PRINCETON UNIVERSITY

Excited State Quantum Cascade Lasers and Lasing in *k*-Space

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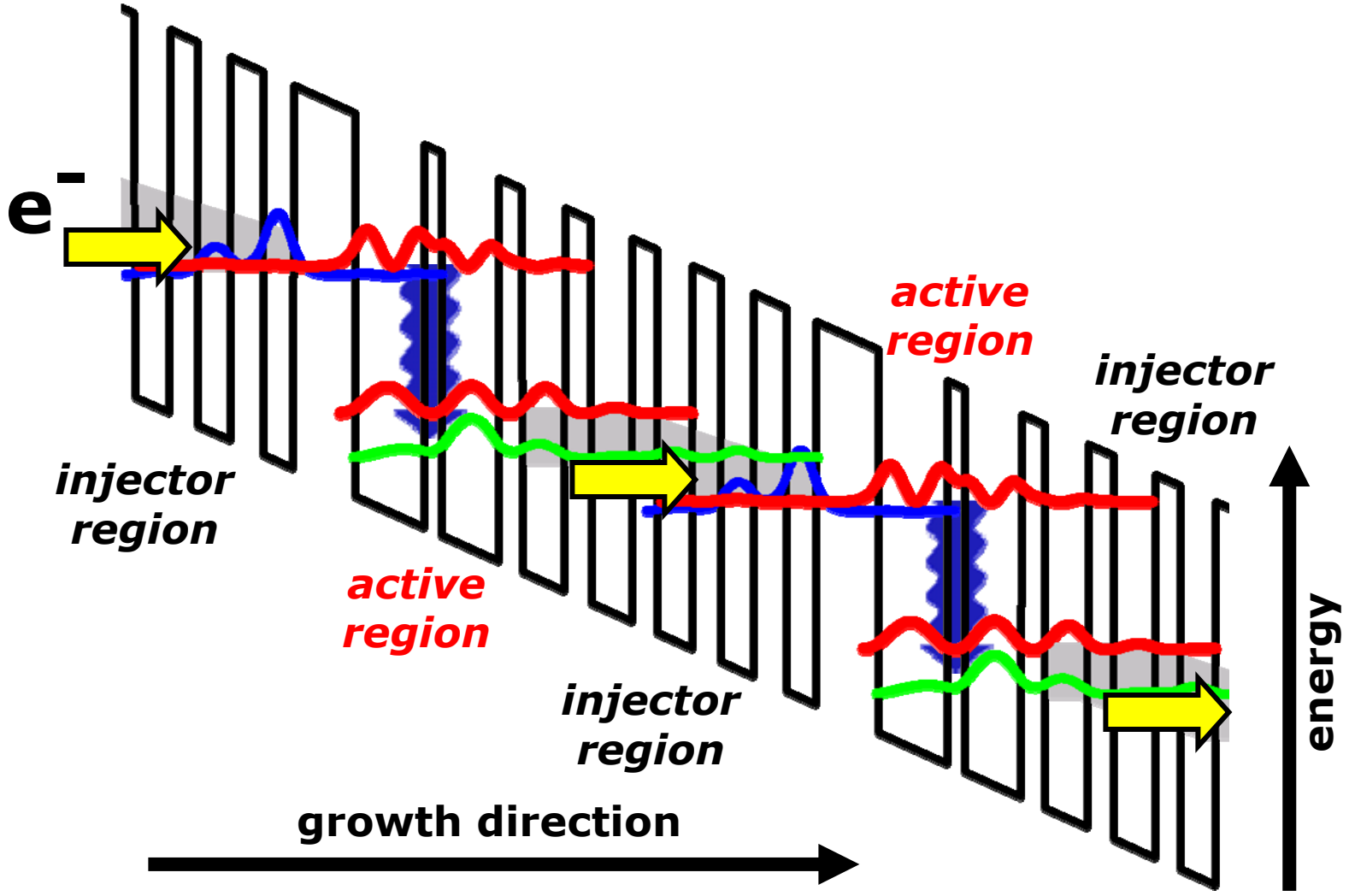
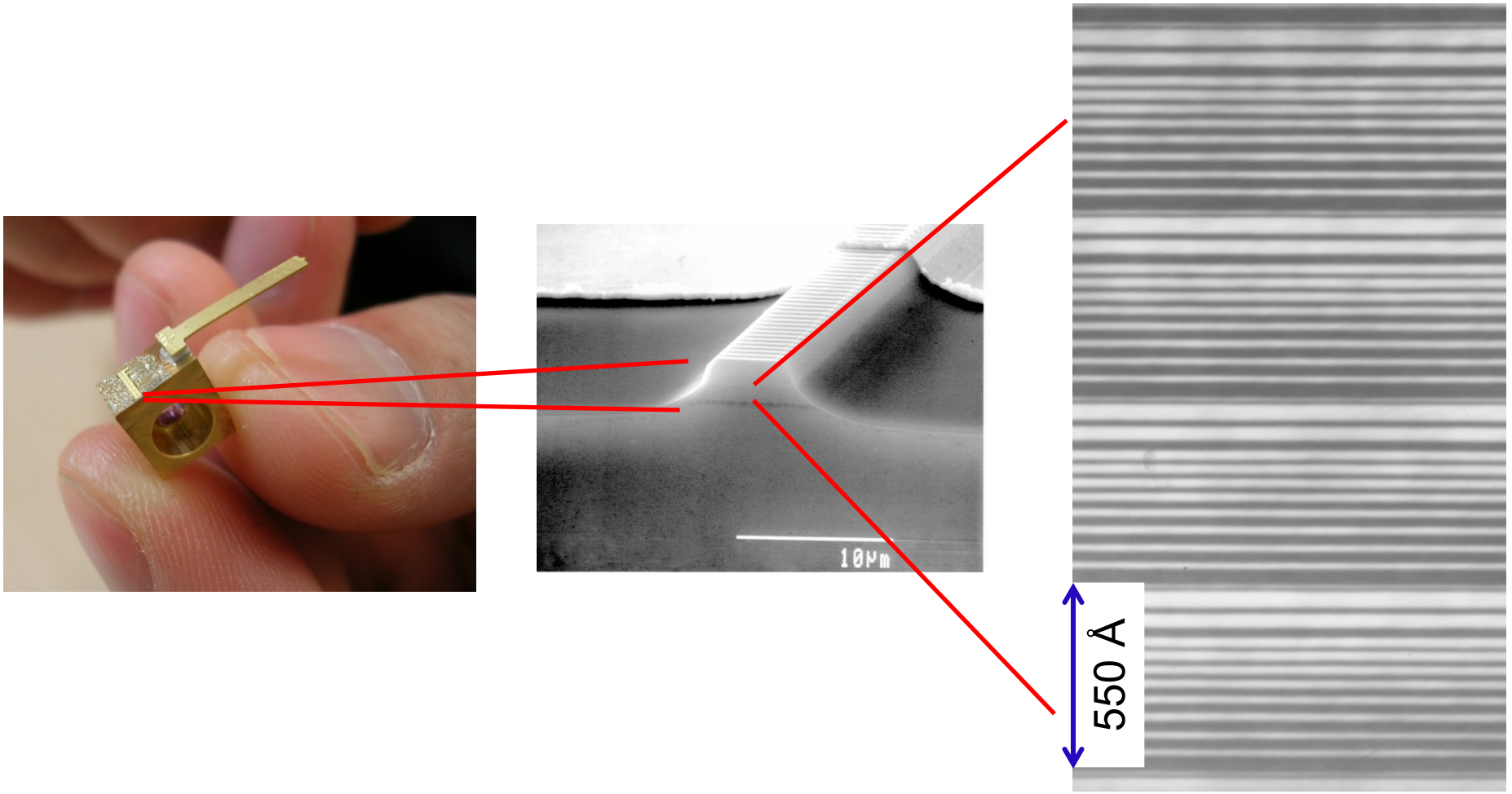
Quantum Cascade Lasers

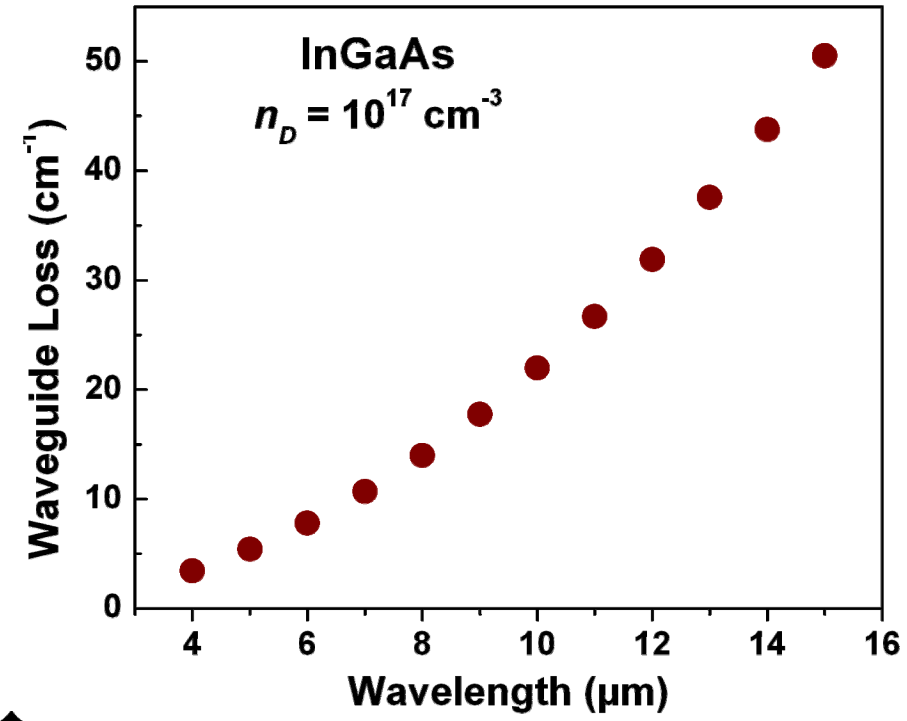


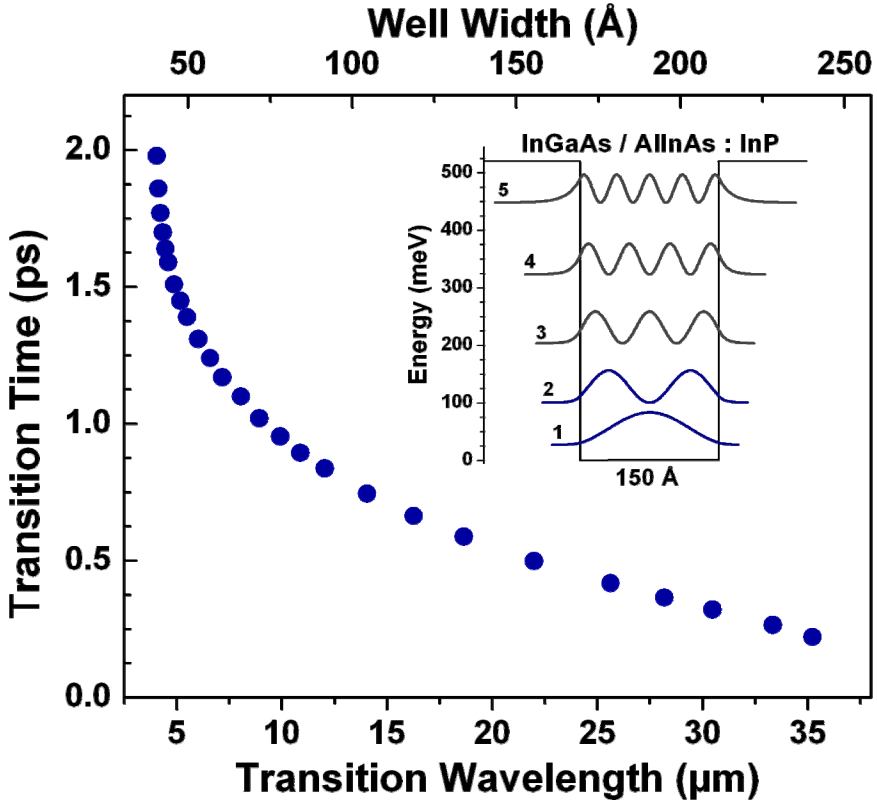
Built “one atom at a time”



Why is long wavelength so hard?

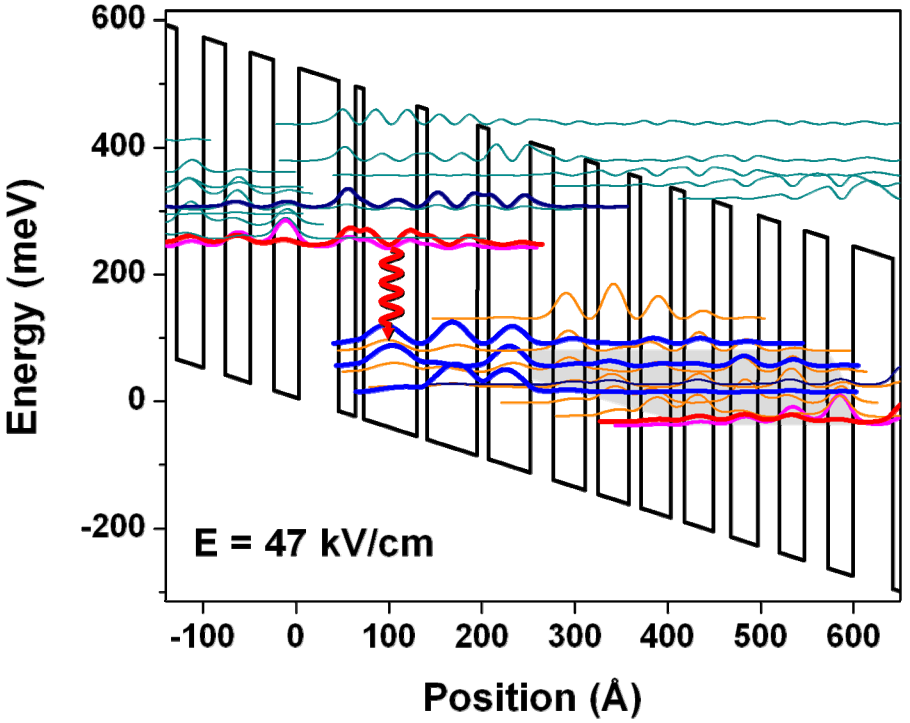
- Optical absorption
- Upper laser level lifetime
- Optical mode impedance mismatch





Designing a Better QC Laser

- **QC emitters: a "designer" material**
- **Limited by design space**



$$J_{th} = \frac{\alpha_m + \alpha_w}{g\Gamma}$$

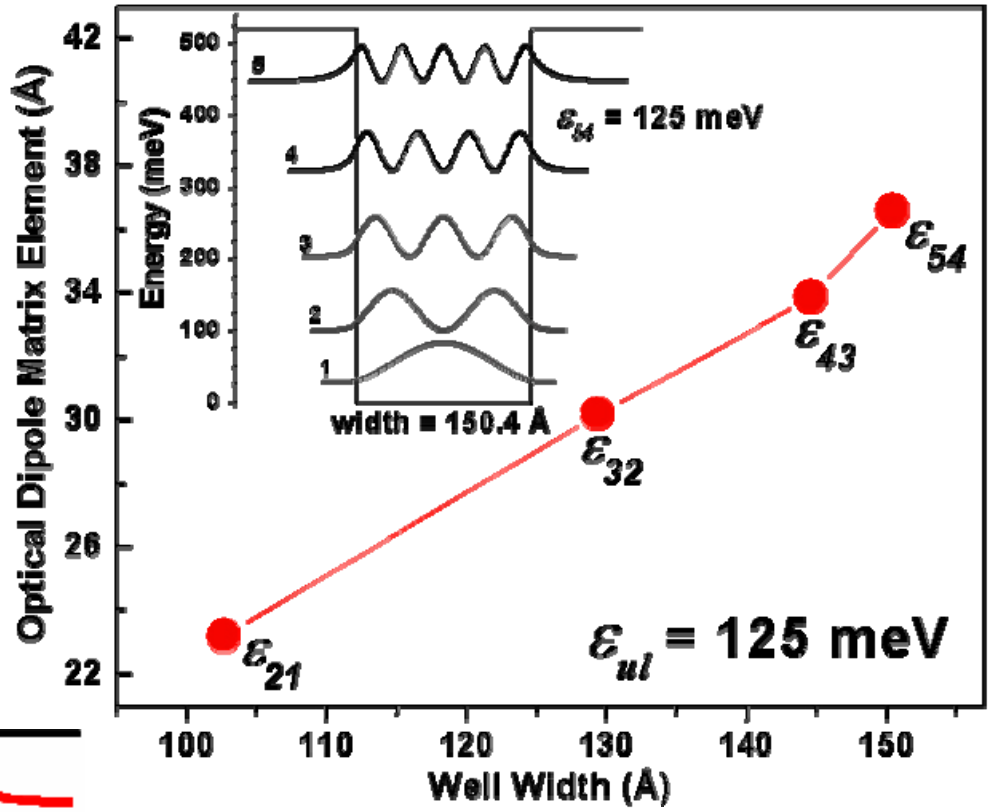
$$g = \tau_u \left(1 - \frac{\tau_l}{\tau_{ul}}\right) \frac{4\pi q}{\varepsilon_0 \lambda_0 n_{eff} L_p \delta E_{ul}} z_{ul}^2$$

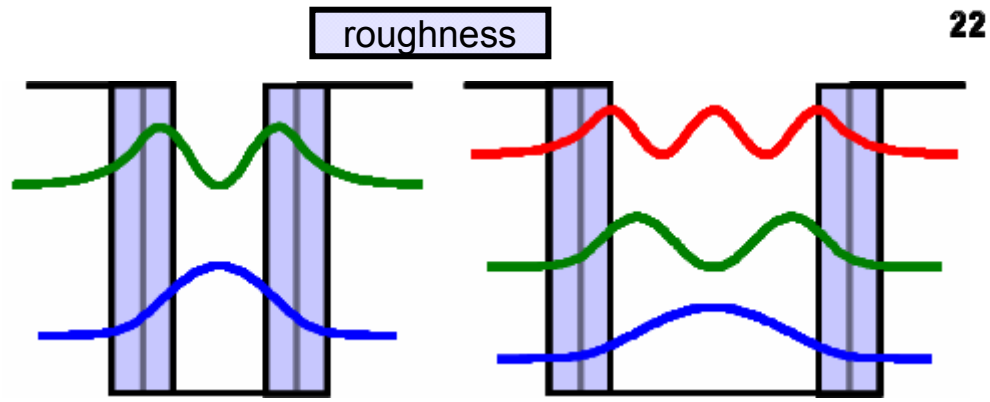
Improving Laser Gain

optical dipole matrix element

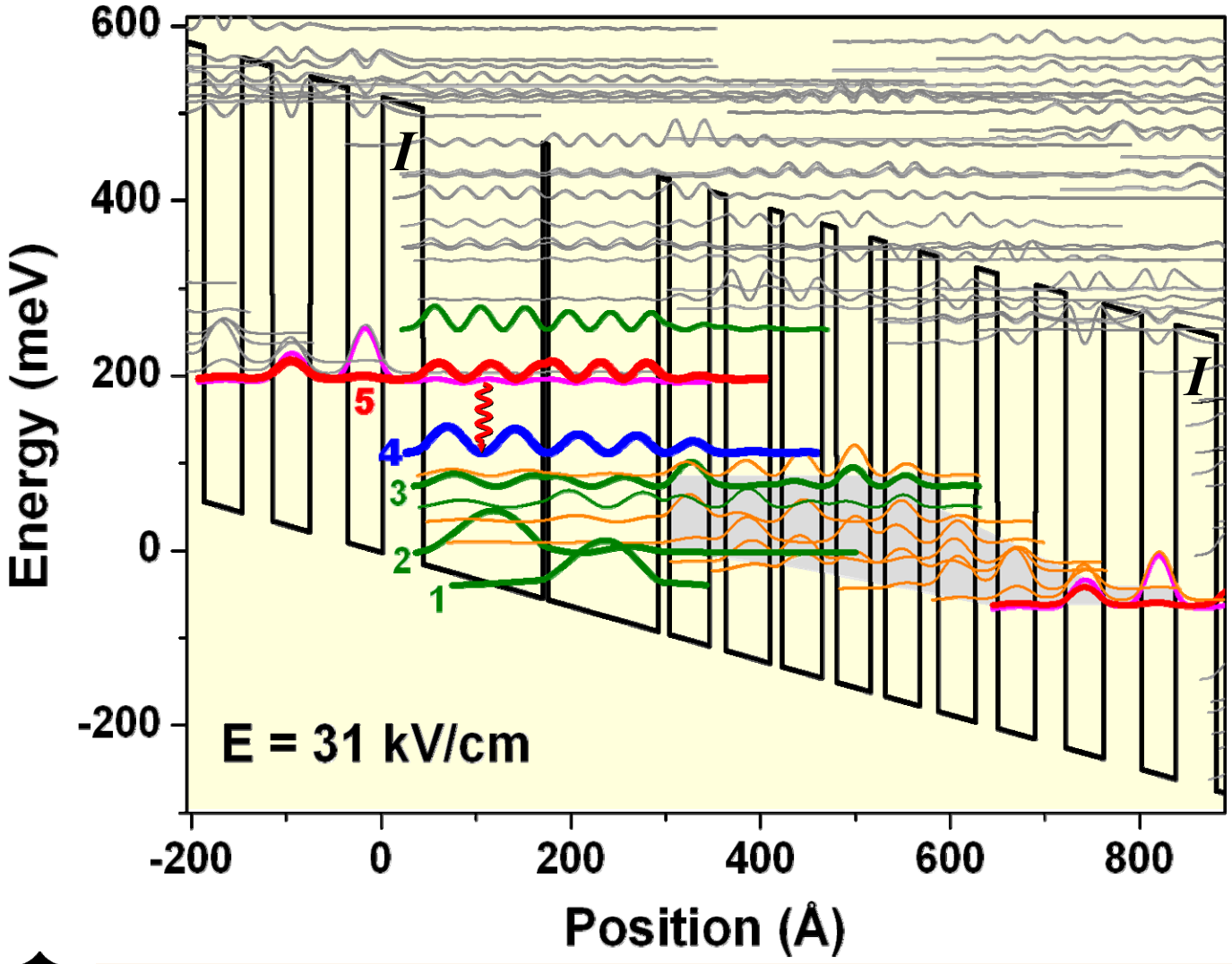
$$g \propto z_{ul}^2 = \left| \left\langle \phi_u(z) \middle| z \middle| \phi_l(z) \right\rangle \right|^2$$

$$g \propto \frac{1}{\delta E_{ul}}$$





14.8 μm Excited State QC Laser

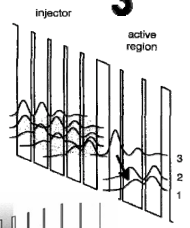


- E_{ul} = 83.6 meV
- z_{ul} = 50.3 Å
- τ_5 = 0.586 ps
- τ_4 = 0.215 ps
- τ_{54} = 1.9 ps
- FoM = 1313 ps Å^2
- $z^2\tau_5$ = 1483 ps Å^2
- $z^2\tau_5 E$ = **124** ps Å^2 eV

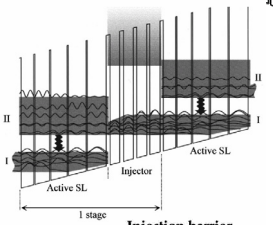
FoM comparison

$\tau_3 z^2 E$ (ps Å^2 eV)

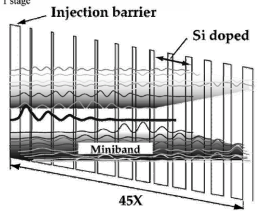
Gmachl 13 μm Diagonal Transition (1998) **69.8**



Tredicucci 17 μm Superlattice (1999) **56.0**

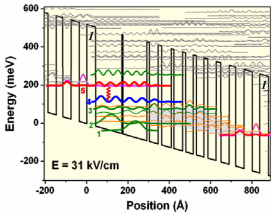


Rochat 15.6 μm Quasi-SL (2001) **70.2**

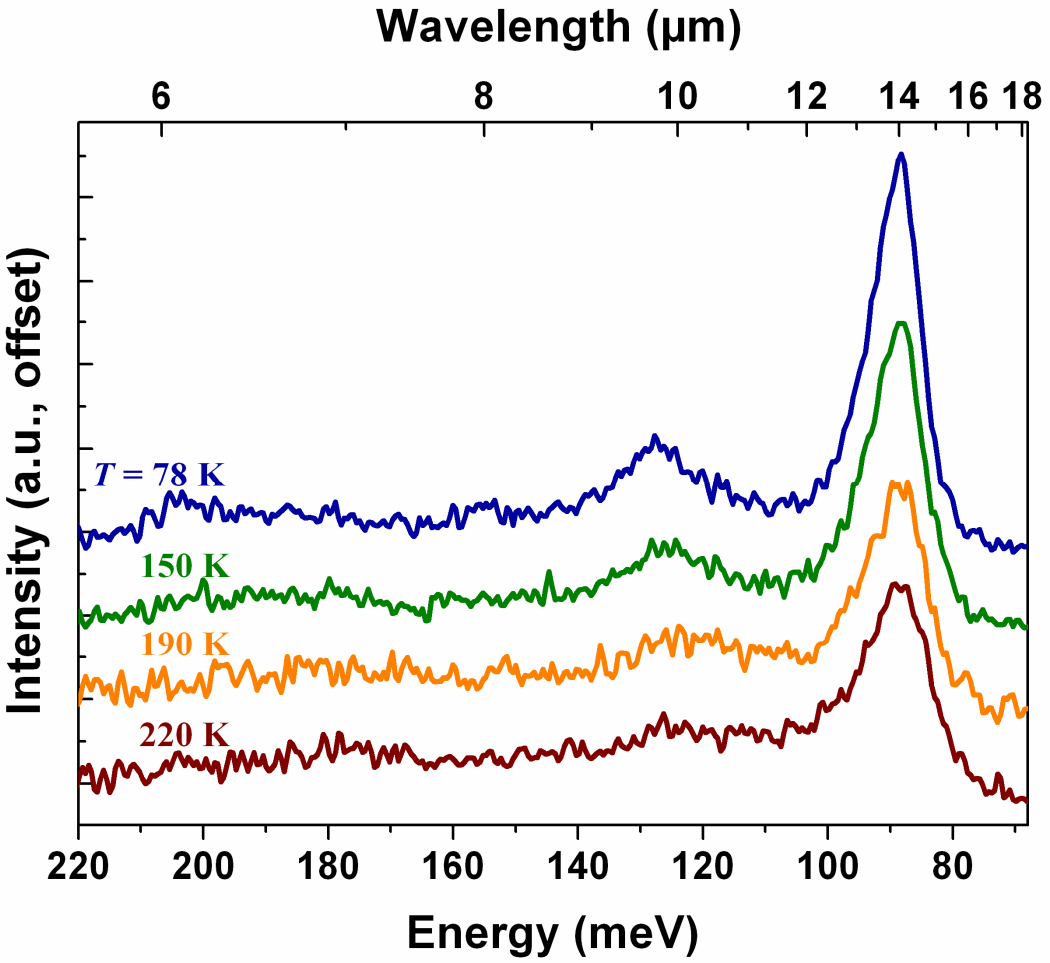


15 μm Vertical Transition (2007) **83.6**

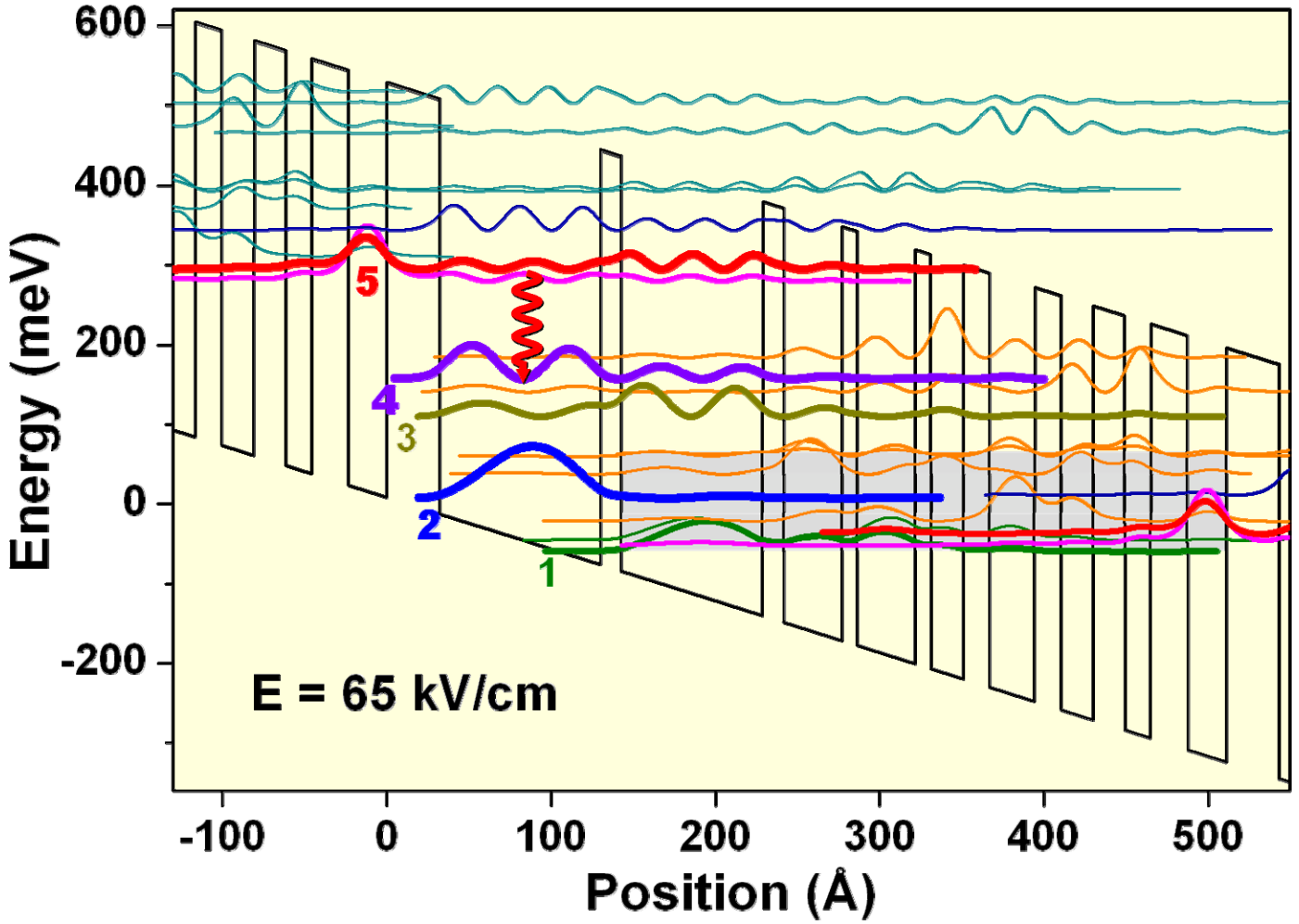
15 μm Excited State (2007) **123.9**



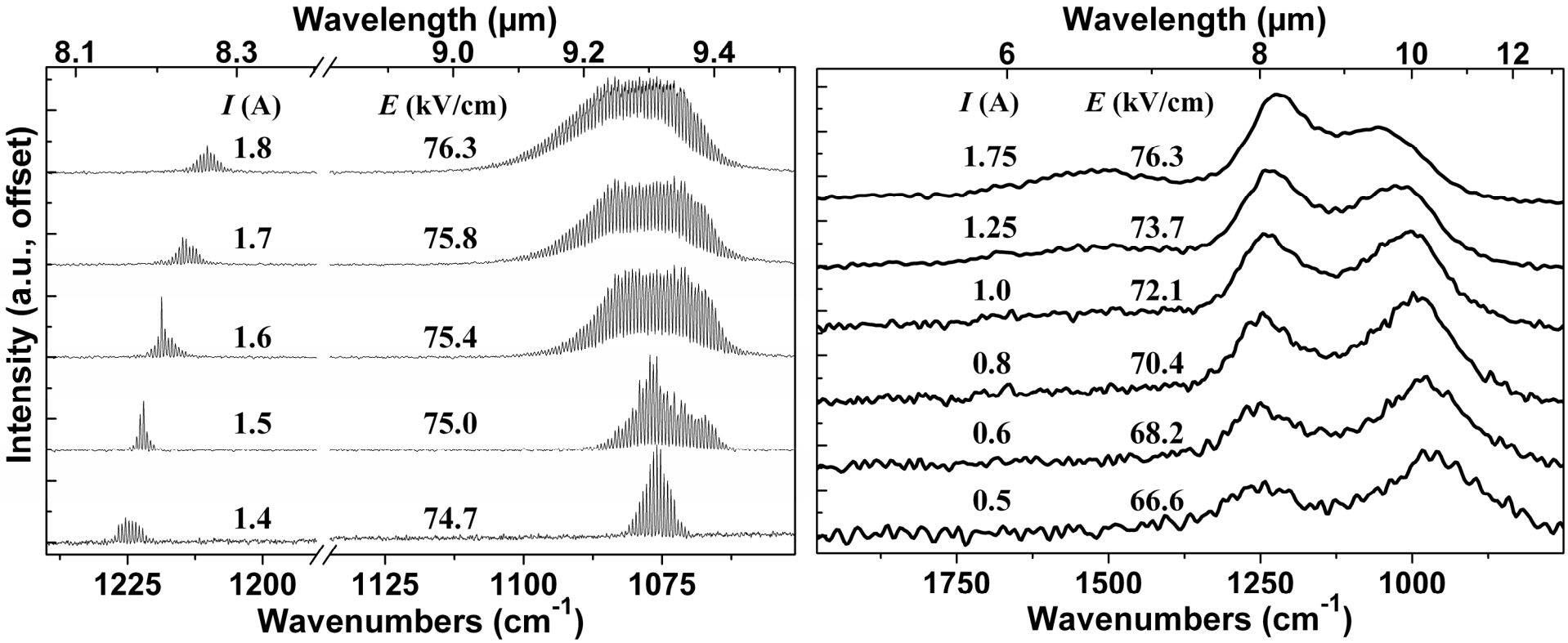
15 μm Emission



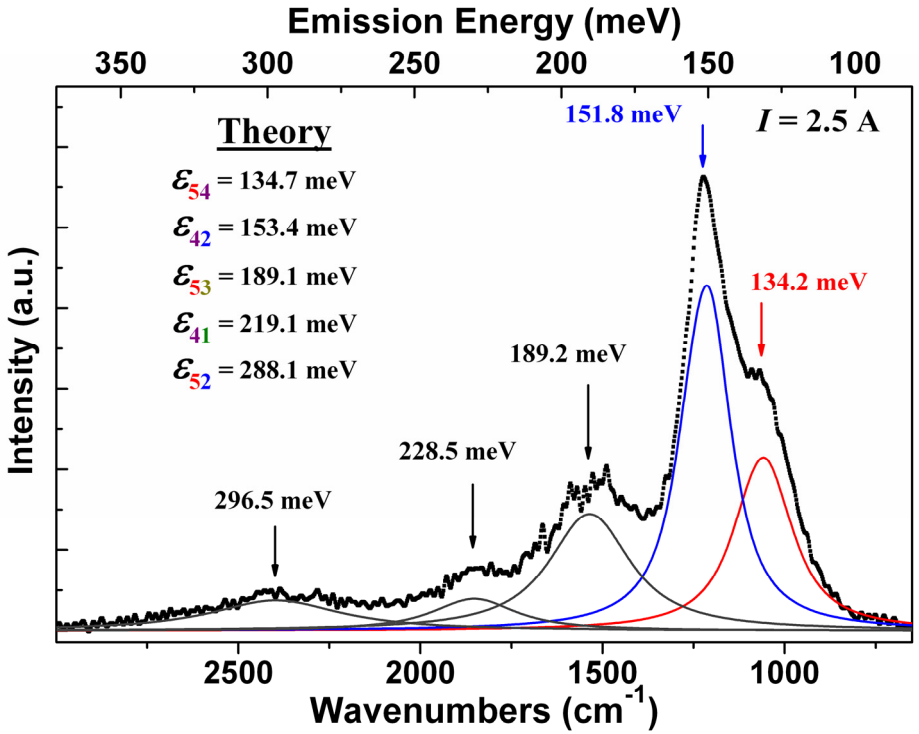
9.5 μm Excited State Laser

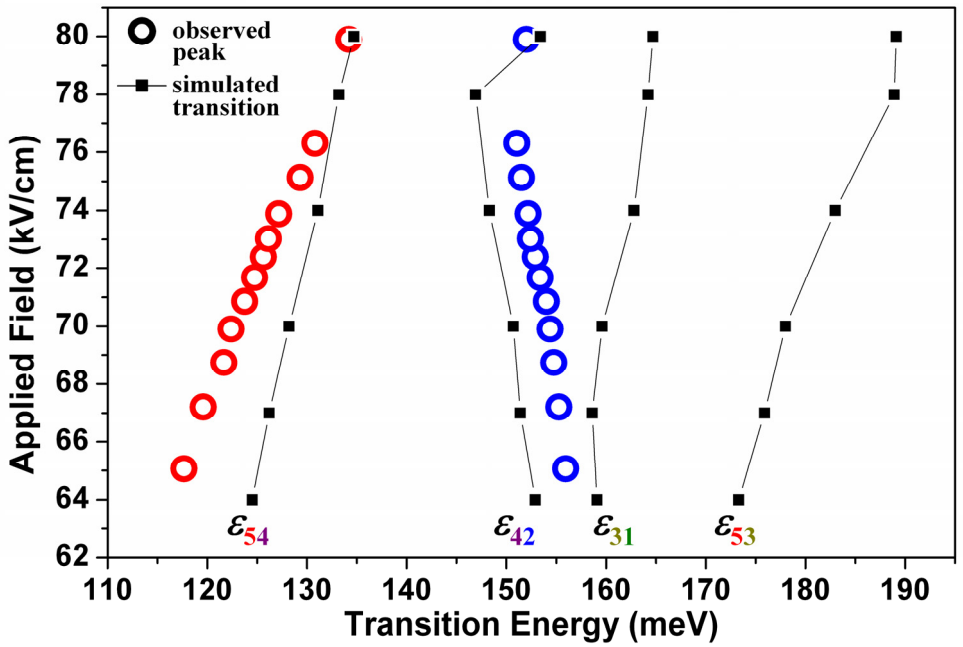


Excited State Emission

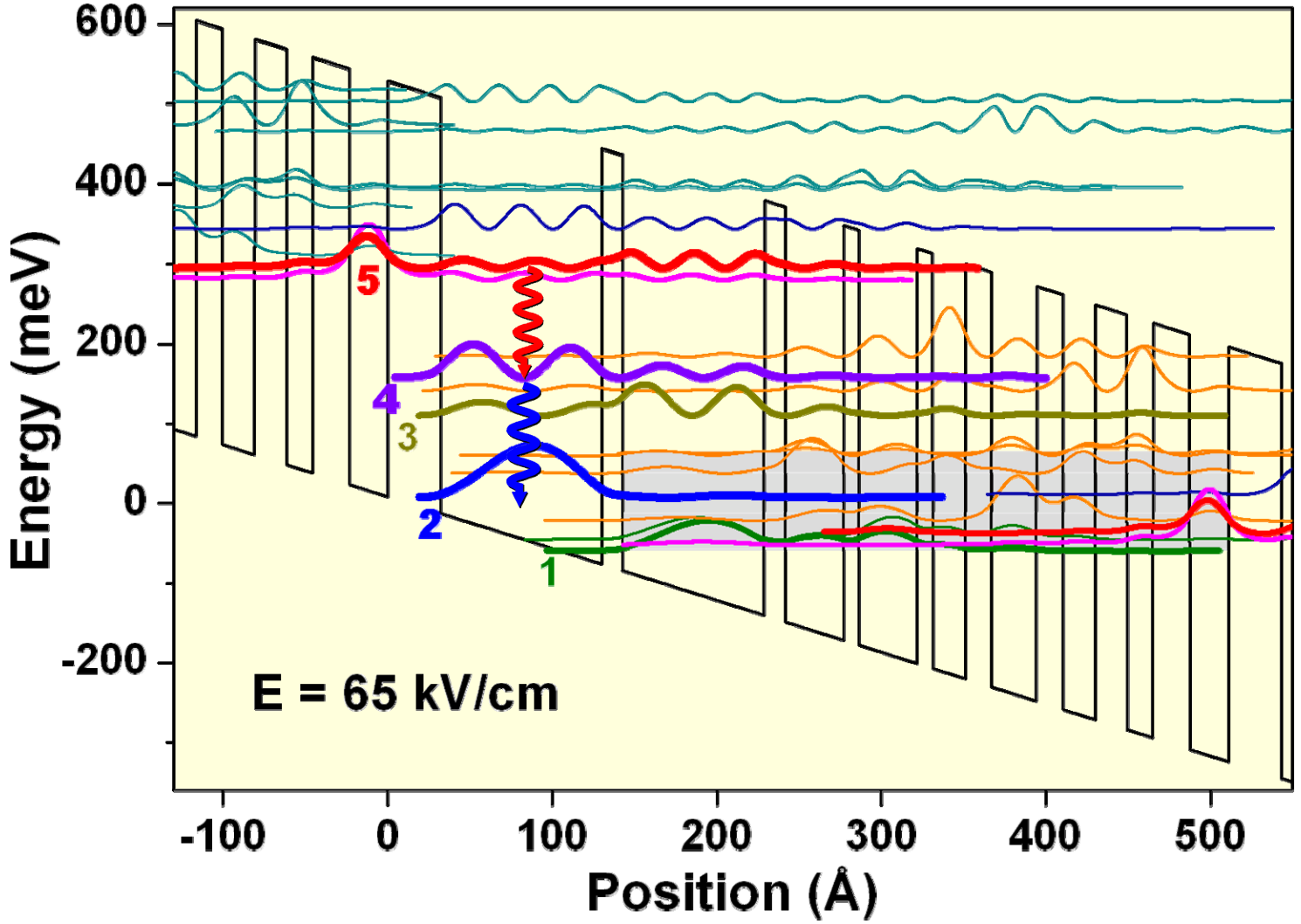


Transition Identification

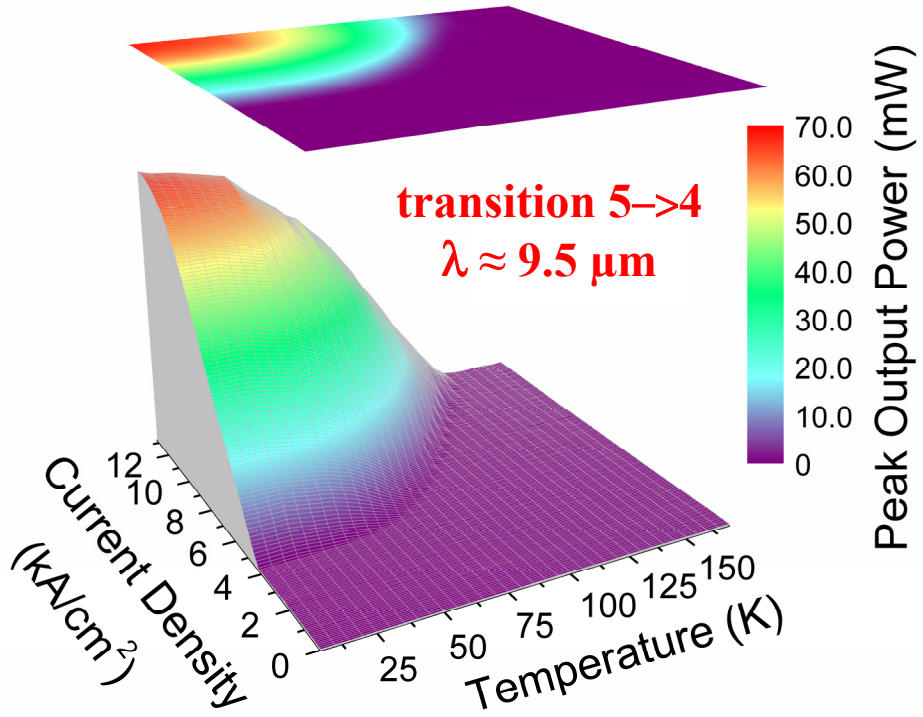


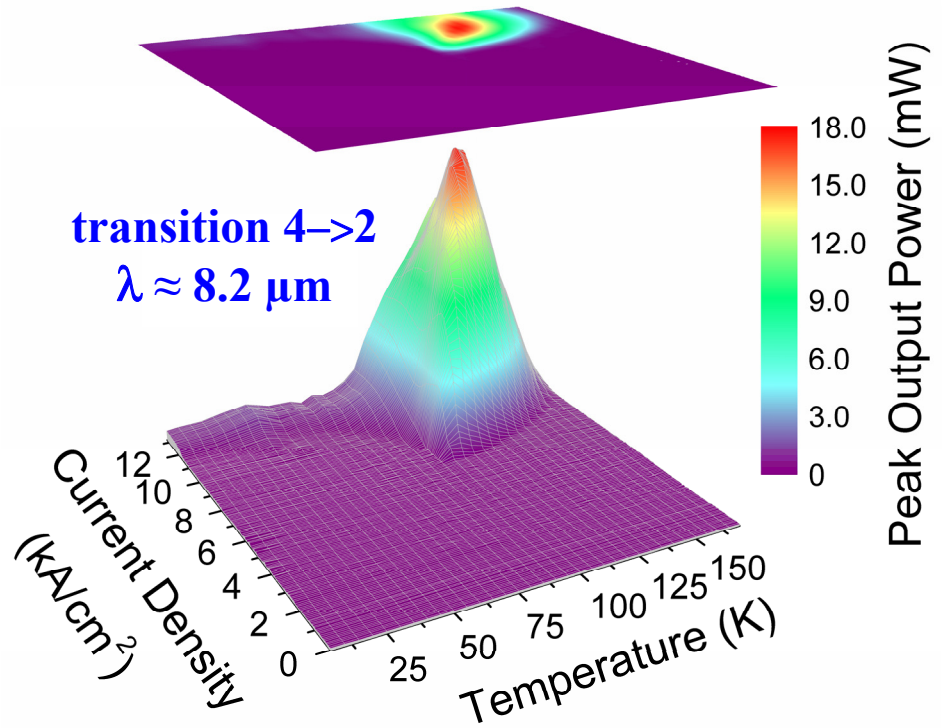


Stacked Transitions

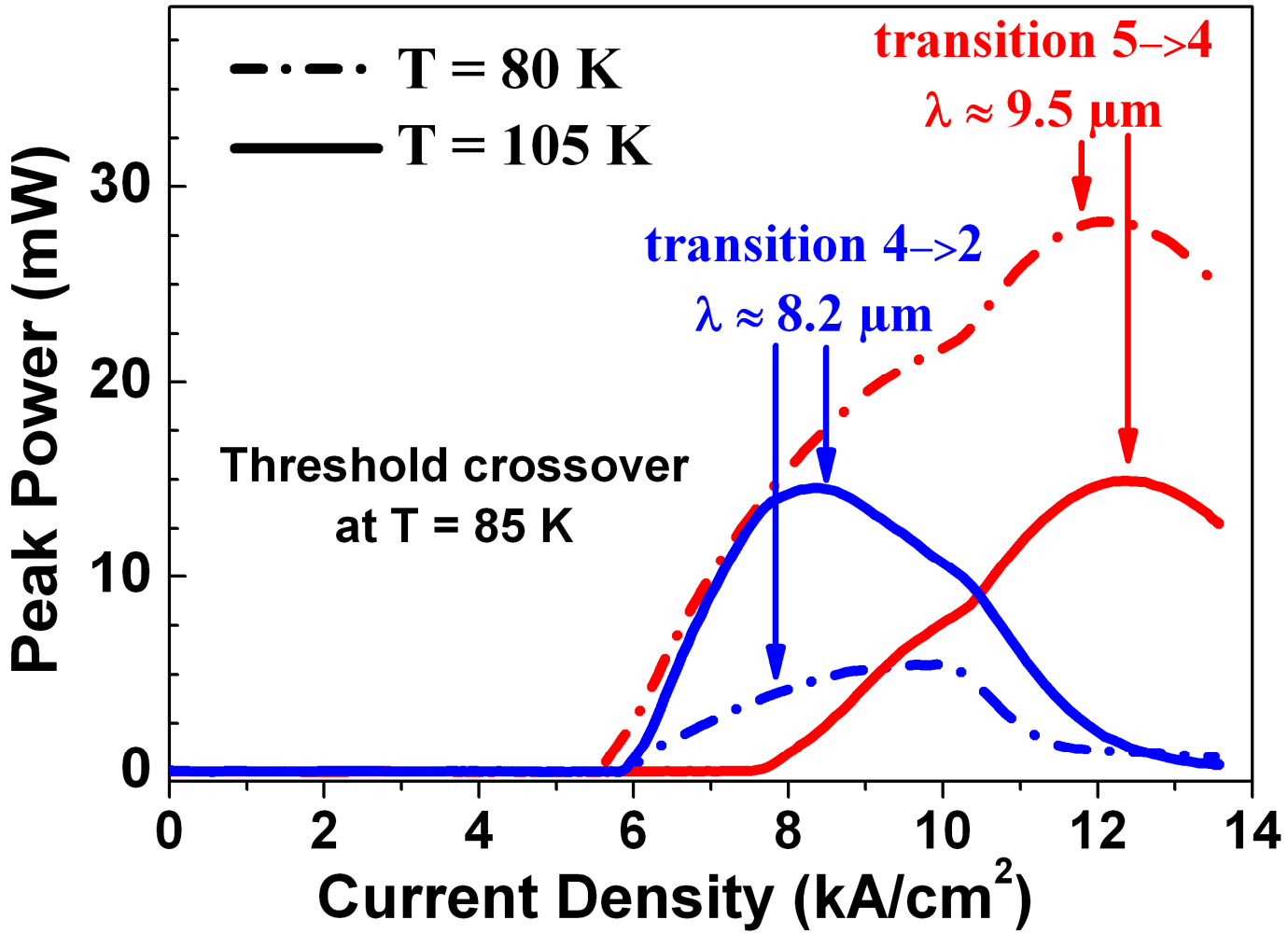


Light – Current

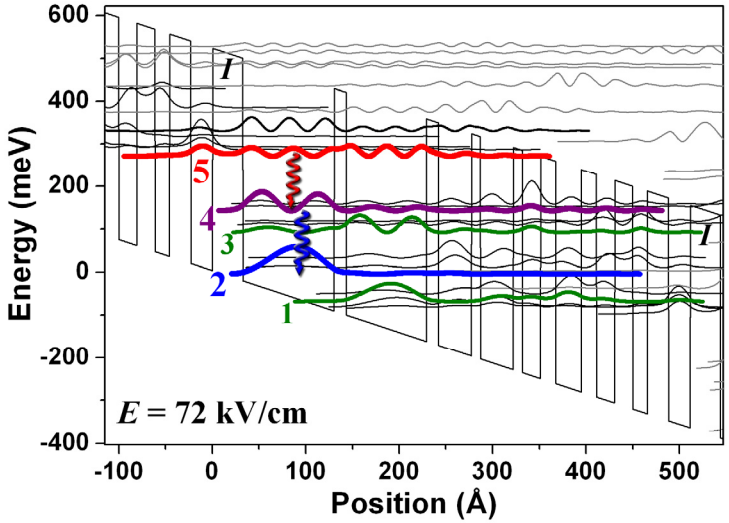


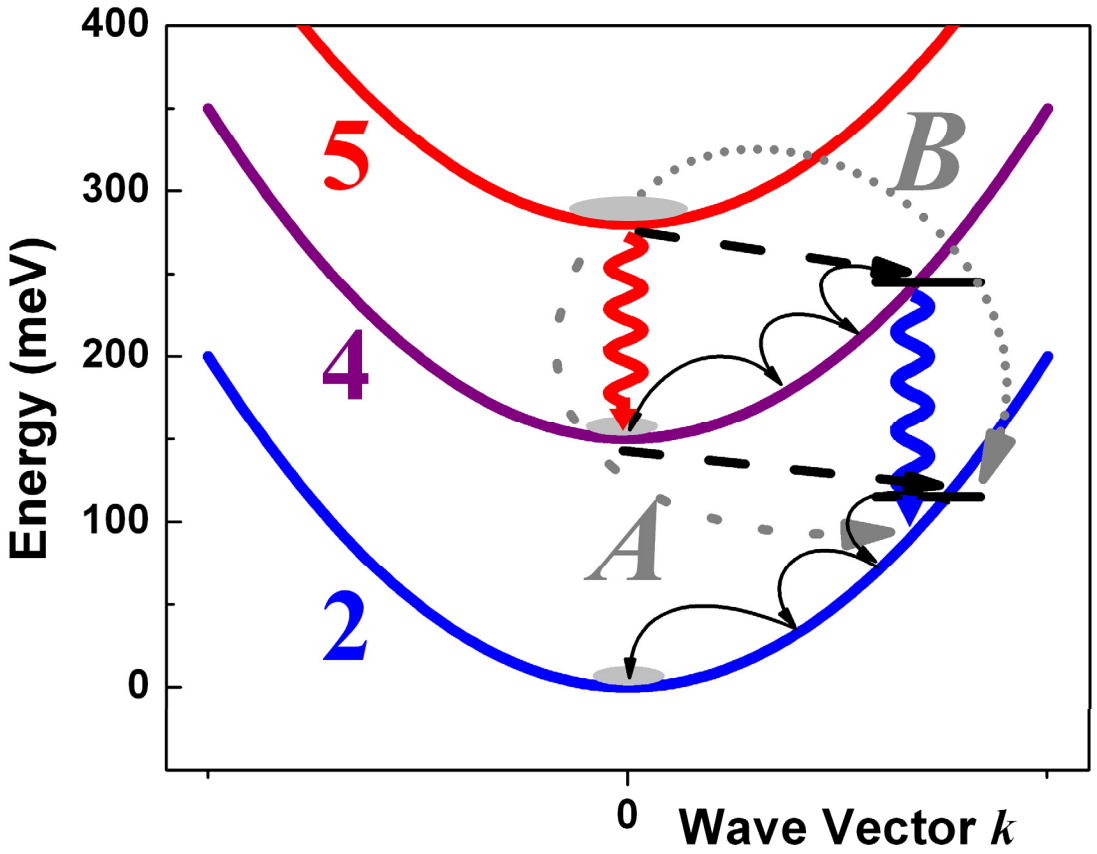


Light – Current Cross Section



High k-Space Model





Rate Equation Modeling

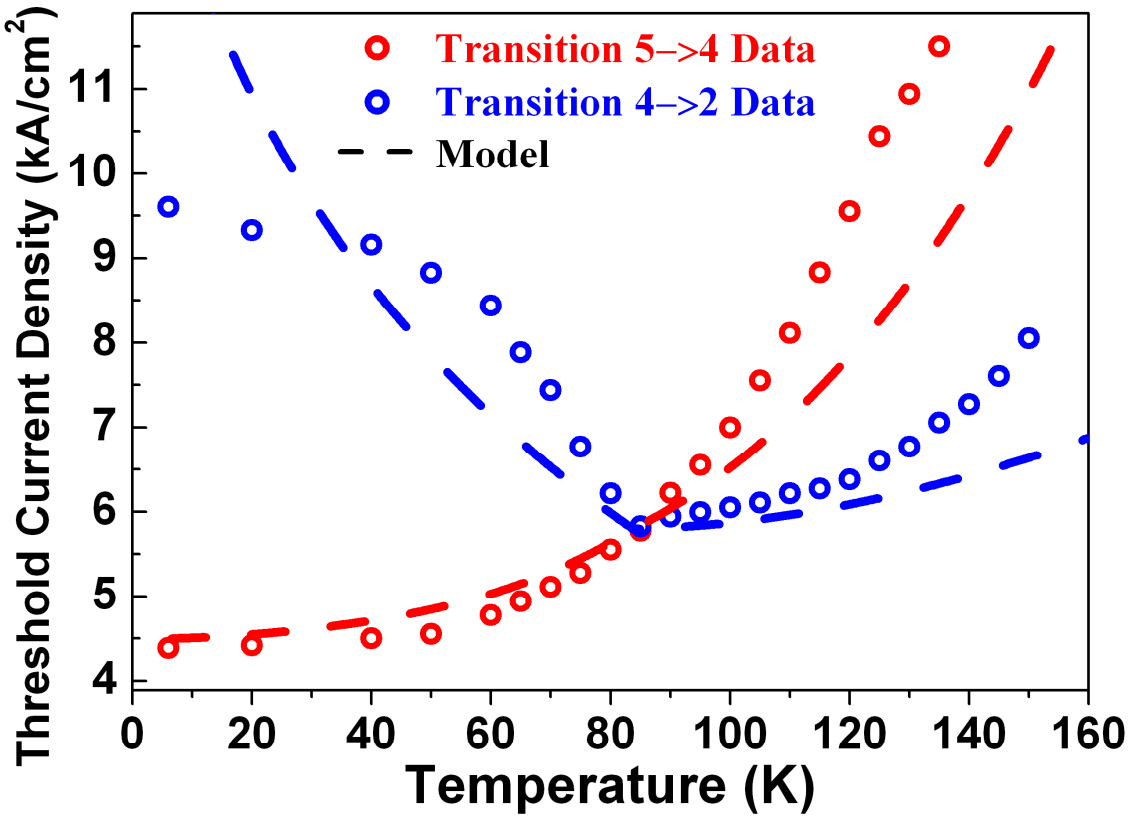
$$\frac{dN_5}{dt} = \eta\frac{J}{q} - \frac{N_5}{\tau_5(T)} - \frac{1}{N_p}\frac{c_0}{n_{eff}} g_c (N_5 - N_4) S_{54}$$

$$\frac{dN_{4k}}{dt} = (1-\eta)\frac{J}{q} + \frac{N_5}{\tau_{54}(T)} - \frac{N_{4k}}{\tau_{4k}(T)} - \frac{1}{N_p}\frac{c_0}{n_{eff}} g_c (N_{4k} - N_{2k}) S_{42}$$

…

$$\frac{dS_{u\ell}}{dt} = \Gamma\frac{c_0}{n_{eff}} g_c (N_u - N_\ell) S_{u\ell} - \frac{S_{u\ell}}{\tau_{ph}}$$

$$g_c = \frac{2q^2 E_{u\ell} z_{u\ell}^2}{\hbar c_0 \varepsilon_0 n_{eff} L_p \delta E_{u\ell}}$$



Summary

- 12 – 16 μm band
- 14 μm excited state emission
- *k*-space lasing