Modeling Carrier Transport and Gain Recovery in Quantum Cascade Lasers

S. Ehsan Jamali Mahabadi[1]

M. Anisuzzaman Talukder[1,2]

Curtis R. Menyuk[1]

[1]CSEE Dept., UMBC, 1000 Hilltop Circle, Baltimore, MD 21250, USA
[2]Dept. Electrical & Electronic Eng., BUET, Dhaka 1000, Bangladesh

Motivation

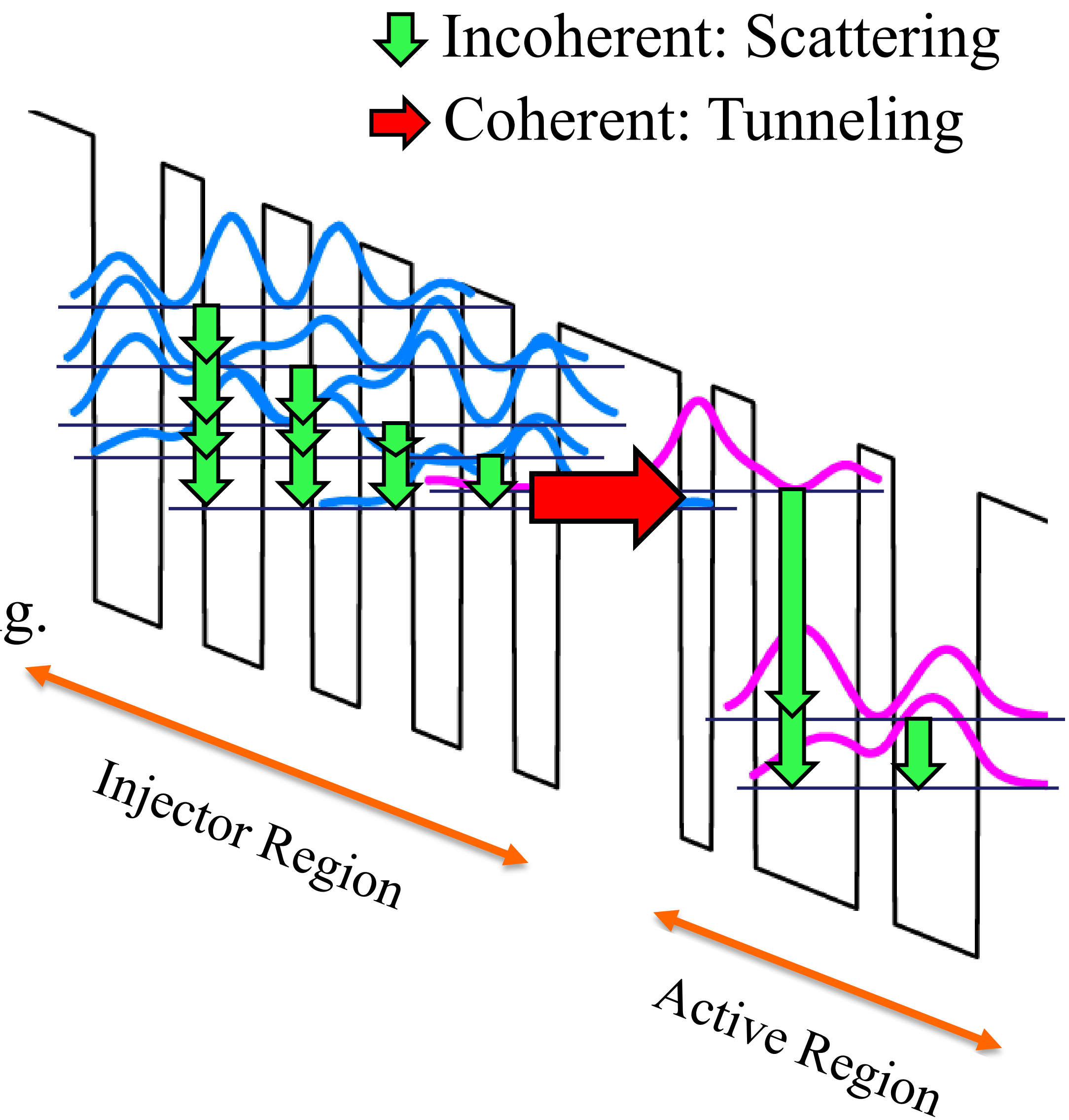
UMBC

The carrier dynamics of quantum cascade lasers are responsible for the overall performance.

Key physical effects include:

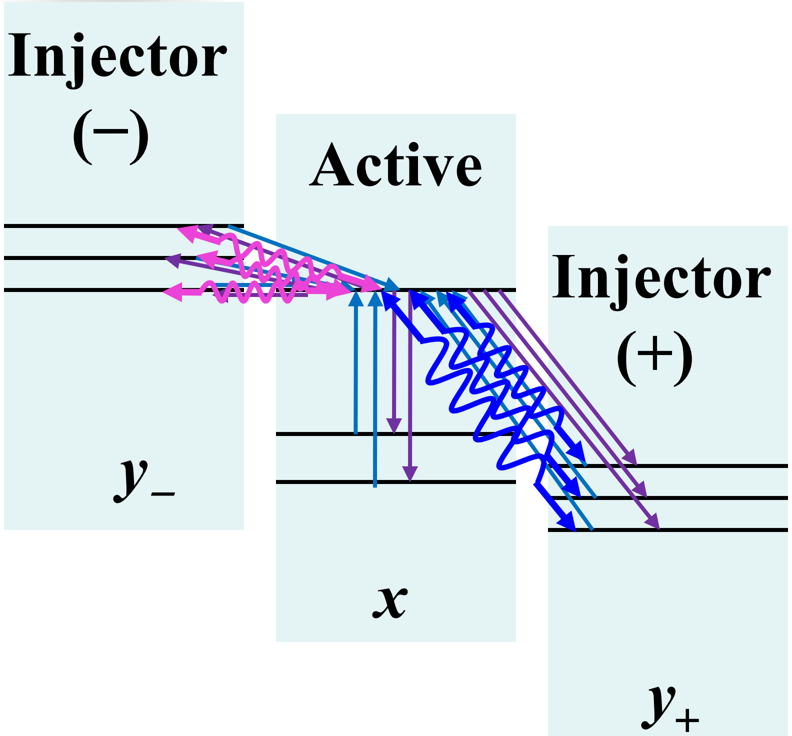
- Incoherent scattering.
- Quantum coherent tunneling.

Both must be modeled!



Modeling Carrier Transport

UMBC



$$\frac{dn_{A,x}}{dt} = ?$$

Variables	Description
n_A	Carrier density in the active region
n_I	Carrier density in the injector region
s_{xy}	Scattering time between levels x and y
C_{xy}	Coherence between levels x and y
Δ_{xy}	Energy splitting at resonance between levels x and y
Subscripts − And +	A quantity in the injector region preceeding and following the active region respectively

Coherence

UMBC

Active ↔ Injector (+)

$$\frac{dC_{xy_+}}{dt} = i\frac{\Delta_{xy_+}}{2\hbar}\left(n_{I,y_+} - n_{A,x}\right) - \frac{C_{xy_+}}{T_{2,xy_+}} - i\frac{E_{xy_+}}{\hbar}C_{xy_+}$$

Injector (−) ↔ Active

$$\frac{dC_{y\_x}}{dt} = i\frac{\Delta_{y\_x}}{2\hbar}\left(n_{A,x} - n_{I,y_-}\right) - \frac{C_{y\_x}}{T_{2,y\_x}} - i\frac{E_{y\_x}}{\hbar}C_{y\_x}$$

Previous work and modeling methods

Density matrix formalism has been used in our group for modeling:

- Gain recovery[1]
- Temperature dynamics[2]
- SIT modelocking[3]

In our model, after carrier densities reach a steady state:

- We excite all energy levels with an incoming pulse.
- We then calculate the gain recovery.

NOTE: We do not need a probe pulse since we directly calculate the recovery of the carrier densities.

[1] M. A. Talukder, "Modeling of gain recovery of quantum cascade lasers," *J. Appl. Phys.* **109**, 033104 (2011).

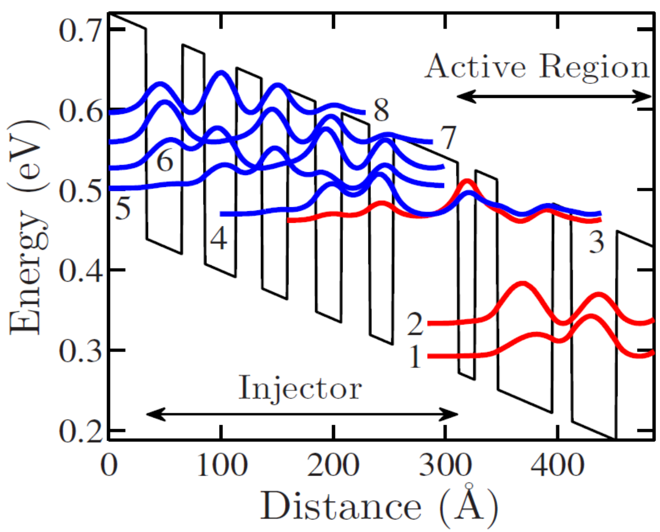
[2] M. A. Talukder, and C. R. Menyuk, "Temperature-dependent coherent carrier transport in quantum cascade lasers," *New J. Phys.* **13**, 083027 (2011).

[3] M. A. Talukder, and C. R. Menyuk, "Calculation of the microscopic parameters of a self-induced transparency modelocked quantum cascade laser," *Opt Commun.* **295**, 115–118 (2013)

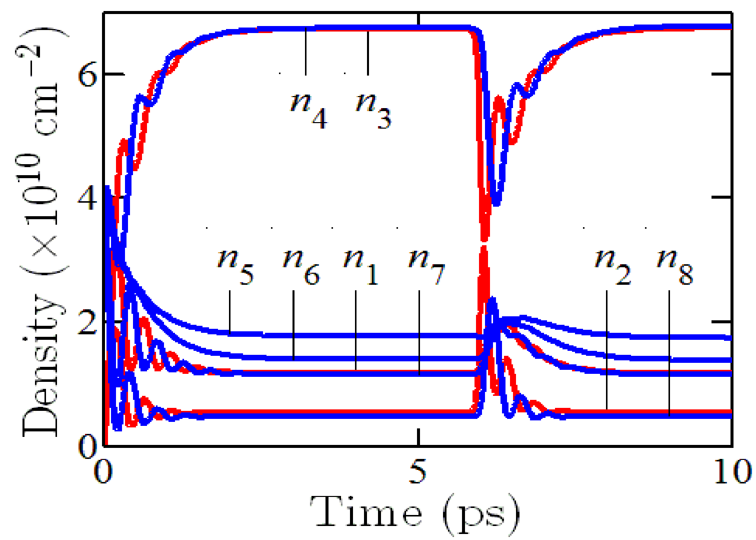
Previous work

UMBC

- In our previous work,[1] in which we modeled the structures of Sirtori et al.,[2] we only considered dipole transitions between the lasing levels.



Ref. 1, Fig. 1 – Sirtori et al.[2] structure



Ref. 2, Fig. 2 – Gain recovery when only the dipole transitions between the lasing levels are included.

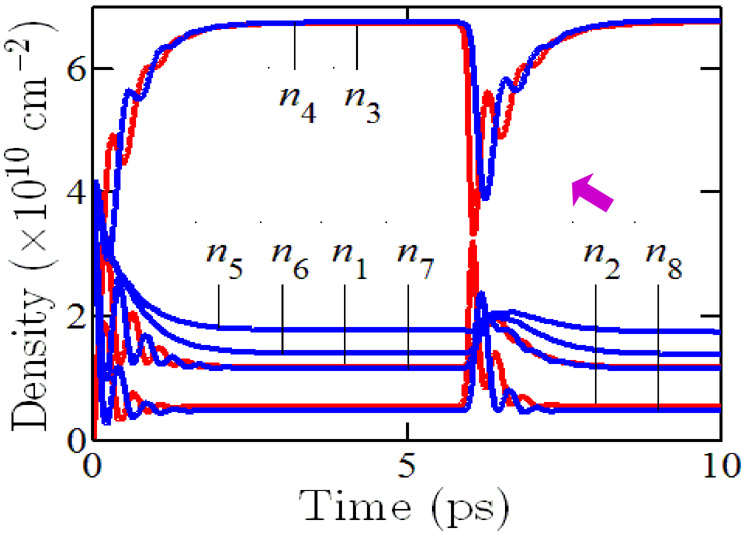
[1] M. A. Talukder, "Modeling of gain recovery of quantum cascade lasers," *J. Appl. Phys.* **109**, 033104 (2011).

[2] C. Sirtori, P. Kruck, S. Barbieri, P. Collot, and J. Nagle, "GaAs/Al$_x$Ga$_{1-x}$ quantum cascade lasers," Appl. Phys. Lett. **73**, 3486–3488 (1998).

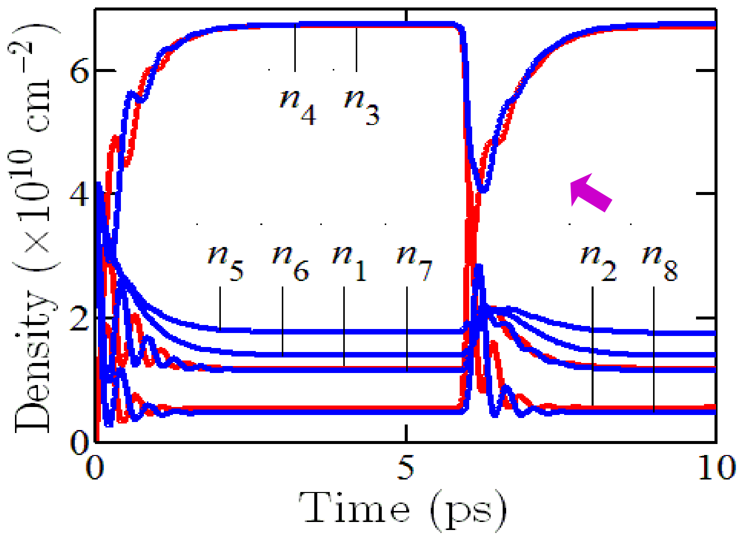
Recent work

In recent work, we have considered dipole transitions between all the energy levels. We find that:

- the gain recovery is smoothed.
- the additional levels do not make a large quantitative difference.



Gain recovery when only the dipole transitions between the lasing levels are included.



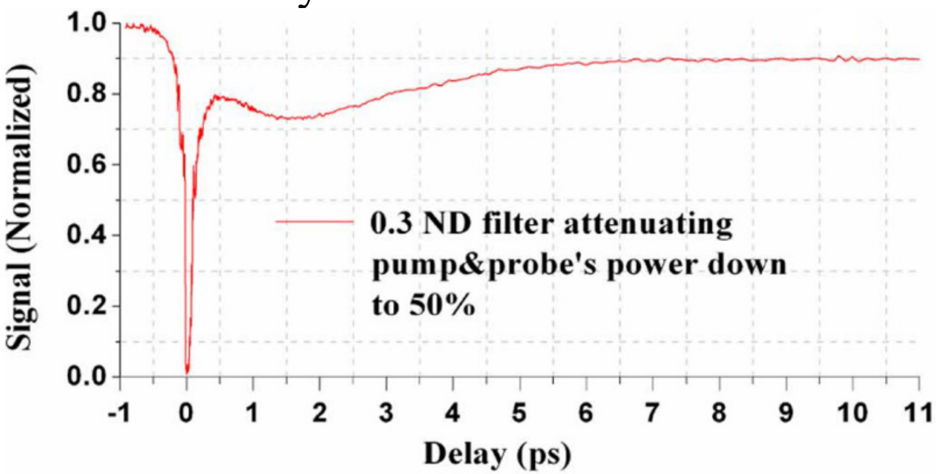
Gain recovery including the dipole transitions between all energy levels.

Current work

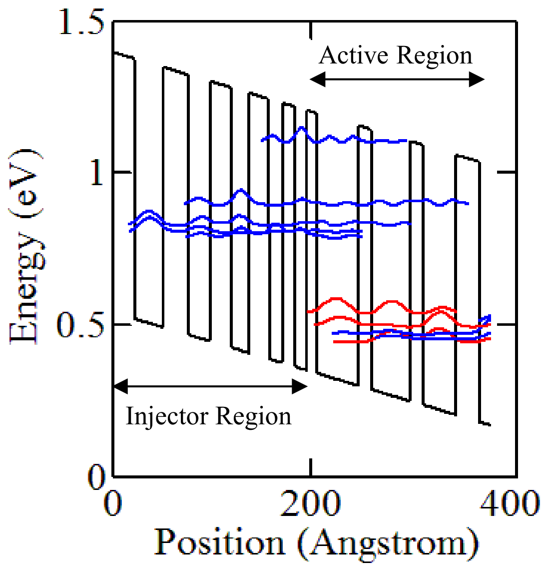
UMBC

GOAL: Modeling the structure of P. Q. Liu et al.[1] and experiments of S. Liu et al.[2]

- METHOD: We will add physical phenomena to our codes:
  1. Effects of one- and two-photon absorption that cause faster depletion.
  2. Effects of electron transitions to and from the continuum that cause slow gain recovery.



Ref. 2, Fig. 7 – Gain recovery

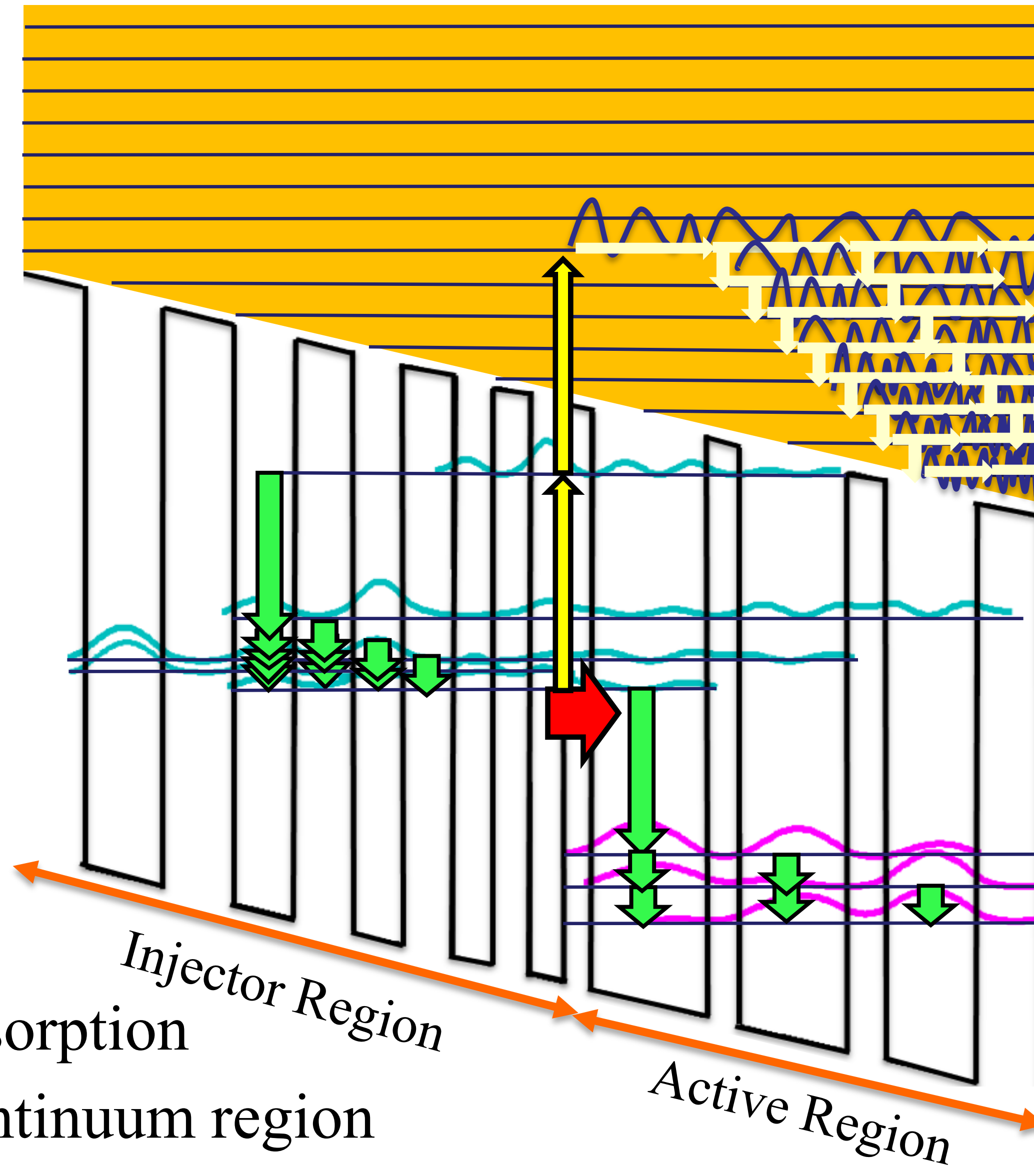


Liu et al.[1] structure

[1] P. Q. Liu, A. J. Hoffman, M. D. Escarra, K. J. Franz, J. B. Khurgin, Y. Dikmelik, X. Wang, J. –Y. Fan, and C. F. Gmachl, "Highly power-efficient quantum cascade lasers," *Nature Photon*. **4**, 95–98 (2010).

[2] S. Liu, E. Lalanne, P. Q. Liu, X. Wang, C. F. Gmachl, and A. M. Johnson, "Femtosecond carrier dynamics and nonlinear effects in quantum cascade lasers," *IEEE J. Sel. Topics Quantum Electron*. **18**, 92–104 (2011).

Current work

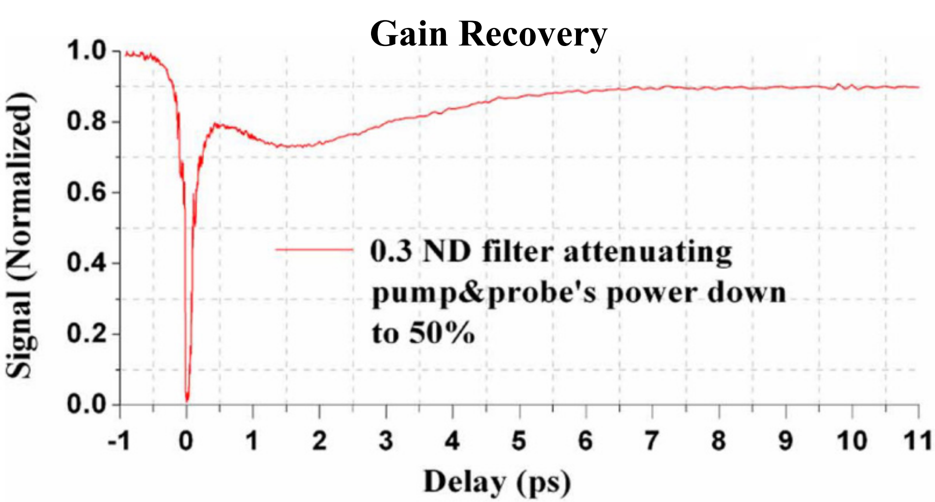


- Incoherent: Scattering
- Coherent: Tunneling
- Continuum region
- Incoming pulse
- One and two photon absorption
- Electron transport in continuum region

Gain Recovery

UMBC

- Initial depletion: Due to the depletion of electrons in upper lasing sub-bands by stimulated emission down to the lower lasing state.
- Short term recovery (<300 fs): Due to e-e and e-phonon scattering.
- Long term recovery: Superlattice transport, transport from upper sub-band or continuum.



Summary

UMBC

We applied our transport code to model the structures of Sirtori et al.[1]

- We have considered dipole transitions between all the energy levels and we found:
  - ✓ The gain recovery is smoothed.
  - ✓ The additional levels do not make a large quantitative difference.
- We modeled the structure of P. Q. Liu et al.[2] and experiments of S. Liu et al.[3] and we found:
  - ✓ The effects of one- and two-photon absorption.
  - ✓ The effects of electron transitions to and from the continuum.

[1] C. Sirtori, P. Kruck, S. Barbieri, P. Collot, and J. Nagle, "GaAs/Al_xGa_{1-x} quantum cascade lasers," Appl. Phys. Lett. **73**, 3486-3488 (1998).

[2] P. Q. Liu, A. J. Hoffman, M. D. Escarra, K. J. Franz, J. B. Khurgin, Y. Dikmelik, X. Wang, J. –Y. Fan, and C. F. Gmachl, "Highly power-efficient quantum cascade lasers," *Nature Photon.* **4**, 95-98 (2010).

[3] S. Liu, E. Lalanne, P. Q. Liu, X. Wang, C. F. Gmachl, and A. M. Johnson, "Femtosecond carrier dynamics and nonlinear effects in quantum cascade lasers," *IEEE J. Sel. Topics Quantum Electron*, **18**, 92–104 (2011).

Thank you