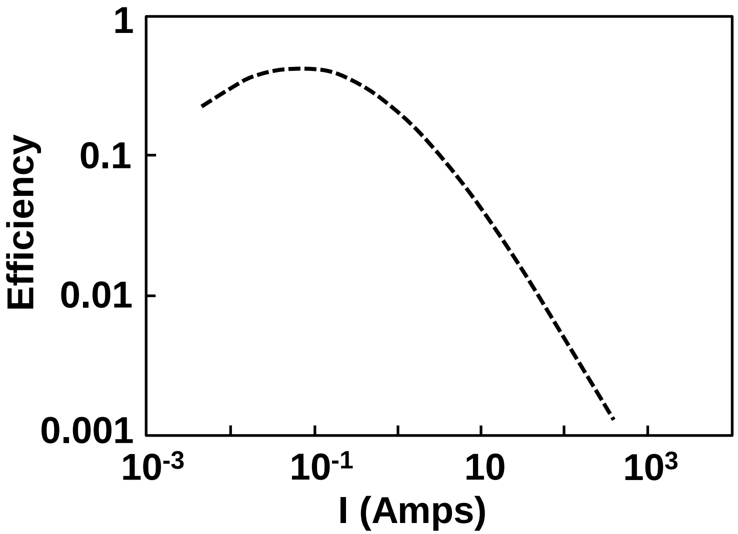
$\langle a^{\dagger}a(\tau)\rangle$ *Coherence time*

$\langle a^{\dagger}a^{\dagger}a\ a\rangle$ *$g^{(2)}(0)$*

Overview: Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)

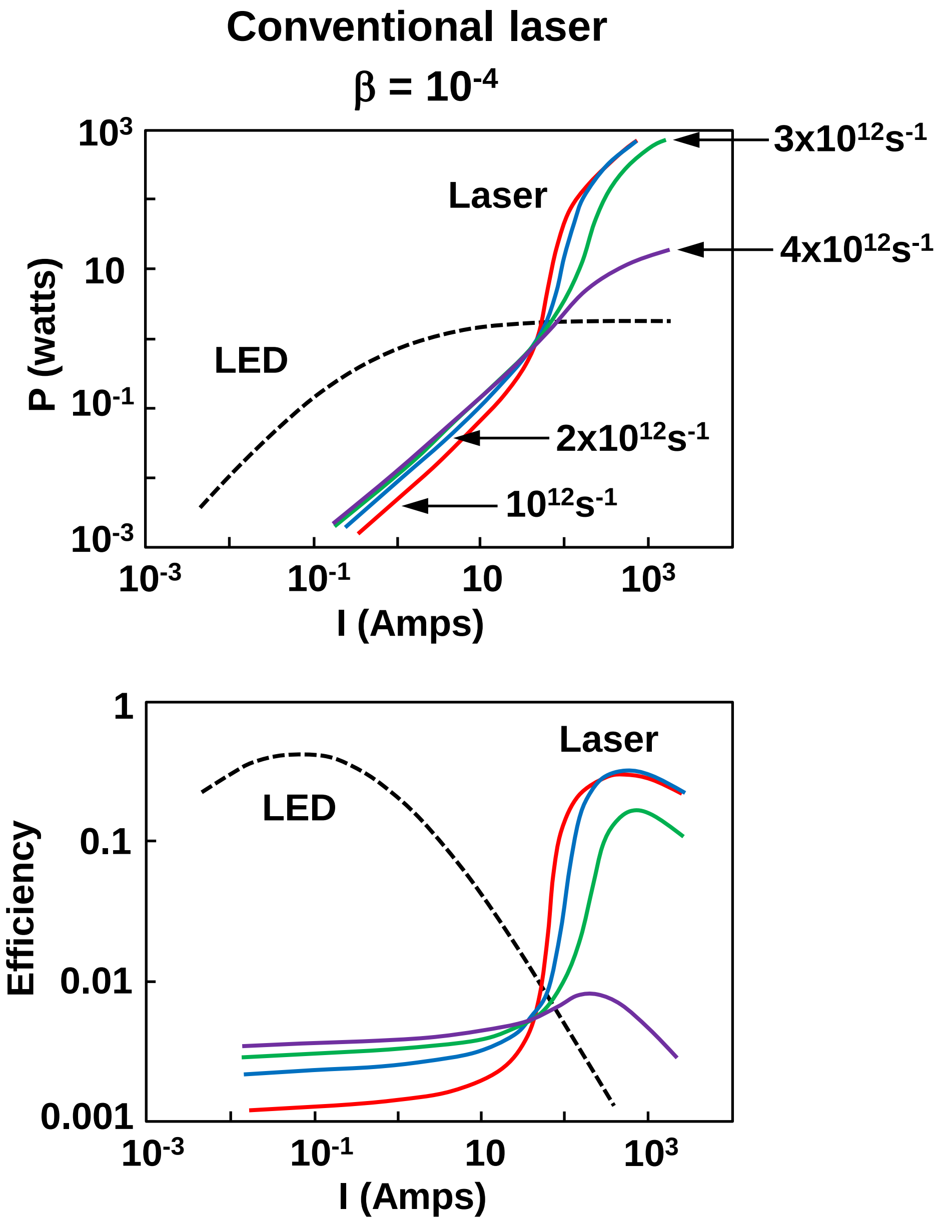
Efficiency droop in solid state lighting





- $A = 10^8 s^{-1}$
- $C = 5 \times 10^{-30} cm^6 s^{-1}$
- 2nm $In_{0.1}Ga_{0.9}N$ QW
- 1mm x 1mm aperture

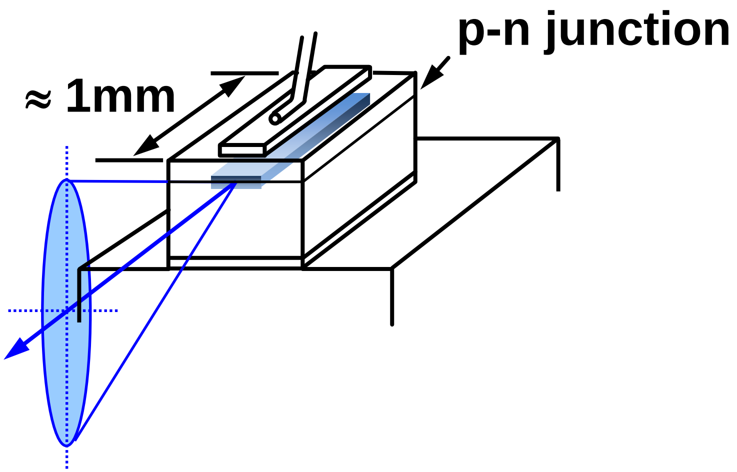
Auger mitigation with lasers



- $A = 10^{8}s^{-1}$
- $C = 5 \times 10^{-30}cm^{6}s^{-1}$
- 2nm $In_{0.1}Ga_{0.9}N$ QW
- 1mm x 1mm aperture
- $\gamma_{abs} = 10^{12}s^{-1}$

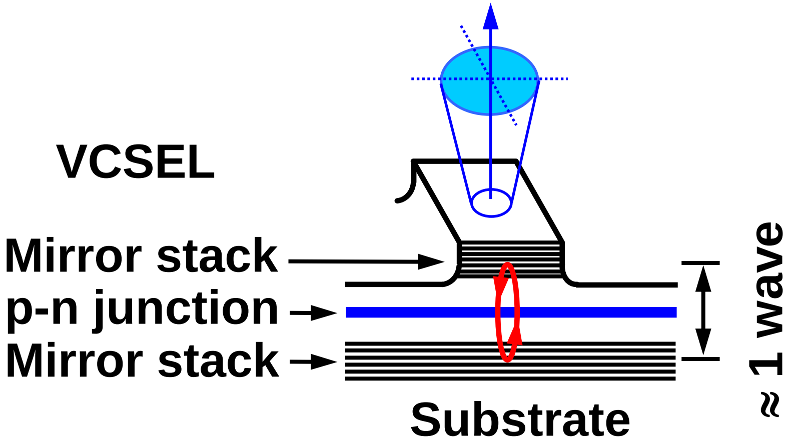
Towards smaller and smaller lasers

Edge - Emitting Laser


≈ 1mm

p-n junction

Vertical-Cavity Surface-Emitting Laser


VCSEL

Mirror stack

p-n junction

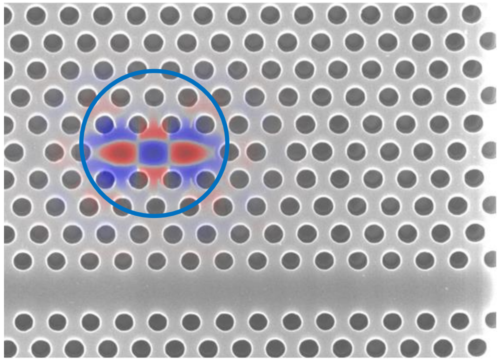
Mirror stack

Substrate

≈ 1 wave

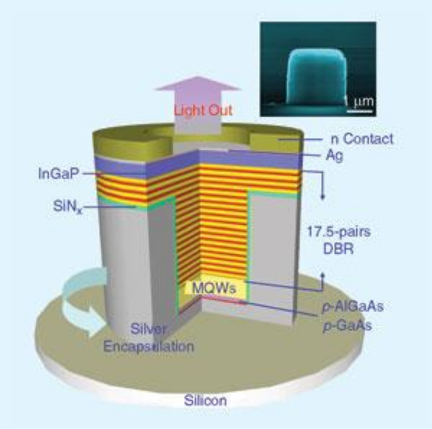
Nanolasers

Photonic crystal



(Courtesy of Willie Luk, Sandia National Labs)

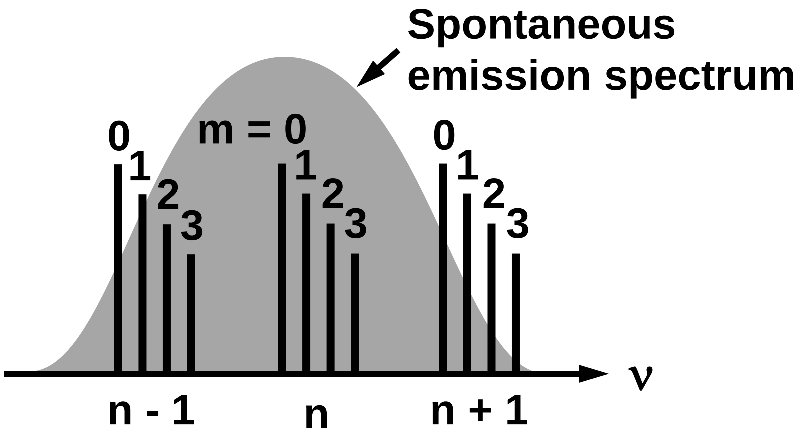
Micro- or nano-cavity



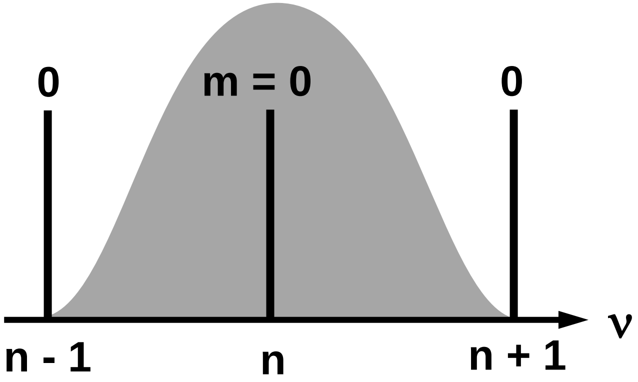
(Adapted from a figure by Lu et al., UIUC)

Nanocavities and unity spontaneous emission factor

Most lasers β << 1



Some nanolasers β = 1



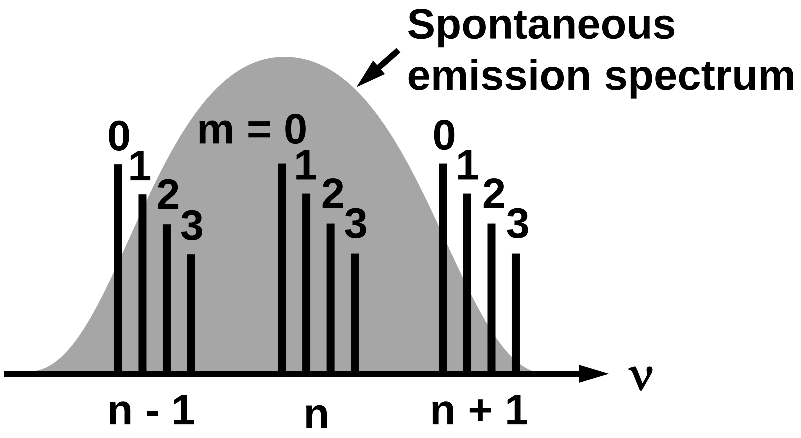
All emission into single resonator mode

Spontaneous emission factor

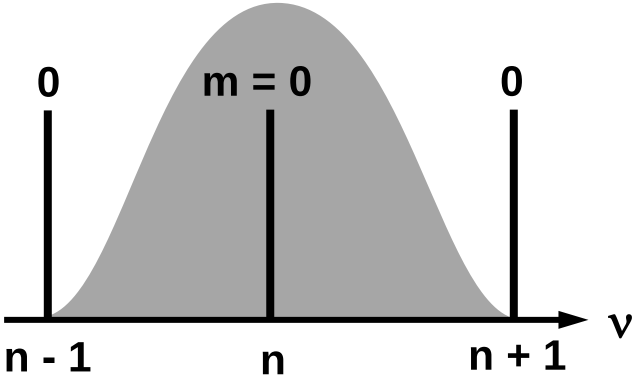
$$\beta = \frac{\gamma_l}{\gamma_{sp}}$$

Nanocavities and unity spontaneous emission factor

Most lasers $\beta << 1$



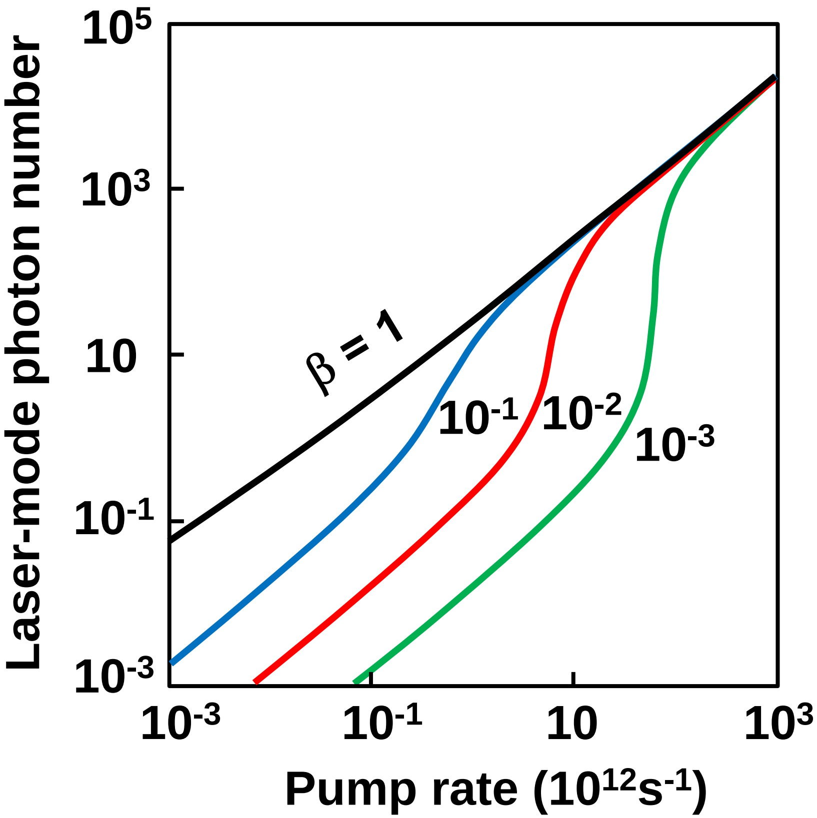
Some nanolasers $\beta = 1$



All emission into single resonator mode

Spontaneous emission factor

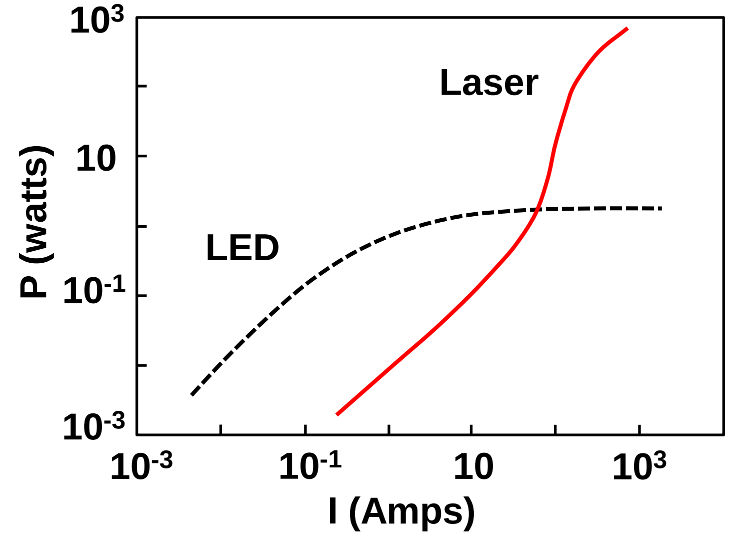
$$\beta = \frac{\gamma_l}{\gamma_{sp}}$$

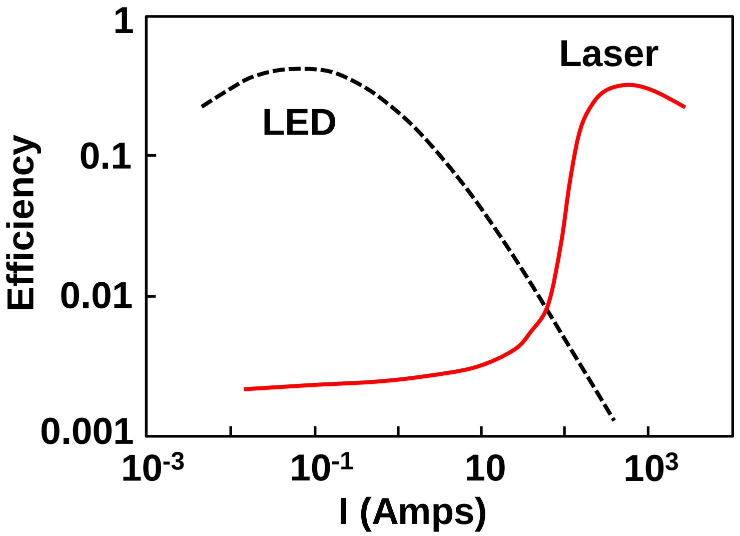


Auger mitigation with lasers

Conventional laser

$\beta = 10^{-4}$





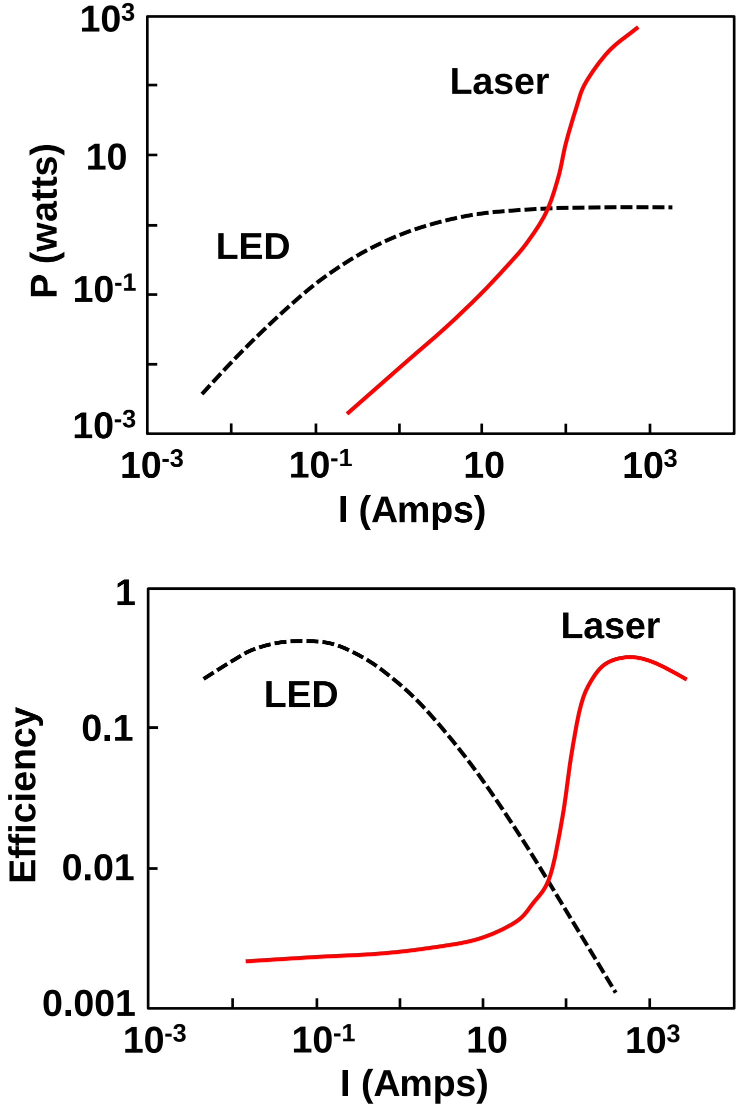
2nm $In_{0.1}Ga_{0.9}N$ QW
1mm x1mm aperture

- $A = 10^8 s^{-1}$
- $C = 5 \times 10^{-30} cm^6 s^{-1}$
- 2nm $In_{0.1}Ga_{0.9}N$ QW
- 1mm x 1mm aperture
- $\gamma_{abs} = 10^{12} s^{-1}$
- $\gamma_c = 2 \times 10^{12} s^{-1}$

Efficient, high power SSL via Auger mitigation with quantum nanophotonics

Conventional laser

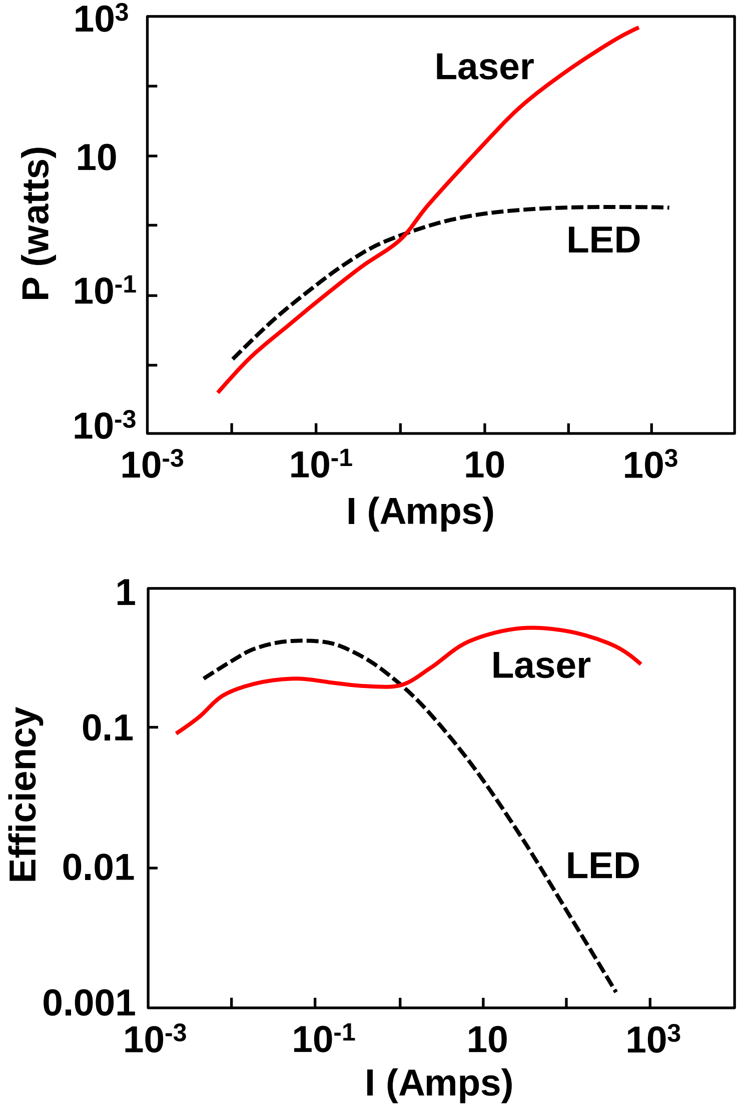
$\beta = 10^{-4}$



2nm $In_{0.1}Ga_{0.9}N$ QW
1mm x1mm aperture

Nanolaser array

$\beta = 1$



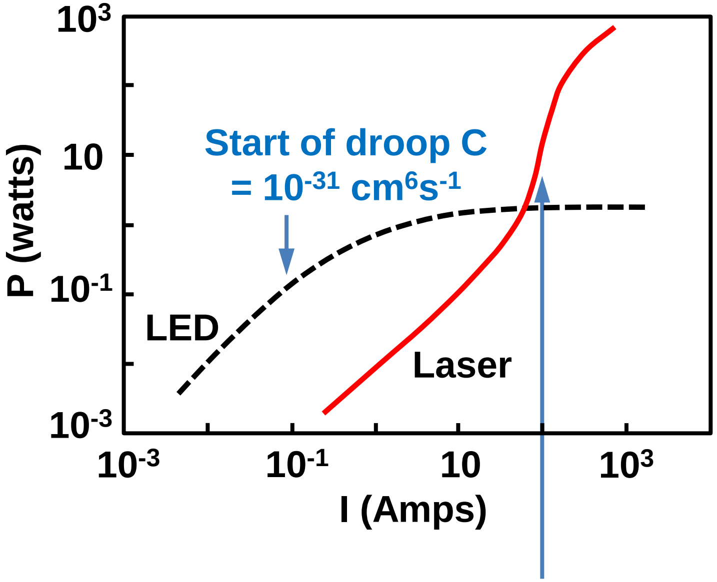
400x400 array
0.2x0.2micron aperture nanolaser

Nanolasers as solution to efficiency droop in solid-state lighting

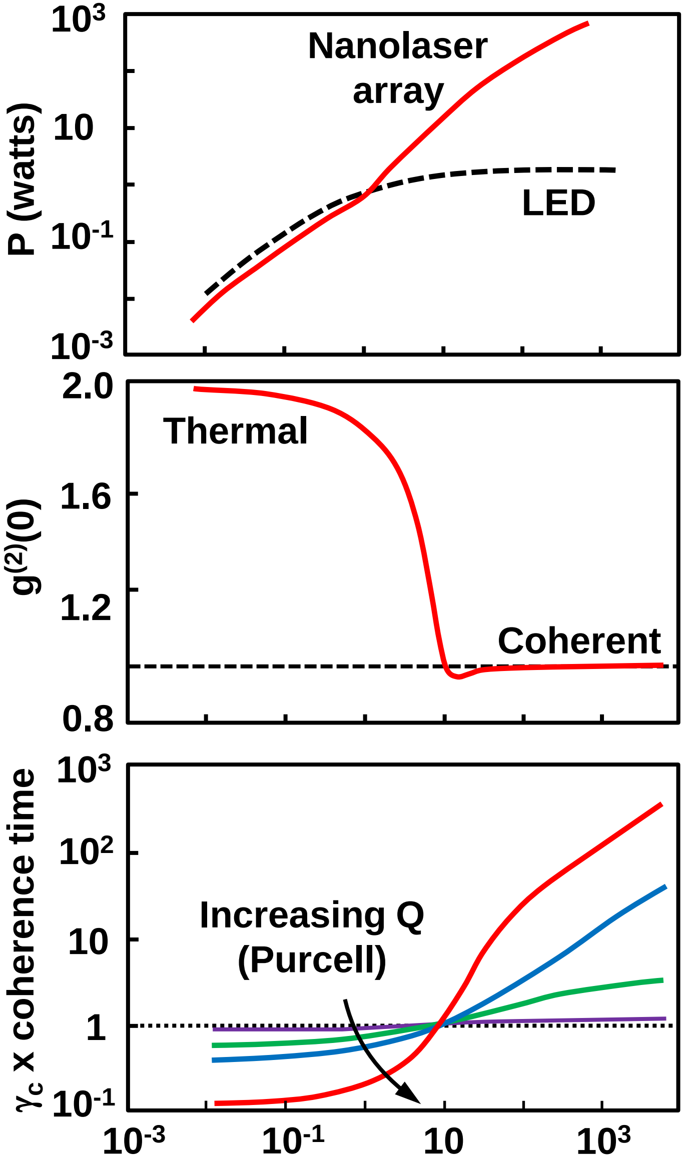
Idea: losses $CN^3 \Rightarrow CN^3_{th}$

Grows with current

Clamps at threshold



- Laser threshold with InGaN QW
- Threshold sensitive to temperature, cavity-Q, defects, etc.



With β = 1 nanolaser, movement of lasing threshold does not affect output intensity

ABC model for LED efficiency

Carrier density rate equation

Injection efficiency (carrier overshoot and escape)

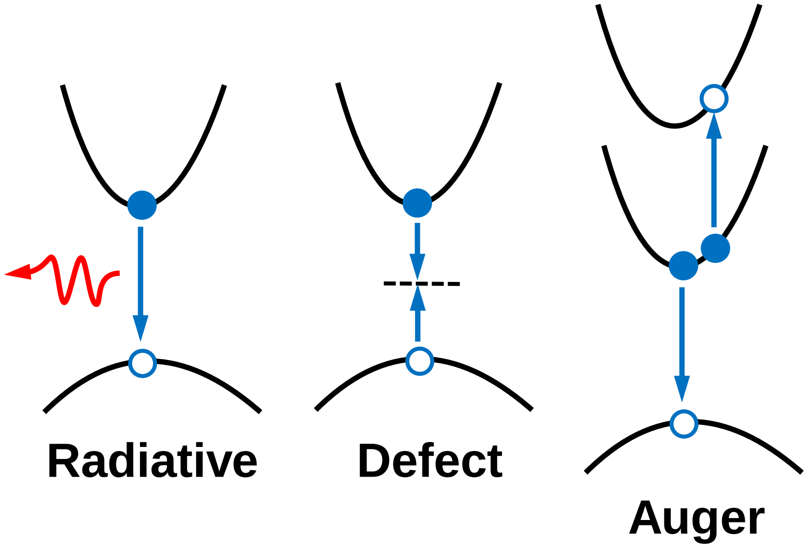
$$\frac{dN}{dt} = \frac{\eta_{inj} J}{ed} - AN - BN^2 - CN^3$$

Defects

Spontaneous emission

Auger

Carrier losses

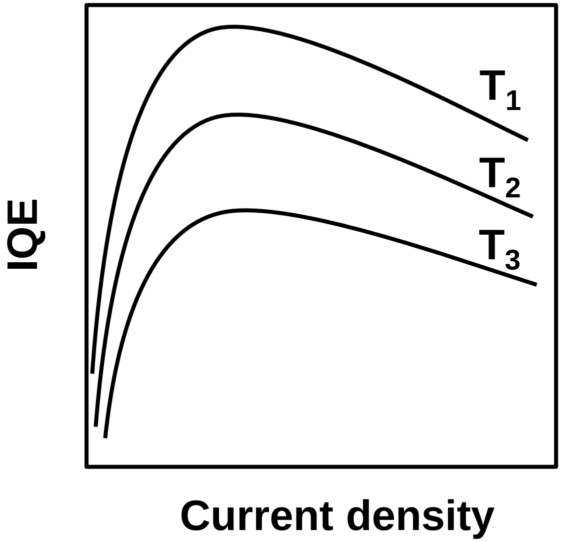


Steady-state

$$\frac{dN}{dt} = 0 \Rightarrow \frac{\eta_{inj} J}{ed} = AN + BN^2 + CN^3$$

Internal quantum efficiency

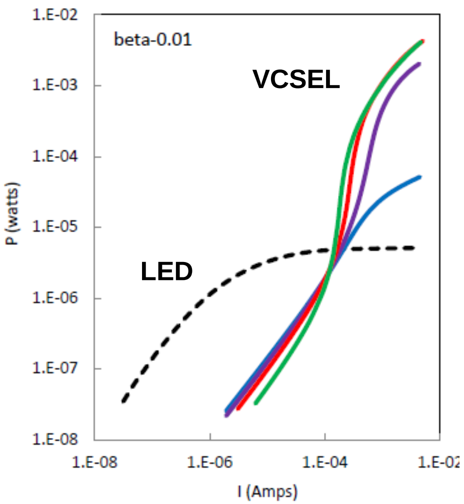
$$\textbf{IQE} = \frac{BN^2}{\frac{J}{ed}} = \frac{\eta_{inj} BN^2}{AN + BN^2 + CN^3}$$

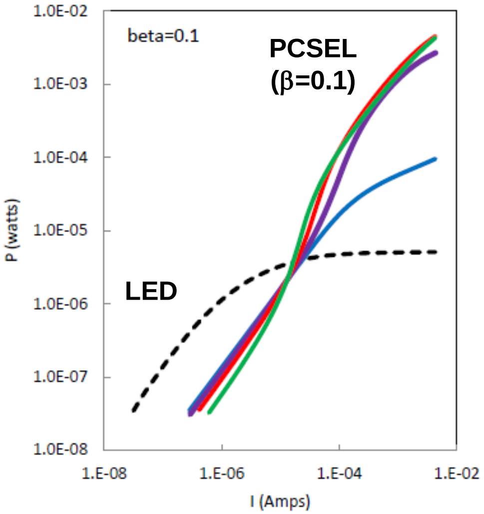


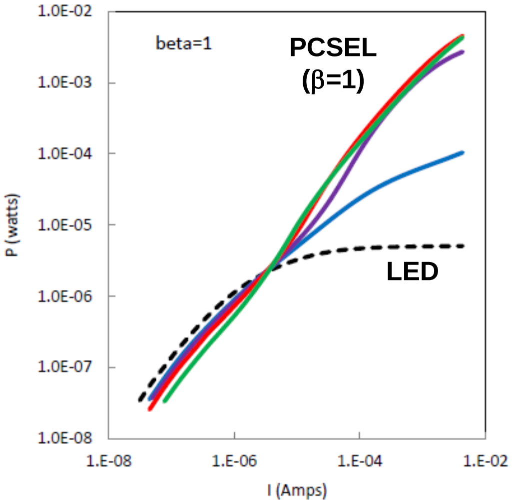
Efficient, high power SSL via Auger mitigation with quantum nanophotonics

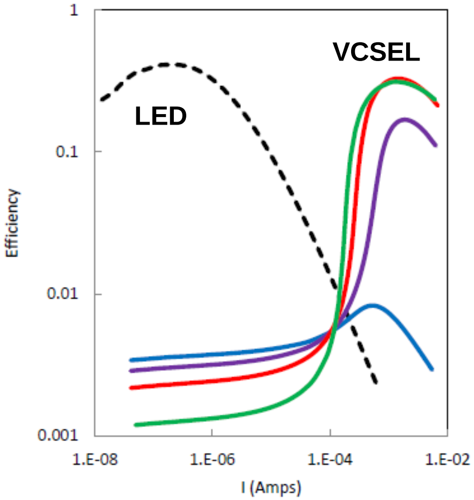
VCSEL

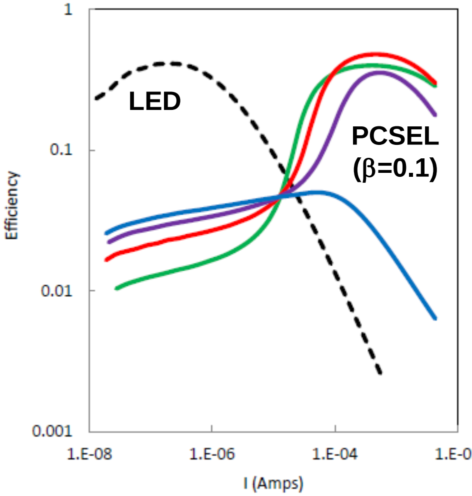
PCSEL



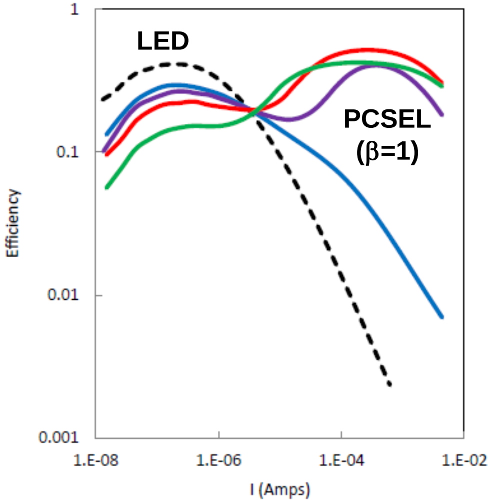






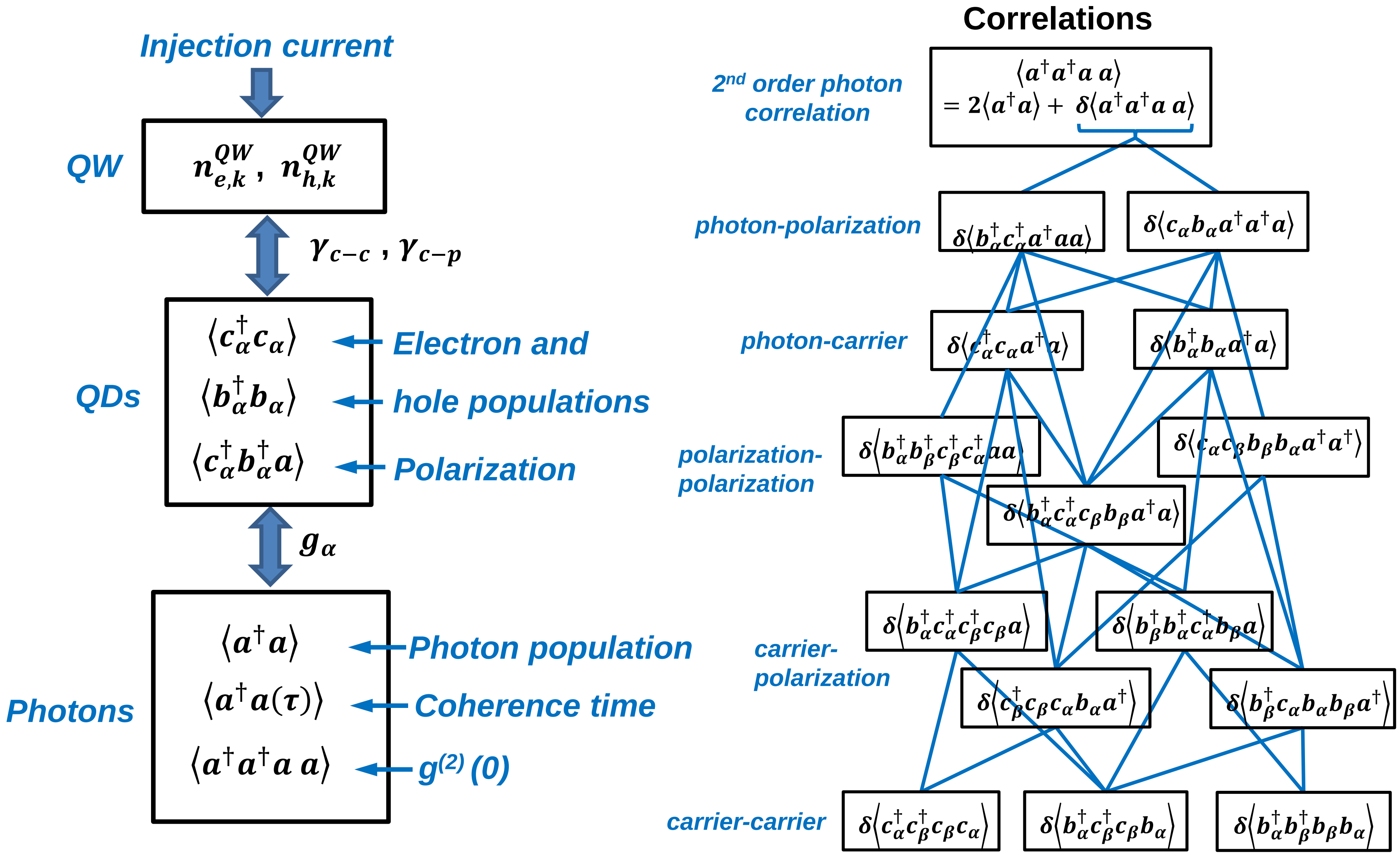


Milestone for Fellow LDRD



Milestone for EFRC2?

Nano-emitter model: population dynamics and correlations



Injection current

QW $n^{QW}_{e,k}\,,\ n^{QW}_{h,k}$

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

QDs

$\langle c^\dagger_\alpha c_\alpha\rangle$
$\langle b^\dagger_\alpha b_\alpha\rangle$
Electron and hole populations

$\langle c^\dagger_\alpha b^\dagger_\alpha a\rangle$ Polarization

g_α

Photons

$\langle a^\dagger a\rangle$ Photon population

$\langle a^\dagger a(\tau)\rangle$ Coherence time

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

Correlations

2nd order photon correlation

$$\langle a^\dagger a^\dagger a\, a\rangle = 2\langle a^\dagger a\rangle + \underbrace{\delta\langle a^\dagger a^\dagger a\, a\rangle}$$

photon-polarization: $\delta\langle b^\dagger_\alpha c^\dagger_\alpha a^\dagger a a\rangle$, $\delta\langle c_\alpha b_\alpha a^\dagger a^\dagger a\rangle$

photon-carrier: $\delta\langle c^\dagger_\alpha c_\alpha a^\dagger a\rangle$, $\delta\langle b^\dagger_\alpha b_\alpha a^\dagger a\rangle$

polarization-polarization: $\delta\langle b^\dagger_\alpha b^\dagger_\beta c^\dagger_\beta c^\dagger_\alpha a a\rangle$, $\delta\langle c_\alpha c_\beta b_\beta b_\alpha a^\dagger a^\dagger\rangle$, $\delta\langle b^\dagger_\alpha c^\dagger_\alpha c_\beta b_\beta a^\dagger a\rangle$

carrier-polarization: $\delta\langle b^\dagger_\alpha c^\dagger_\alpha c^\dagger_\beta c_\beta a\rangle$, $\delta\langle b^\dagger_\beta b^\dagger_\alpha c^\dagger_\alpha b_\beta a\rangle$, $\delta\langle c^\dagger_\beta c_\beta c_\alpha b_\alpha a^\dagger\rangle$, $\delta\langle b^\dagger_\beta c_\alpha b_\alpha b_\beta a^\dagger\rangle$

carrier-carrier: $\delta\langle c^\dagger_\alpha c^\dagger_\beta c_\beta c_\alpha\rangle$, $\delta\langle b^\dagger_\alpha c^\dagger_\beta c_\beta b_\alpha\rangle$, $\delta\langle b^\dagger_\alpha b^\dagger_\beta b_\beta b_\alpha\rangle$

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