Monolithic Mid-Infrared Photonic Integration of a Quantum Cascade Laser and a Passive Semiconductor Waveguide

Kale J. Franz, Kuen-Ting Shiu*, Stephen R. Forrest*, and Claire Gmachl

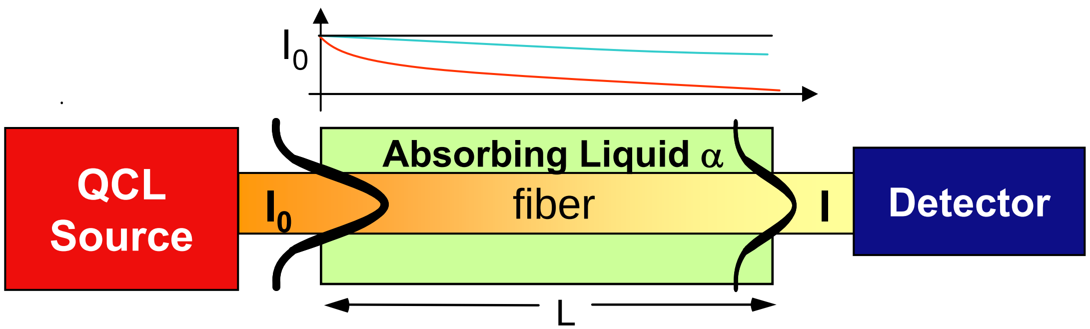
Department of Electrical Engineering
Princeton Institute for the Science and Technology of Materials
Princeton University, Princeton, NJ 08544

* Current address: Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI 48109

Motivation

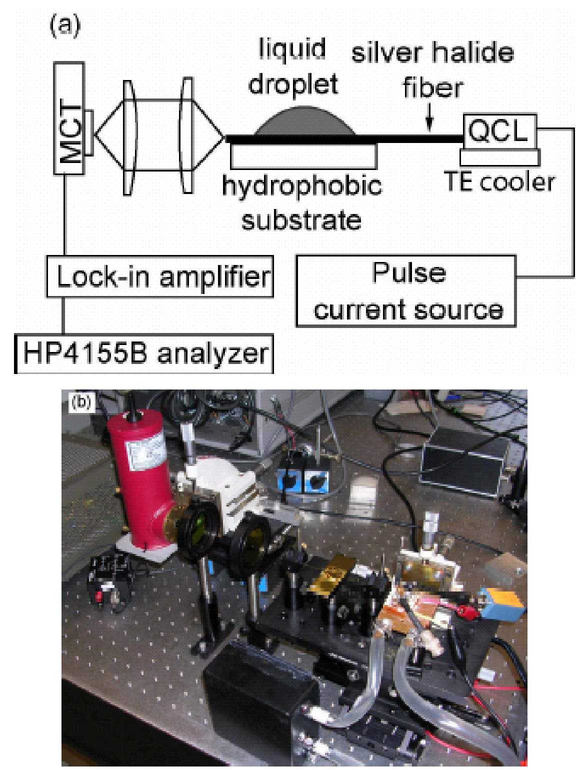
Liquid Sensing

J.Z. Chen *et al.*, "Silver halide fiber-based evanescent-wave liquid droplet sensing…" *Optics Express* **13**, 5953 (2005).



$$\frac{I}{I_0} = e^{-\alpha L}$$

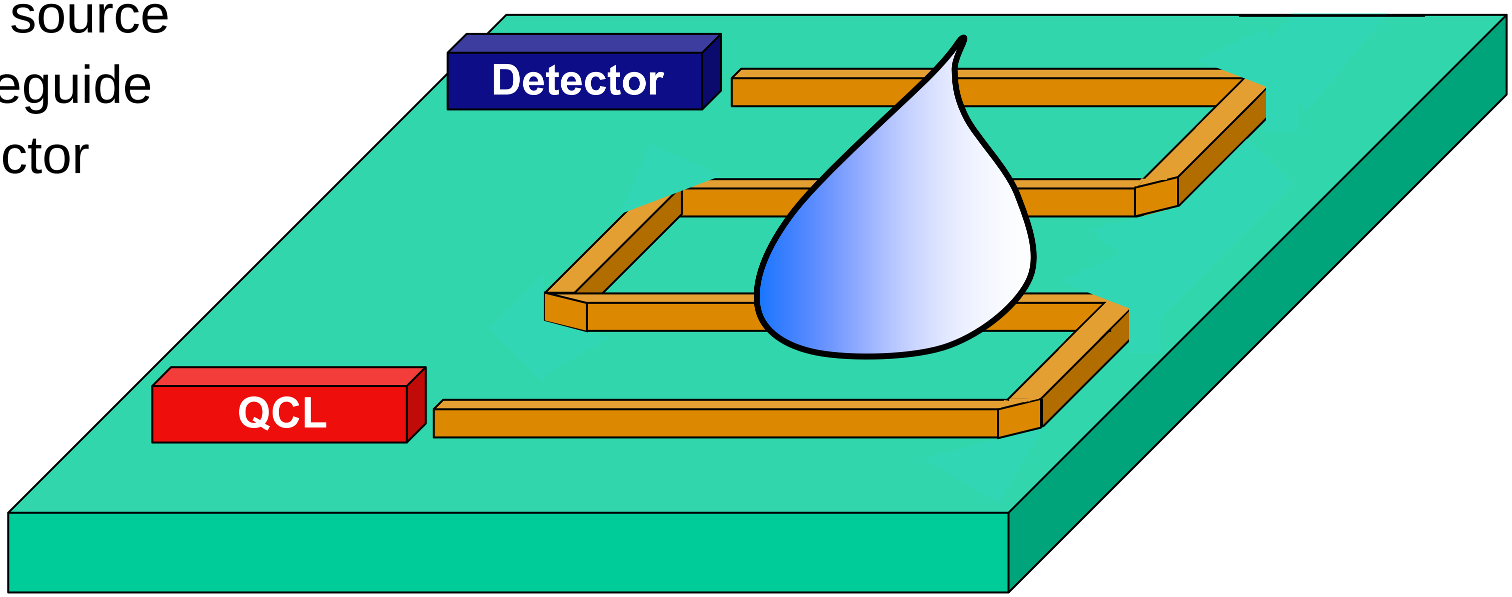
2 vol%
Acetone in H_2O



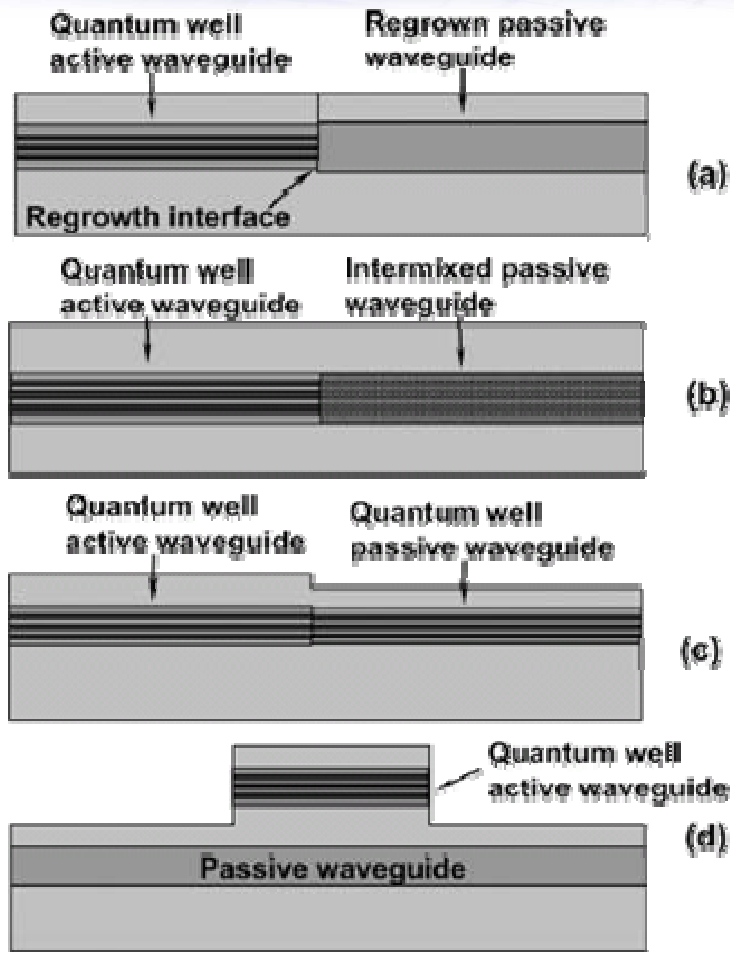
C. Charlton, A. Katzir, B. Mizaikoff, "Infrared Evanescent Field Sensing with Quantum Cascade Lasers and Planar Silver Halide Waveguides" *Anal. Chem.* **77**, 4398 (2005).

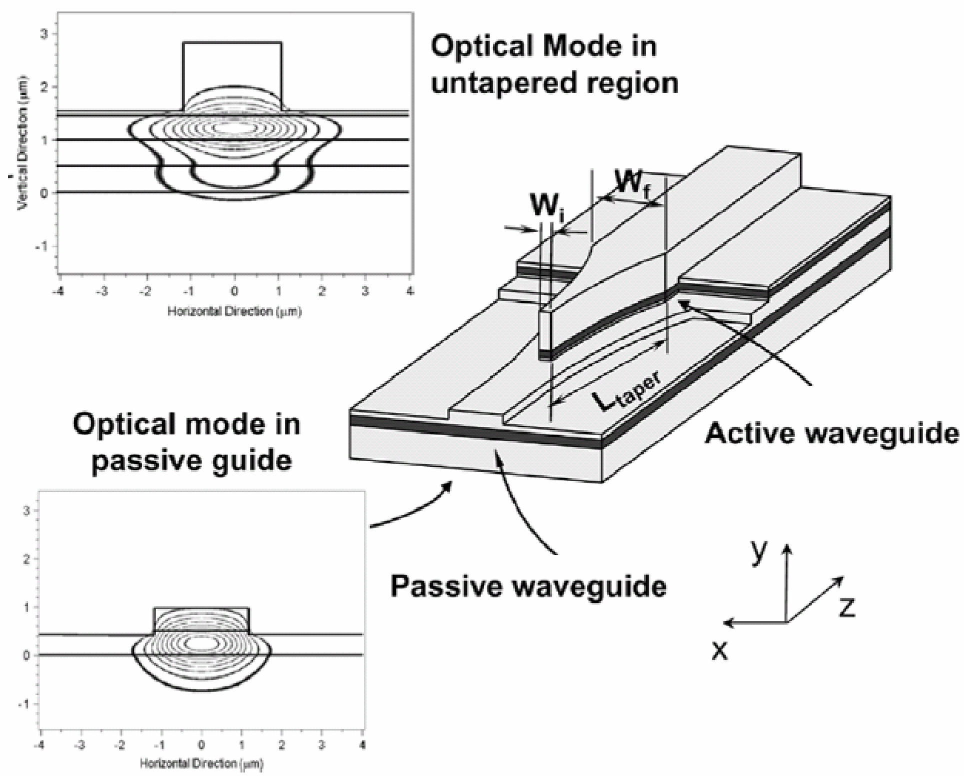
Motivation
Mid-IR Integration

- Our goals in this work
  - Create on-chip mid-IR integration scheme
  - Increase sensitivity for liquid-phase detection
- Three key components
  - light source
  - waveguide
  - detector



Integration Methods

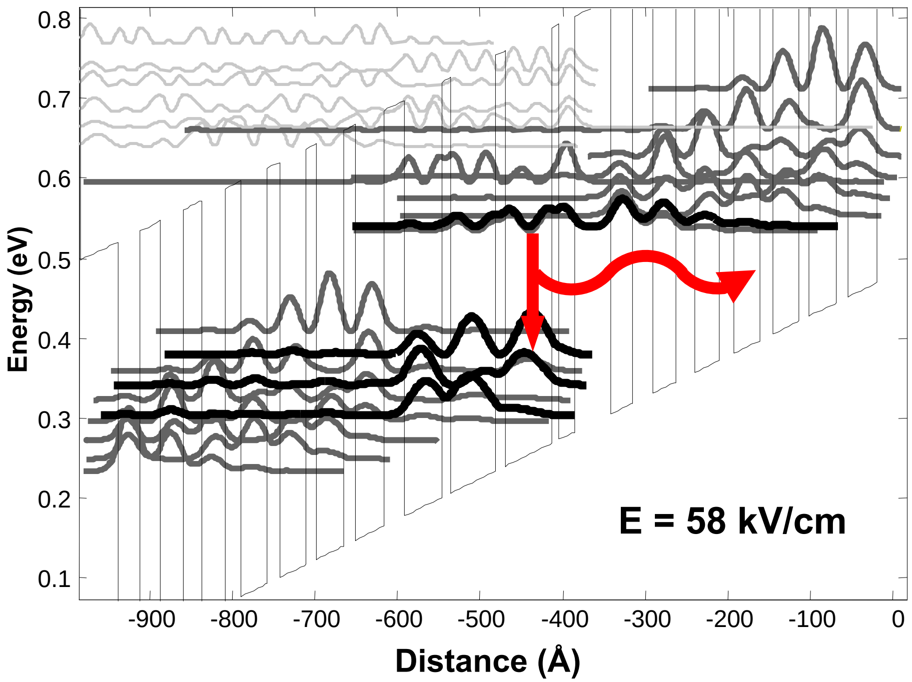


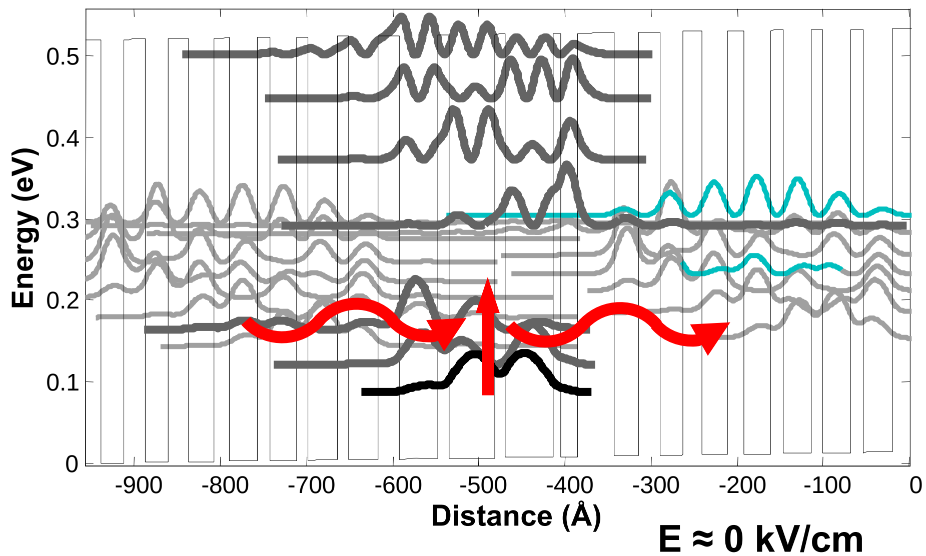


F. Xia, V.M. Menon, and S.R. Forrest, "Photonic Integration Using Asymmetric Twin-Waveguide (ATG) Technology: Part I—Concepts and Theory," *J. Selected Topics in Quant. Elec.* **11**, 17-29 (2005).

Integration Methods

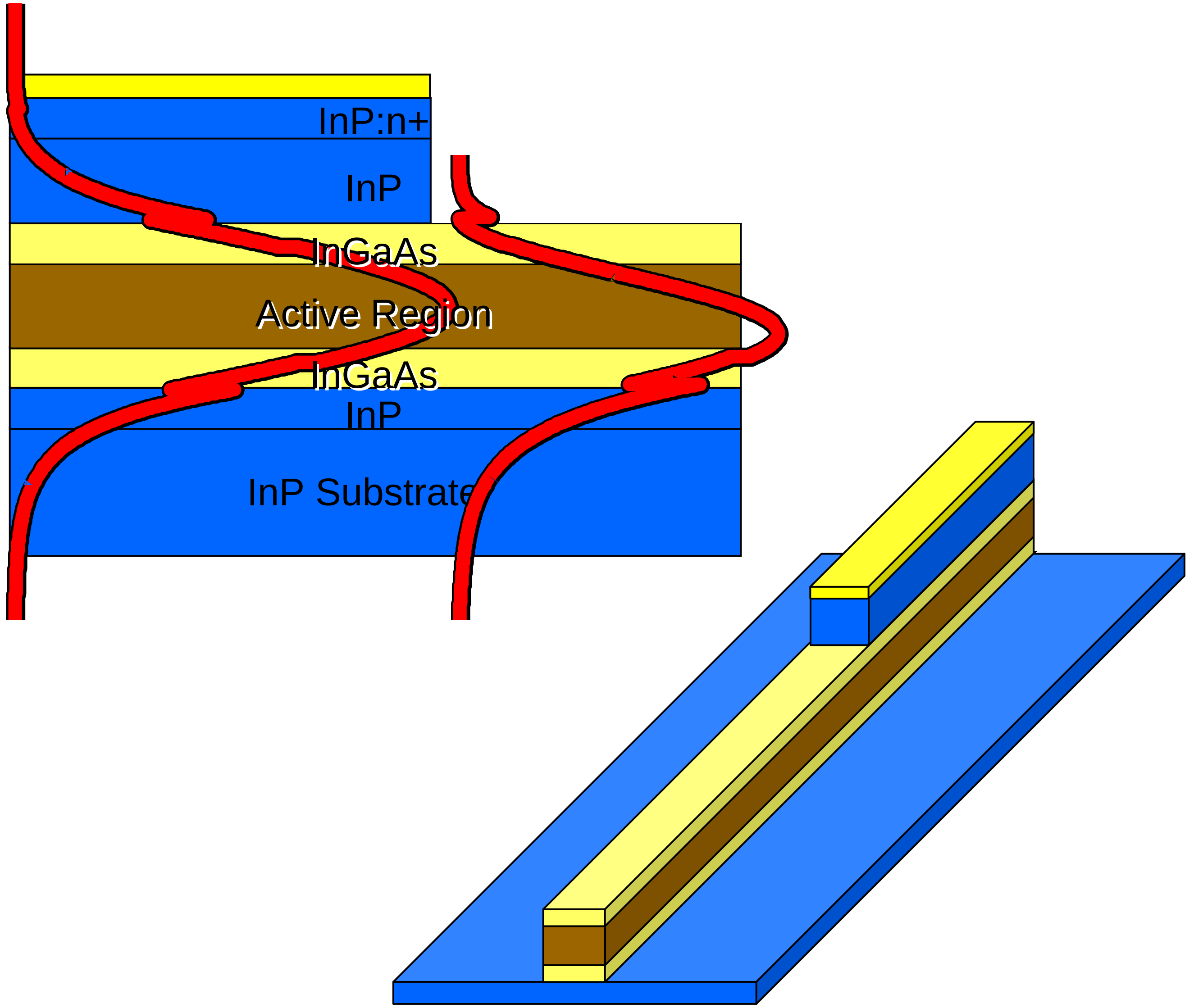
QC laser structures as waveguides



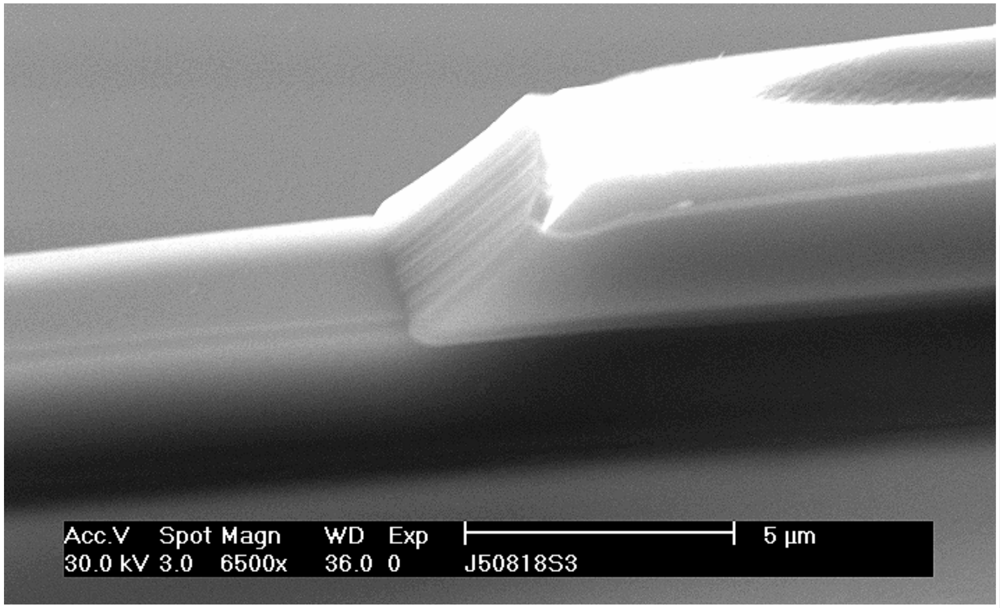


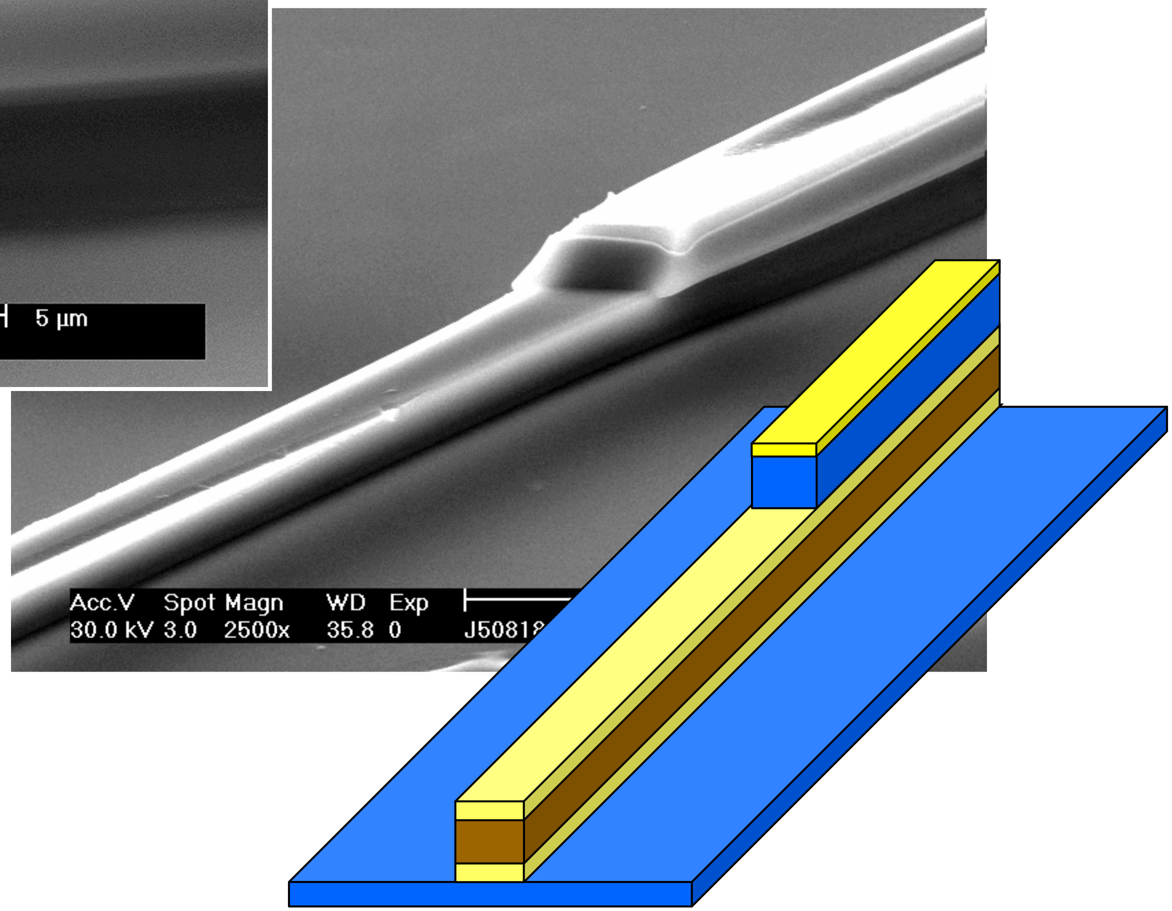
Fabrication

1. Start with epitaxial growth
2. Use photoresist to block half of wafer
3. Use HCl selective etch to remove top InP
4. Continue making laser ridge as before



Fabrication





HBr:HNO_3 wet etch

3 mm laser
8 mm total length

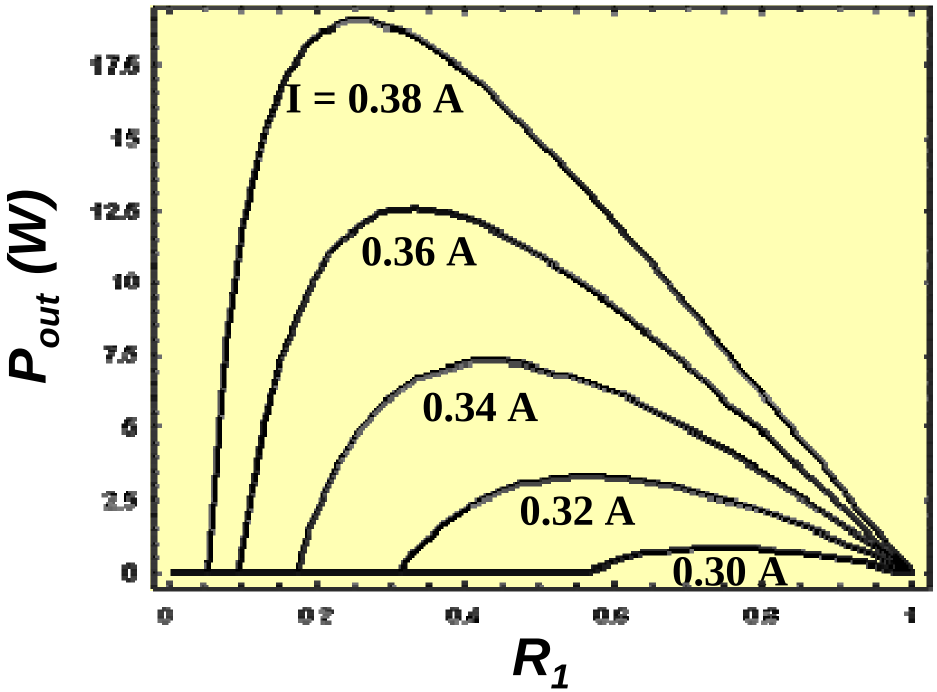
Reflection at the Laser-Waveguide Interface

$$P_{out} = \eta_{ext}(I - I_{th})$$

$$\eta_{ext} = \frac{1}{2}\frac{\varepsilon_{32}}{q}N_p\left(1-\frac{\tau_2}{\tau_{32}}\right)\frac{\frac{1}{2L}\ln\frac{1}{R_1}}{\alpha_m+\alpha_w}$$

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

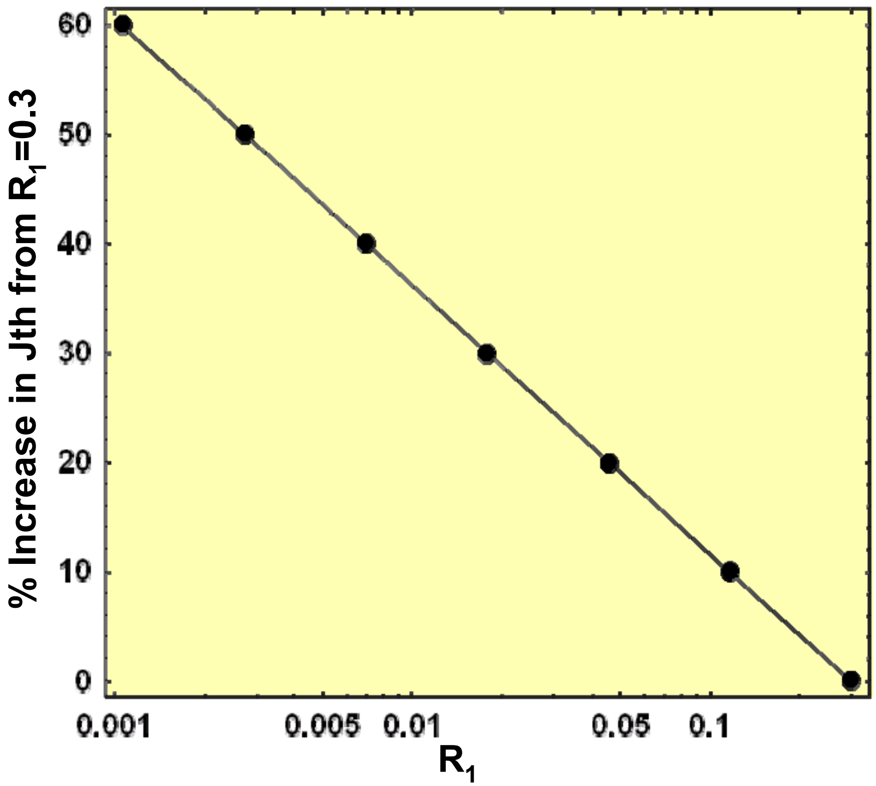
$$\alpha_m = \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

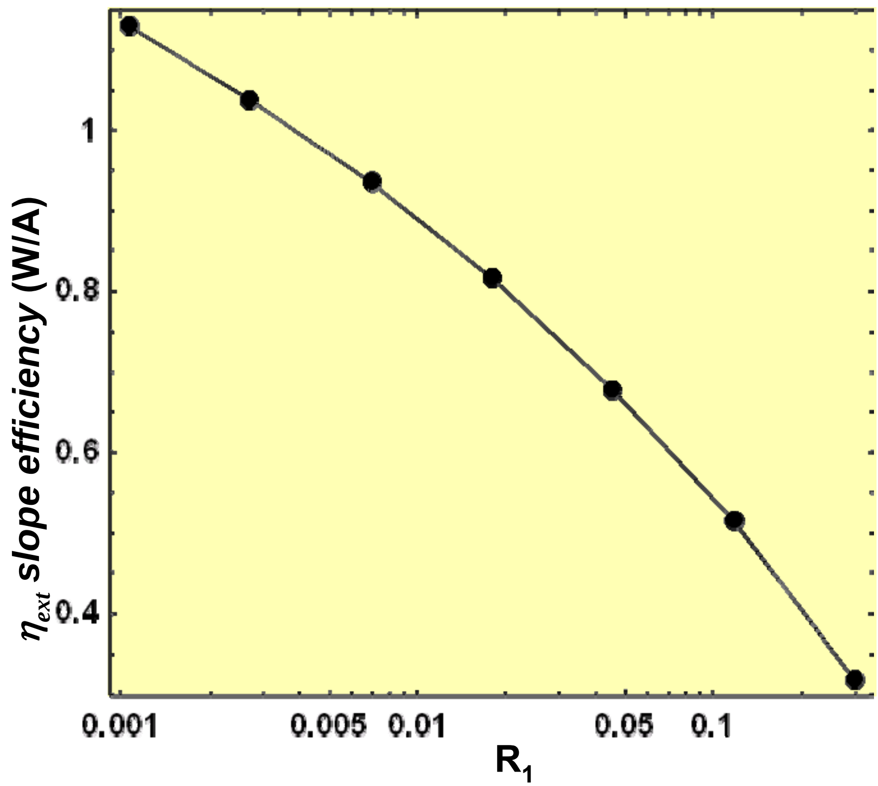


L = 0.25 cm	Γ = 0.55	g = 0.04 cm/A
$A = 3.8\times10^{-4}$ cm^2	E_{32} = 155 meV	N_p = 40
τ_2 = 0.3 ps	τ_{32} = 1.5 ps	$\alpha_w = 14$ cm^{-1}
	R_2 = 0.3	

$I_{th}(R_1 = 0.3) = 0.32$ A

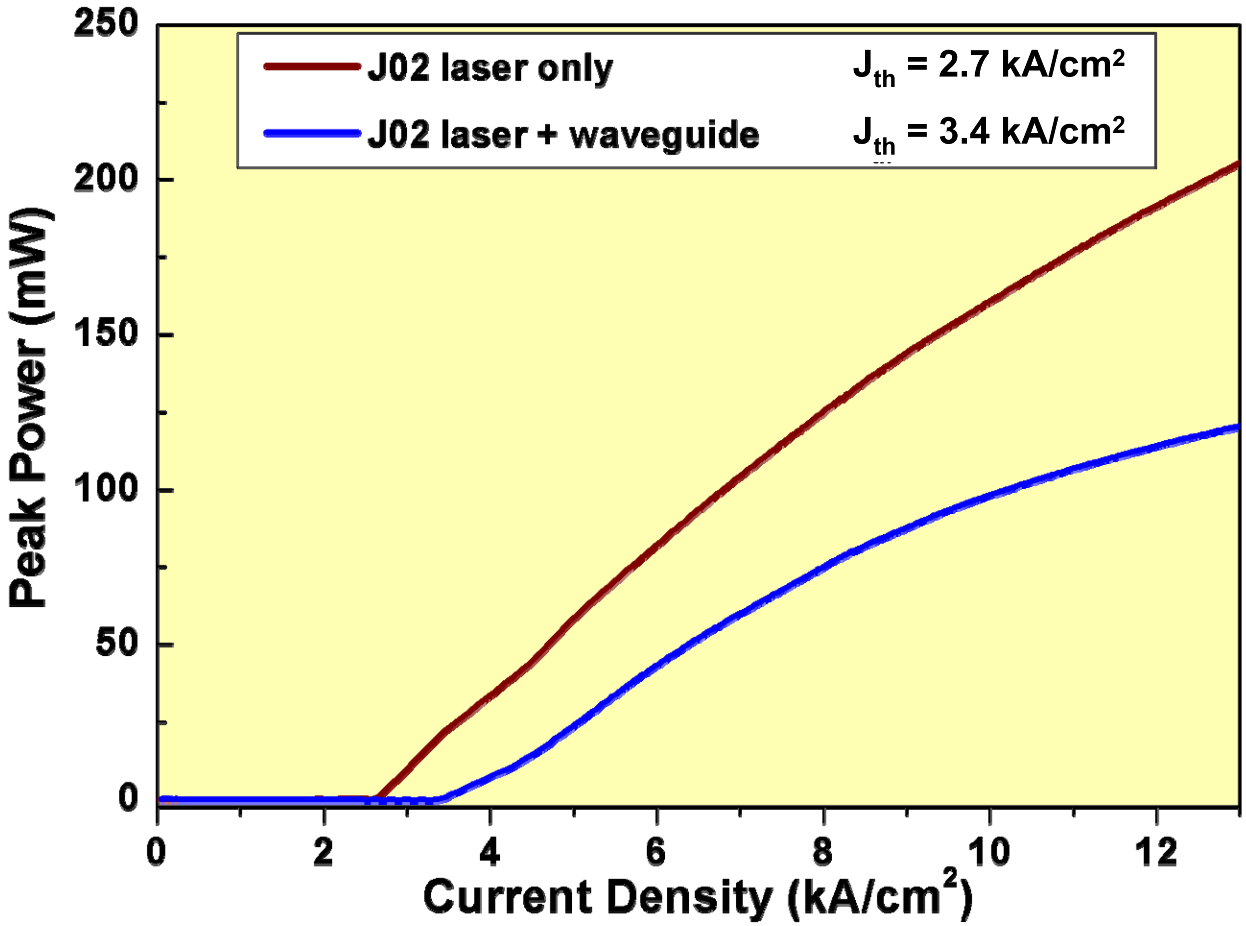
Reflection at the Laser-Waveguide Interface





$R_2 = 0.3$	$g = 0.04$ cm/A	$\alpha_w = 14$ cm^{-1}	$\Gamma = 0.55$
$E_{32} = 155$ meV	$N_p = 40$	$\tau_2 = 0.3$ ps	$\tau_{32} = 1.5$ ps
	$L = 0.25$ cm	$A = 3.8\times10^{-4}$ cm^2	

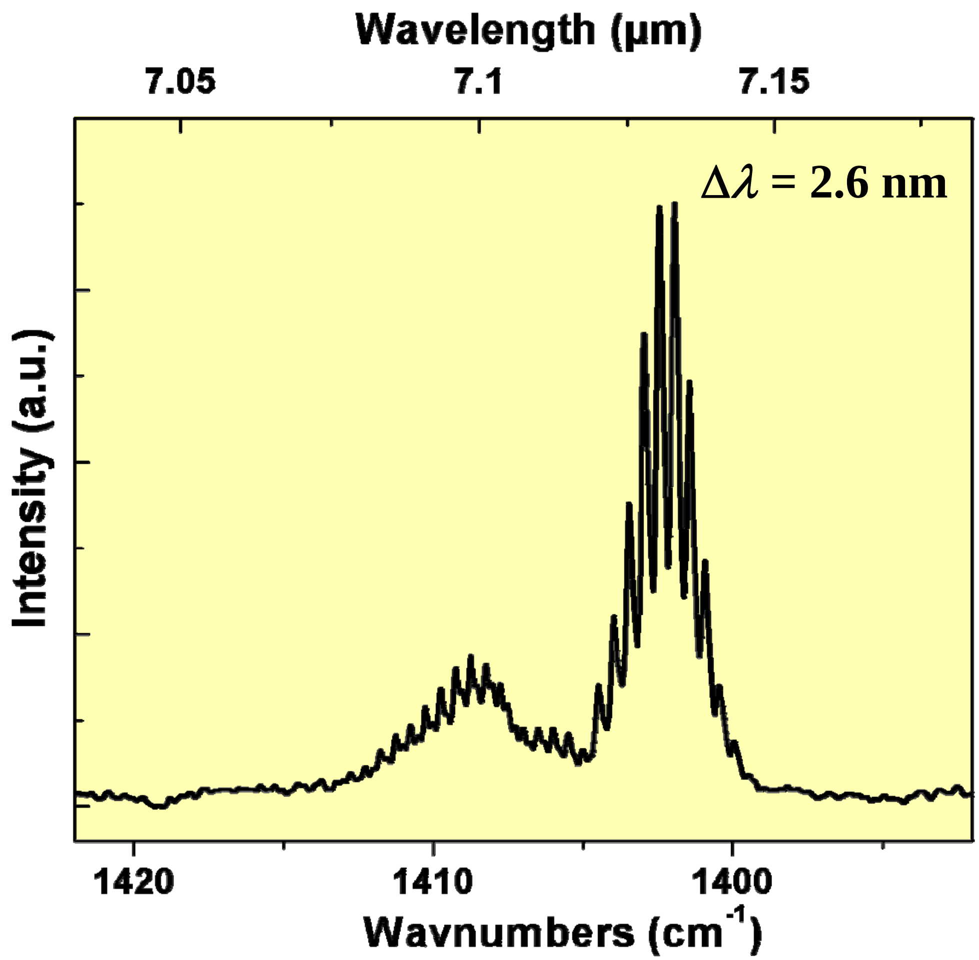
Results: L–I



25% increase in J_{th}

$R_1 \approx 0.03$

Results: Spectra



$$\Delta\lambda = \frac{\lambda^2}{2 n_{eff} L}$$

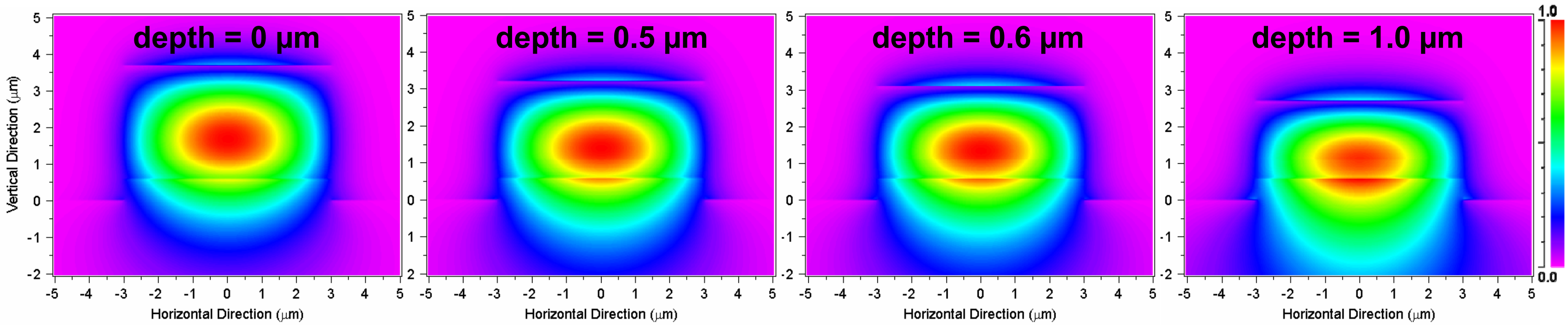
λ = 7.1 μm

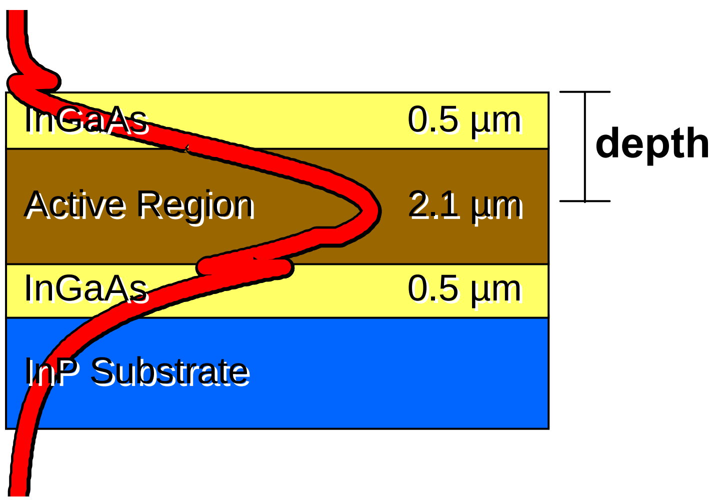
n_{eff} = 3.2

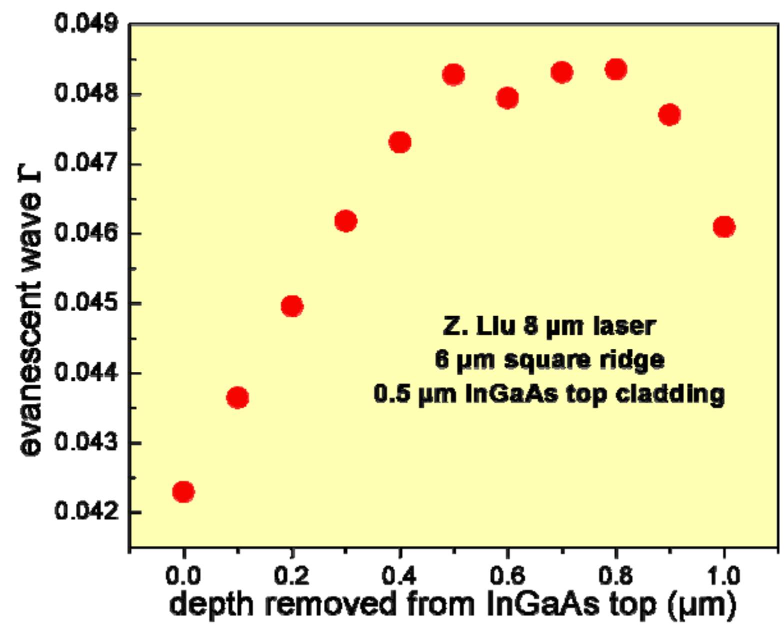
L = 3 mm

$\Delta\lambda$ = 2.6 nm

Mode Optimization







Summary

- Motivation: on-chip sensing capabilities for liquid-based molecular detection
- Demonstration of a monolithic QC integration method
- Acknowledgements
  + DARPA L-PAS
  + PRISM
  + NSF Graduate Research Fellowship Program