Semiconductor laser wish list
MTO Symposium

MICROSYSTEMS TECHNOLOGY OFFICE

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San Jose, CA

March 5-7, 2007

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Semiconductor laser wish list

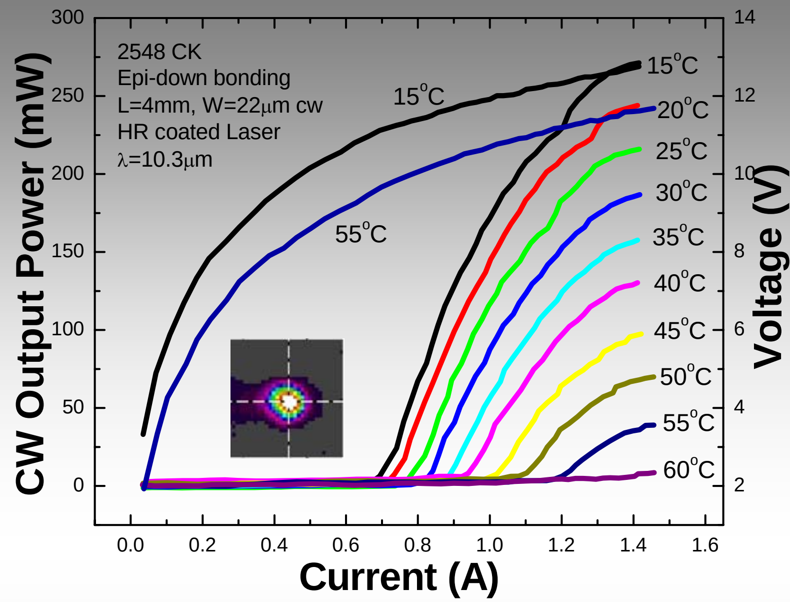
Today

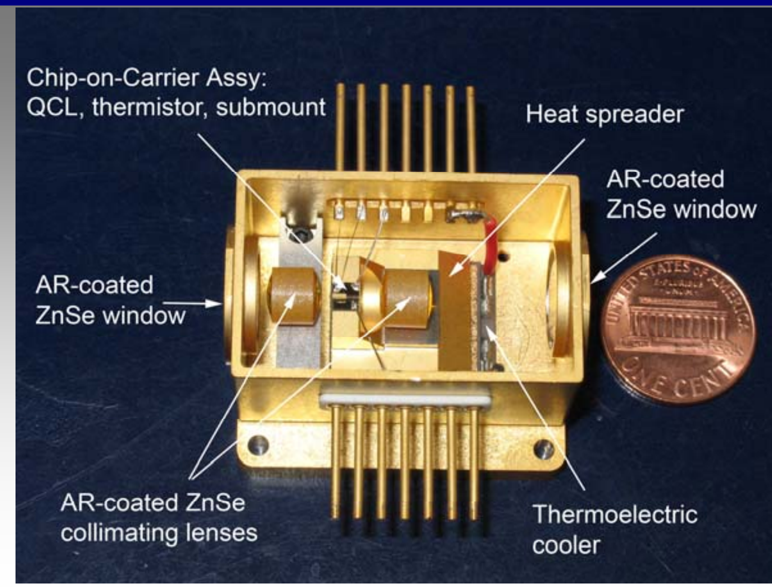
- Wide wavelength range and tunability (L-PAS, SAIL)
- Efficient mid-IR operation (EMIL)
- Scalable Power

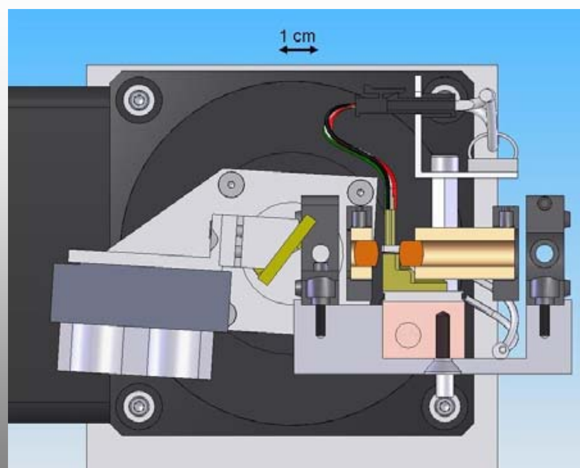
Tomorrow

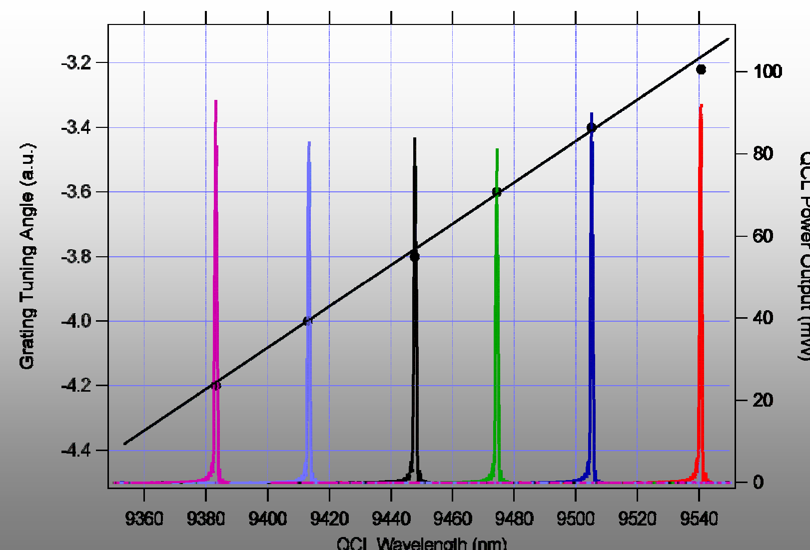
- Really small lasers
- Really fast lasers with engineered RF response
- Lasers and non-linear waveguides

Quantum Cascade Laser

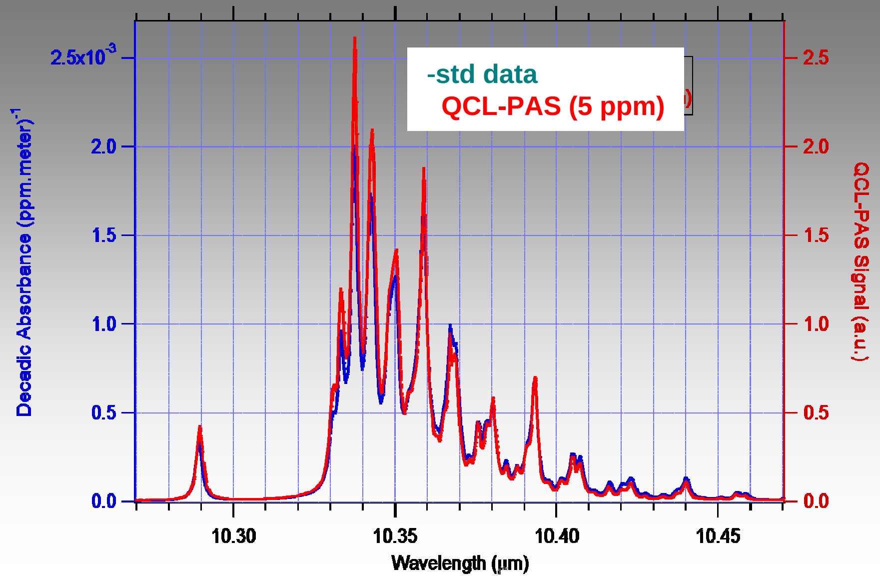




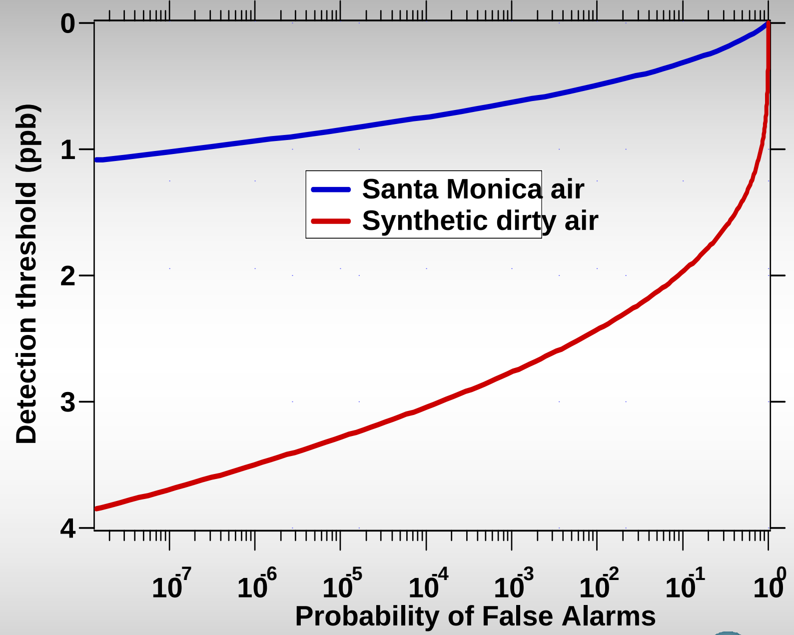




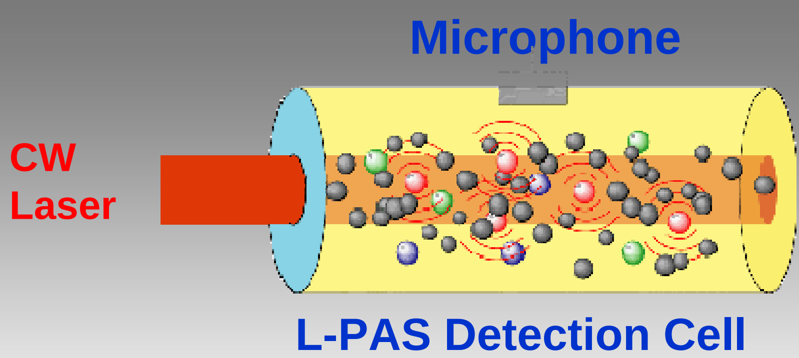
Tuning is a big deal



Detection in the presence of interferents



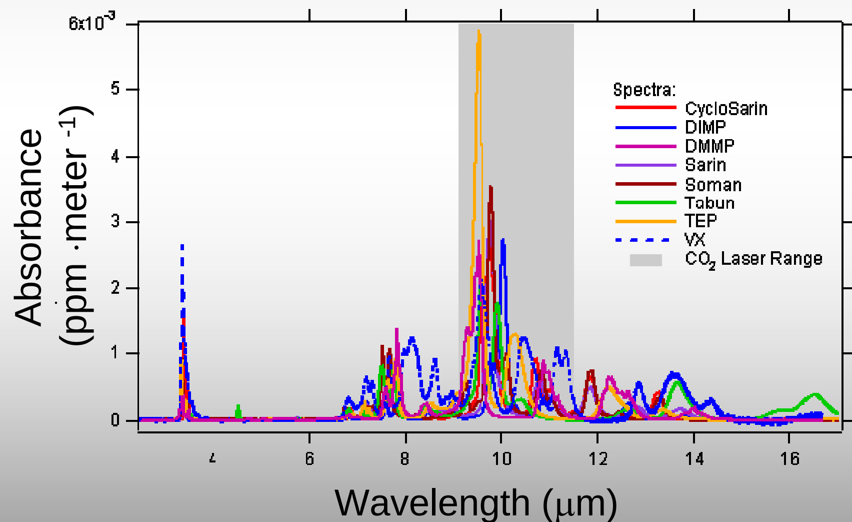
Laser Photoacoustic Spectroscopy (L-PAS)

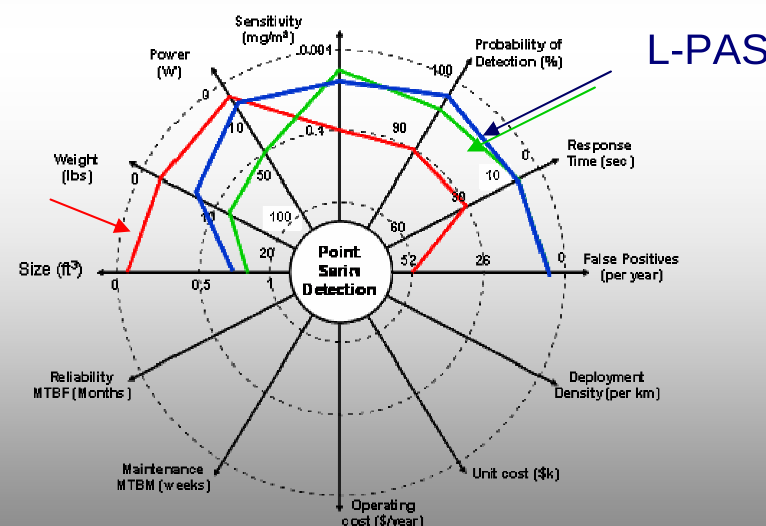


Quantum Cascade Lasers enable development of new CWA sensors:

- 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

Absorption spectra of CWAs

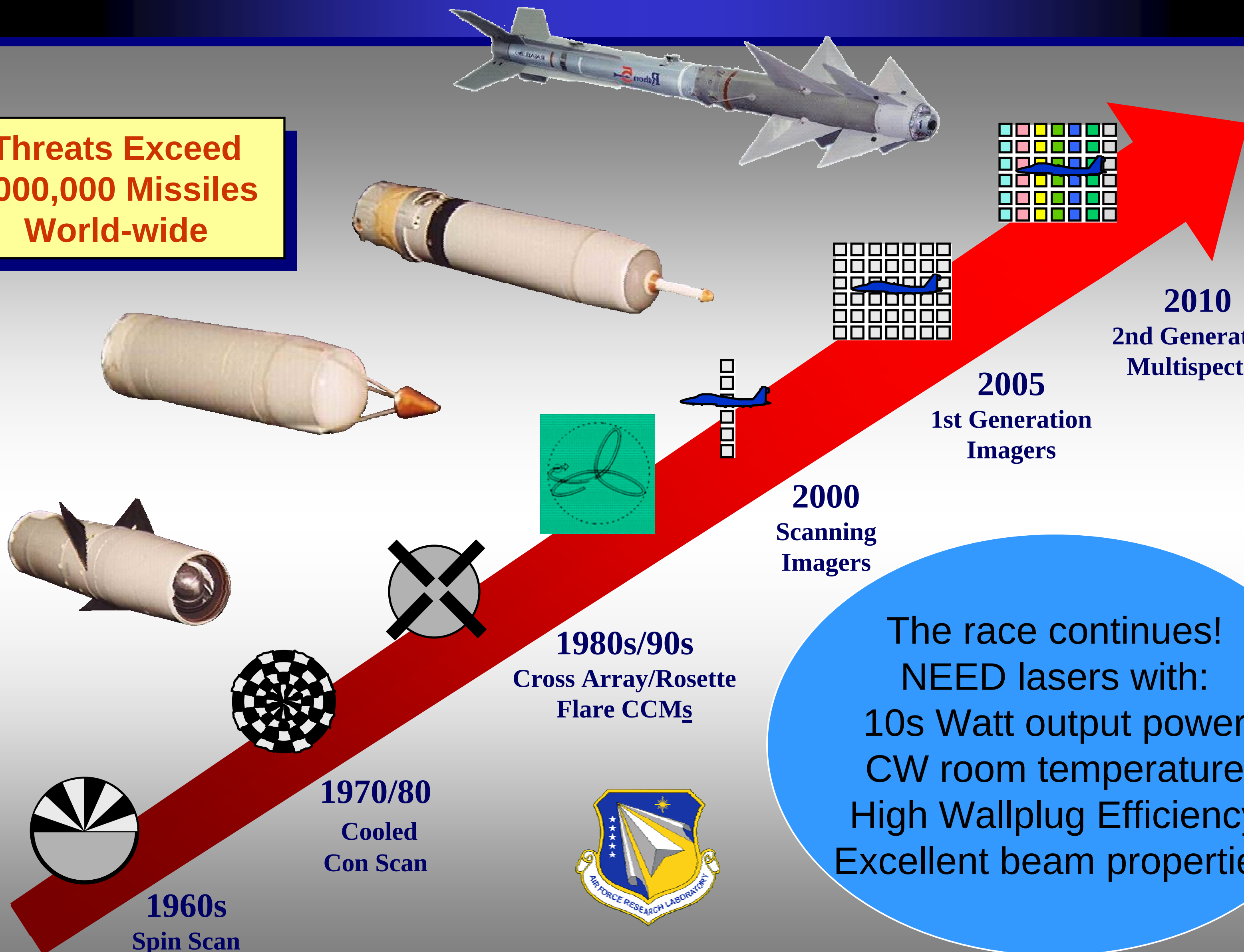




LASER PHOTOACOUSTIC SPECTROSCOPY LPAS

Need For IRCM

Threats Exceed 1,000,000 Missiles World-wide



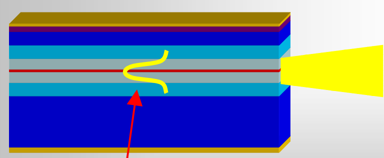
The race continues!
NEED lasers with:
10s Watt output power
CW room temperature
High Wallplug Efficiency
Excellent beam properties

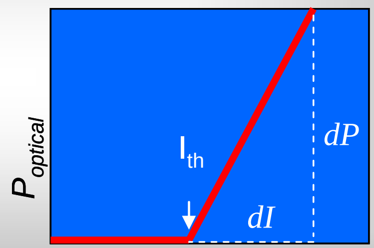
Fundamental Limits for MWIR Lasers in Wall-Plug Efficiency (WPE)

Current efficiency = η_c

$$\eta_c = \frac{I - I_{th}(T)}{I}\,\frac{\alpha_m}{\alpha_{tot}(T)}$$

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

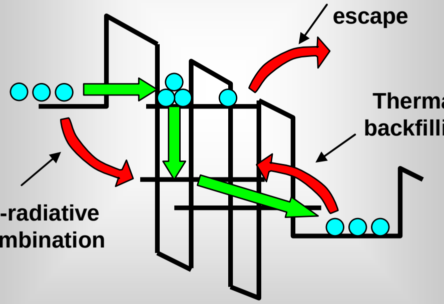




$$\eta_{WPE} = \frac{P_{Optical}}{P_{Electrical}} = \eta_V \eta_C \eta_i \eta_{mo}$$

Internal efficiency = η_i

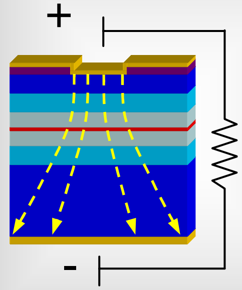
$$\eta_i = \xi\,\frac{\tau_{eff}}{\tau_{eff} + \tau_2}$$



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

Voltage efficiency = η_V

$$\frac{N\hbar\omega}{N\left(\hbar\omega + \Delta\right) + qR_s I}$$

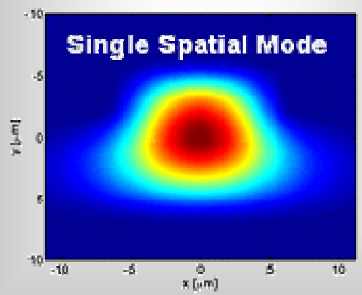


$$V = N_p(V_{act} + V_{inj}) + IR_s$$

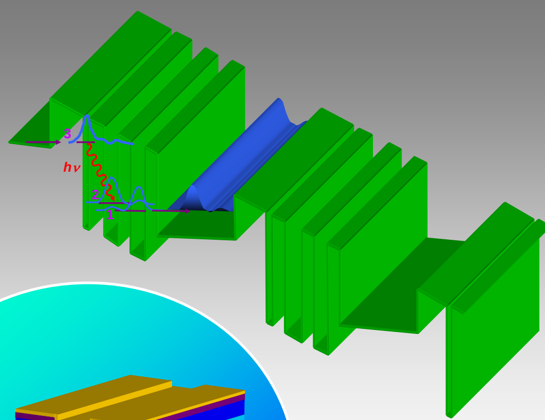
$$\frac{\text{photon energy}}{\text{bias per stage}} = \frac{\hbar\omega}{\hbar\omega + 2\hbar\omega_{LO} + \Delta E} \rightarrow \frac{\hbar\omega}{\hbar\omega + 2\hbar\omega_{LO}}$$

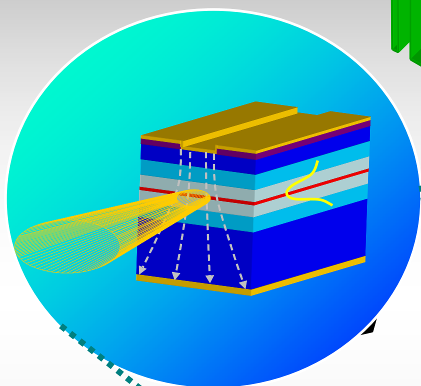
Modal efficiency = η_{mo}

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



Efficient Mid-Wave Infrared Lasers (EMIL)





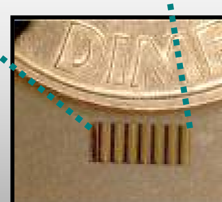
Program Objective

- 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)

SOA Mid IR Optical Bench



"IRCM laser-on-a-chip"

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

Slide 8

MJR1 BAE LAMBS
51 optics
4 resonators
Mark J. Rosker, 11/23/2005

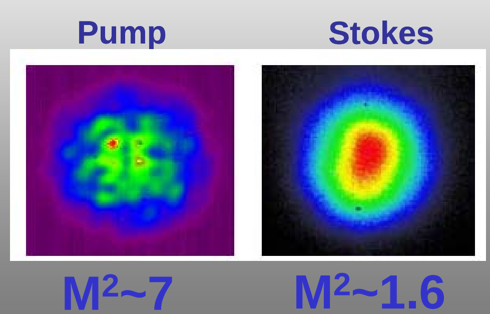
Raman beam combining and cleanup

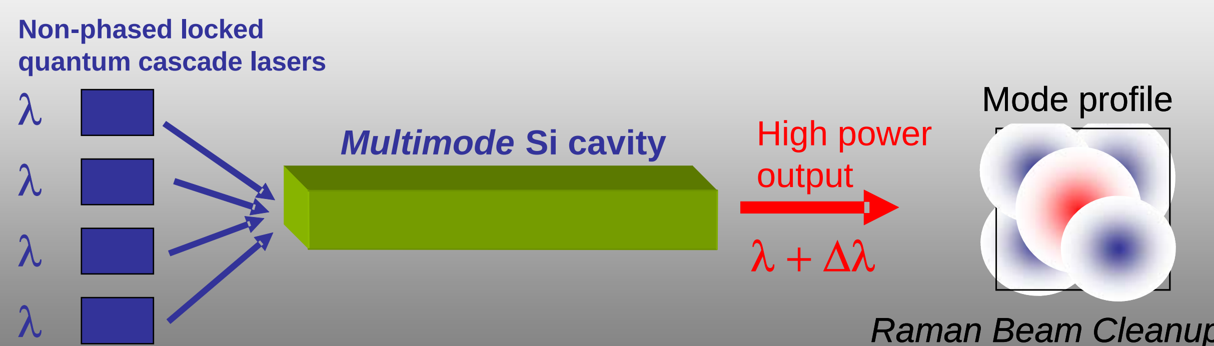
1. **Raman beam cleanup**

   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**



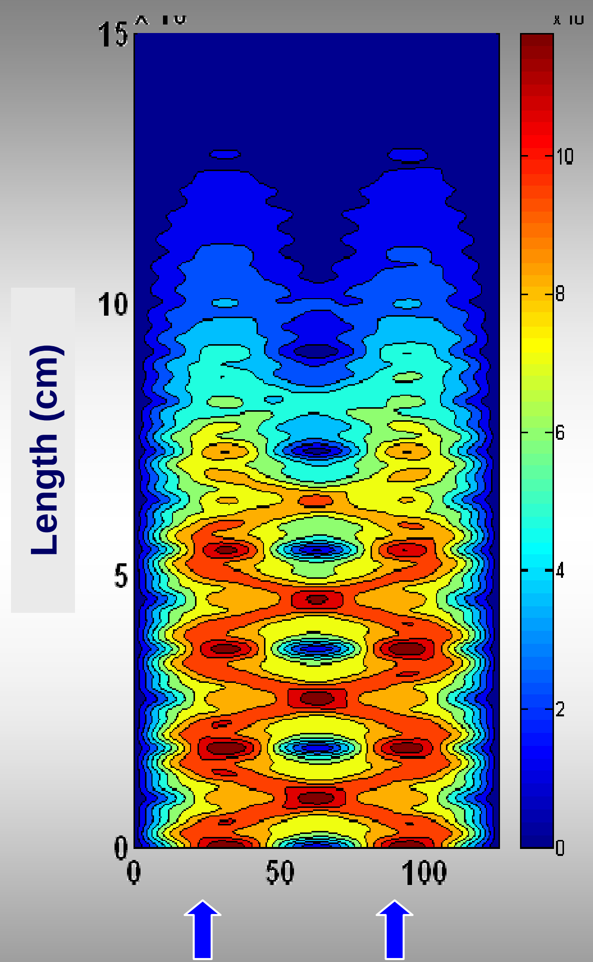


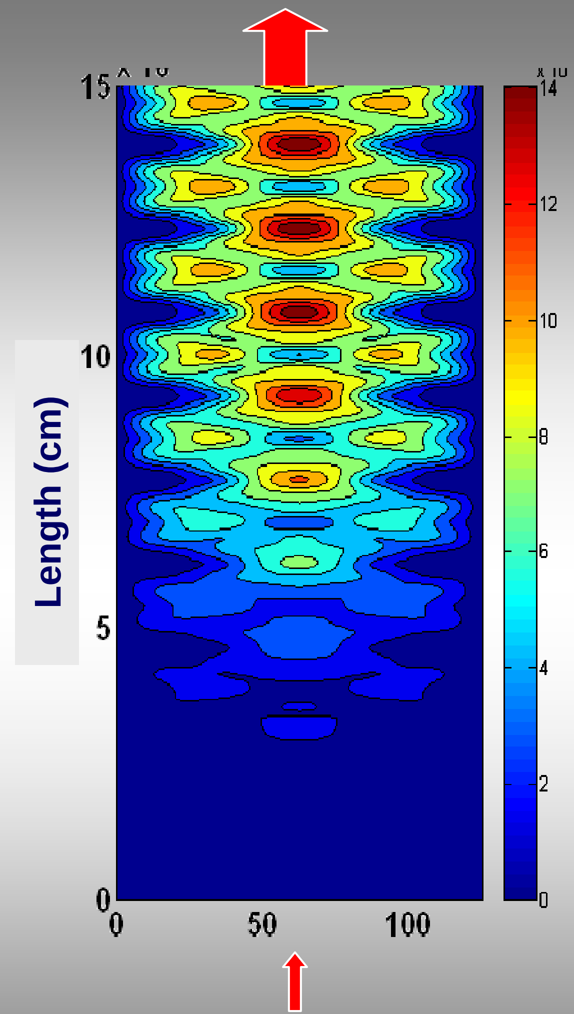
Raman Beam Cleanup

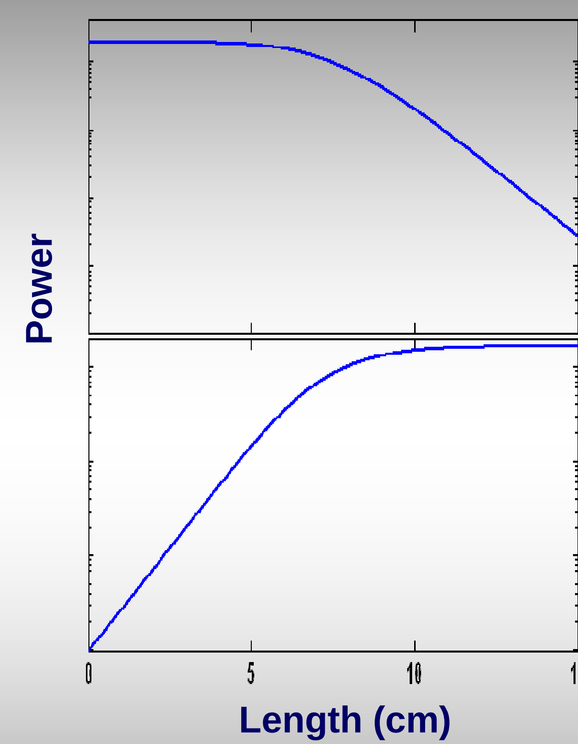
UCLA Prof. B. Jalali

Simulation of Amplification Via Self Imaging in Multimode Si Waveguide

Power evolu







PUMP1 and 2 each 1KW

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

1W Stokes

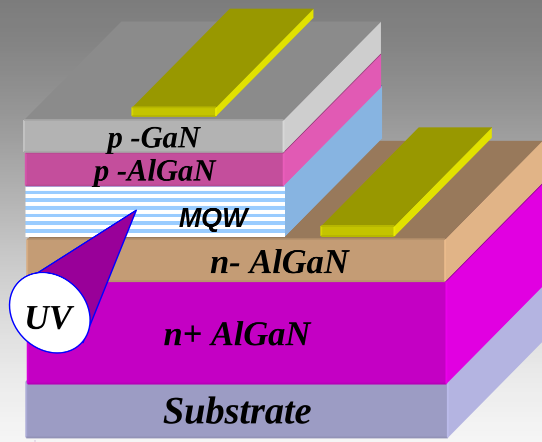
Si and conventional Raman crystals

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

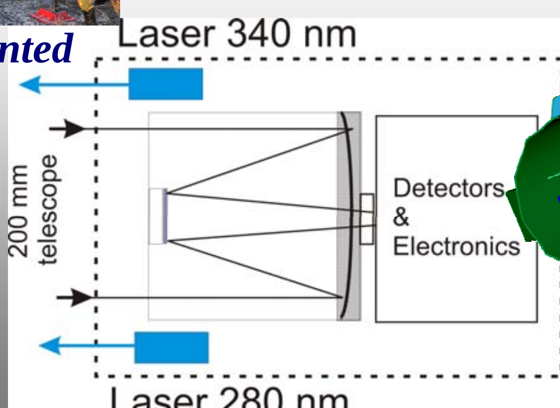
UCLA

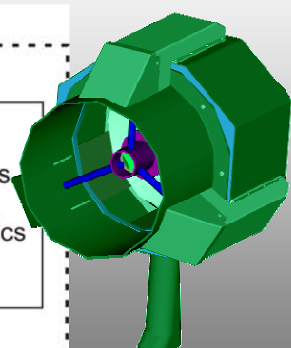
Semiconductor AlGaN Injection Lasers (SAIL)



Truck mounted

Hand held





Objective

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

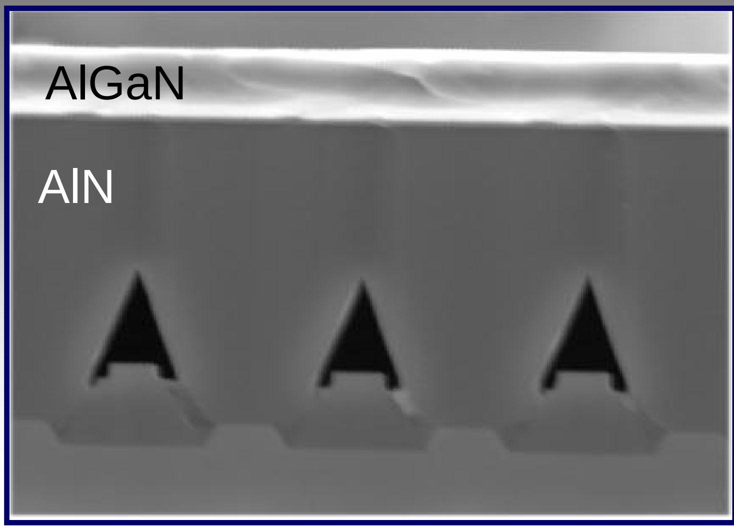
Impact

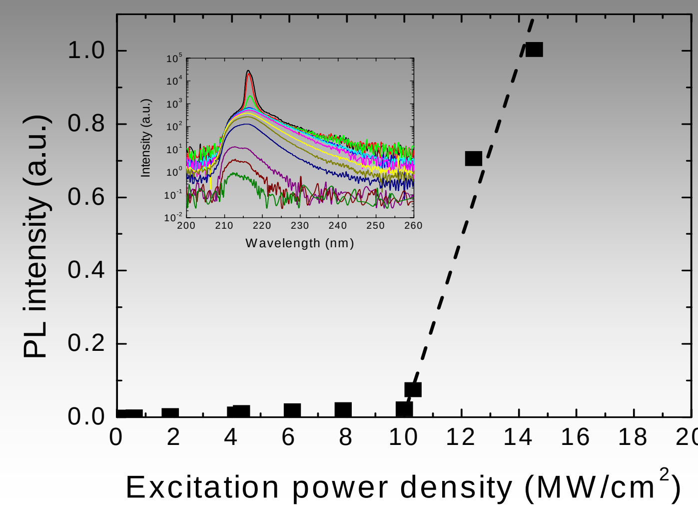
- **Stand-off bio-agent detection; Bio-LIDAR**

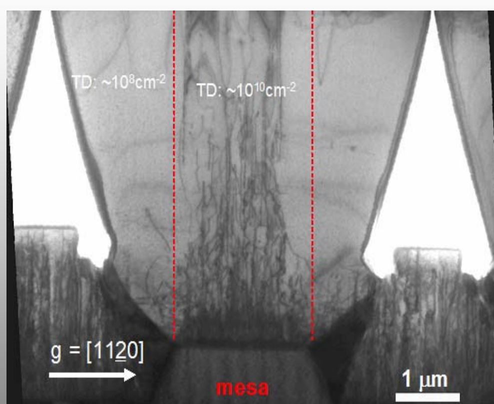
Key technical goals

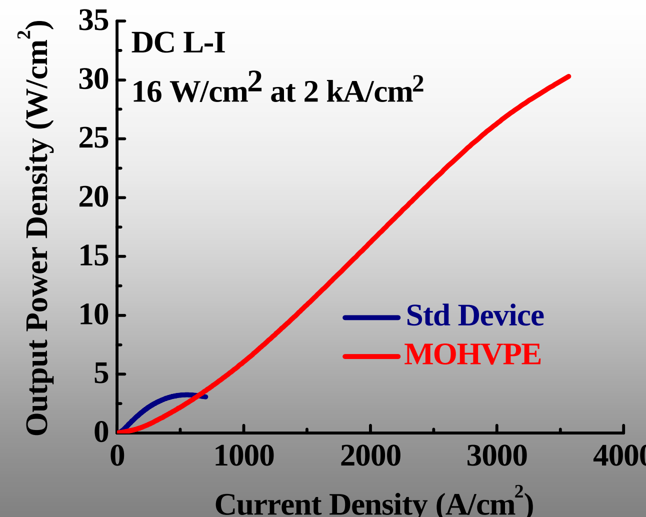
- Reduce dislocation density of AlGaN structures by three orders of magnitude, to less than $10^7/cm^2$
- Increase p-type doping in AlGaN to support current densities of 10 kA/cm^2, to *1×10^{18} cm^{-3}*
- Increase luminescence efficiency of AlGaN active layer to *IQE~60%*
- Demonstrate stable laser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

SAIL – Pulsed Lateral Overgrowth





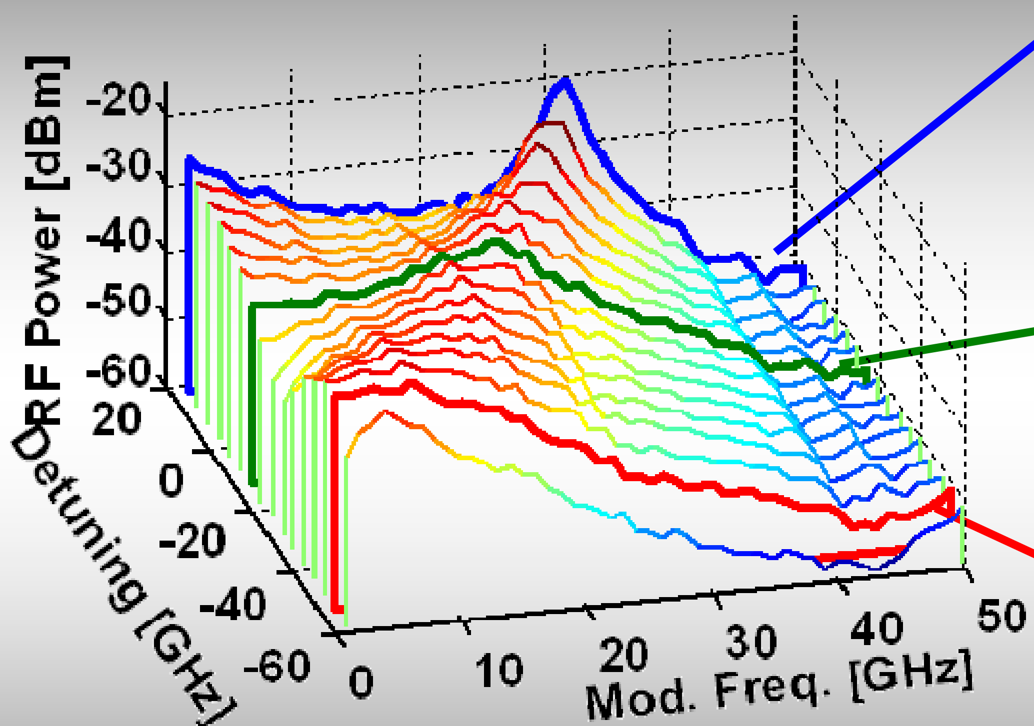


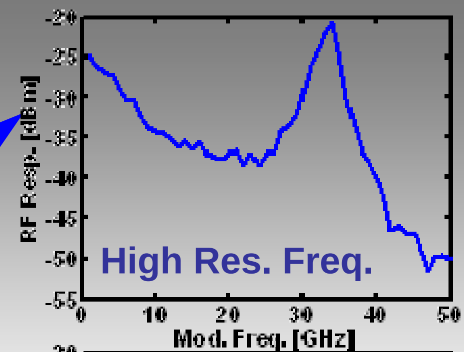


UNIVERSITY OF SOUTH CAROLINA

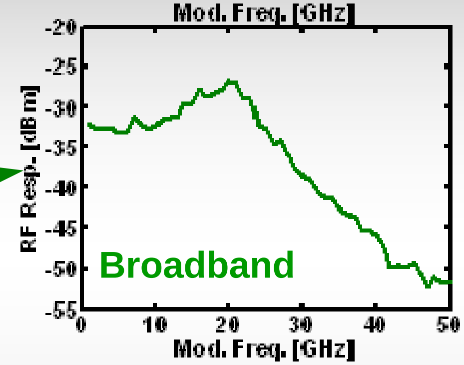
Frequency Response of Injection-Locked DFB Lasers

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

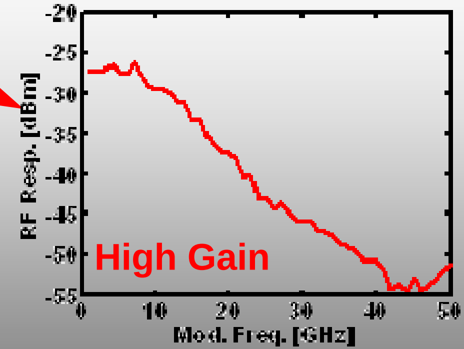




Large Positive Frequency Detuning



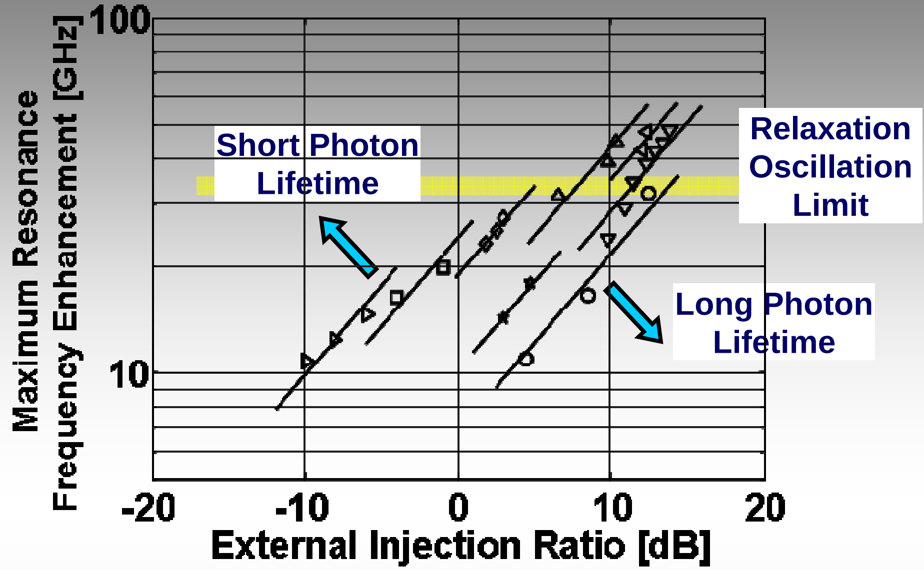
Small Positive Frequency Detuning



Negative Frequency Detuning

Profs. Wu and Chang-Hasnain
UC Berkeley

State of the Art



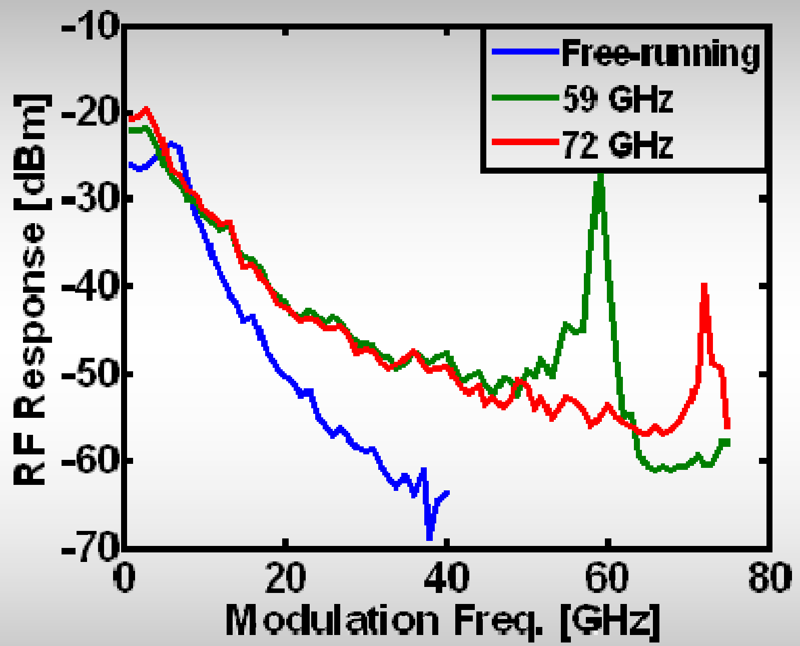
- **Strong injection locking can overcome the fundamental limit of relaxation oscillation**
- **Maximum enhanced resonance frequency under optical injection:**

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

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

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

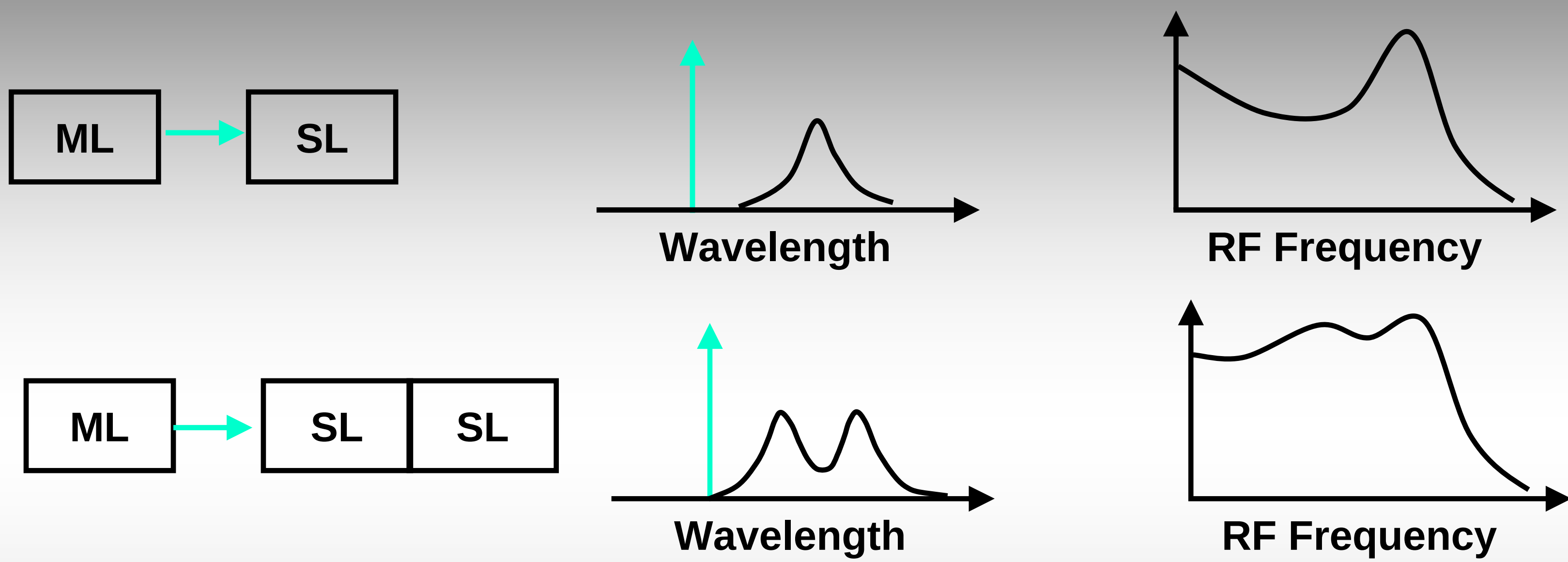
Ultra-high injection ratio and near positive detuning edge



Lau, Sung, and Wu, OFC 2006

Optical Cavity Engineering For High Speed

- "Optical doublet" cavity



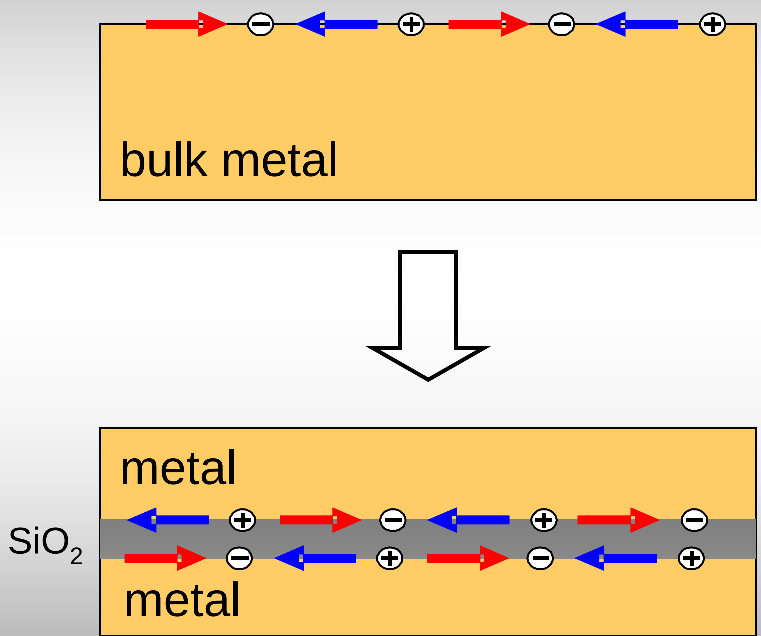
- Similar to high-order filter theory
  - "Chebyshev" cavity

How can this concept be implemented in an integrated structure?

Sub-λ cavity with surface plasmons

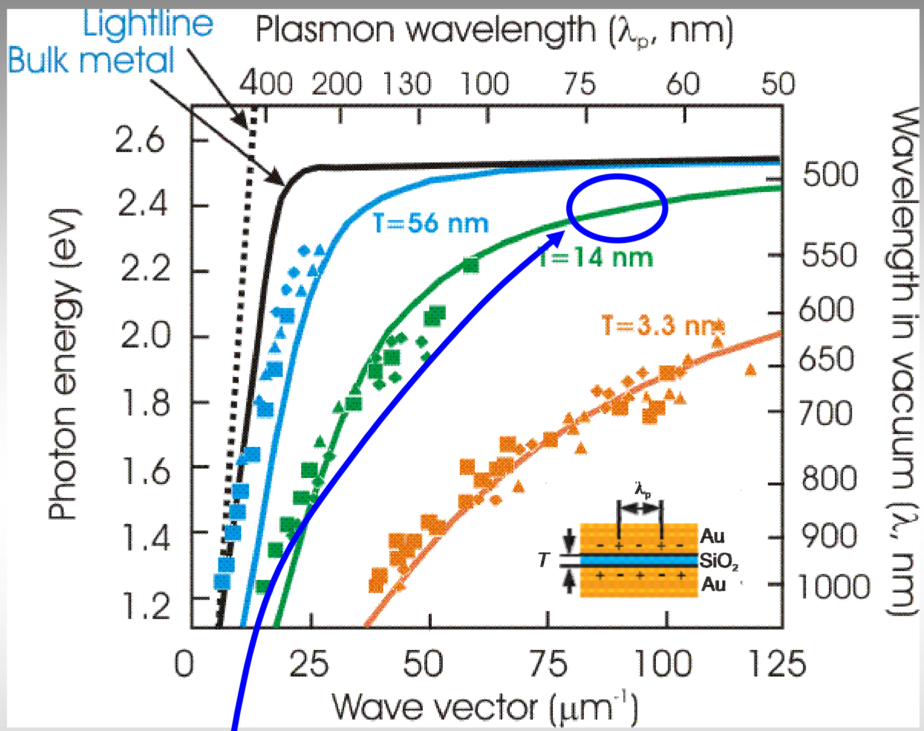
Miyazaki *et al*, Tsukuba (Japan), PRL **96,** 097401 (2006)

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

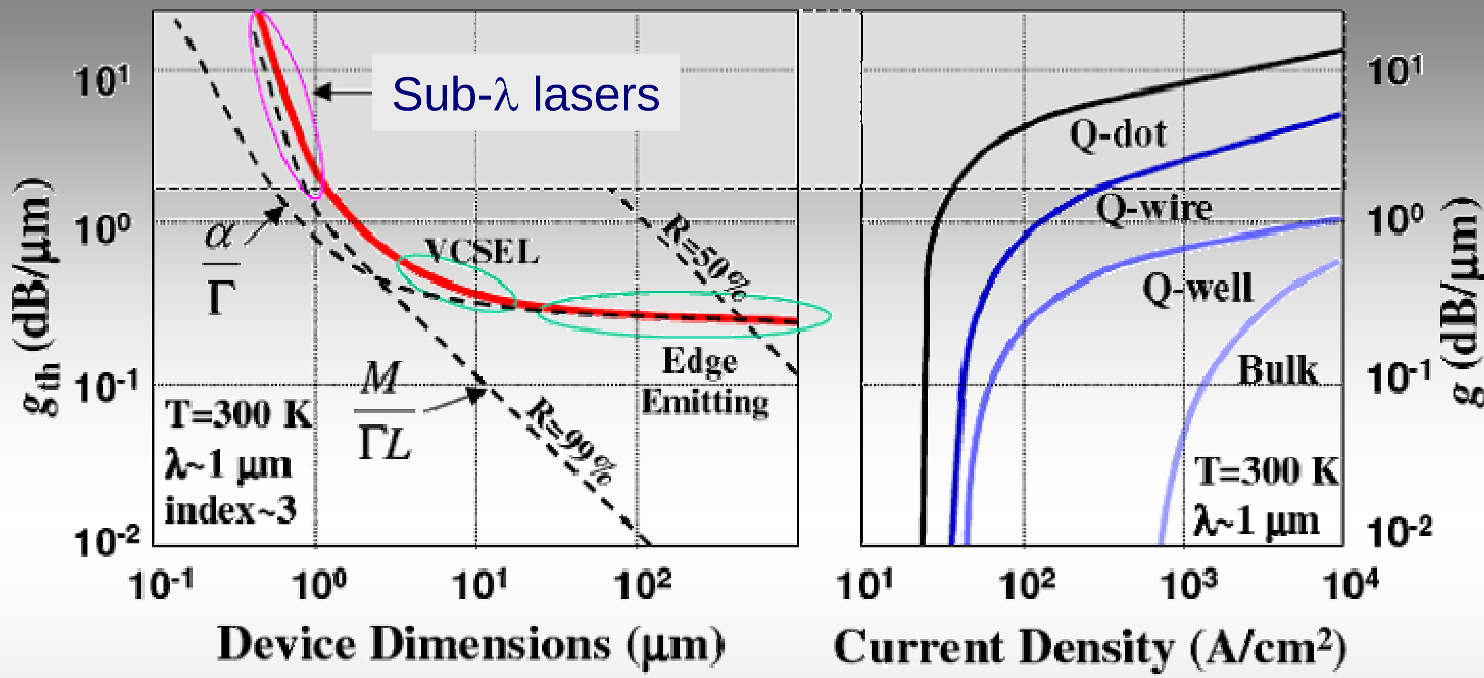


For visible free-space wavelength we get plasmons with soft x-ray wavelengths!

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?



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

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

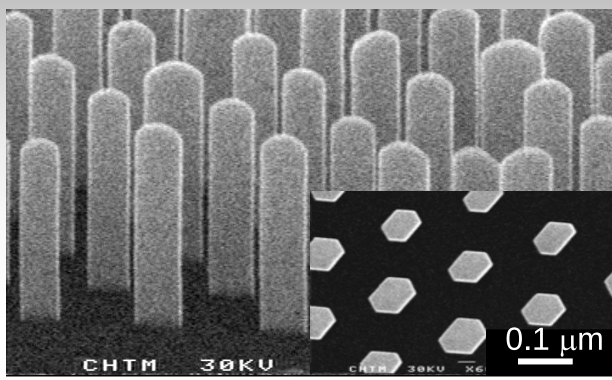
$$R_{th} \sim \frac{1}{Q}\frac{V_c}{V_m} + (1-\beta)\frac{N_{th}V_c}{\tau_r} + \frac{N_{th}V_c}{\tau_{nr}}$$

Prof. Hooman Mohseni
Northwestern

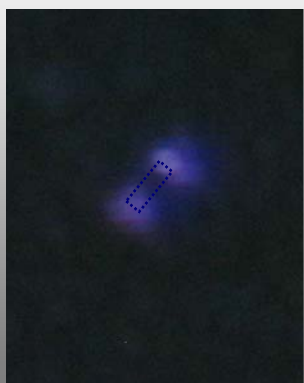
Need higher gain and new laser concepts

Lithographic placement and selective growth of GaN nanowires

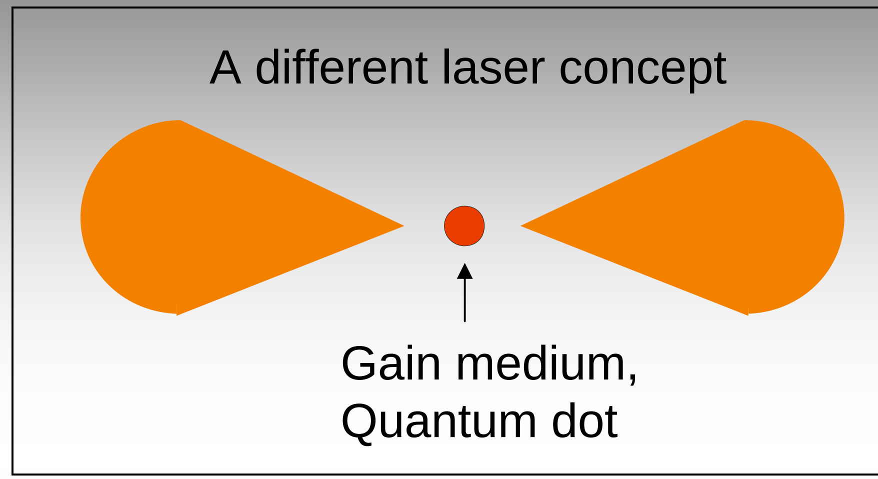
Defect-free structures for d<100 nm!

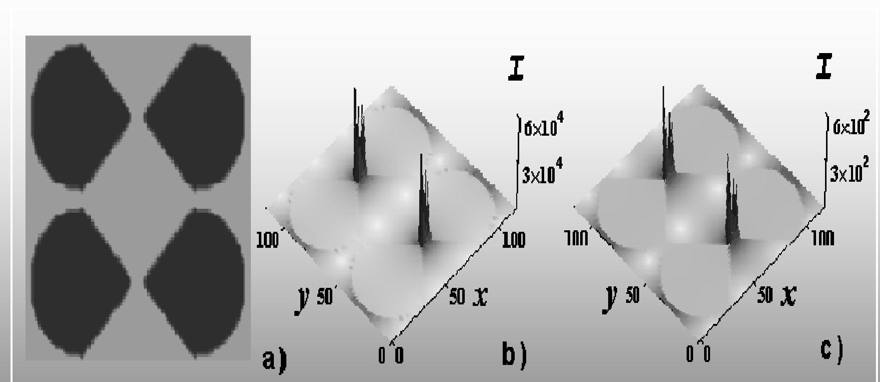


UNM, Prof. Steve Brueck



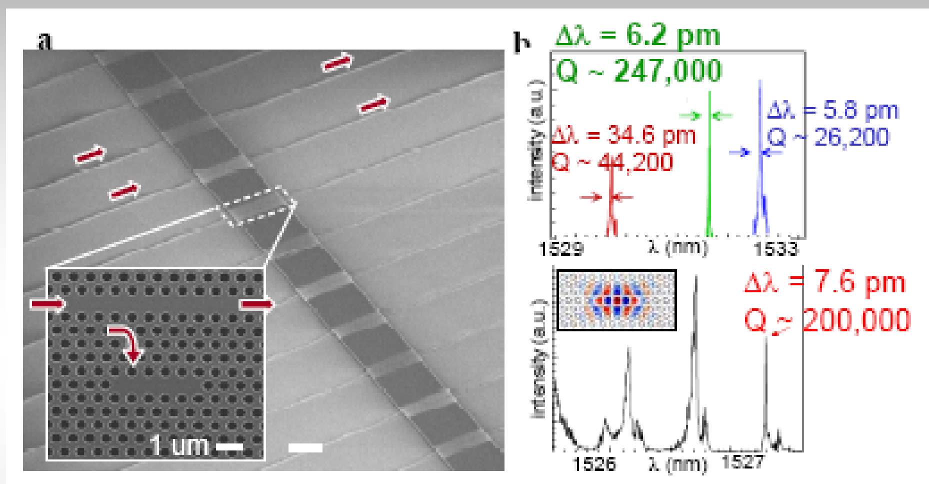
Lasing GaN nanowire, UNM and Sandia NL, L=5 μm

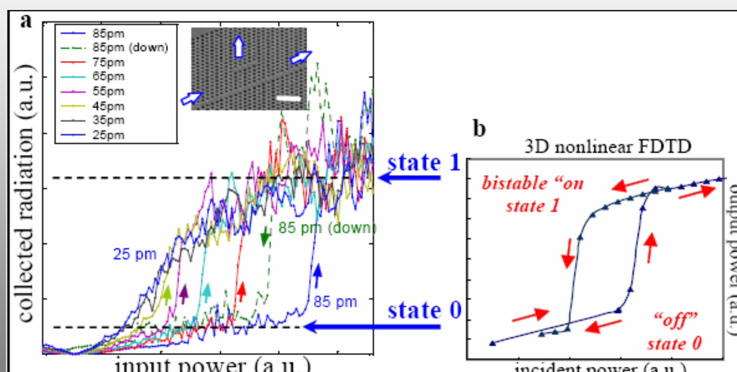




Young Faculty Award (YFA)

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~(λ/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~1 x 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.