Quantum dots for applications in semiconductor lasers and quantum optics

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Physics changes from QW to QD

Lasers

Quantum optics

Influences of carrier interaction processes

Thanks to:

Frank Jahnke, Michael Lorke – Bremen University

Andreas Knorr, Alex Carmele, Julia Kabuss – Technical University Berlin

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Stephan Koch – Philipps University Marburg

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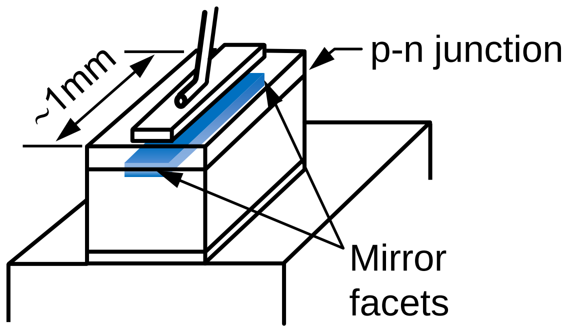
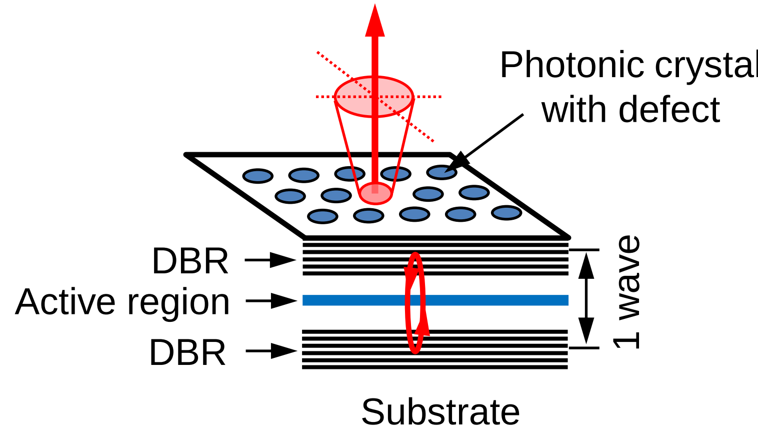
Experimental platforms

Edge-emitting laser

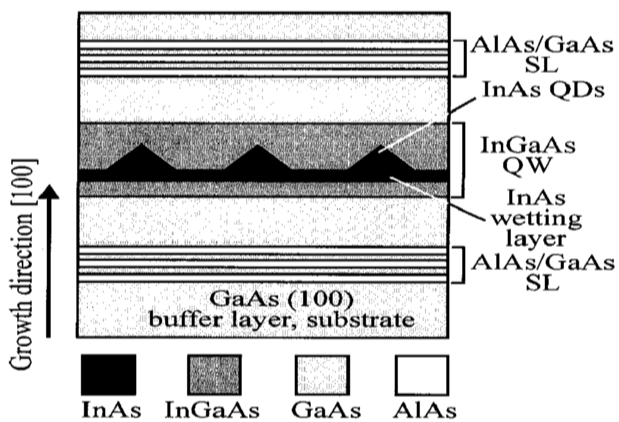


Microcavity laser

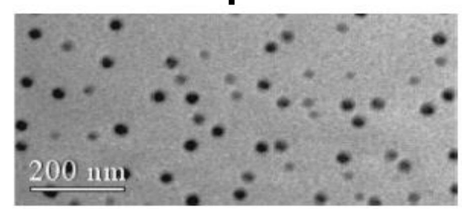


Quantum-dot active region

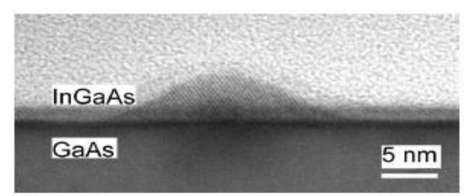
Cross section



TEM top view



TEM cross section



Casey and Panish, Heterostructure Lasers - Part A: Fundamental Principles, Academic Press, New York, 1978

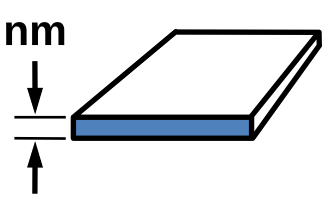
Semiconductor quantum-dot optical properties

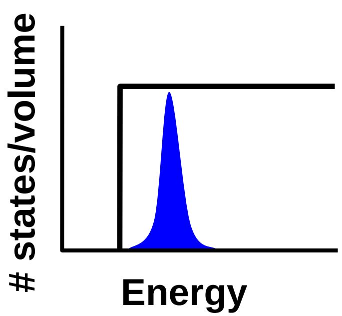
Underlying physics

Free-carrier effects

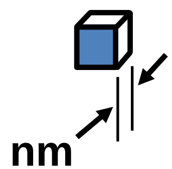
Density of states

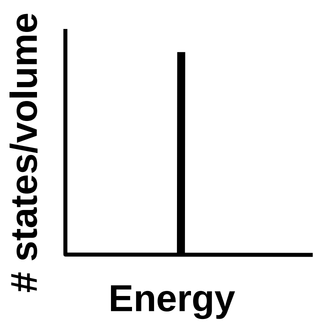
Quantum well





Quantum dot





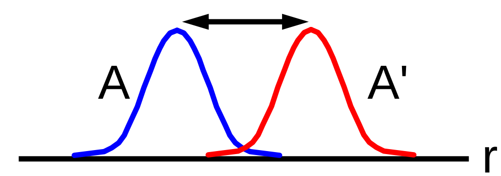
Carrier-interaction effects

Many-body effects

Quantum statistics **+** **Coulomb interaction**

$$\{A, B\} = AB + BA$$

$$\frac{e^2}{4\pi\varepsilon_0 r}$$



Carrier-interaction (many-body) effects

Hartree-Fock (mean-field)

Bandgap renormalization

Exciton/Coulomb enhancement

Correlations

Relaxation, dephasing and screening by carrier-carrier and carrier-phonon collisions

Motivation for rigorous treatment

Agreement with experiment

Chow, Smowton, Blood, Girdnt, Jahnke, Koch, Appl. Phys. Lett. **71**, 157 (1997)

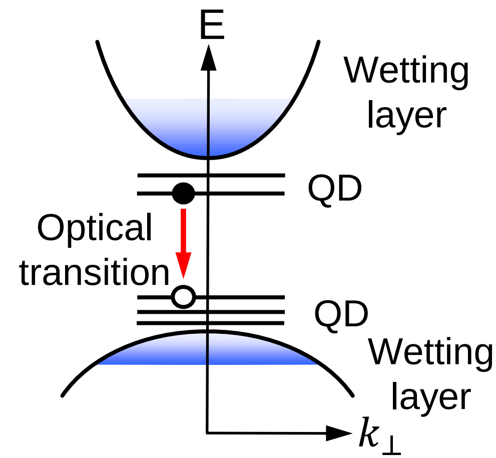
No free parameter

- **Eliminate dephasing rate as free parameter**
- **Input: growth sheet and bulk-material parameters**

Hamiltonian

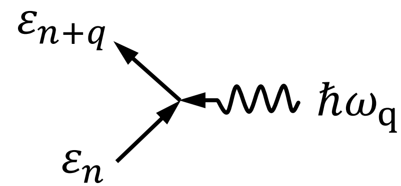
$$H = \sum_{n} \varepsilon_{e,n} a_n^{\dagger} a_n + \sum_{m} \varepsilon_{h,m} b_m^{\dagger} b_m$$ ***Single-particle***

Electronic structure



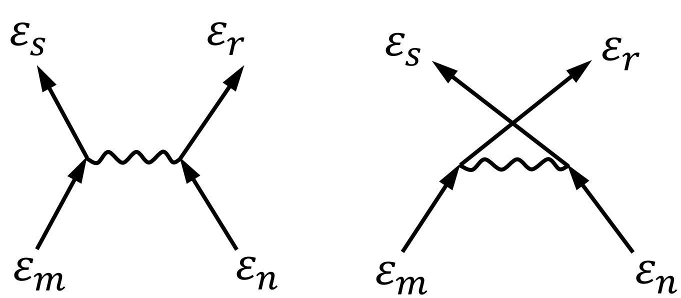
$$-\sum_{m} \left(\mu_{nm} a_n^{\dagger} b_m^{\dagger} + \mu_{nm}^{*} b_m a_n \right) E(z,t)$$ ***Light-matter***

$$+\sum_{n,q} \hbar G_q a_{n+q}^{\dagger} a_n \left(b_q + b_{-q}^{\dagger} \right)$$ ***Carrier - phonon***



Carrier – carrier

$$+\frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} a_r^{\dagger} a_s^{\dagger} a_m a_n + \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} b_r^{\dagger} b_s^{\dagger} b_m b_n - \sum_{n,m,r,s} W_{nm}^{rs} a_r^{\dagger} b_s^{\dagger} b_m a_n$$



Direct Exchange

$$\int d^3r\, d^3r' \phi_r^{*}(r) \phi_s^{*}(r') \frac{e^2}{4\pi\varepsilon_b |r - r'|} \phi_m(r') \phi_n(r)$$

Bare Coulomb potential

Standard treatment

(e.g., leading to the Boltzmann integral for electron-electron scattering)

Populations or polarizations

Markov approx

$$A_\alpha(t) = A_\alpha(t_0) + \int_{t_0}^{t} dt'\, K(t-t')A_\alpha(t') \approx A_\alpha(t_0) + A_\alpha(t) \overbrace{\int_{t_0}^{\infty} dt'\, K^{(2)}(t-t')}^{-\gamma \times (t-t_0)}$$

$$\frac{\mathrm{dK}}{\mathrm{dt}} = \mathrm{F}\left(q_1, q_2, \dots, t\right)$$

2nd Born approx

$$\boxed{\left.\frac{\mathrm{d}A_\alpha}{\mathrm{dt}}\right|_{scat} = -\gamma A_\alpha}$$

Perturbation theory and without memory

Indication of problem with using QW theory for QD

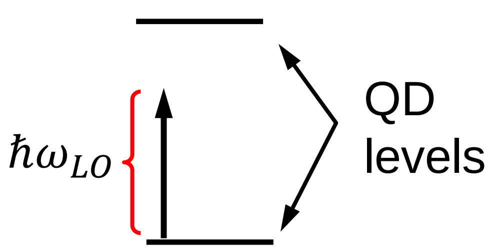
Standard scattering treatment

Perturbation theory and without memory

$$\boxed{\left.\frac{\mathrm{d}A_\alpha}{\mathrm{dt}}\right|_{scat} = -\gamma A_\alpha}$$

Energy conservation: $\delta\left(\varepsilon_f - \varepsilon_i \pm \hbar\omega_{LO}\right)$

Phonon bottleneck problem



Not found to be severe in devices

Physics changes from QW to QD

Present Theory: Quantum kinetic equations

$$A_\alpha(t) = A_\alpha(t_0) + \int_{t_0}^{t} dt'\, K(t-t')A_\alpha(t') \cancel{\approx A_\alpha(t_0) + A_\alpha(t)\int_{t_0}^{\infty} dt'\, K^{(2)}(t-t')}$$

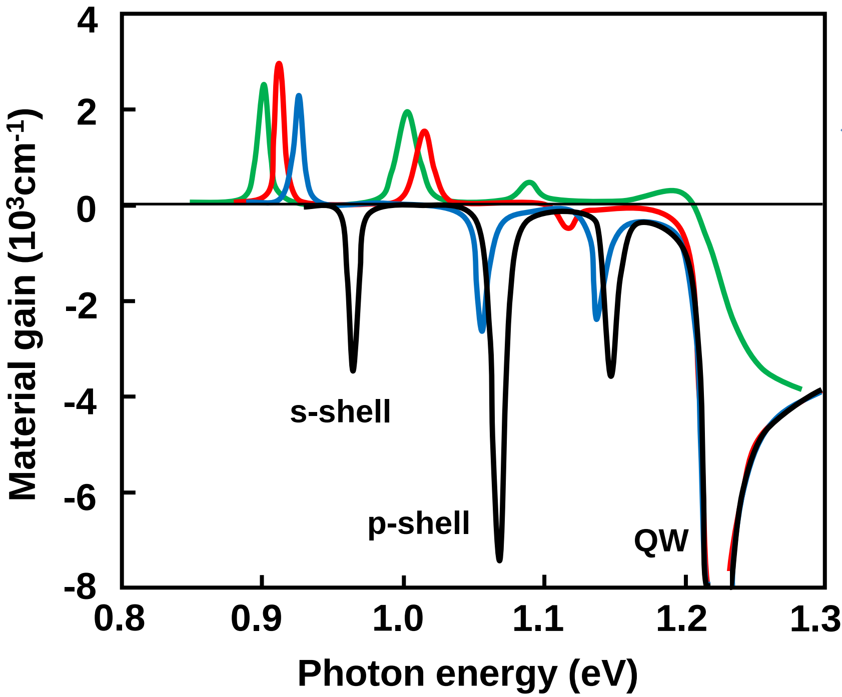
$$\frac{\mathrm{dK}}{\mathrm{dt}} = \mathrm{F}\left(q_1, q_{2,} \ldots, t\right)$$

- **Memory effects** Non-Markovian dephasing: Schneider, Chow, Koch, PRB **70** 235308, (2004)
- **Non perturbation** Polarons: Seebeck, … Gartner, Jahnke, PRB **71** 125327 (2005)
- **No free parameters** QD/QW laser comparison: Chow, Lorke, Jahnke, IEEE J. Selected Topics Quantum Electron. **17** 1349 (2011)

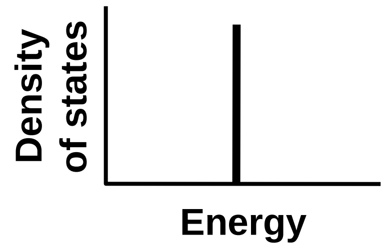
For general review: Chow and Jahnke, Progress in Quantum Electronics **37**, 109 (2013)

Quantum-dot absorption/gain spectra

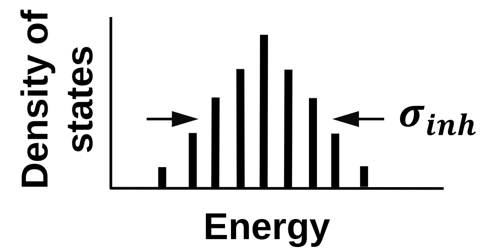
Intrinsic (calculated)

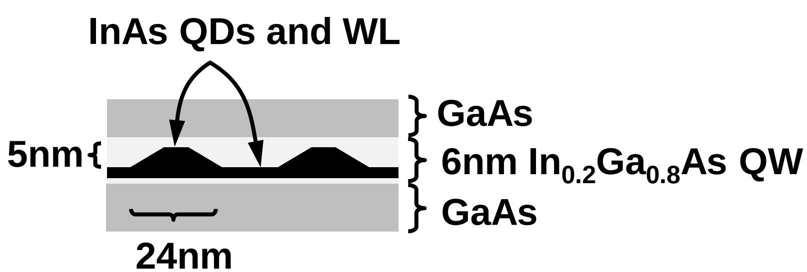


Homogeneously broadened



Inhomogeneously broadened

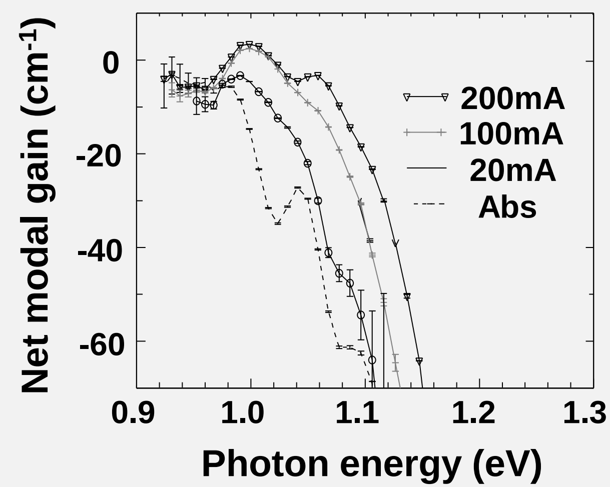




$N_{dot} = 2 \times 10^{11} cm^{11}$ T = 300K

Carrier density: N = 10^{11}, 10^{12}, 2×10^{12}, 3×10^{12} cm^{11}

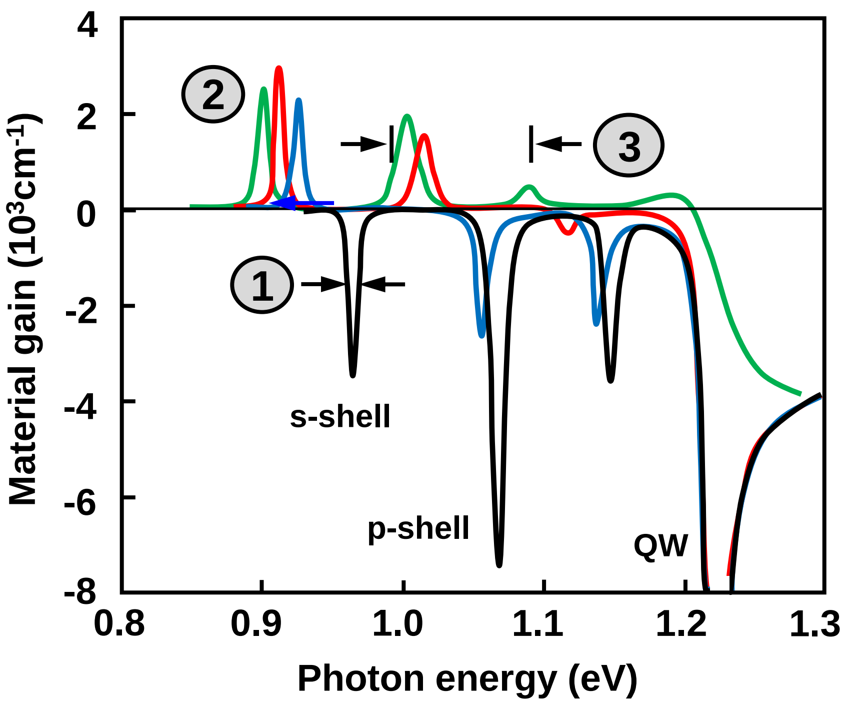
Experiment

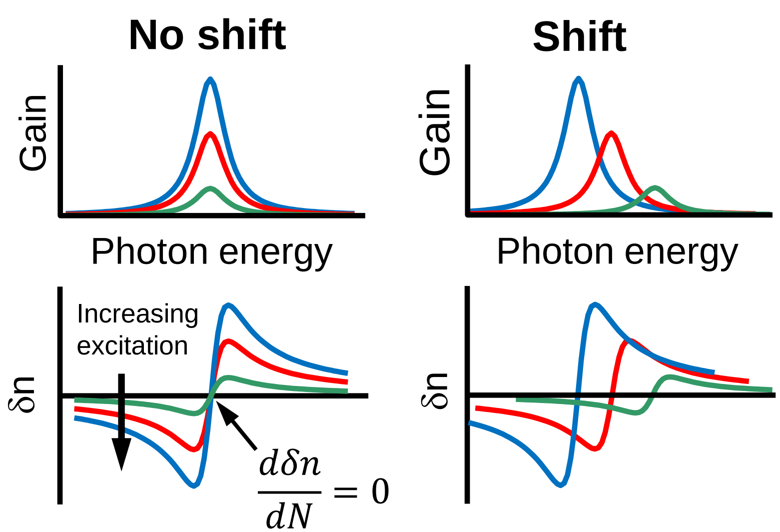


(measured at Cardiff University)

Quantum-dot absorption/gain spectra

Intrinsic (calculated)





1 Homogeneous width

- Relates directly to gain
- Inhomogeneous broadening determination
- Calc: PRB 70 235308 (2004)

2 Saturation

- Maximum available gain
- Calc: PRB 74, 35334 (2006)
- Expt: APL 99, 61104 (2011) -- $\frac{dG_{pk}}{dN} < 0$

3 Shift

Expt: APL 71, 2791 (1997)
Calc: PRB 66, 41315(R) (2002)

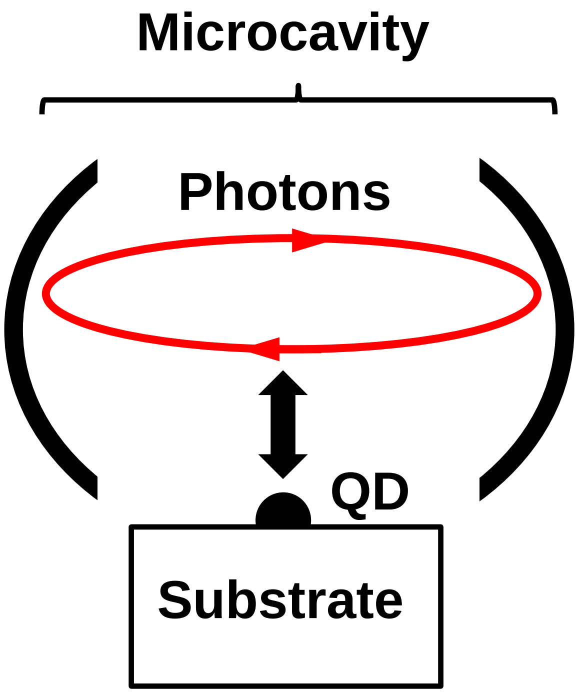
- Causes carrier-induced refractive index
- Filamentation

  Expt: Smowton, et al, APL 81 3251 (2002)
- Frequency chirp
- Dynamical instabilities

  Lingnau, et al, Phys. Rev. E 86 (R) 065201 (2012)

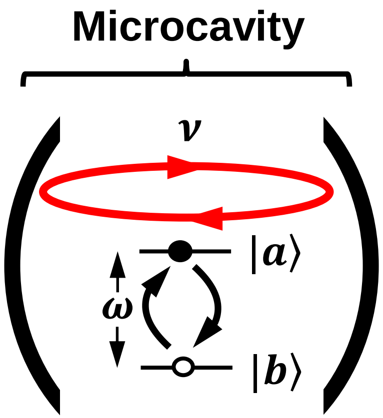
Quantum Optics

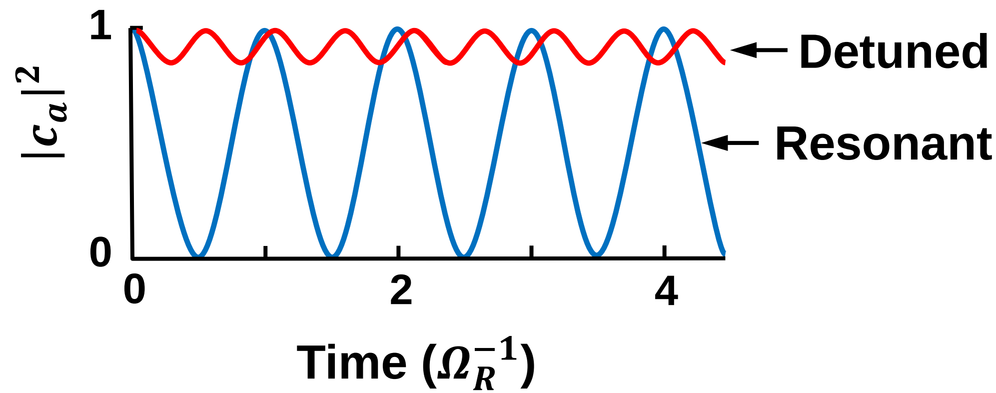
Cavity QED: control of spontaneous emission



Semiconductor provides rich, many-body environment for studies

Atomic-molecular-optical (AMO) Rabi oscillations

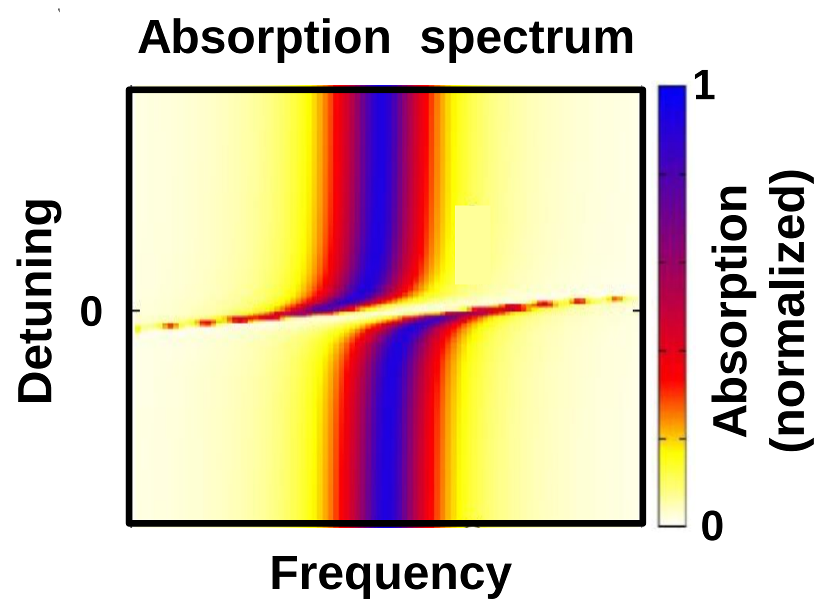




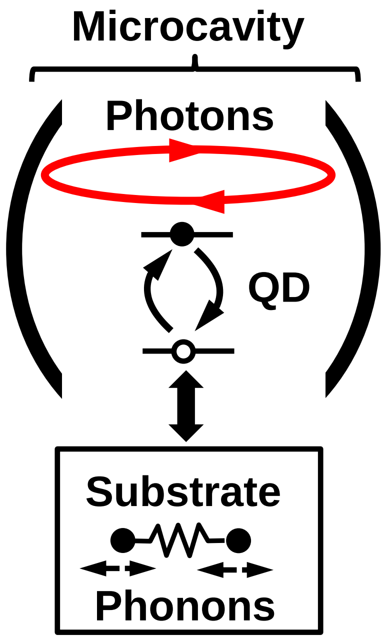
Excited state population

$$|c_a|^2 \sim \frac{\Omega_R^2}{\sqrt{\Omega_R^2+\Delta^2}}\, cos^2\left(\sqrt{\Omega_R^2+\Delta^2}\,\frac{t}{2}\right)$$

Detuning: $\Delta = \nu - \omega$



Semiconductor QD Rabi oscillations

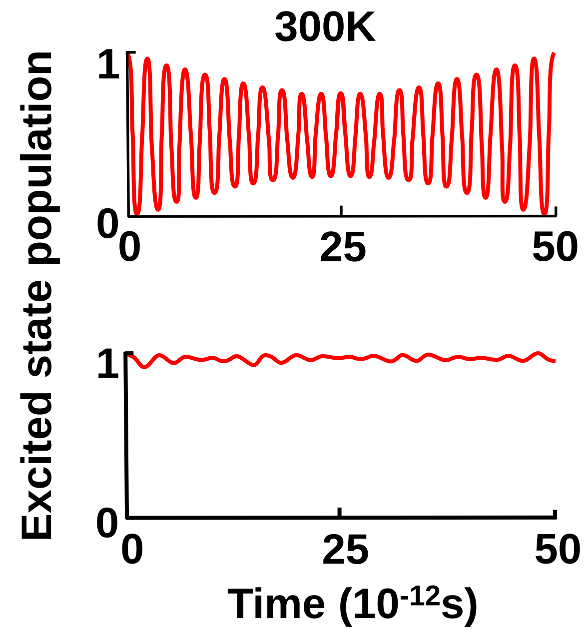


Resonant

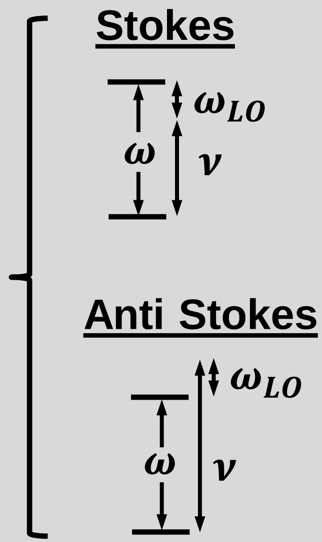
$\omega = \nu$

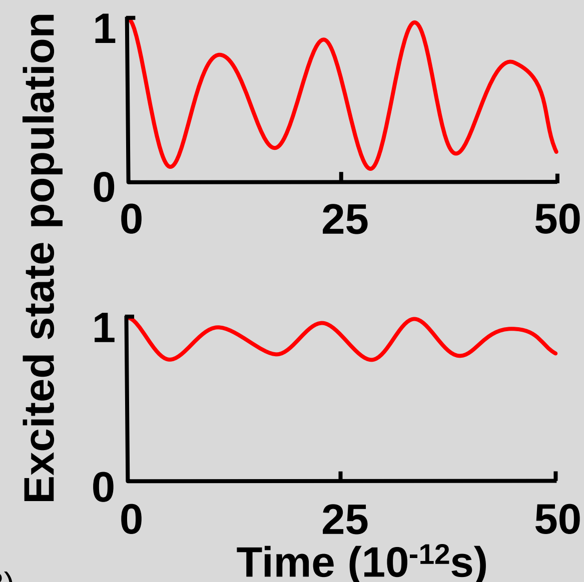
Detuned

$\omega \neq \nu$



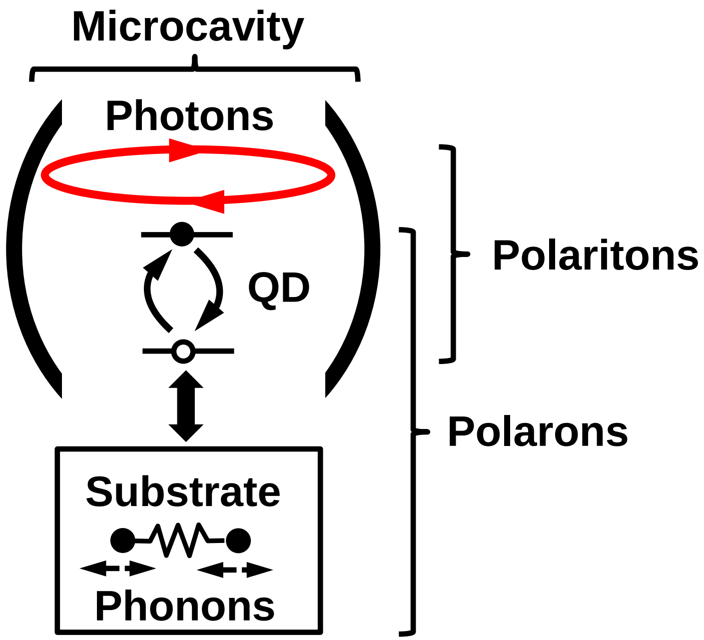
LO-phonon-assisted Rabi oscillation

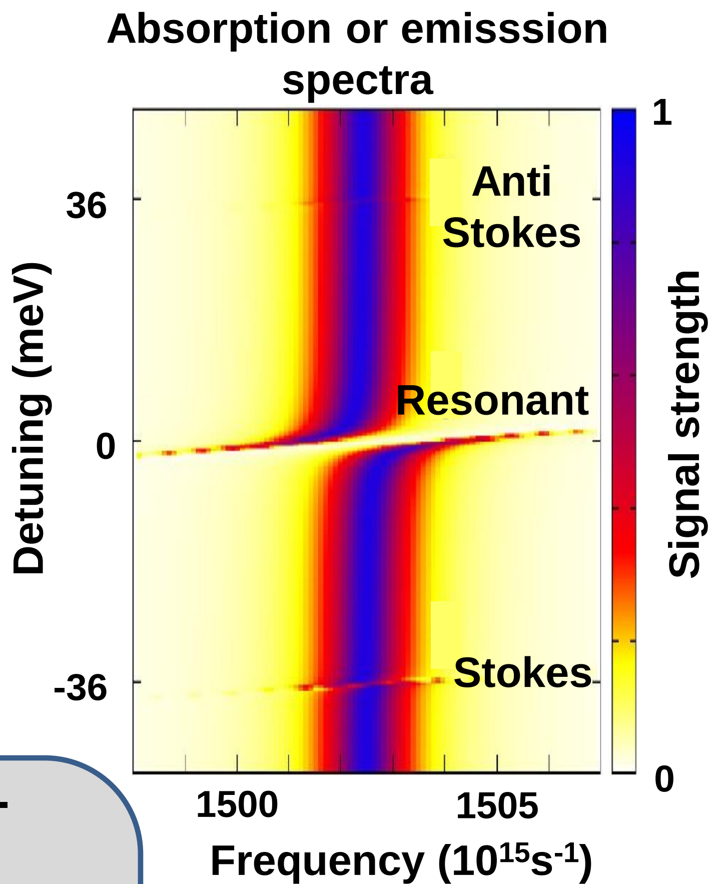




Carmele, Kabuss, Chow PRB 87 041305 (R) (2013)

Phonon-assisted Rabi splittings





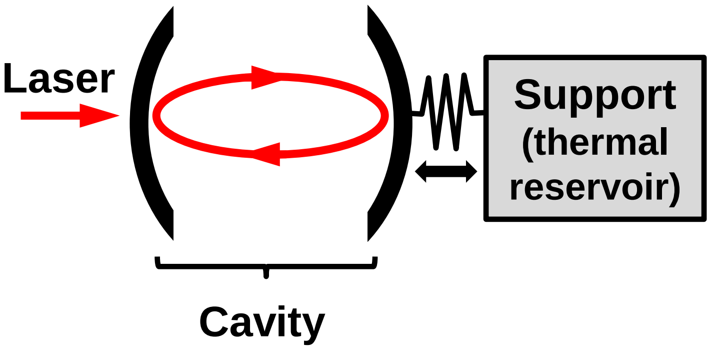
Theory of strongly-coupled electron-photon-phonon system

- Jaynes-Cummings (AMO) problem with quantum statistics
- Phonon-bath effects beyond standard 2nd Born approximation and with memory effects
- Correlations treated to arbitrarily high ($\gtrsim$150th) level
- Tracks changes phonon bath statistics

Carmele, Kabuss, Richter, Knorr and Chow, J. Mod. Optics 58, 1951 (2011)

Connection to quantum optomechanics

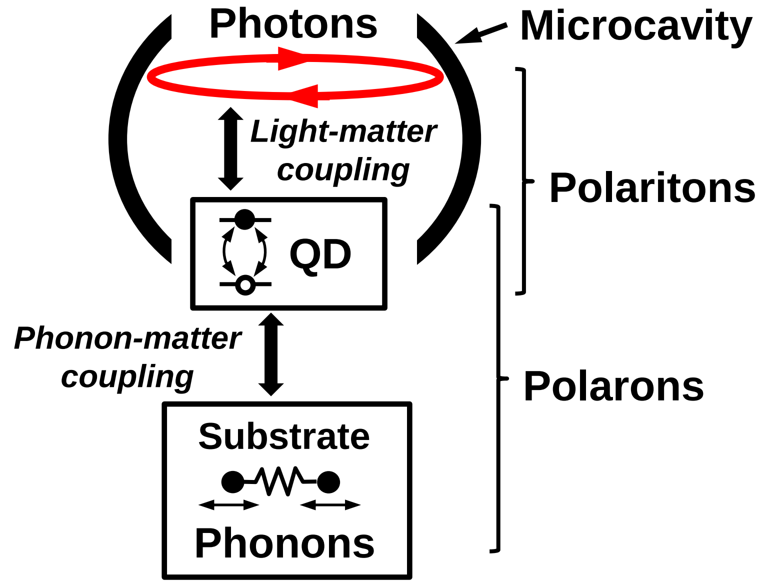
AMO



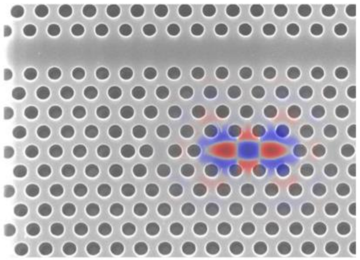
$$H_I = \frac{\hbar\omega_c}{L}\sqrt{\frac{\hbar}{2m\Omega_m}}\,\underbrace{a^\dagger a}_{\text{Photons}}\,\overbrace{\left(b + b^\dagger\right)}^{\text{Mirror displacement}}$$

Laser interferometer gravitational-wave observatory (LIGO)

Semiconductor



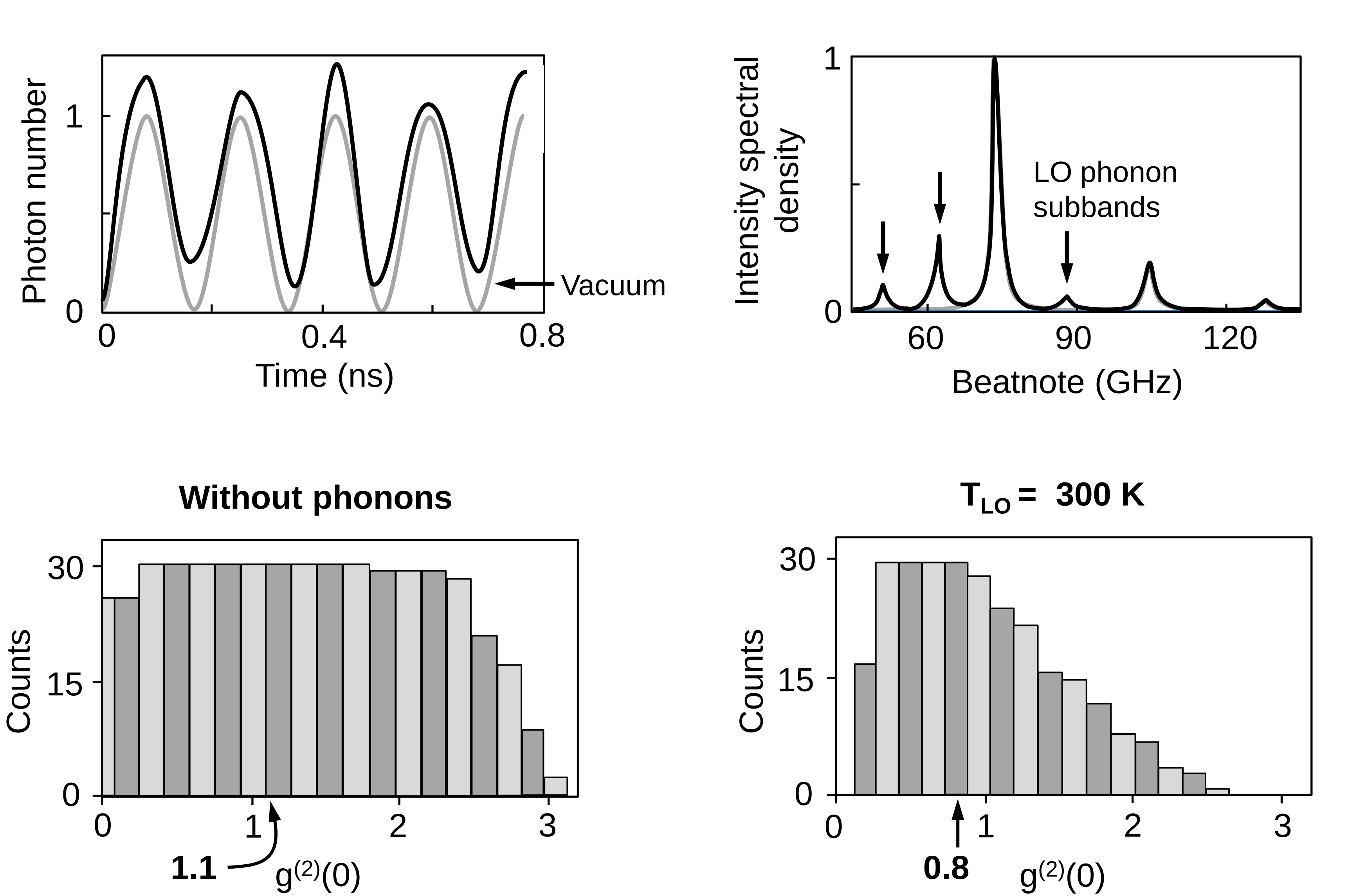
$$H_I = \sum_{n,q}\hbar\sqrt{\frac{\omega_{LO}V_{sq}}{2\hbar m}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_0}\right)}\,\underbrace{c_n^\dagger c_n}_{\text{Electron}}\,\overbrace{\left(b_q + b_{-q}^\dagger\right)}^{\text{Lattice displacement}}$$



Quantum dots on photonic-crystal microcavity

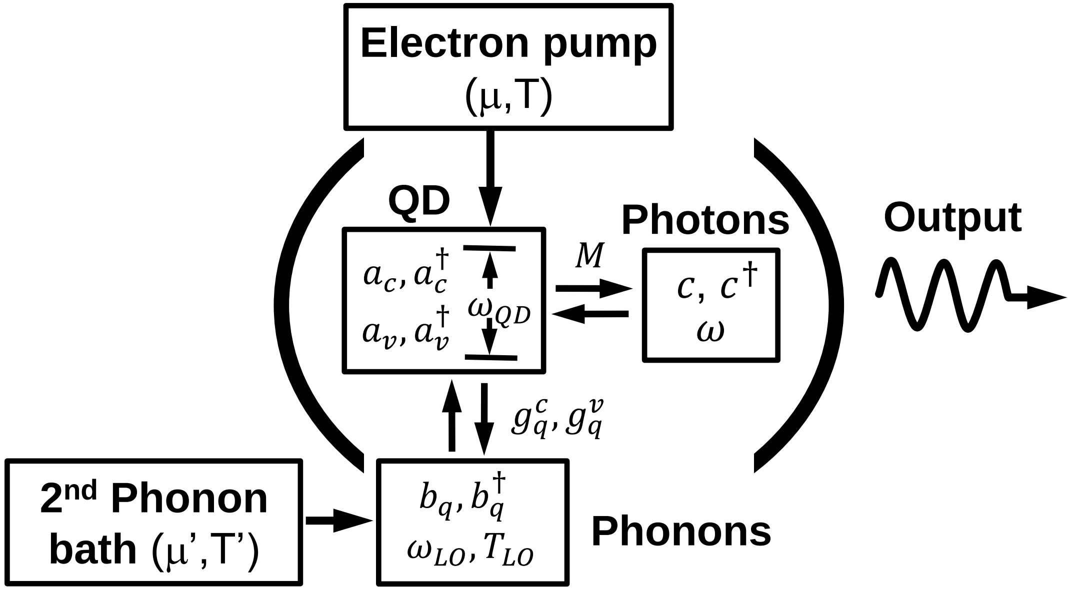
T. S. Luk, et al, J. Opt. Soc. B 28, 1365 (2011)

Antibunching of thermal radiation by room-temperature phonon bath



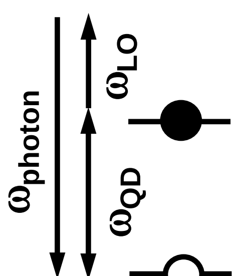
Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)

Tamu/princeton2009



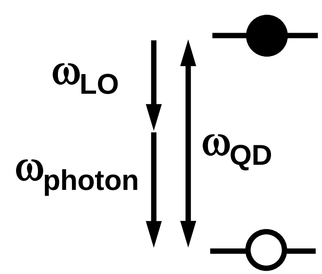
Self-cooled optoelectronics

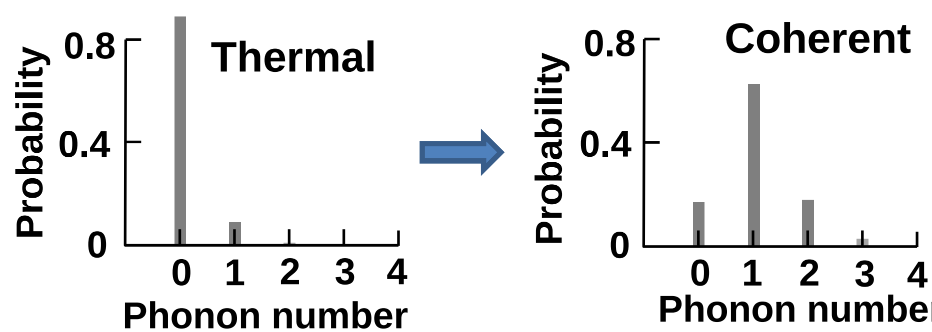
Anti Stokes



Non-thermal phonon generation

Stokes



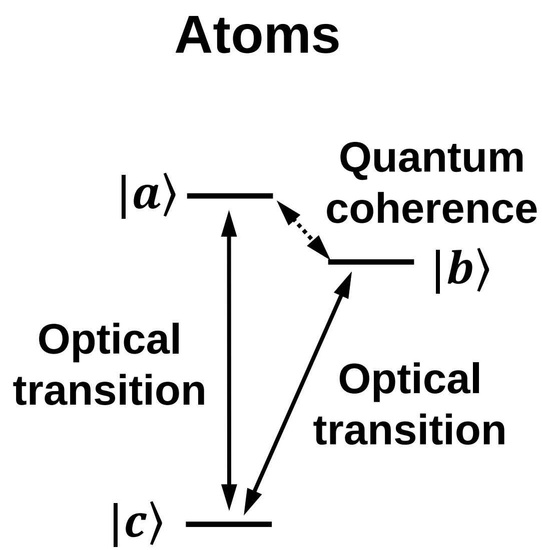


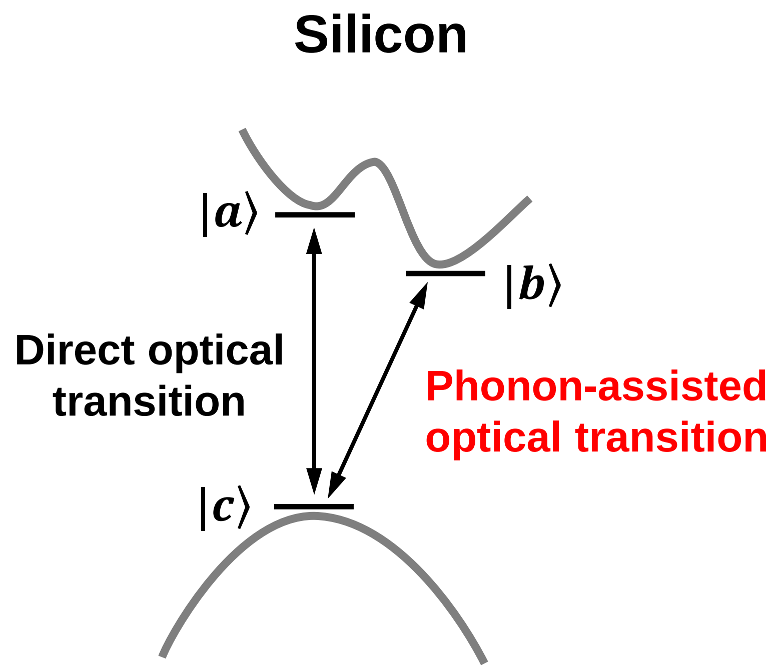
Like electroluminescent cooling* but in strong-coupling regime

* Santhanam, Gray and Ram, PRL 108, 097403, 2012

Silicon quantum electronics and optics

Quantum coherence phenomena





Slow light (memory)	⇒	**Optical memory**
Electromagnetically induced transparency (EIT)	⇒	**Exceeding PVC Shockley-Queisser limit**
Lasing without inversion (LWI)	⇒	**Lasing in indirect band-gap materials**

Quantum-dot physics for lasers and quantum optics

Lasers

Improving semiconductor laser performance at fundamental level

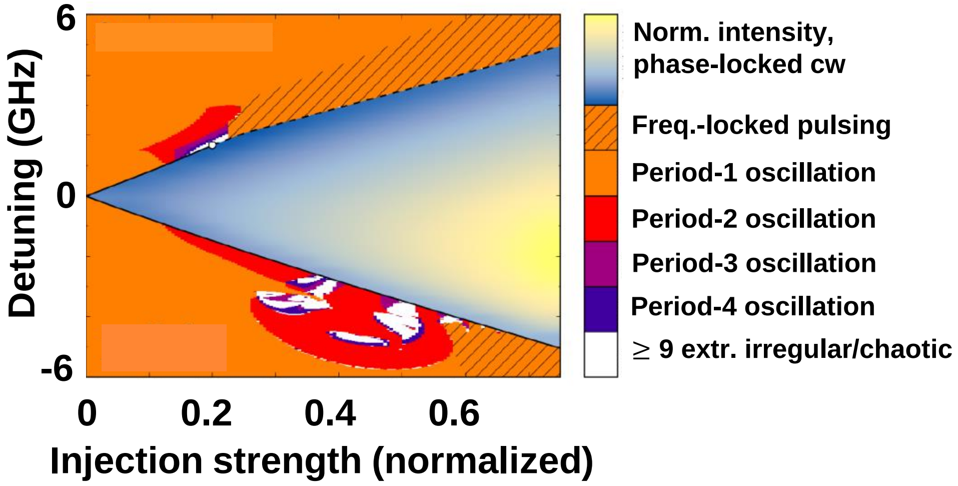
Quantum optics

Phonon-assisted strong-coupling: a new path to cavity quantum optomechanics

Nonlinear dynamics

Motivation for developing new bifurcation analysis techniques

Dynamical instabilities in injection-locking of QD laser



Lingnau, Luedge, Chow, Scholl, Phys. Rev. E 86 (R), 065201, 2012

QD physics and applications overview: Chow and Jahnke, Progress in Quantum Electronics 37, 109 (2013)