Semiconductor laser wish list
MTO Symposium

Dr. Henryk Temkin

San Jose, CA

March 5-7, 2007

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
05 MAR 2007	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Semiconductor laser wish list	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **DARPA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
DARPA Microsystems Technology Symposium held in San Jose, California on March 5-7, 2007. Presentations, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**21**	

Semiconductor laser wish list

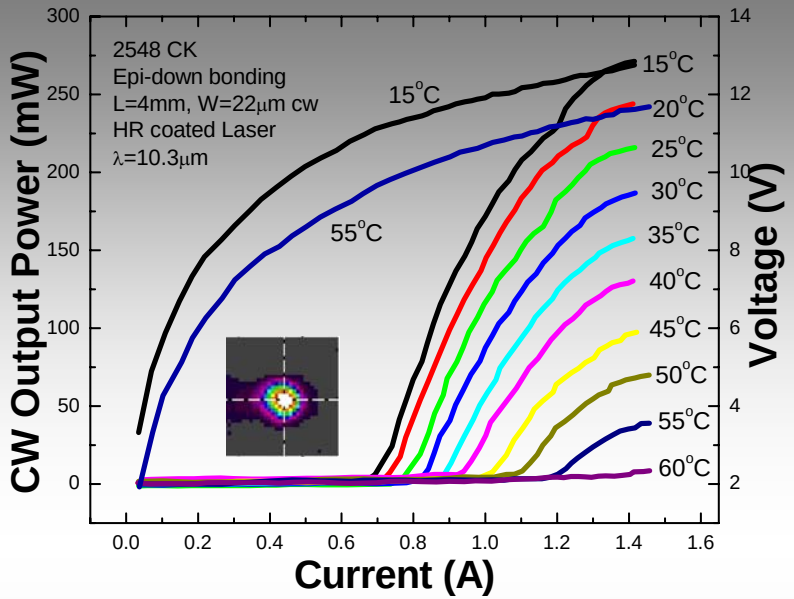
Today

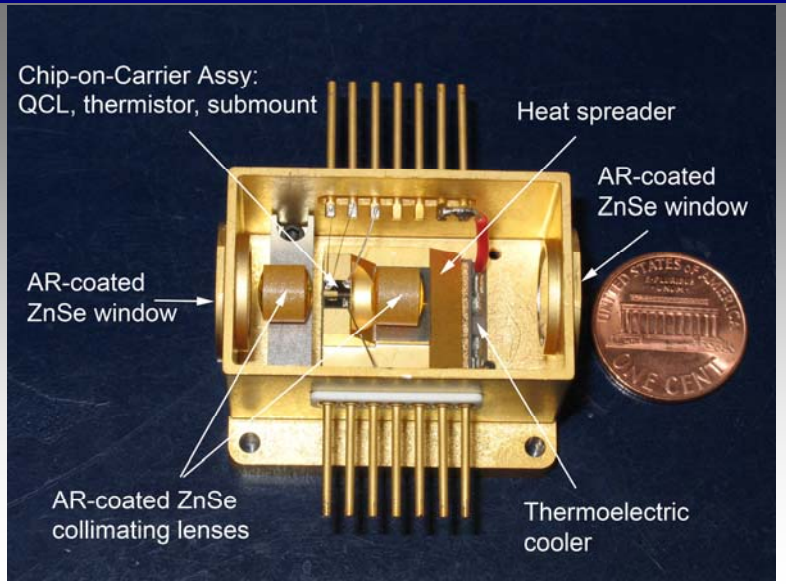
- **Wide wavelength range and tunability (L-PAS, SAIL)**
- **Efficient mid-IR operation (EMIL)**
- **Scalable Power**

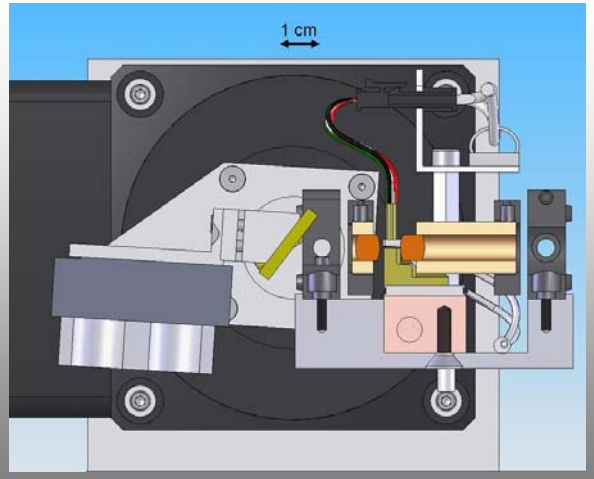
Tomorrow

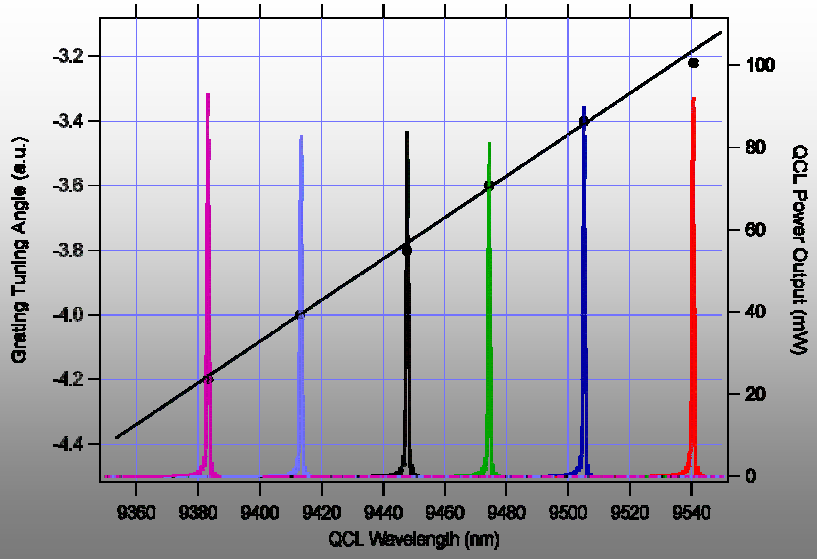
- **Really small lasers**
- **Really fast lasers with engineered RF response**
- **Lasers and non-linear waveguides**

Quantum Cascade Laser

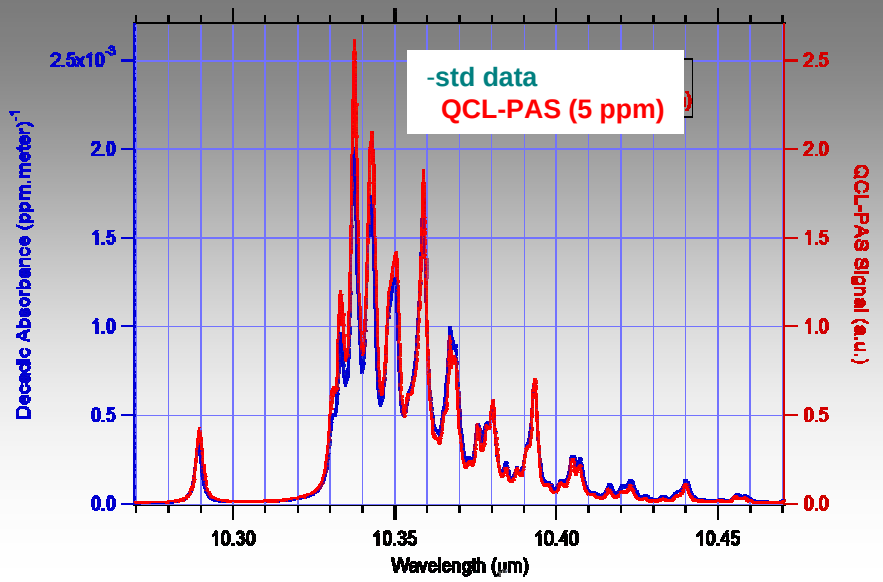




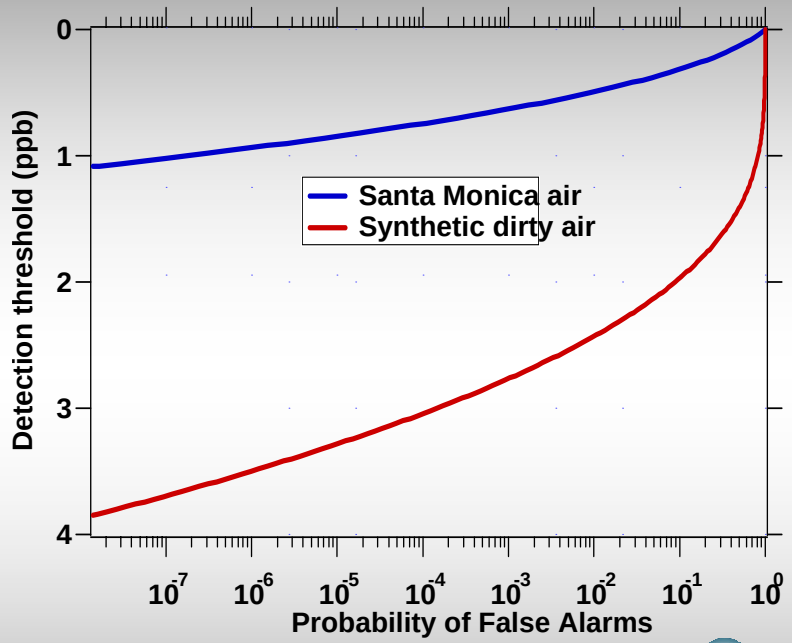




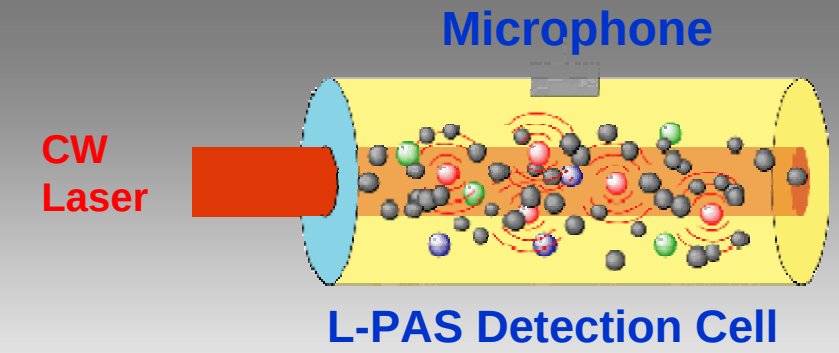
Tuning is a big deal



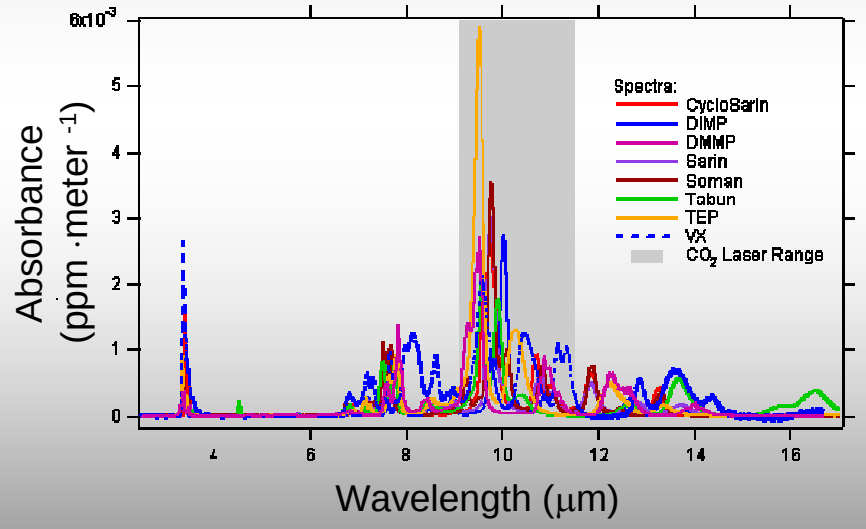
Detection in the presence of interferents



Laser Photoacoustic Spectroscopy (L-PAS)

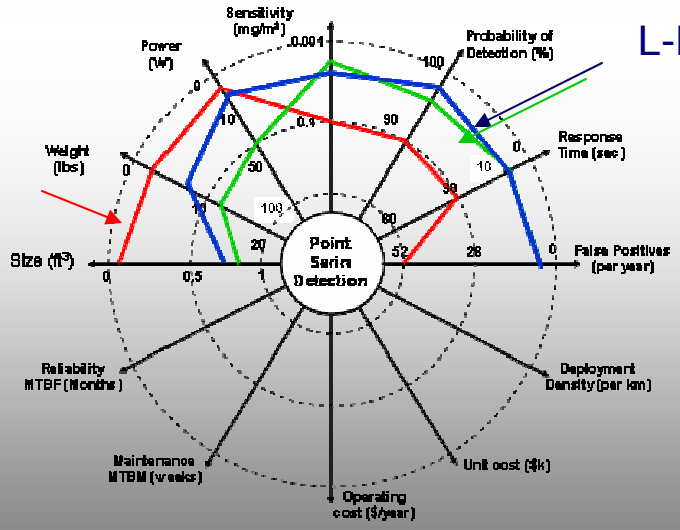


Absorption spectra of CWAs



Quantum Cascade Lasers enable development of new CWA sensors:

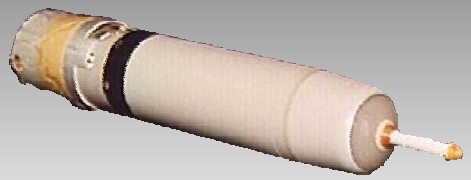
- Sub-ppb sensitivity (order of magnitude improvement over SOA)
- High specificity with false alarm rate reduced to < 10^{-6}
- Response time reduced from ~ 1 min to ~ 10 seconds

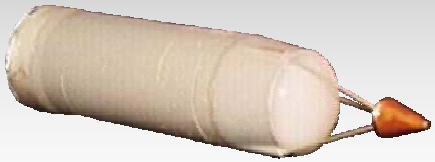


LASER PHOTOACOUSTIC SPECTROSCOPY LPAS

Need For IRCM

Threats Exceed 1,000,000 Missiles World-wide





1960s
Spin Scan

1970/80
Cooled Con Scan

1980s/90s
Cross Array/Rosette Flare CCMs

2000
Scanning Imagers

2005
1st Generation Imagers

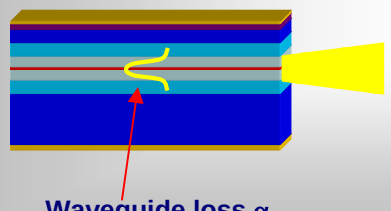
2010
2nd Generation Multispectral

The race continues!
NEED lasers with:
10s Watt output power
CW room temperature
High Wallplug Efficiency
Excellent beam properties

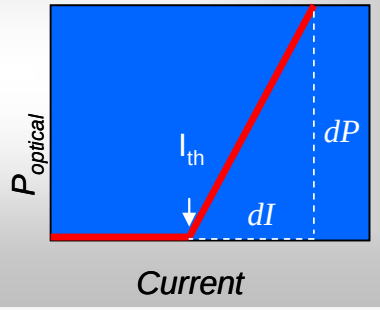
Fundamental Limits for MWIR Lasers in Wall-Plug Efficiency (WPE)

Current efficiency = η_c

$$\eta_c = \frac{I - I_{th}(T)}{I} \frac{\alpha_m}{\alpha_{tot}(T)} \qquad I_{th} = \frac{1}{\tau_3(1-\tau_2/\tau_{32})}\left[\frac{\varepsilon_0 n_{eff}\lambda L_p(2\gamma_{32})}{4\pi z_{32}^2}\frac{\alpha_{tot}}{\Gamma} + qn_{2D}e^{-\Delta/k_BT}\right]$$



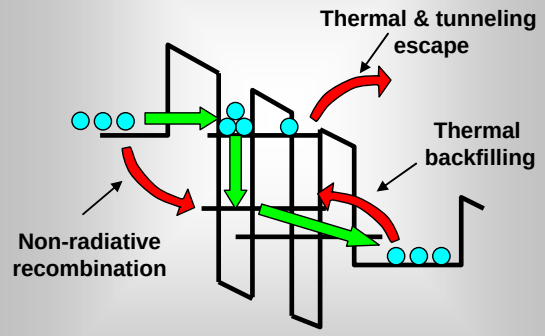
Waveguide loss α_w



$$\eta_{WPE} = \frac{P_{Optical}}{P_{Electrical}} = \eta_V \eta_C \eta_i \eta_{mo}$$

Internal efficiency = η_i

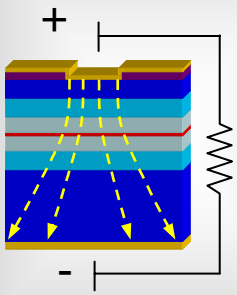
$$\eta_i = \xi \frac{\tau_{eff}}{\tau_{eff} + \tau_2}$$



$$\tau_{eff} = \tau_3 \frac{\tau_{32} - \tau_2}{\tau_{32}}$$

Voltage efficiency = η_V

$$\frac{N\hbar\omega}{N(\hbar\omega + \Delta) + qR_S I}$$

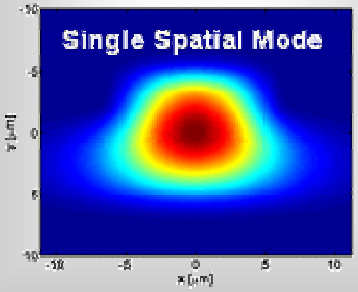


$$V = N_P(V_{act} + V_{inj}) + IR_s$$

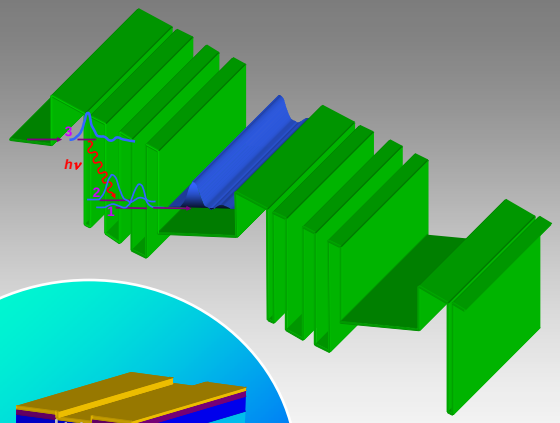
$$\frac{\text{photon energy}}{\text{bias per stage}} = \frac{\hbar\omega}{\hbar\omega + 2\hbar\omega_{LO} + \Delta E} \rightarrow \frac{\hbar\omega}{\hbar\omega + 2\hbar\omega_{LO}}$$

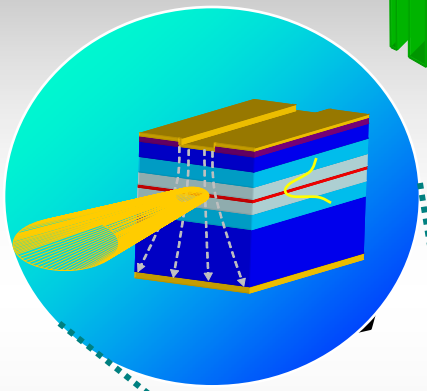
Modal efficiency = η_{mo}

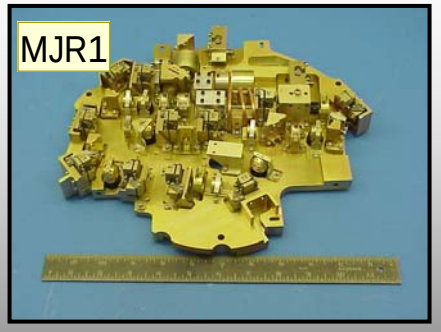
$$\eta_{mo} = \frac{(\sum_{i=1}^{N_p}\Gamma_i)^2}{N_p\sum_{i=1}^{N_p}\Gamma_i^2}$$



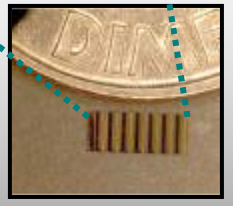
Efficient Mid-Wave Infrared Lasers (EMIL)







SOA Mid IR Optical Bench



"IRCM laser-on-a-chip"

Program Objective

- **Breakthrough in wall-plug efficiency for lasers in the critical mid-wave infrared bands**
  - **Band IVa (3.8 – 4.2 µm)**
  - **Band IVb (4.5 – 4.8 µm)**

DoD Benefits

- **Reduce laser size/weight/power**
  - **Enable IRCM systems on smaller, vulnerable platforms (e.g., rotorcraft, UAVs)**
- **IRCM with higher modulation rates than SOA**
  - **Counter emerging threats (e.g., FPAs)**

"2W in, 1W out!"
T. Tether
06 Jan 2006

MJR1

BAE LAMBS
51 optics
4 resonators
Mark J. Rosker, 11/23/2005

Raman beam combining and cleanup

1. **Raman beam cleanup**

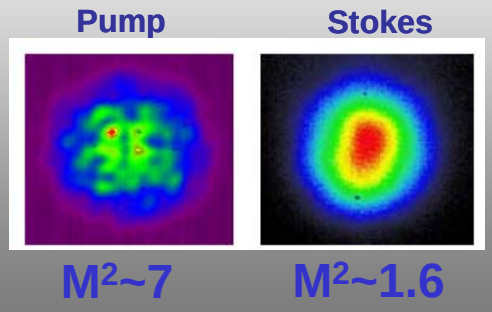
   Converts a low quality pump into a diffraction limited beam

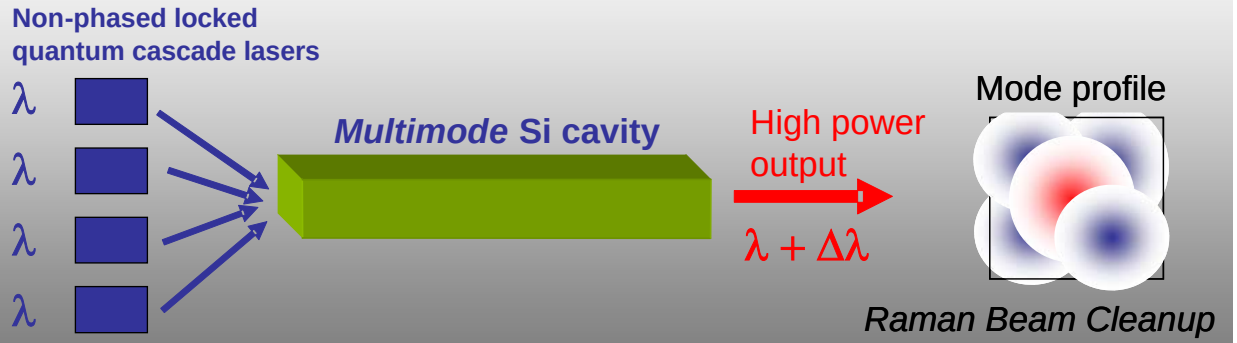
2. **Combine multiple pumps via self imaging in multimode waveguide**

   - *Incoherent* power combining of N oscillators – phase control not necessary

3. **Silicon as the active material**

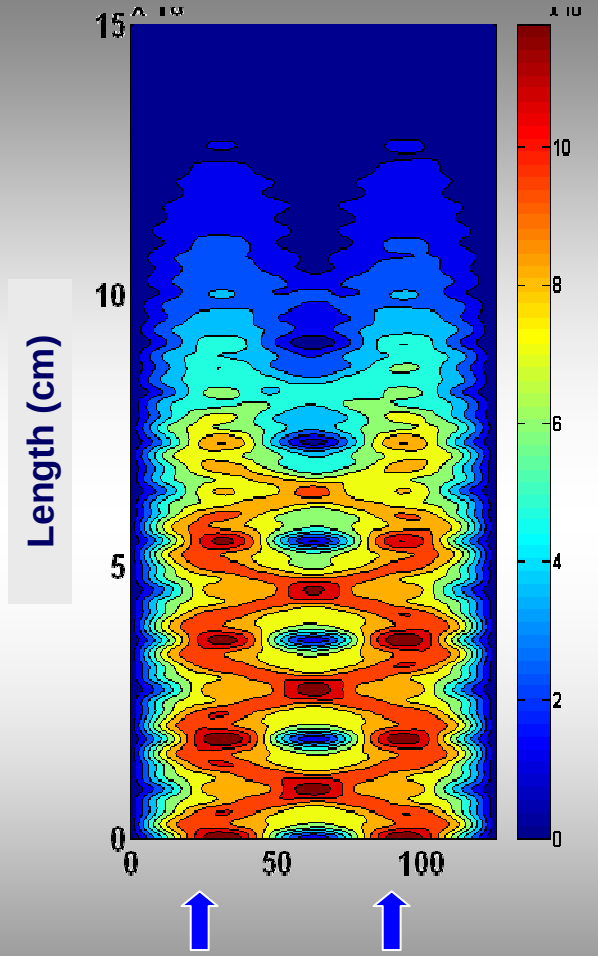
   - High gain coefficient → compact lasers and amplifiers
   - High thermal conductivity → power scaling, excellent cooling
   - High optical damage threshold → high pulse energy
   - Low dn/dT and elasto-optic coefficient → high beam quality

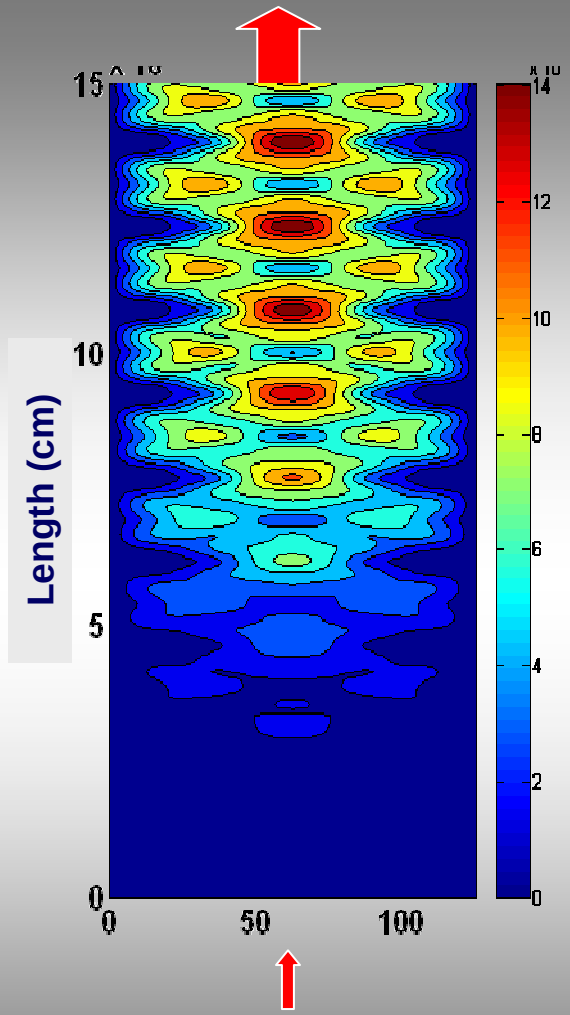


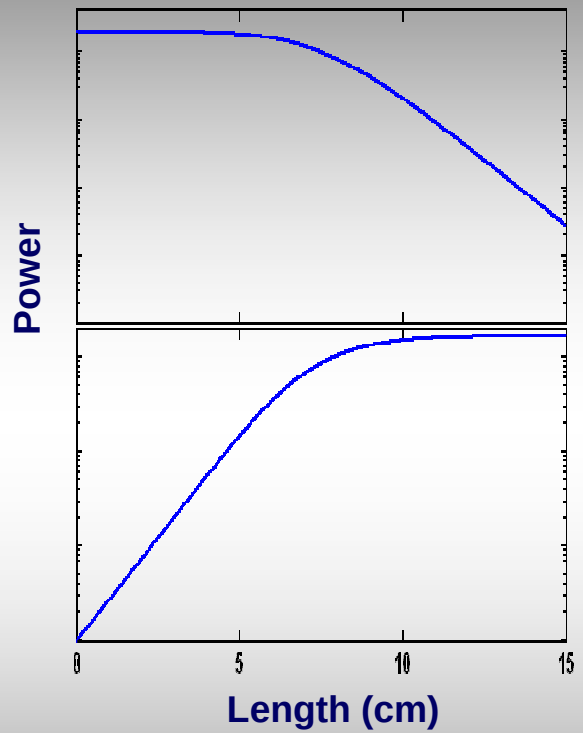


UCLA Prof. B. Jalali

Simulation of Amplification Via Self Imaging in Multimode Si Waveguide







PUMP1 and 2 each 1KW

1kW is peak pulse power, average pump power is in milli-Watts range

1W Stokes

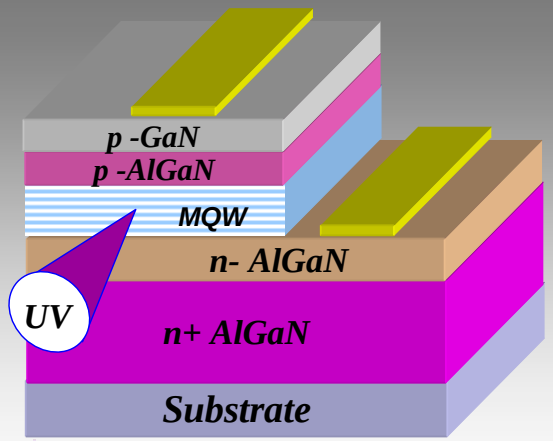
Si and conventional Raman crystals

Property	Silicon	$Ba(NO_3)_2$	$LiIO_3$	$KGd(WO_4)_2$	$CaWO_4$
Optical damage threshold (MW/cm^2)	~1000-4000	~400	~100	-	-
Thermal conductivity (W/m-K)	148	1.17	-	2.6 [1 0 0] 3.8 [0 1 0] 3.4 [0 0 1]	16
Raman gain (cm/GW)	20 (1550nm)	11 (1064nm)	4.8 (1064nm)	3.3 (1064 nm)	-
Transmission Range (μm)	1.1-6.5	0.38-1.8	0.38-5.5	0.35-5.5	0.2-5.3
Refractive index	3.42	1.556	1.84	1.986 - 2.033	1.884
Raman shift at 300K (cm^{-1})	521	1047.3	770 822	901 768	910.7
Spontaneous Raman linewidth (cm^{-1})	3.5	0.4	5.0	5.9	4.8

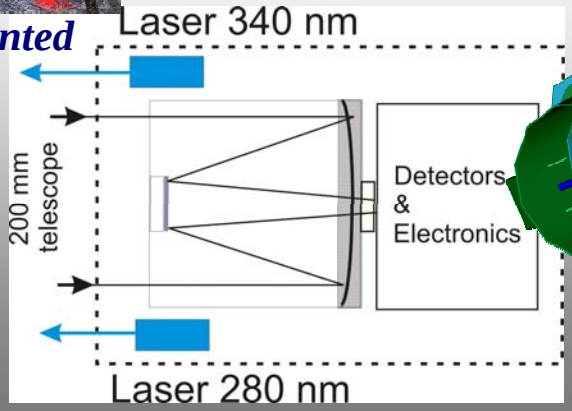
- 10x higher optical damage threshold
- 100x higher thermal conductivity
- High Raman gain, excellent large crystals

UCLA

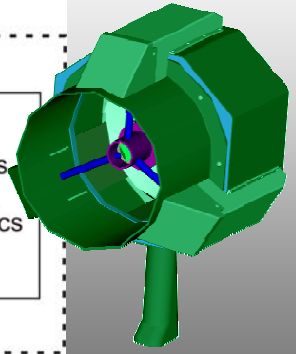
Semiconductor AlGaN Injection Lasers (SAIL)



Truck mounted



Hand held



Objective

- **Develop AlGaN injection lasers emitting in the ultraviolet; λ=340-280 nm.**

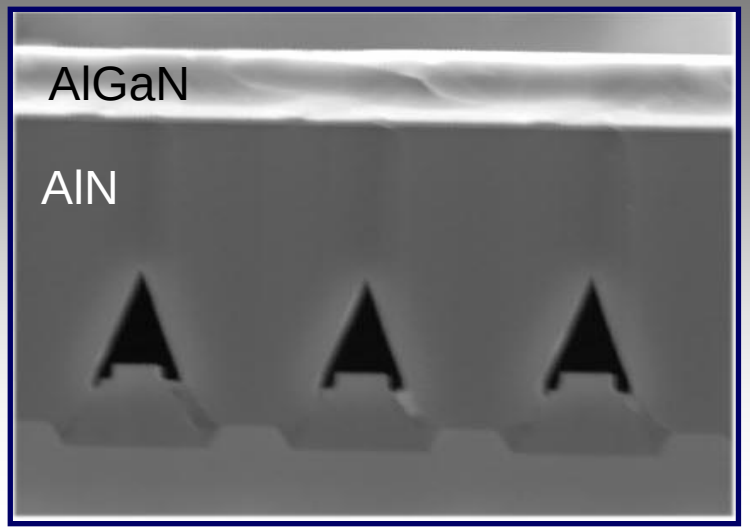
Impact

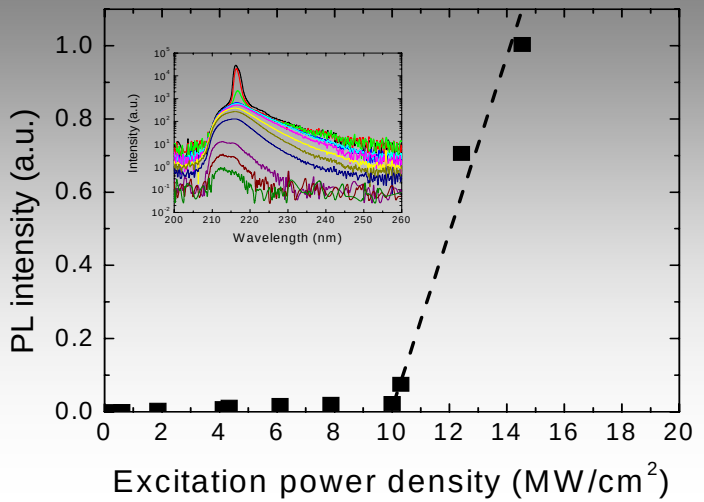
- **Stand-off bio-agent detection; Bio-LIDAR**

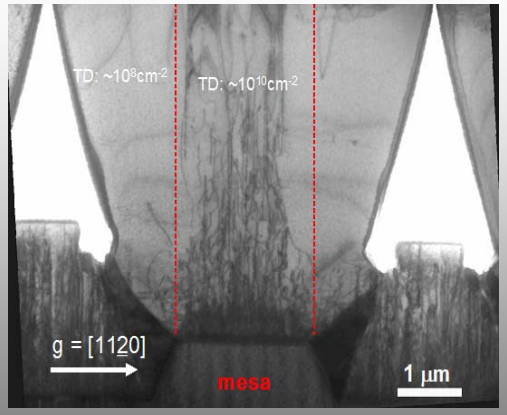
Key technical goals

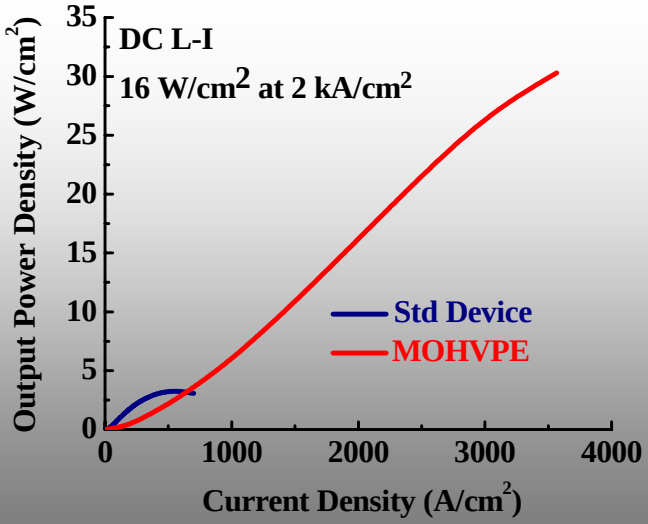
- Reduce dislocation density of AlGaN structures by three orders of magnitude, to less than $10^7/cm^2$
- Increase p-type doping in AlGaN to support current densities of 10 kA/cm^2, to *1 x 10^{18} cm^{-3}*
- Increase luminescence efficiency of AlGaN active layer to *IQE~60%*
- Demonstrate stable laser operation

SAIL – Pulsed Lateral Overgrowth





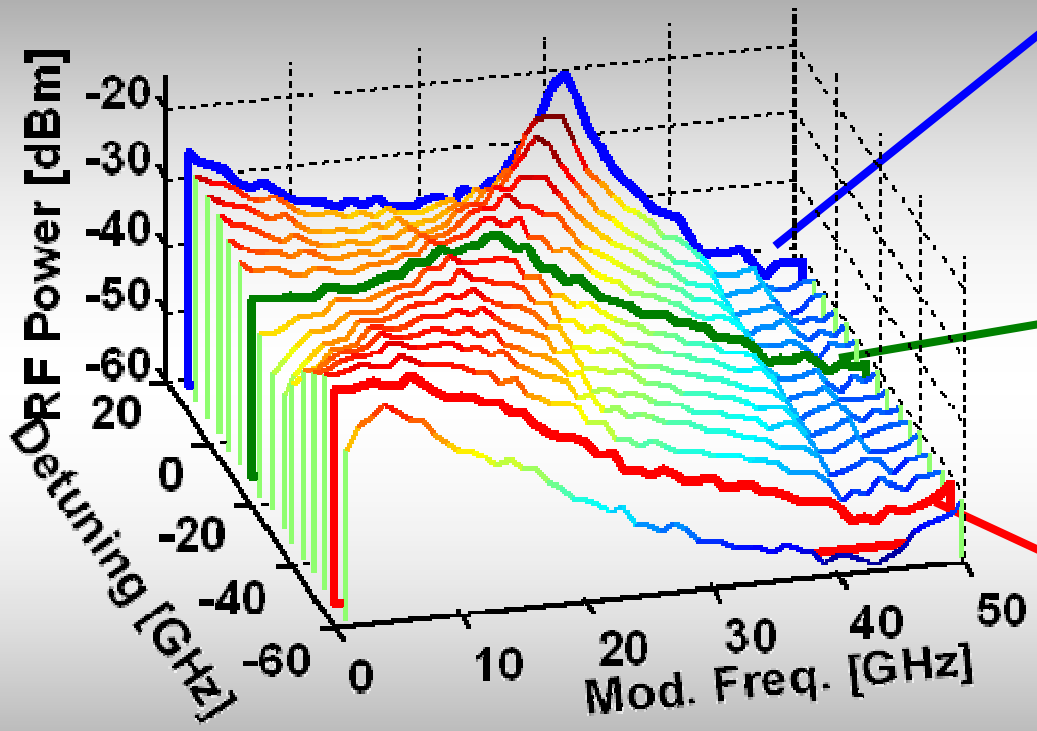


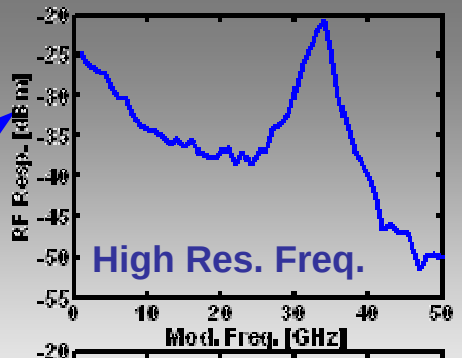


UNIVERSITY OF SOUTH CAROLINA

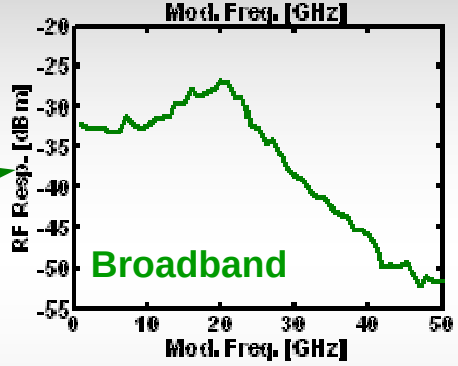
Frequency Response of Injection-Locked DFB Lasers

Electrical Frequency Response, P_{ratio} = +8 dB

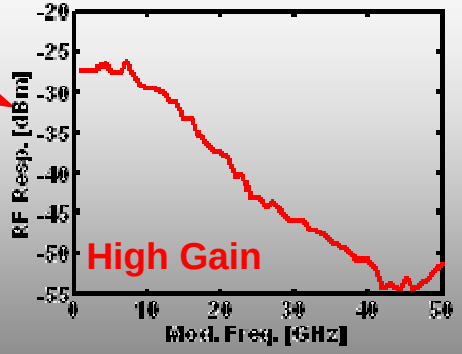




Large Positive Frequency Detuning



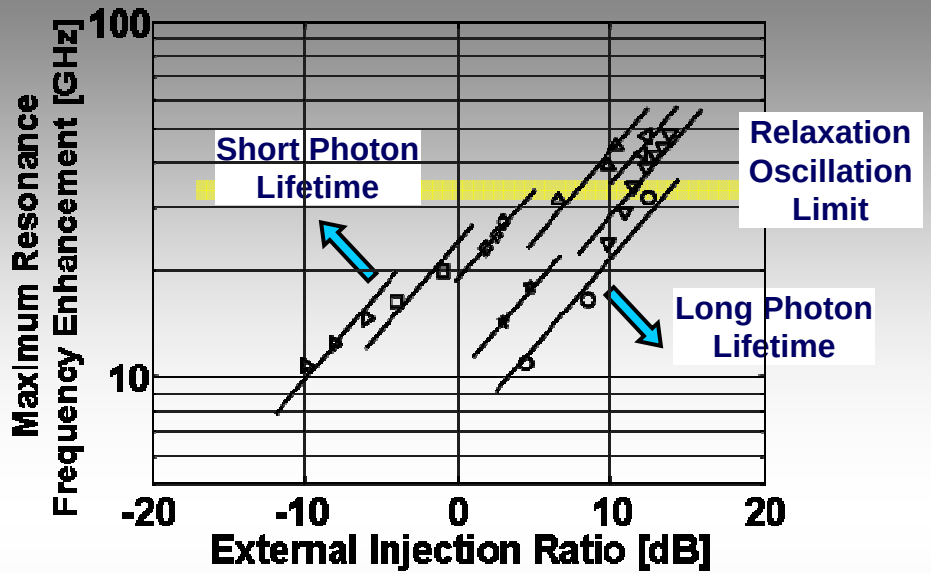
Small Positive Frequency Detuning



Negative Frequency Detuning

Profs. Wu and Chang-Hasnain
UC Berkeley

State of the Art



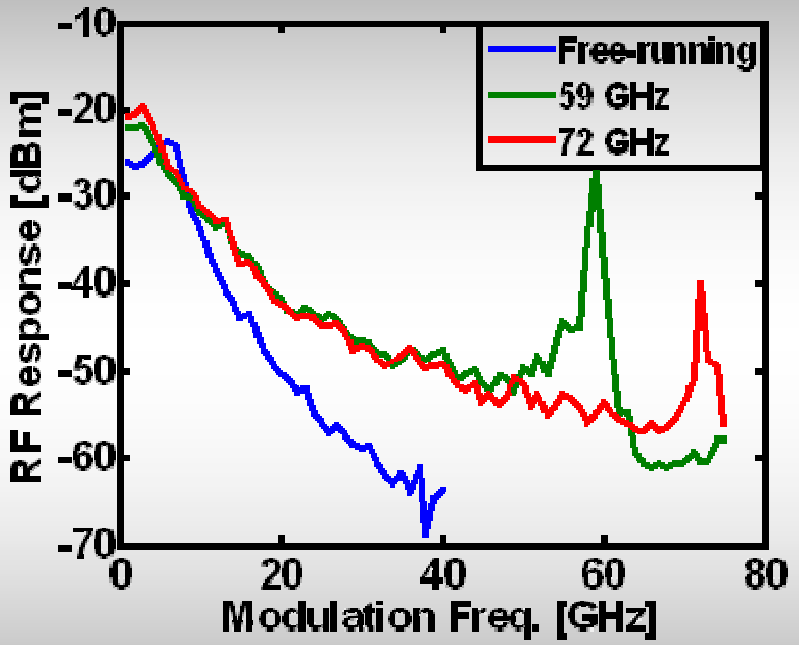
- **Strong injection locking can overcome the fundamental limit of relaxation oscillation**
- **Maximum enhanced resonance frequency under optical injection:**

$$\tau_p \cdot f_{R,\max} = \frac{1}{4\pi}\sqrt{R_{\text{ext}}}$$

τ_p : photon lifetime
R_{ext} : ext. injection ratio

- **This "time-bandwidth product" provides a guideline for device optimization**

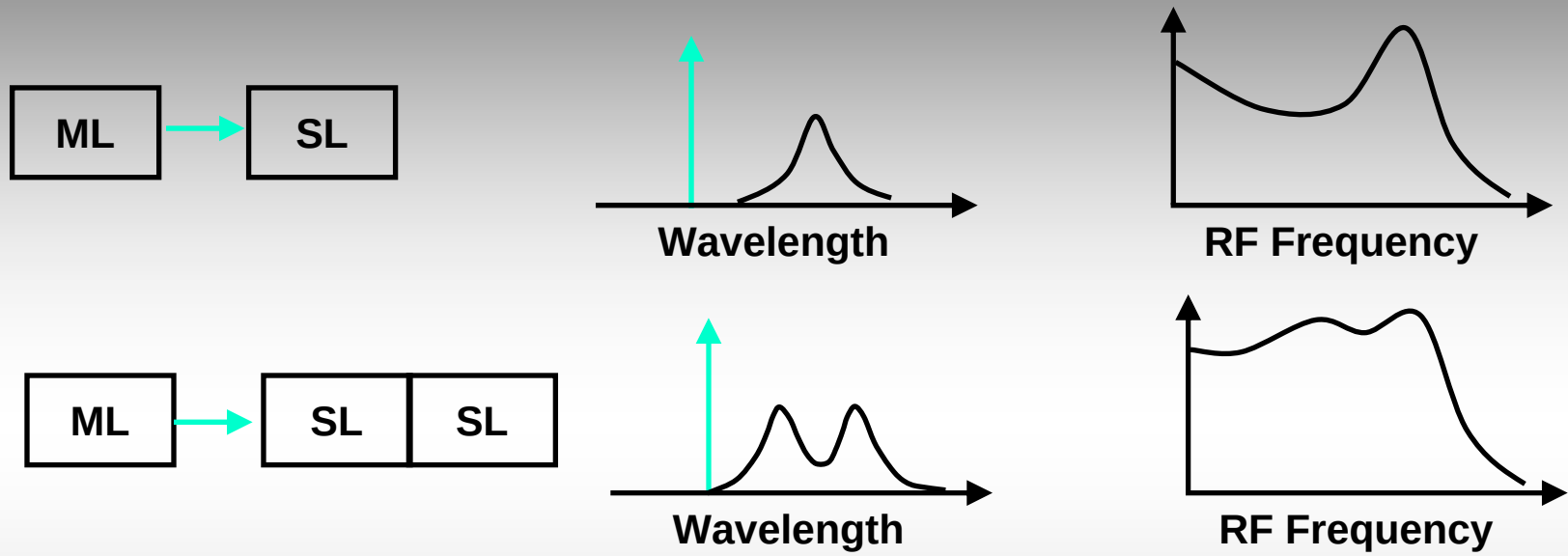
Ultra-high injection ratio and near positive detuning edge



Lau, Sung, and Wu, OFC 2006

Optical Cavity Engineering For High Speed

- "Optical doublet" cavity



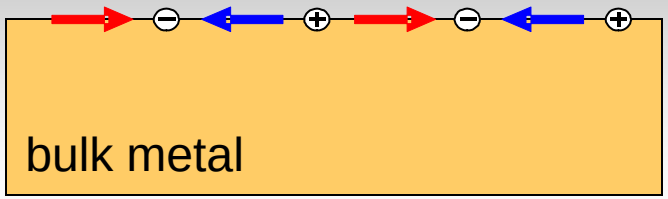
- Similar to high-order filter theory
  - "Chebyshev" cavity

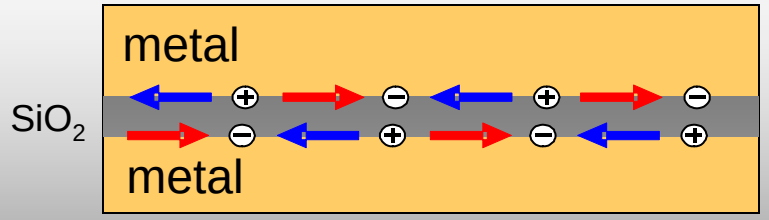
How can this concept be implemented in an integrated structure?

Sub-λ cavity with surface plasmons

Miyazaki *et al*, Tsukuba (Japan), PRL **96,** 097401 (2006)

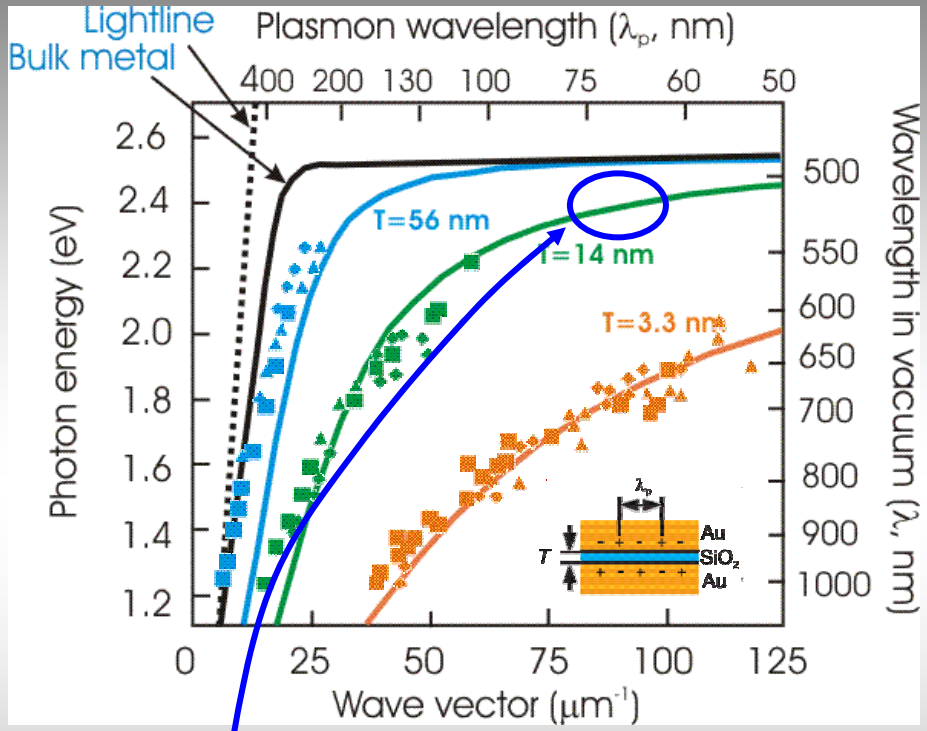
Surface plasmons are longitudinal charge density fluctuations on the surface of a conductor





Plasmons confined to nm thick layers propagate through μm-length distances

Calculated dispersion relation

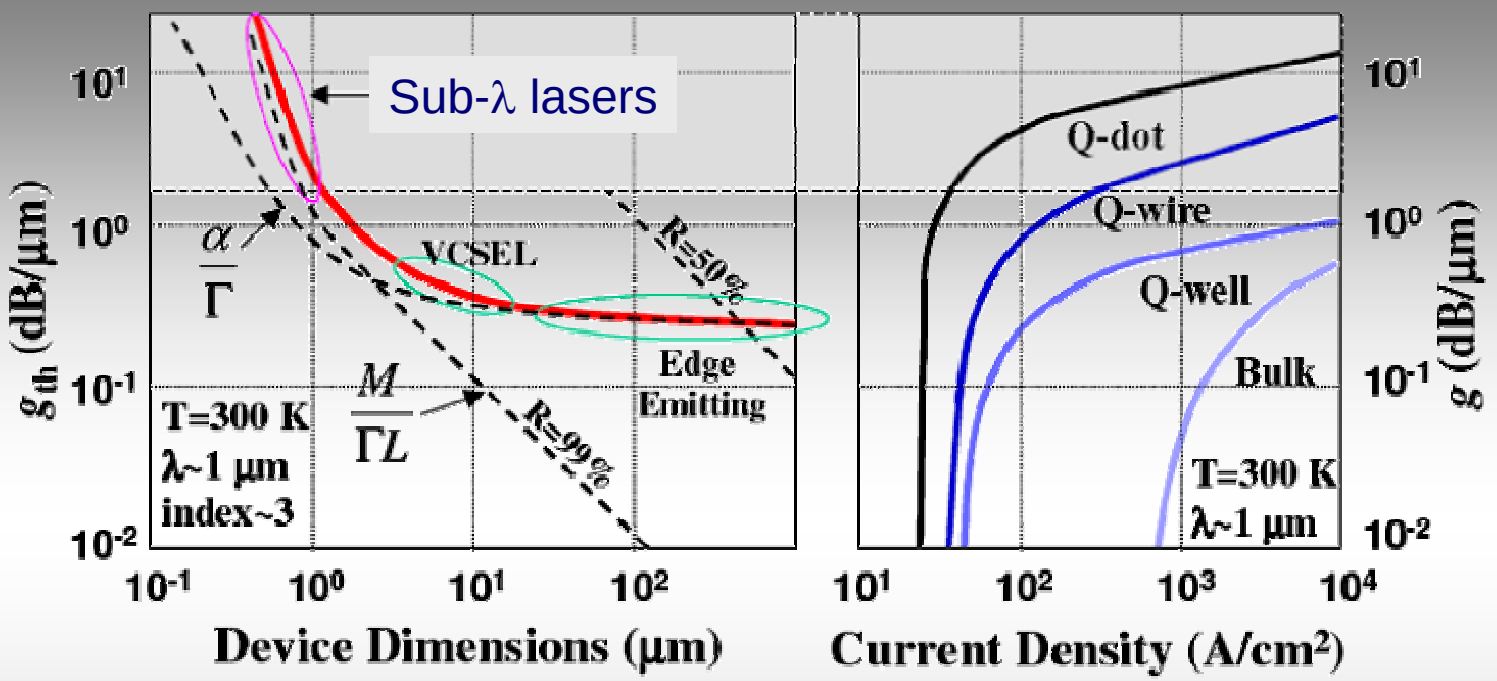


For visible free-space wavelength we get plasmons with soft x-ray wavelengths!

Visible light squeezed into a 3.3 nm core and its λ reduced by 92%, to λ_p~51-55 nm.

BUT: unknown loss-confinement relationship!

What does it take to make a small laser?



$$g_{th} = \frac{1}{\Gamma}(\alpha + \frac{M}{L})$$

M is the mirror loss (dB), Γ is the modal confinement factor, and *L* is the cavity length

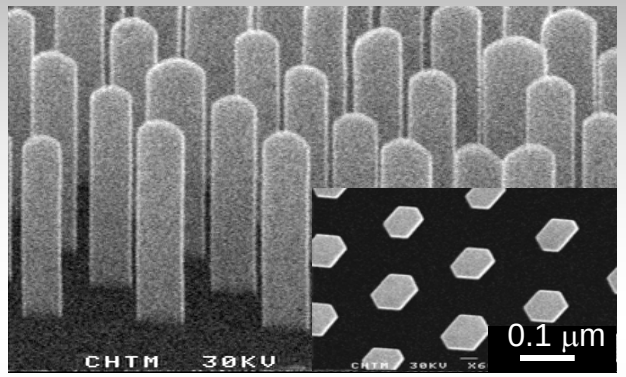
$$R_{th} \sim \frac{1}{Q}\frac{V_c}{V_m} + (1-\beta)\frac{N_{th}V_c}{\tau_r} + \frac{N_{th}V_c}{\tau_{nr}}$$

Prof. Hooman Mohseni
Northwestern

Need higher gain and new laser concepts

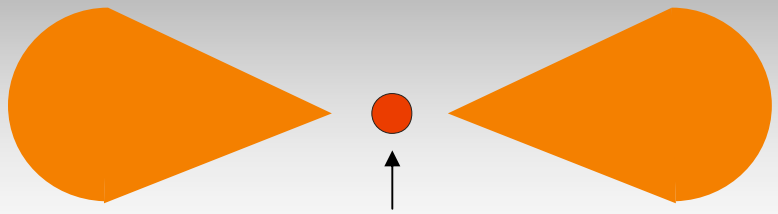
Lithographic placement and selective growth of GaN nanowires

Defect-free structures for d<100 nm!

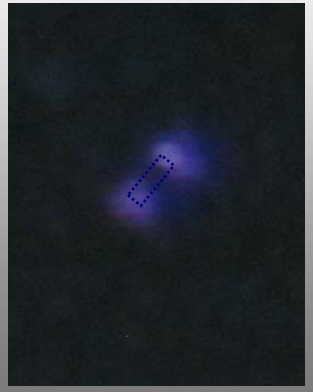


UNM, Prof. Steve Brueck

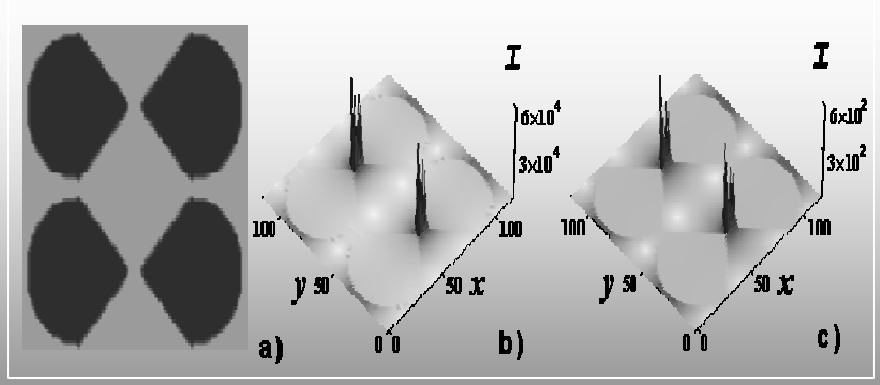
A different laser concept



Gain medium,
Quantum dot

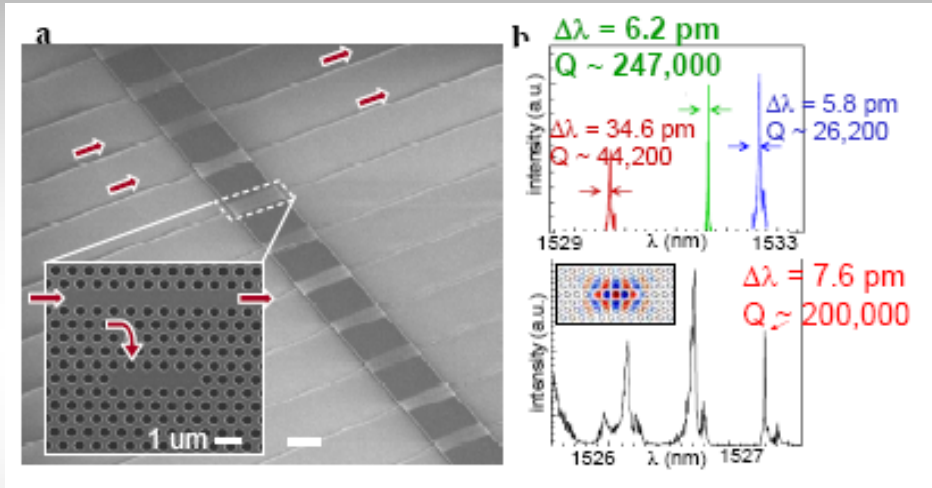


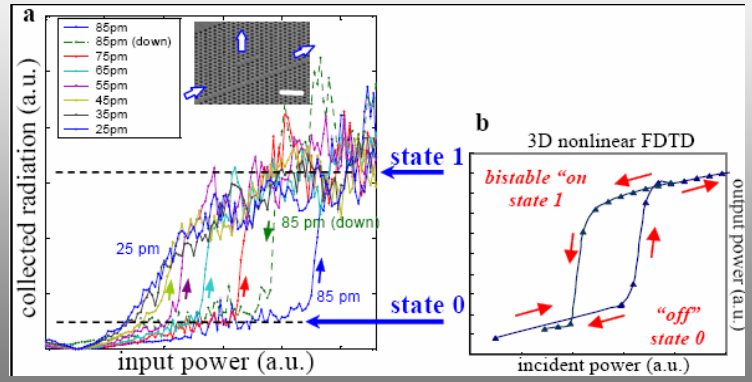
Lasing GaN nanowire, UNM and Sandia NL, L=5 μm



Young Faculty Award (YFA)

126 submissions from 72 Universities, from Harvard College to Texas Woman's. 24 Awards at $150,000 each





Prof. C.W. Wong, Columbia

Waveguide coupled photonic cavity devices with high Q~ 247,000 and, at the same time, tightly confined mode with $V_m \sim (\lambda/n)^3$ have been obtained.

These Si-based structures show cavity-enhanced optical bistability at low input powers, ~ 1mW, and thermal TPA-induced free-carrier dispersion. This result, attributed to suppression of radiative modes and excellent fabrication procedures, opens the possibility of $Q \sim 1 \times 10^6$.

a) Cavity radiation against input power vs detuning. Bistable contrast increases with larger detuning but at a higher threshold.
a) 3D nonlinear FDTD bistable simulation.