Simulation of two-state lasing dynamics in quantum-dot lasers

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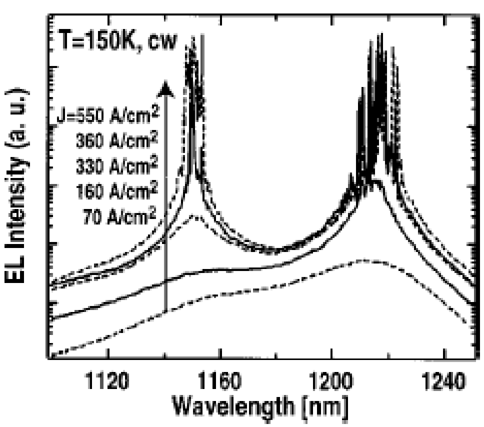
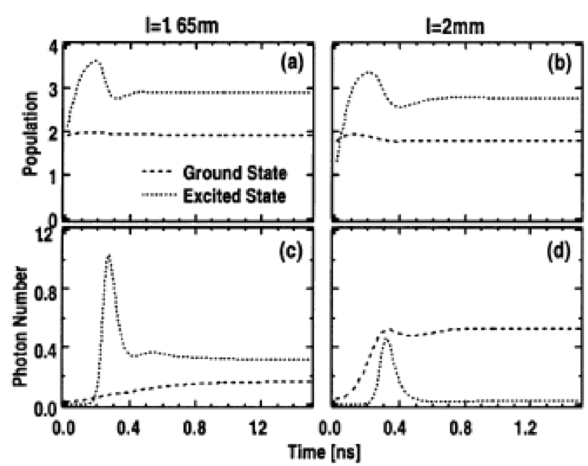
Outline

- Introduction
- Theoretical model
  - Rate-equation model
- Simulation results
- Conclusions

Introduction - previous works

- Steady states
  - With increasing excitation, ground states always achieve lasing first.
  - Simultaneous lasing from GS and ES can occur under some conditions.
- Dynamic
  - Some theoretical predictions were reported.

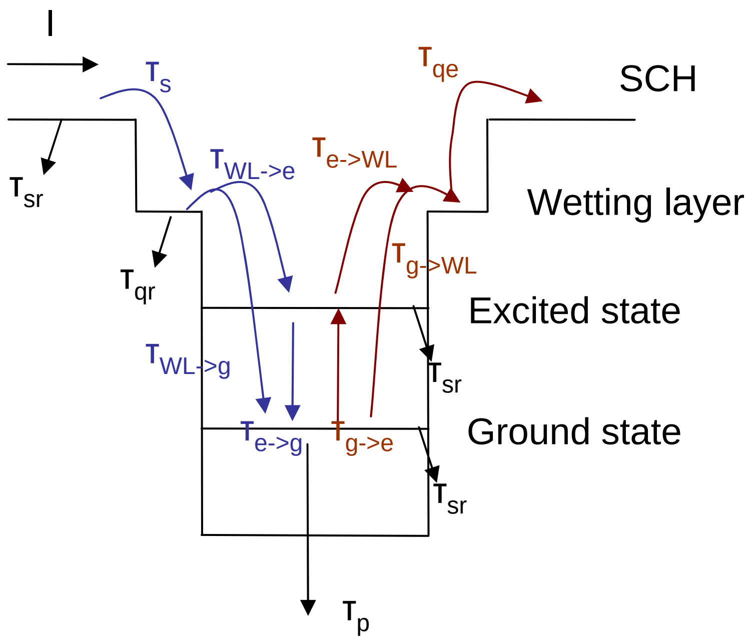




Ref. A. Markus et. al, Appl. Phys. Lett.. 82, 1818 (2003)
Ref. M. Sugawara et. al, J. Appl. Phys. 97, 0435243 (2005)
Ref. A. Markus et. al, IEEE J. Select. Top. Quantum Electron. 9, 1308 (2003)

Simulation model

- Include
  - Four energy levels
  - Carrier thermal escape effect
  - Homogeneous Broadening
  - Inhomogeneous Broadening



Ref. M. Sugawara et. al, Phys. Rev. B 61, 7595 (2000)

Simulation model (cont.)

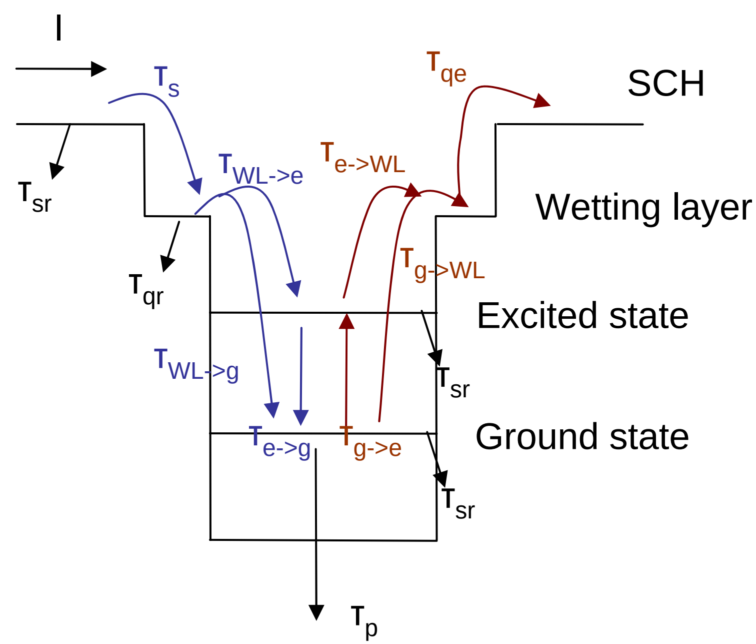
$$\frac{dN_s}{dt} = \frac{I}{q} - \frac{N_s}{\tau_s} - \frac{N_s}{\tau_{sr}} + \frac{N_q}{\tau_{qe}}$$

$$\frac{dN_q}{dt} = \frac{N_s}{\tau_s} + \sum_n \frac{N_{e,n}}{\tau_{e,n\to w}} + \sum_n \frac{N_{g,n}}{\tau_{g,n\to w}} - \frac{N_q}{\tau_{w\to g}} - \frac{N_q}{\tau_{w\to e}} - \frac{N_q}{\tau_{qr}} - \frac{N_q}{\tau_{qe}}$$

$$\frac{dN_{g,n}}{dt} = \frac{N_q G_{g,n}}{\tau_{w\to g,n}} + \frac{N_{e,n}}{\tau_{e,n\to g,n}} - \frac{N_{g,n}}{\tau_{rn}} - \frac{N_{g,n}}{\tau_{g,n\to w}} - \frac{N_{g,n}}{\tau_{g,n\to e,n}} - \frac{c\Gamma}{n_r}\frac{\sum_m g_{g,mn} S_m}{1+\frac{\varepsilon\Gamma}{V_A}\sum_m S_m}$$

$$\frac{dN_{e,n}}{dt} = \frac{N_q G_{e,n}}{\tau_{w\to g,n}} + \frac{N_{g,n}}{\tau_{g,n\to e,n}} - \frac{N_{e,n}}{\tau_{rn}} - \frac{N_{e,n}}{\tau_{e,n\to w}} - \frac{N_{e,n}}{\tau_{e,n\to g,n}} - \frac{c\Gamma}{n_r}\frac{\sum_m g_{e,mn} S_m}{1+\frac{\varepsilon\Gamma}{V_A}\sum_m S_m}$$

$$\frac{dS_m}{dt} = \beta B N_{g,n}^2 + \beta B N_{e,n}^2 + \frac{c\Gamma}{n_r}\frac{\sum_n (g_{g,mn}+g_{e,mn}) S_m}{1+\frac{\varepsilon\Gamma}{V_A}\sum_m S_m} - \frac{S_m}{\tau_p}$$



Ref. M. Sugawara et. al, Phys. Rev. B 61, 7595 (2000)

Simulation model (cont.)

- Photon lifetime

$$\tau_p^{-1} = \frac{c}{n_r}[\alpha_i + (\frac{1}{2L_{ca}})\ln(\frac{1}{R_1 R_2})]$$

- Carrier lifetime

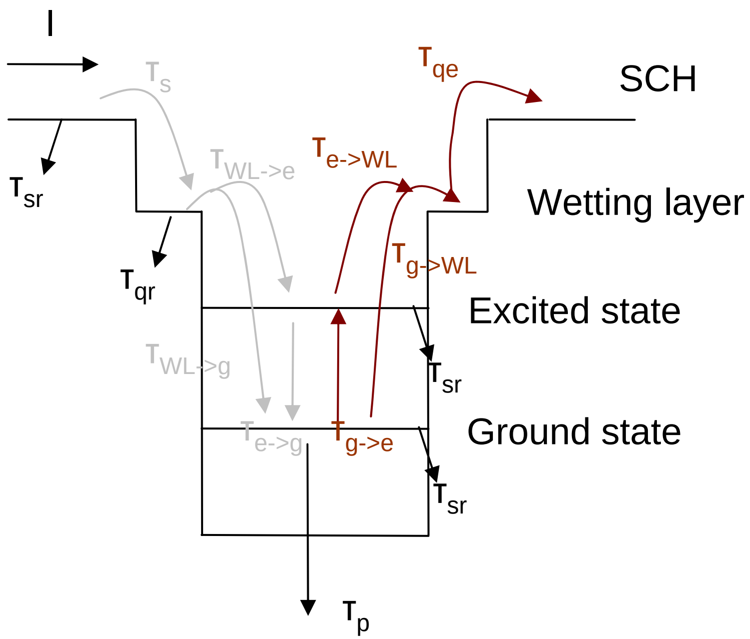
$$\tau_{rn}^{-1} = A + BN + CN^2$$

- Optical gain modal

$$g_{mn} = a_0(2P_n - 1)G_n B_{cv}(E_m - E_n)$$

Homogeneous broadening function (Lorentz distribution)

Inhomogeneous broadening function (Gaussian distribution)



Ref. M. Sugawara et. al, Phys. Rev. B 61, 7595 (2000)

Simulation model (cont.)

- Consider (Pauli exclusion principle)

$$P_{n,j} = \frac{N_{j,n}}{2D_j N_D V_A G_n}$$

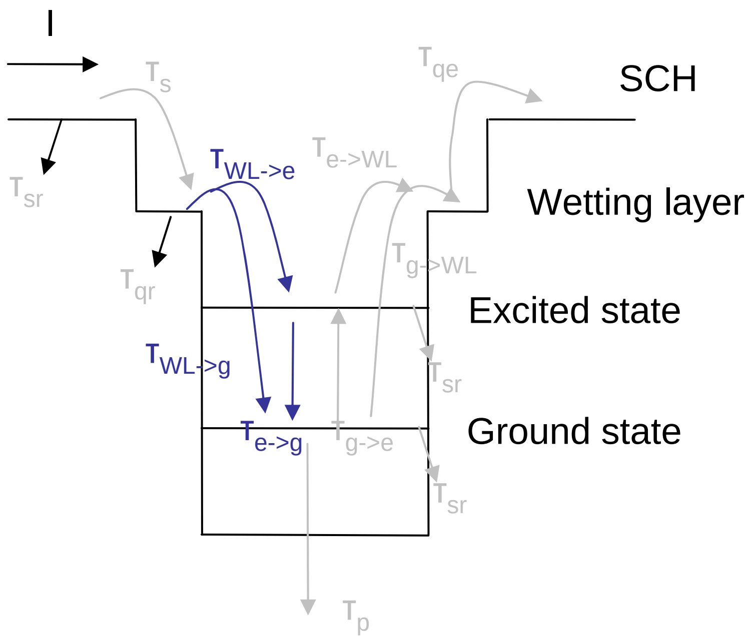
↑ occupation probability

$$\tau_{e->g}^{-1} = \tau_{0,e->g}^{-1}(1 - P_{n,g})$$

↑ relaxation time from ES to GS

$$\tau_{WL->g}^{-1} = \tau_{0,WL->g}^{-1}(1 - P_{n,g})$$

↑ capture time from WL to GS



$N_{j,n}$: the number of filled carrier in j state

N_D : total number of quantum dots

D_j : degeneracy for j state

V_A : total volume of active region

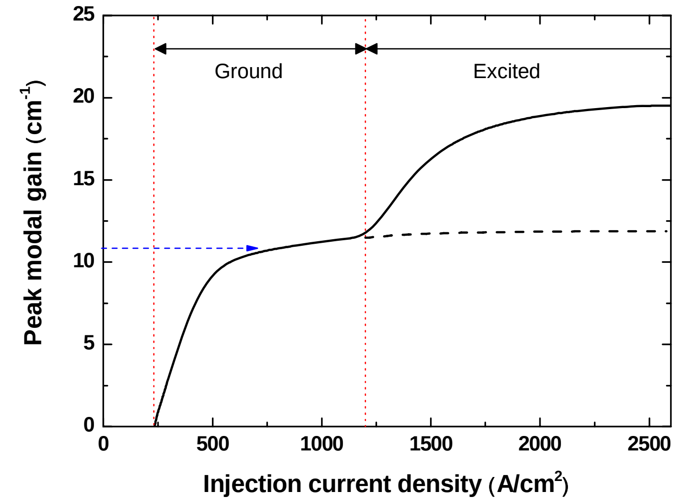
G_n : inhomogeneous broadening function

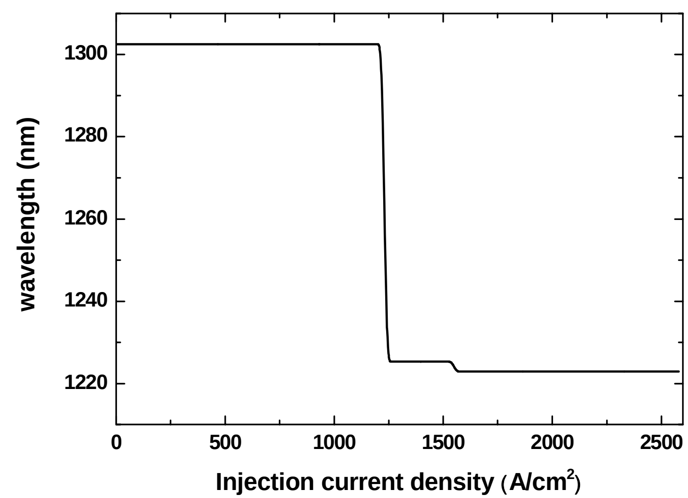
j : g or e (ground state or excited state)

Ref. M. Sugawara et. al, Meas. Sci. Technol. 13, 1683 (2002)

Simulation condition

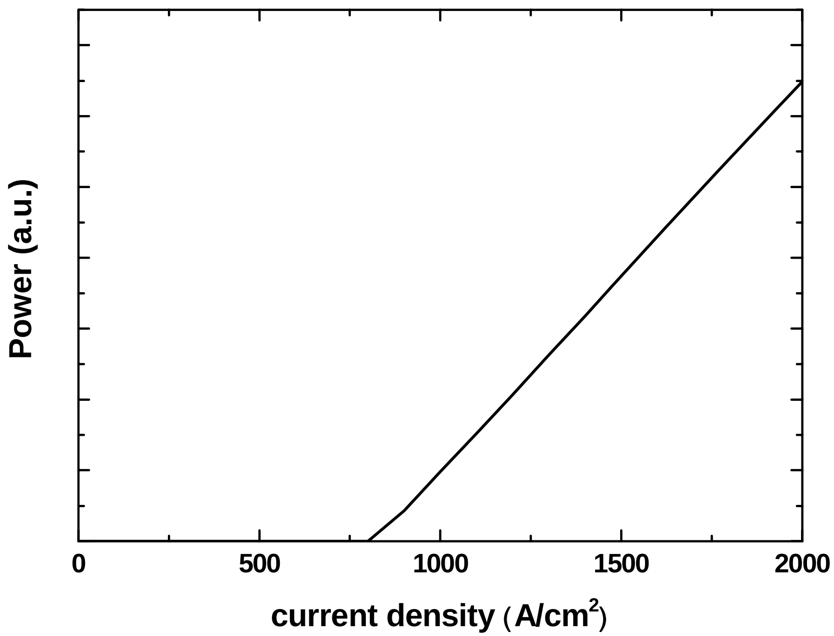
- Ground-state gain will saturate.
- When optical loss is larger than ground-state peak modal gain (11.5 cm^{-1}), this QD laser diode will lase from ES.
- In our simulation, the optical loss is assumed 10.9 cm^{-1}.

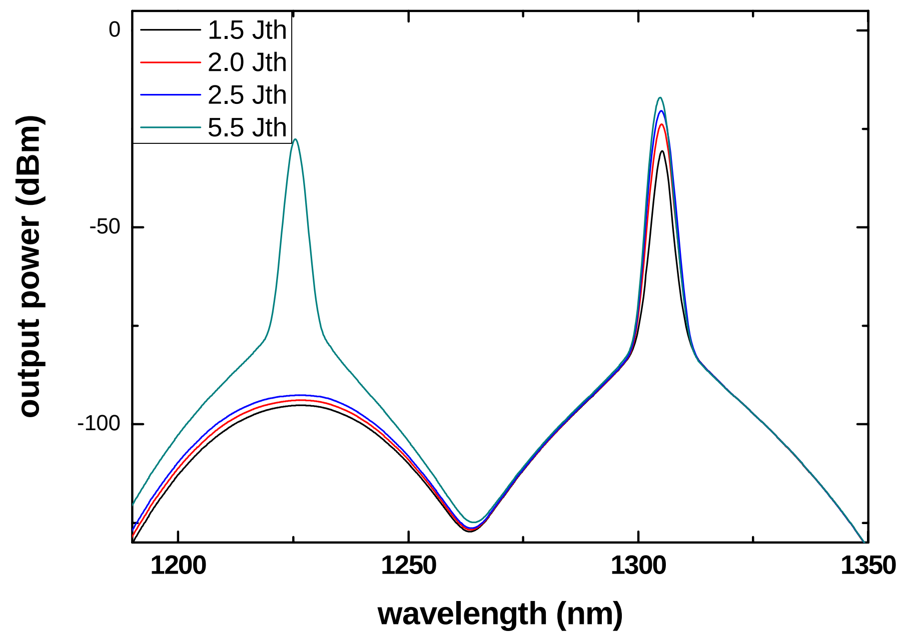




Theoretical results (I)

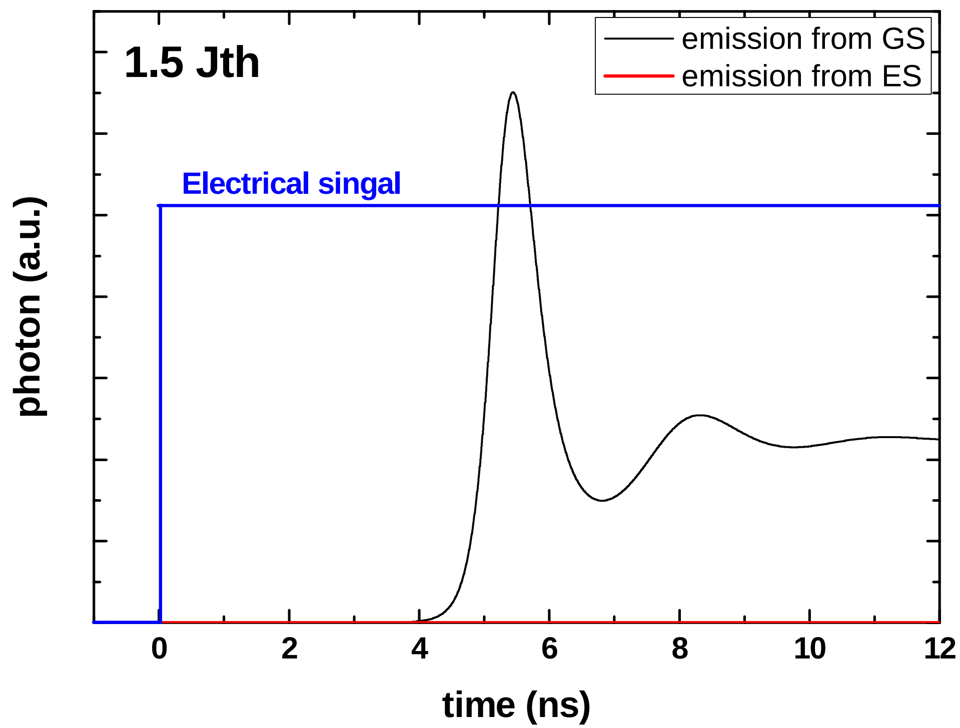
- Static properties of two-state lasing in quantum dot lasers
- Threshold current density J_{th} : 810 A/cm^2
- Under 1.5 J_{th}, 2.0 J_{th} and 2.5 J_{th}, no lasing from ES





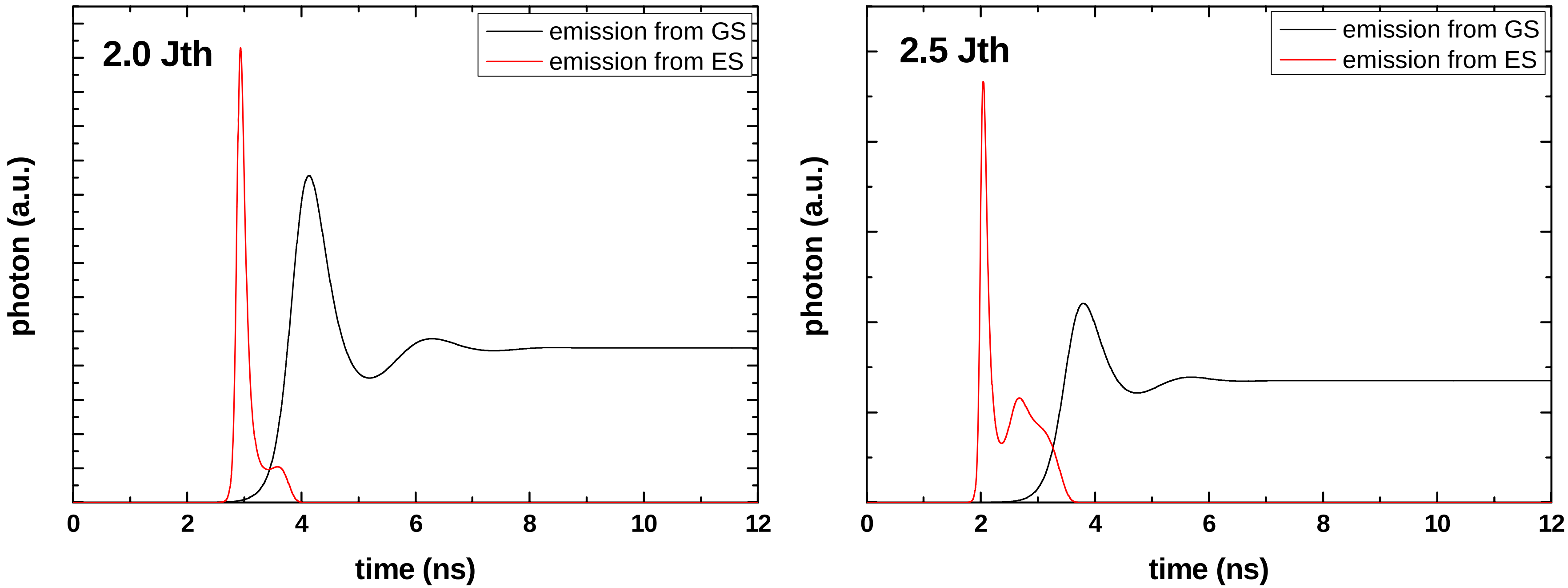
Theoretical results (II)

- Large signal modulation
- Electrical was turn on at t = 0.



Theoretical results (III)

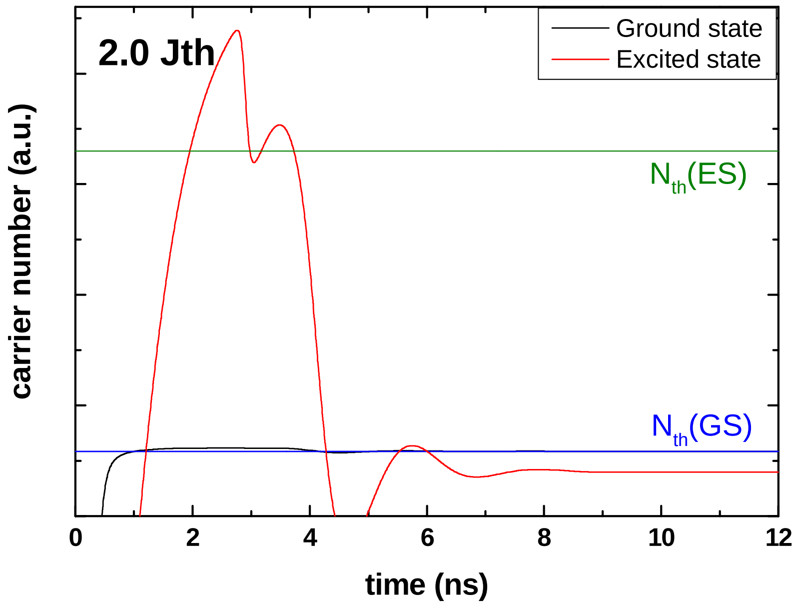
- Excited-state lasing occurs prior to ground-state lasing.
- Excited-state photons decrease after ground states start lasing.
- Only ground-state lase in steady states.

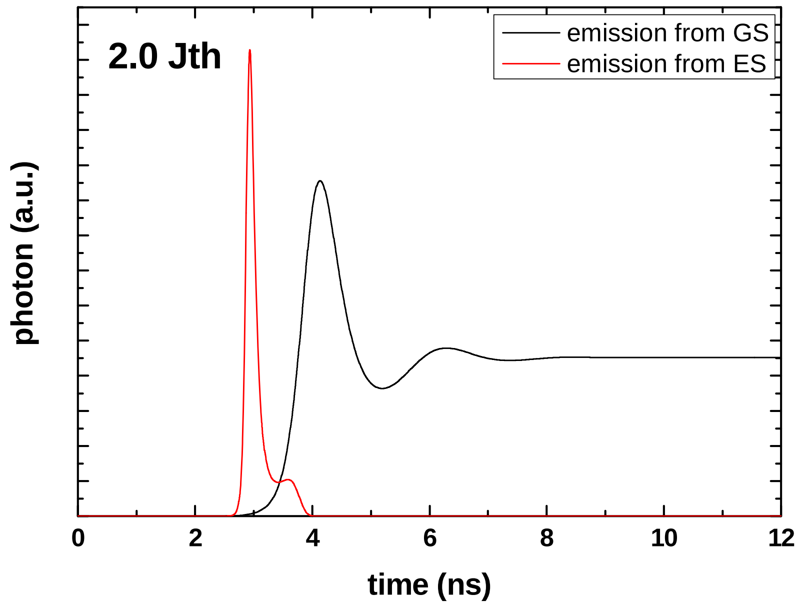


Theoretical results (IV)

$\tau_{WL\text{->}g,n}$ & $\tau_{e,n\text{->}g,n} \propto (1 - P_{n,g})$

- $\tau_{WL\text{->}g,n}$ and $\tau_{e,n\text{->}g,n}$ become larger.
- Ground-state carriers increase slowly.
- When ground-state finally achieve lasing, excited-state carriers can relax into ground states.





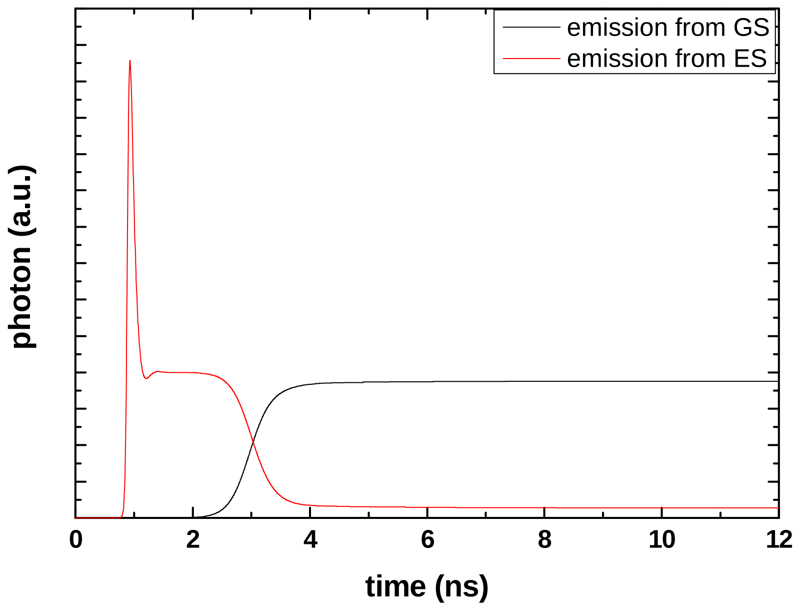
Conclusions

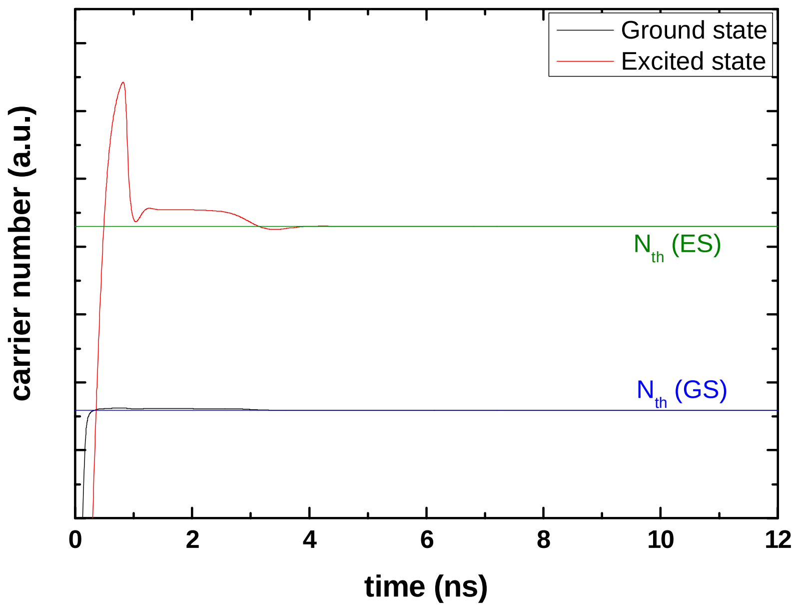
- The details of dynamic phenomena of two-state lasing in quantum-dot lasers is theoretically demonstrated in this study.
- We show that excited states achieve lasing prior to ground states in transient behavior under certain conditions, especially when the optical loss level is close to ground-state saturation gain.
- This phenomenon is dramatically different from the static two-state lasing behavior in quantum-dot lasers.

Thank you for your attention.

Theoretical results

- Excited-state lasing occurs prior to ground-state lasing.
- Excited-state photons decrease after ground states start lasing.
- Both ground-state and excited-state lase in steady states.





Simulation parameters

Γ_{homo} = 10 meV	n_r = 3.3
Γ_{inhomo} = 25 meV	$N_D = 2.5 * 10^{23}\ m^{-3}$
λ_{GS} = 1305 nm	Γ = 0.05
λ_{ES} = 1222 nm	$\beta = 0.896 * 10^{-4}$
L_{ca} = 2000 μm	$V_A = 7.5 * 10\text{-}^{16}\ m^3$
$R_1 = R_2 = 0.32$	$\tau_{0,WL->g}$ = 10 ps
$\alpha_i = 5.2\ cm^{-1}$	$\tau_{0,WL->e}$ = 5 ps
$\tau_{0,g}$ = 10 ps	$\tau_{0,e->g}$ = 1 ps
$\tau_{0,e}$ = 7 ps	τ_s = 15 ps
$A = 7 * 10^8\ s^{-1}$	$C = 1.56 * 10^{-14}\ s^{-1}$
$B = 0.067\ s^{-1}$	