III-V Photonics at Sandia

SAND2013-7505P

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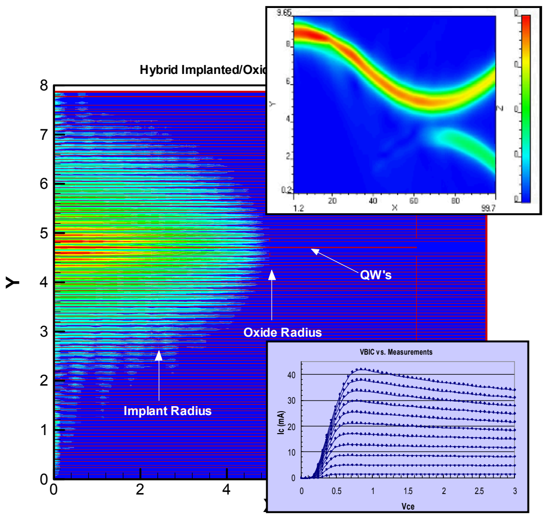
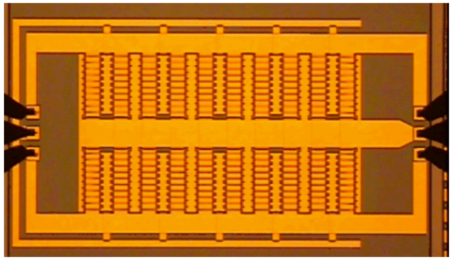
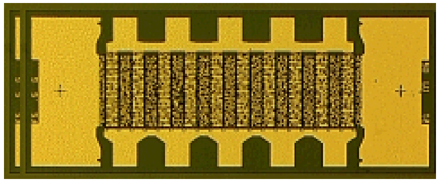
- Foundational Capabilities
  - III-V compound semiconductor epitaxy, microfabrication, integration
  - Device physics, modeling, simulation
  - Microelectronics/optoelectronics, and complex mono/hetero-circuits
- Prove, Advance Technology Readiness Level, Productize
  - TRL1-6+: create, develop, prototype
  - NNSA QMS/QC-1-10; trusted
- Trusted, custom, low-volume, high-reliability products for harsh environments when industry is unwilling or unable to deliver

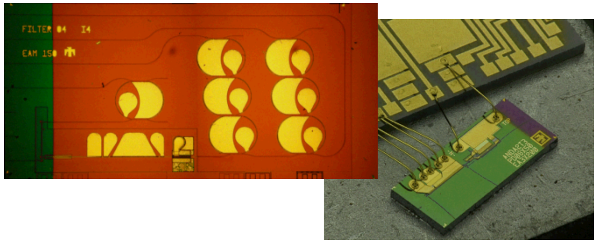


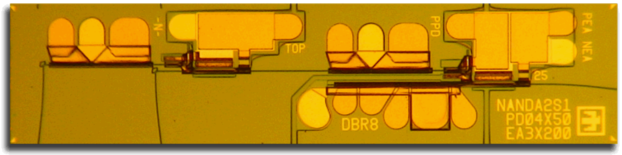
Modeling and Simulation



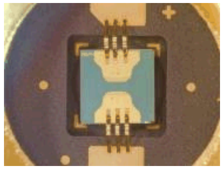


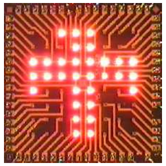
Compound Semiconductor Microelectronics

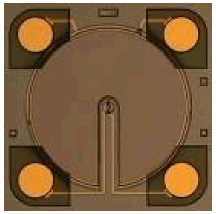


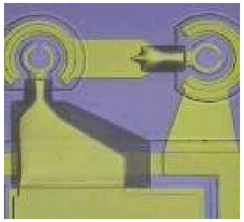


Photonic Integrated Circuits

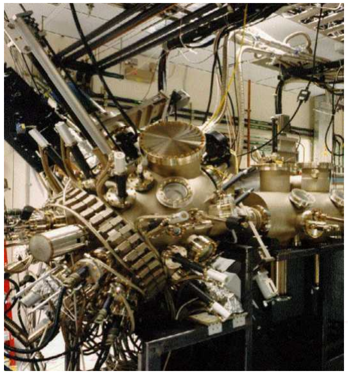








VCSELs/RCPDs/EAMs/PCSS



Epitaxy

TRL 6 Lifetest

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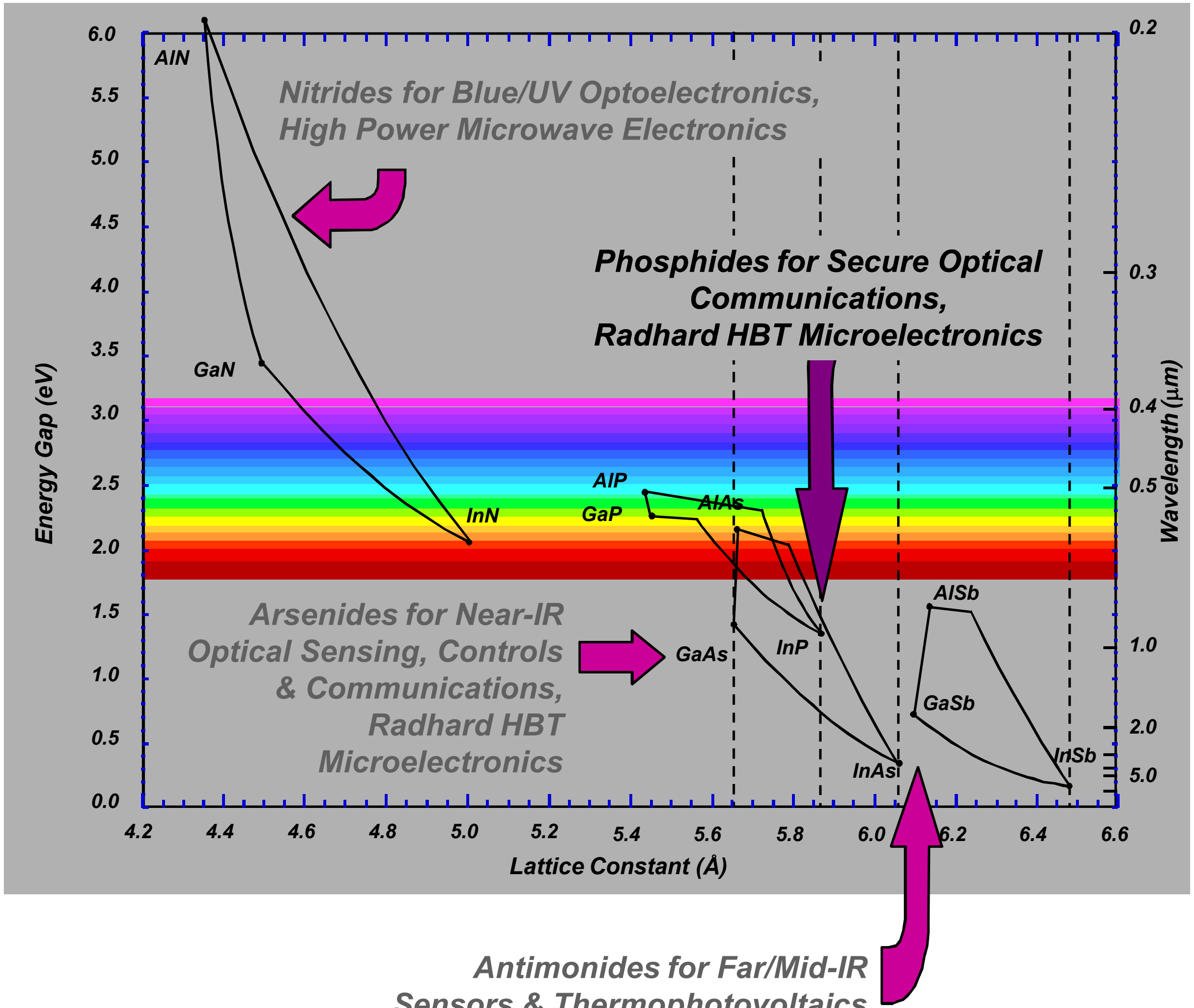
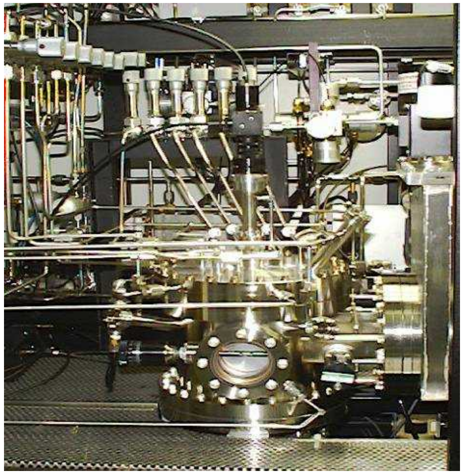
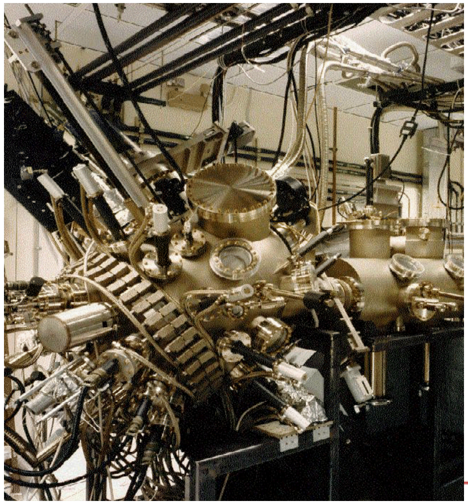
Group III-V Semiconductor Photonics at Sandia

Sandia Grows the Full Spectrum of III-V Materials

6 – MOCVD: As, P, Sb, N
4 – MBE: As, P, Sb
3 – research tools

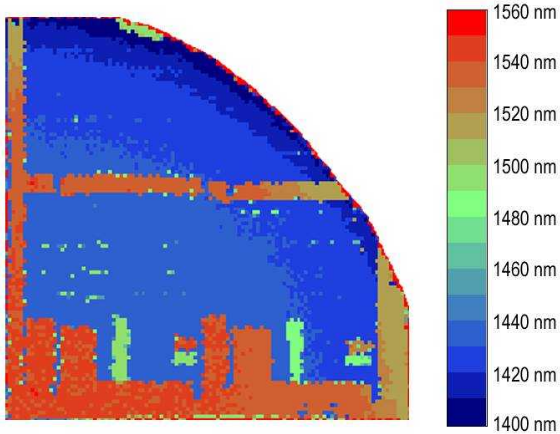




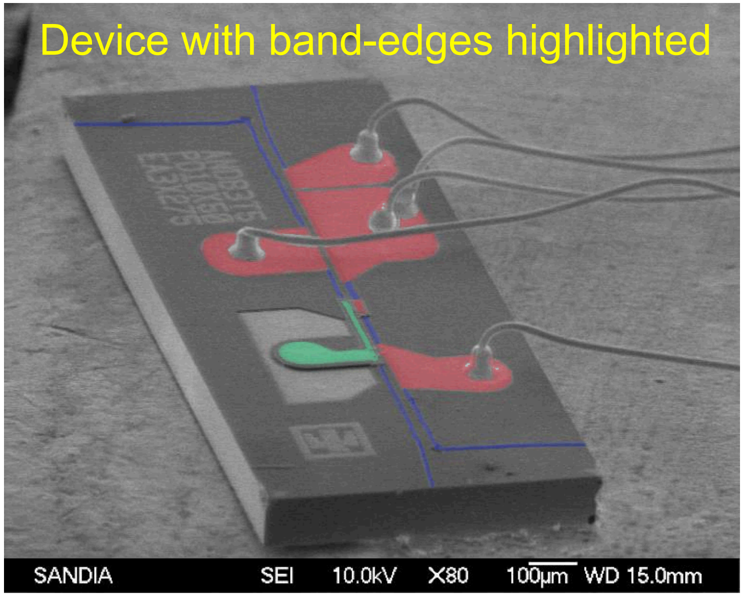


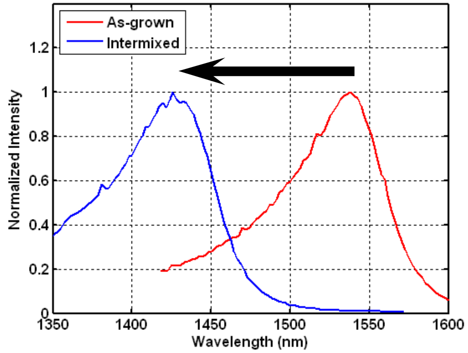
Post-Growth Bandgap Engineering

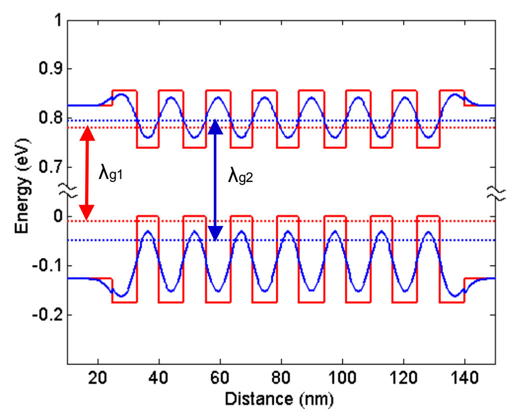
- Integrate devices with different functionalities
  - Ability to **program QW band edge -> shift from absorbing to transmitting**
- Artificially introduced defects reduce the activation energy for migration of atoms on lattice sites



PL map of intermixed quarter wafer



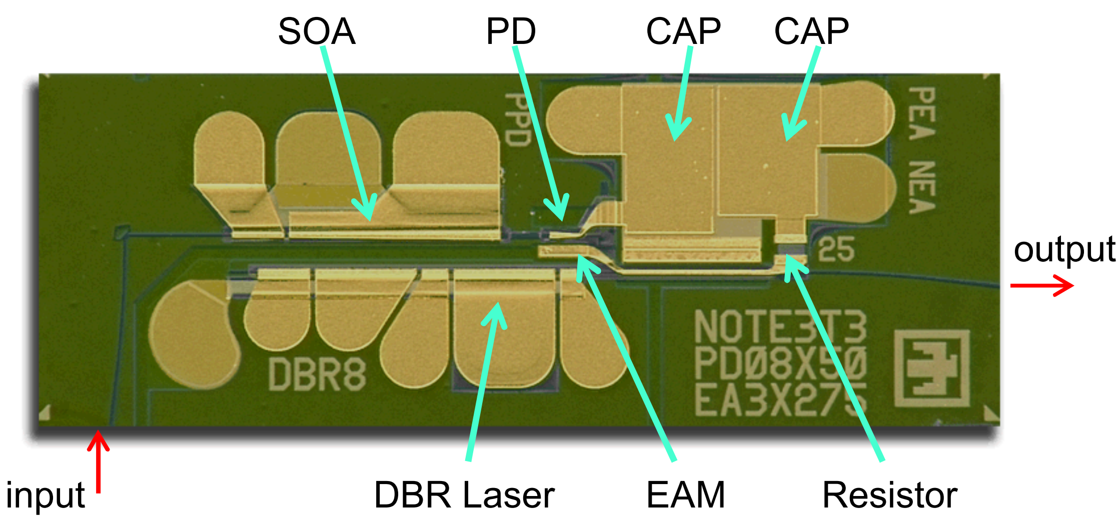




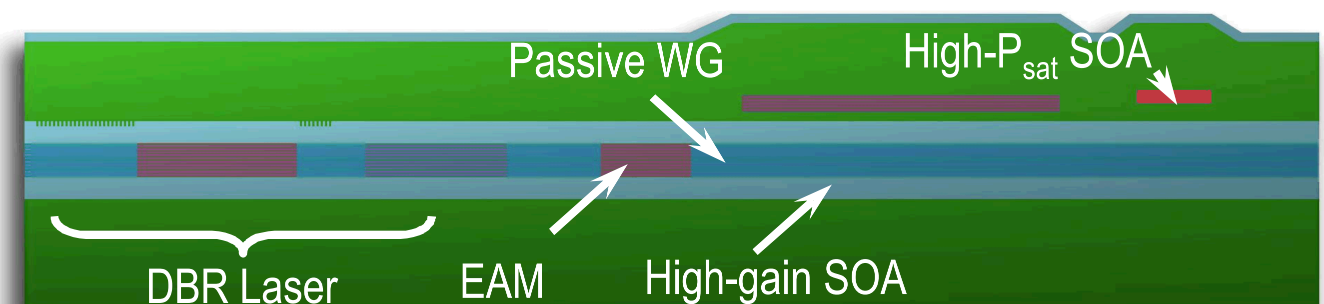
- Photoluminescence
  - Active =1540nm, Passive = 1425nm

InP PICs for Multi-λ, High-Performance Optical Circuits

- InGaAsP/InP
  - 1550 nm wavelength
  - State-of-the-art discrete photonic component performance from a single chip
    - Light generation, modulation, amplification, routing, switching and detection
  - 40Gb/s optical transceivers
  - WDM systems for avionics networks



- Complete integration toolbox
- Diverse set of devices
  - DBR lasers, EAMs, WGs, High-gain SOAs, High-P_{sat} SOAs, Evanescent PD
- Low internal interconnect losses
- Low reflections and optical feedback



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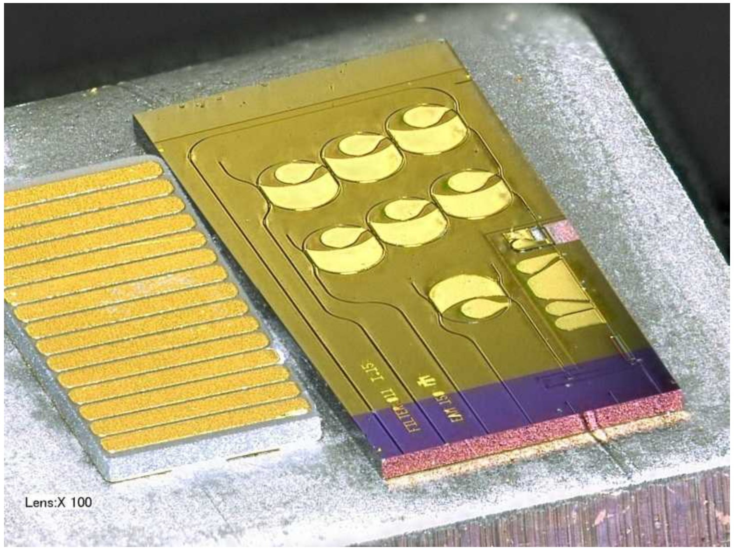
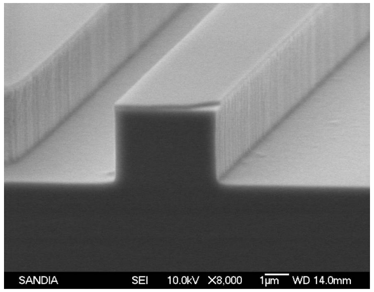
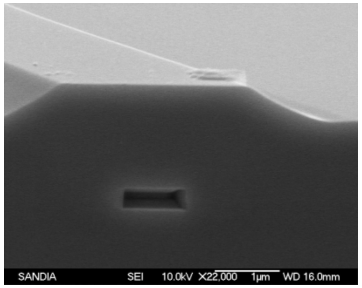
SNL Photonic Integrated Circuits

- State of the art – InP Photonic Integrated Circuits

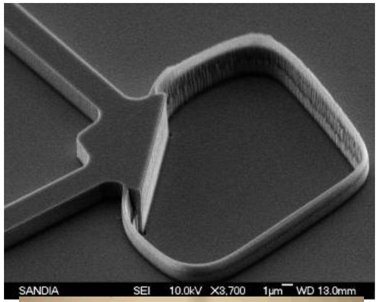


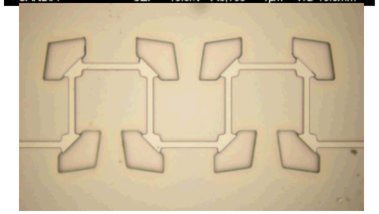


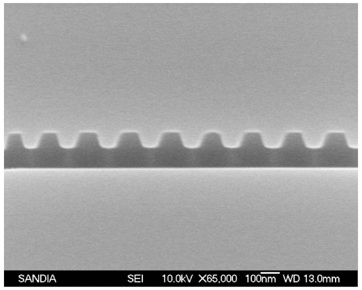


# of unique components

Infinera	UCSB	Sandia
6	**8**	**10**
Waveguides	Waveguides	Waveguides
Laser	Laser	Laser
SOA	SOA	SOA High Gain
EAM	Delay Line	SOA High P_{sat}
Power Monitor	Phase Shifter	Power Monitor
AWG	Optical Atten.	EAM
	MMI	Photodiode
	AWG	TIR Mirror
		Resistor
		Capacitor







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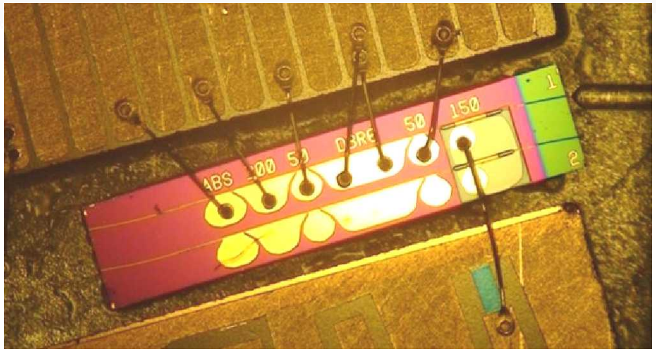
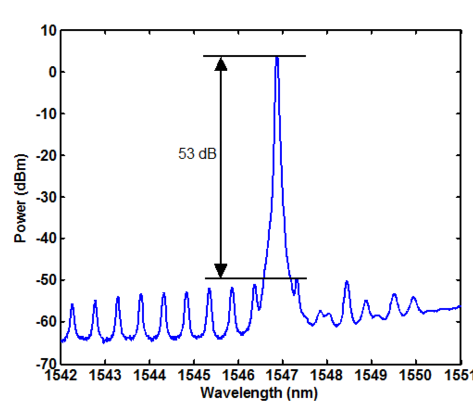
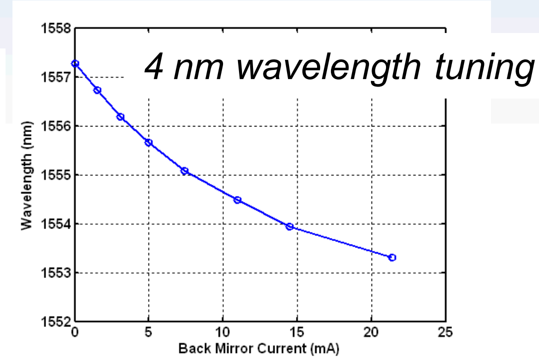
High-Speed Electrical-to-Optical (EO) Transmitter



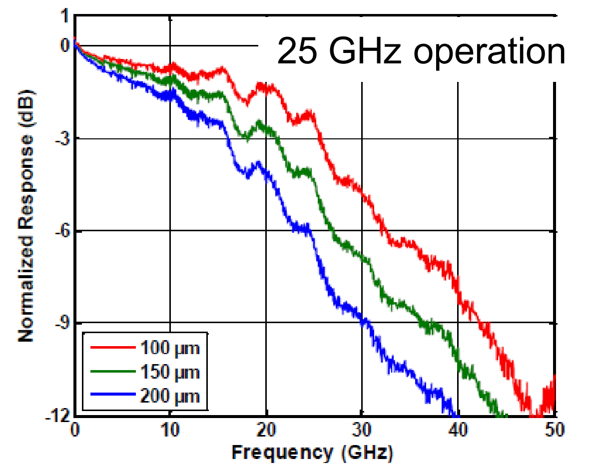


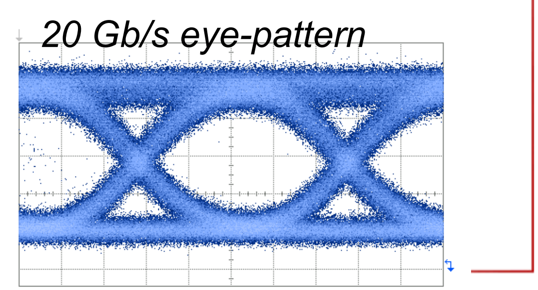


- InGaAsP Diode laser and modulator chip
  - DBR lasers
    - 6 mW fiber-coupled power
      - ~20 mW out from chip
    - 4 nm wavelength tuning
  - EAMs
    - Efficiency ~19dB/V DC
    - Bandwidth 20GHz
- Wavelength tuning
  - Track filter frequencies
  - Tune to WDM channels

Power for RF photonics
Wavelength agility

Scalable to mm-wave





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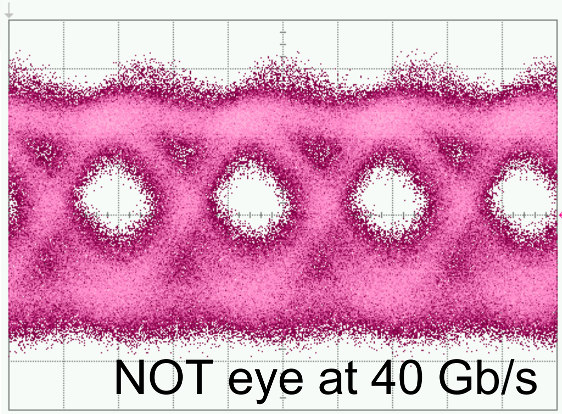
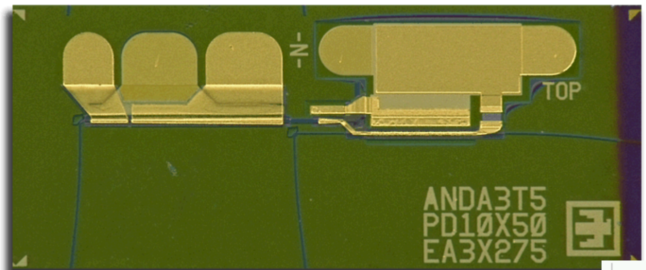
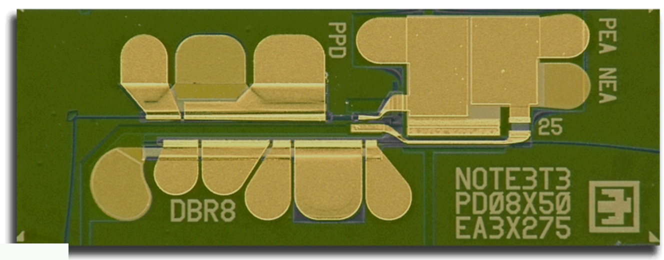
Sandia InGaAsP/InP All-Optical Logic Chips

- EAMs, PDs, DFB lasers, etc. integrated to form all-optical logic gates
  - AND, NOT gates operating at 40 Gb/s
  - PDs detect input light and drive EAMs to modulate output
- Presented at Photonics in Switching 2010 conf.
  - Skogen, Vawter, Tauke-Pedretti, „*Optical Logic Gates Using Interconnected Photodiodes and Electro-Absorption Modulators*"

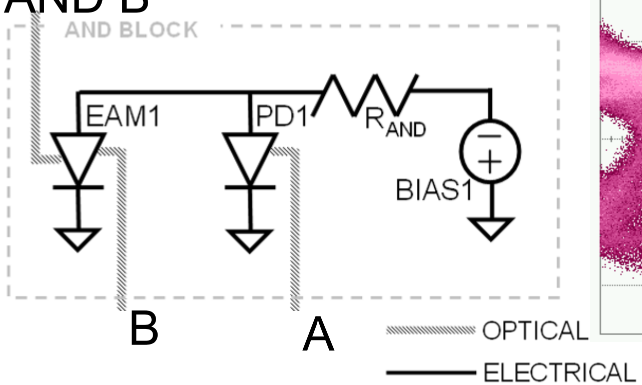


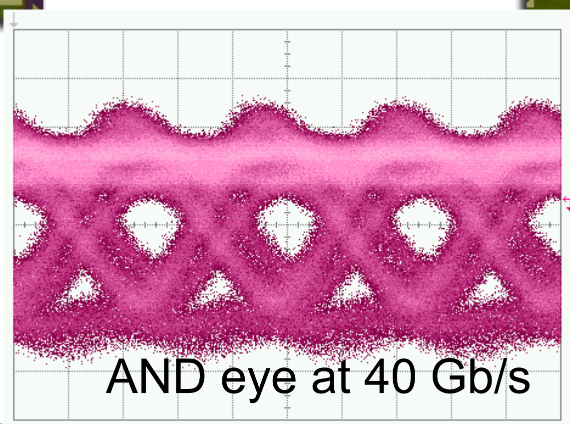
NOT eye at 40 Gb/s





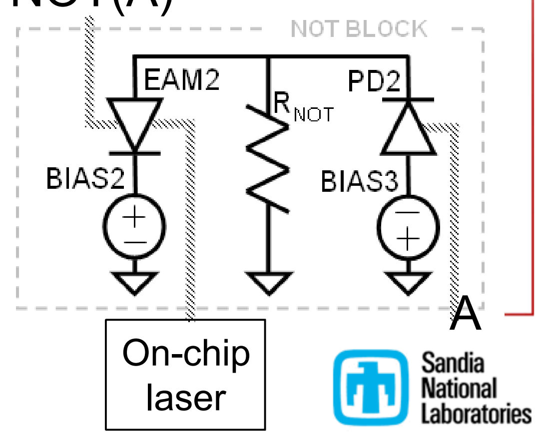
A AND B





AND eye at 40 Gb/s

NOT(A)



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40 Gb/s Optical Logic Chips

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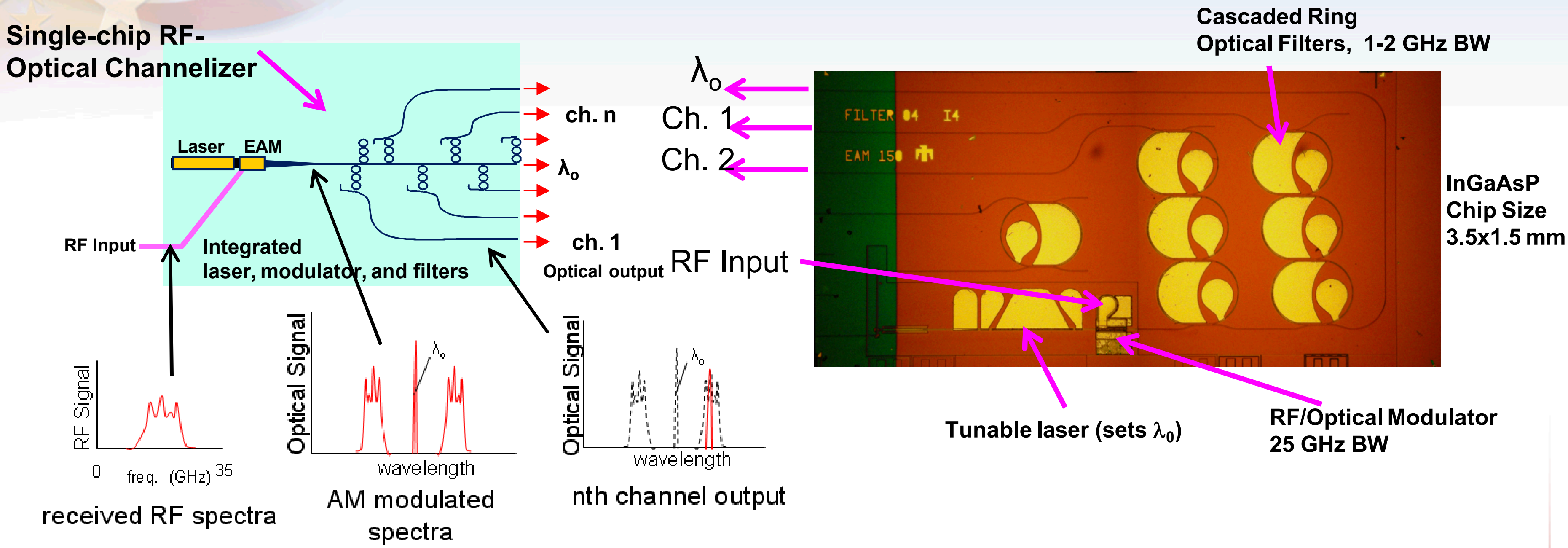
SNL Optical Channelized RF Receiver PIC

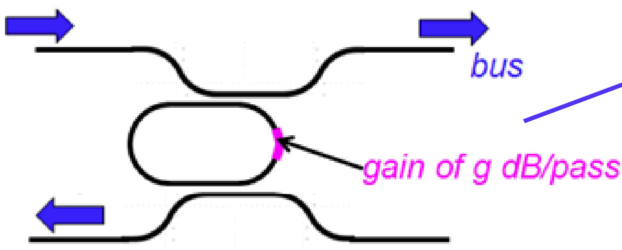


- Analyze an RF signal for frequency content
  - Filter outputs are spectral power density integrated over the filter bandwidth
- Monolithic integration with active components such as lasers and modulators enables compact, highly functional photonic integrated circuits (PICs)

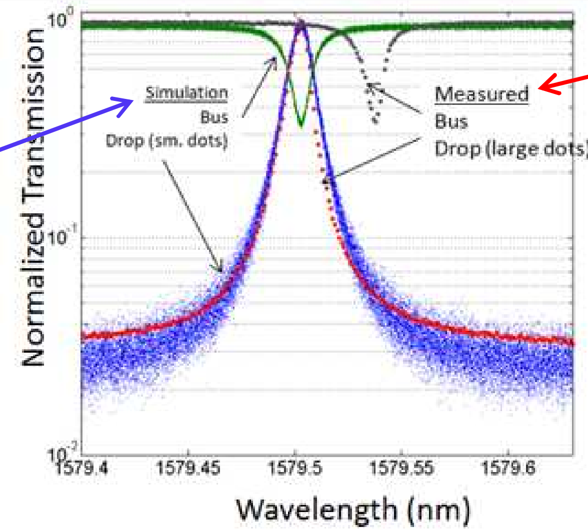
- US Patent Application
  - "Photonic Circuit", Oct. 2011
- Publications at OFC 2011
  - "Wide Dynamic Range of Ring Resonator Channel Dropping Filters with Integrated SOAs"
  - "Cascaded Double Ring Resonator Filter with Integrated SOAs"

A. Vawter, org. 1742

Simulation is a Key Element of Design: Simulation Benchmark to Experiment



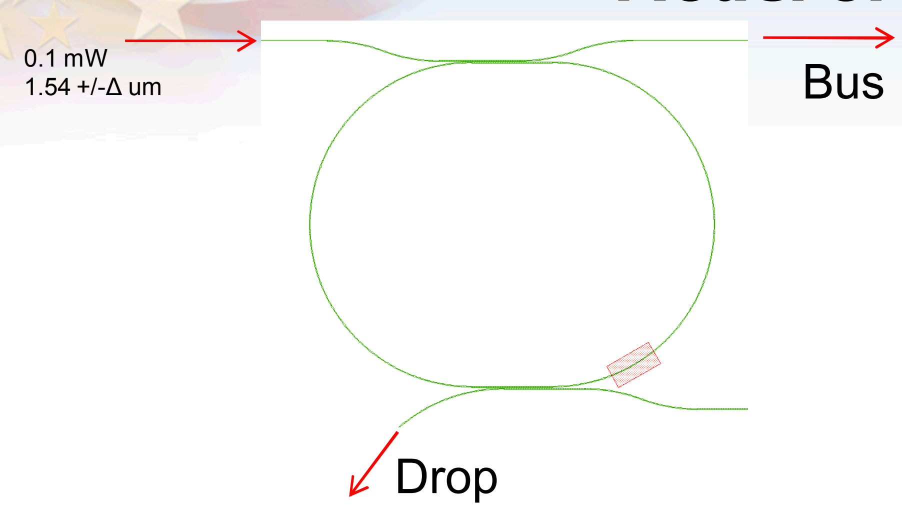
Blue & green data



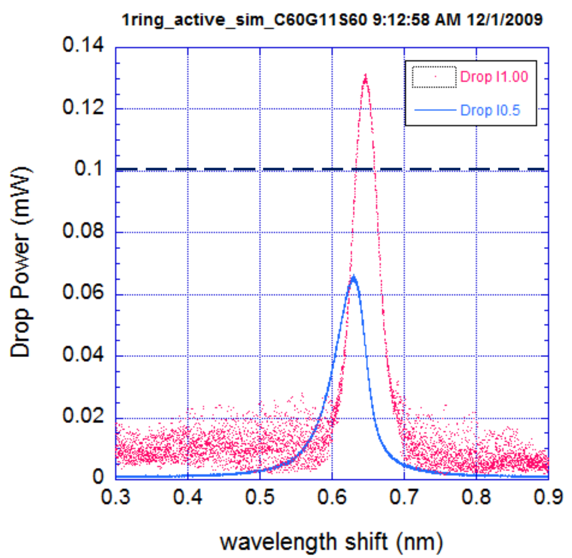
Red & black data

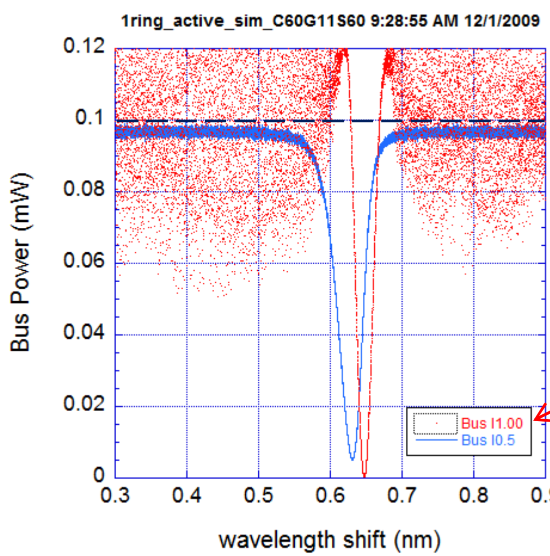
- Complete simulation of dynamic range and noise of active InGaAsP multi-ring filters
  - Include gain distortions and spontaneous emission noise
- Time dependent rate equation method
  - Gain and spontaneous emission modeled as function of injection current at all wavelengths simultaneously

Model of Active Ring



Radius: 200 um
Couplers: 17% power cross-coupling
Passive guides: 3 cm^{-1}
SOA: 60 um long
- 7 QW centered, 25C
- 1 um wide BH
- current flow *only* in the MQW
- Spontaneous Coupling: 0.0037





J = 1.67 KA/cm^2
I = 1.0 mA

- Operation at very high gain (SOA injected current)
  - Negative insertion loss achievable, but very noisy

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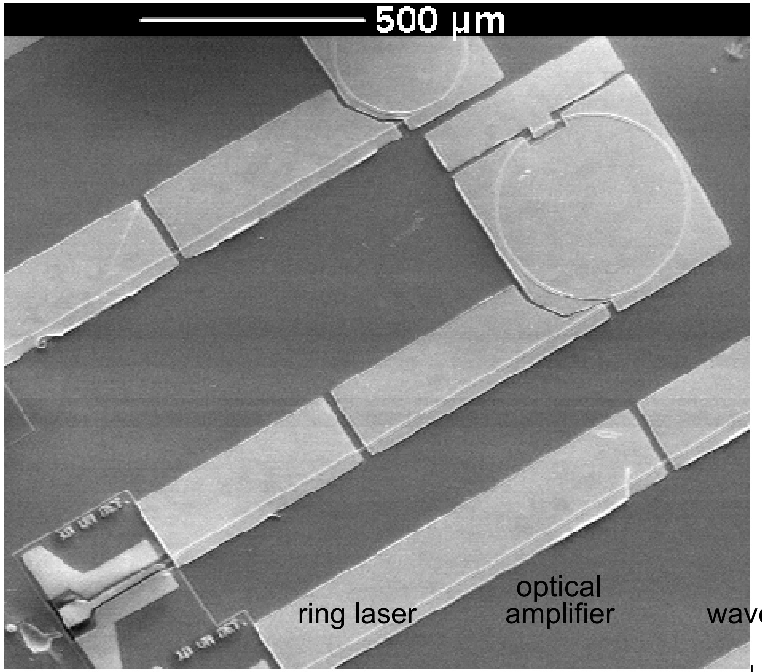
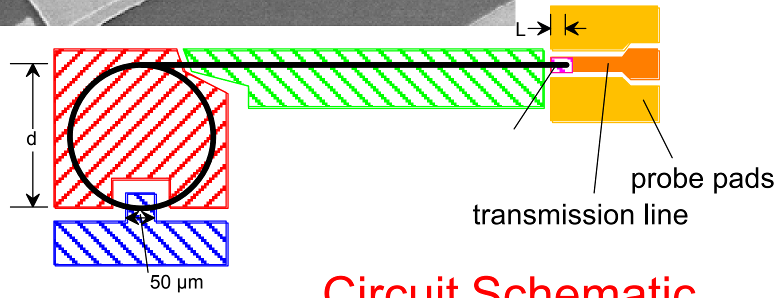
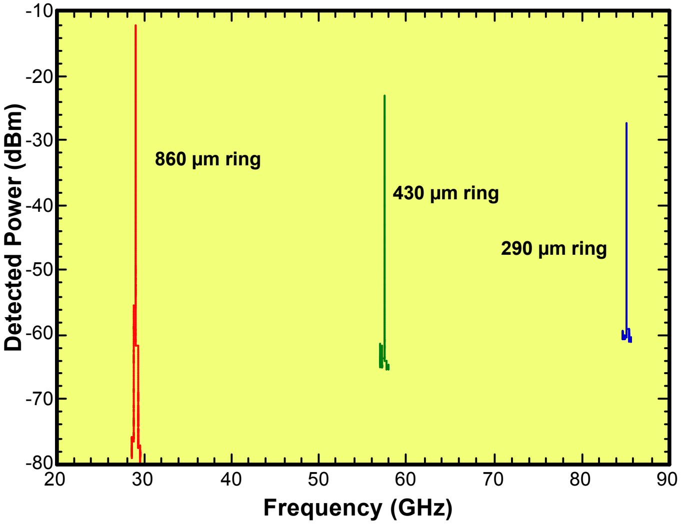
PICs for All-Optical Generation of mm-Wave Frequencies

- Monolithically integrated AlGaAs/GaAs PIC
  Chip size < 2mm
- DC-biased PIC generates 30-90 GHz electrical output determined by the ring laser diameter
- Active mode-locking, singlemode rings needed for best mm-wave performance





Circuit Schematic



RF Spectral Output of Three Different Circuits with Different Ring Laser Diameters

Vawter, et al., *IEEE Photonics Technol. Lett.*, 9(12), pg.1634 (1997).

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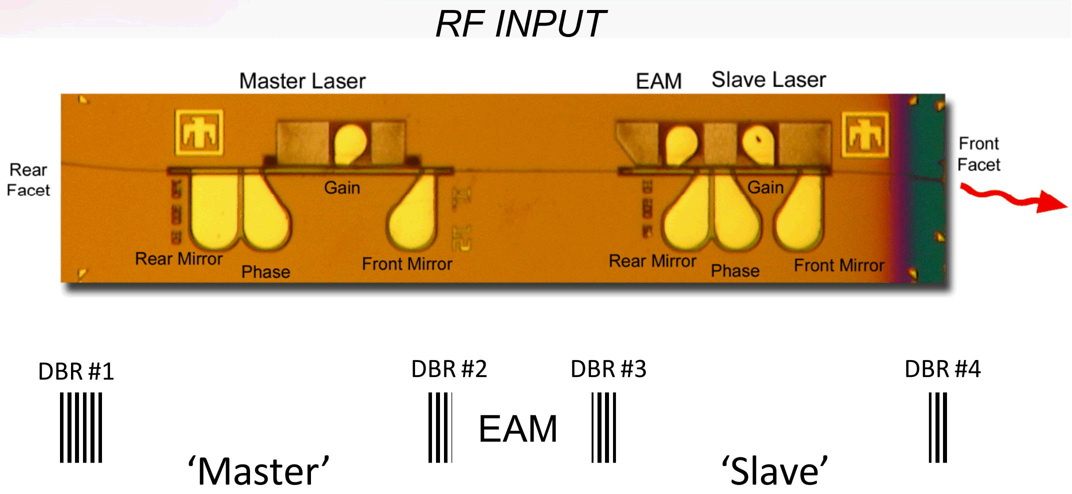
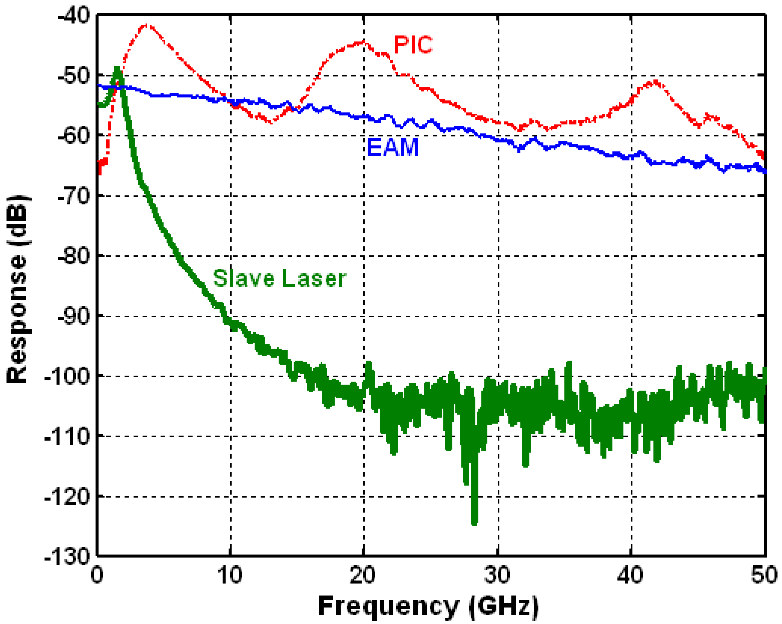
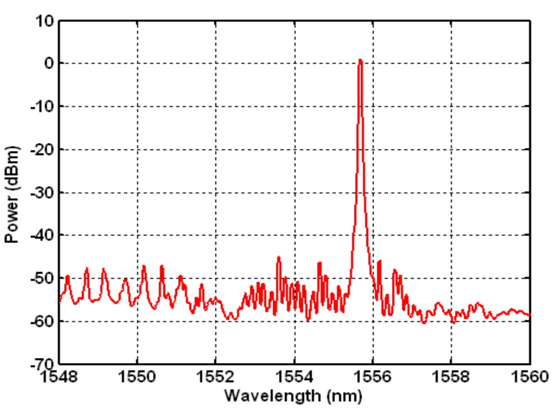
BW Enhancement by On-Chip Injection Locking





- Mutual injection locking of monolithically integrated coupled-cavity DBR lasers and EAM
  - Enhancement at difference of lasing wavelength and cavity modes of free-running lasers
  - Complex triple cavity offers many closely-spaced modes for resonance as RF tracks across frequency
- Bandwidth increased from 10 GHz to >50 GHz when operating in the mutual injection locking regime
- Increased efficiency up to 10 dB compared to laser-EAM



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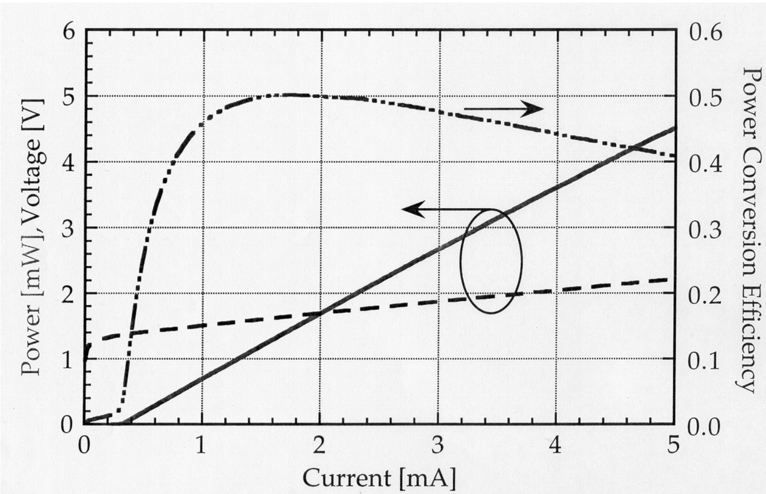
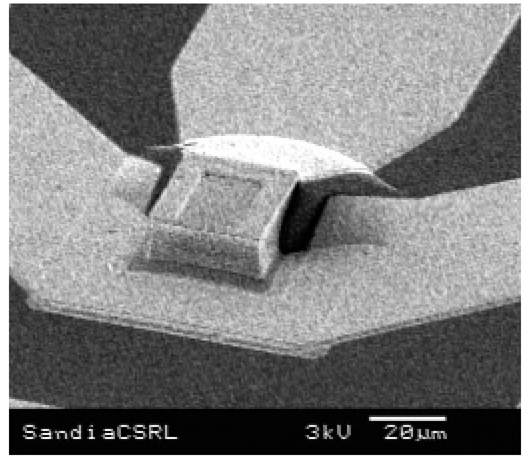
(In,Al,Ga)As/GaAs VCSELs

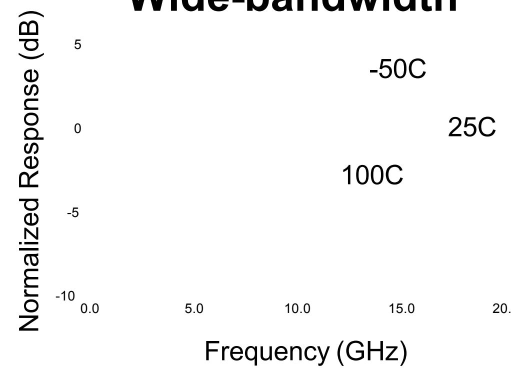
A radhard, efficient, low-power, wideband emitter for microsystems

Efficient

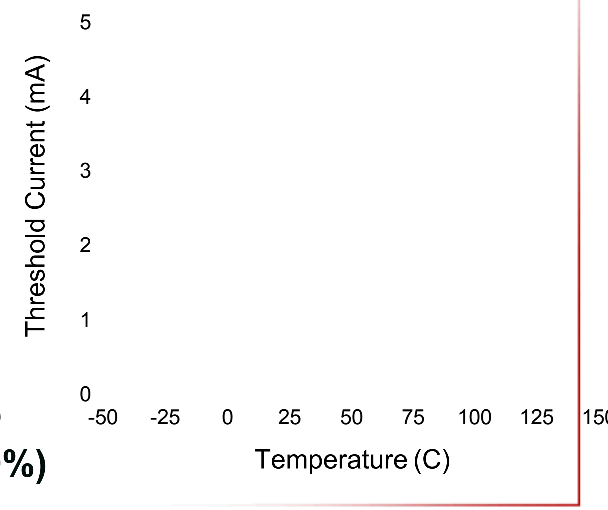




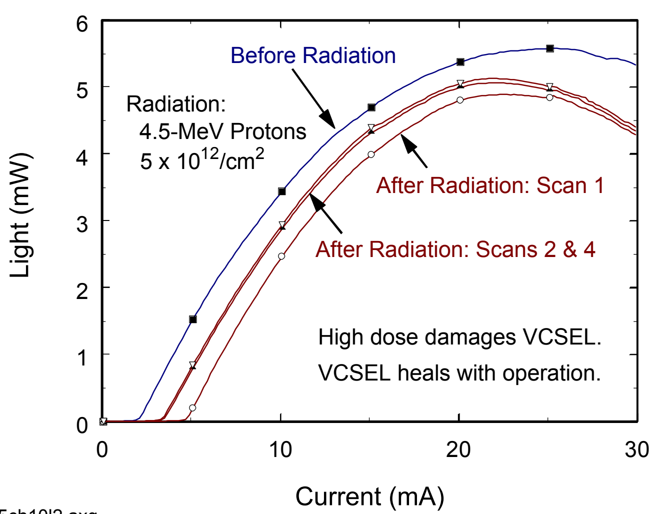
Wide-bandwidth



Thermal Stability



Radhard



VCSEL Attributes

- On-wafer testing/screening
- Ease of package integration
  - surface-normal circular output
  - low beam divergence
- Small active volumes (3X8nm QWs)
- Low threshold current (<1mA)
- High efficiency operation (>30%)
- Thermal stability ($\Delta T \sim 150°C$)
- High-speed (>5GHz)

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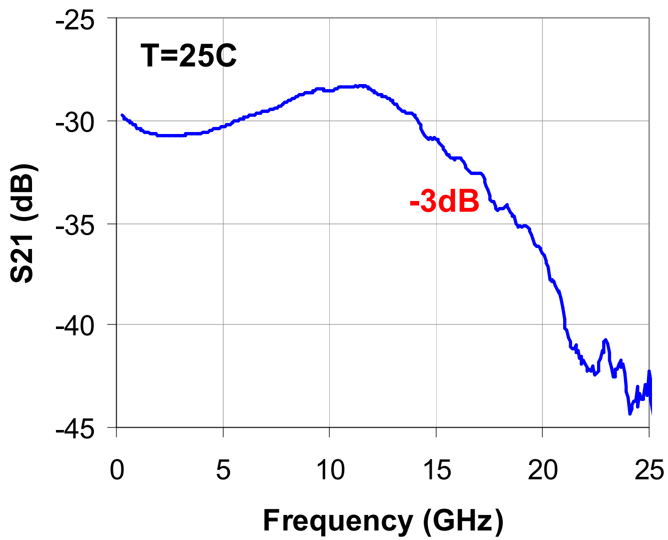
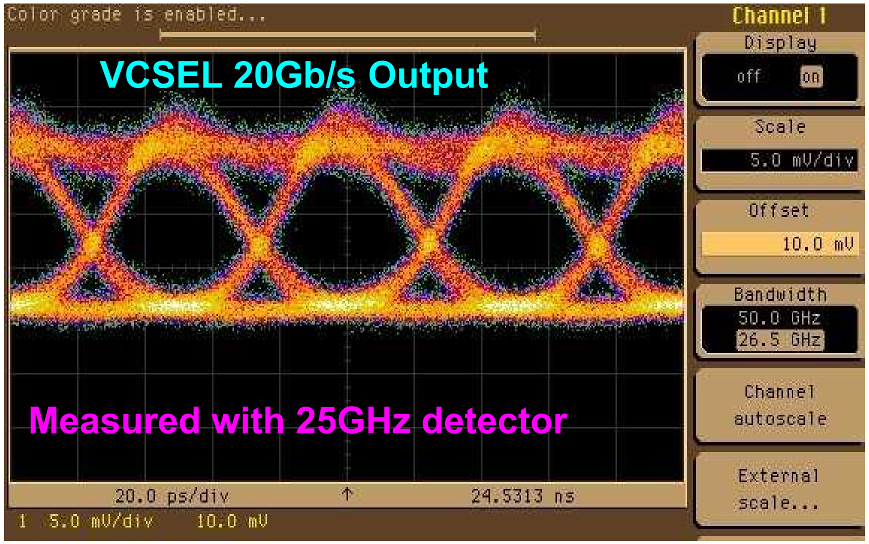
High-Speed VCSELs: 20 Gb/s at 850 nm

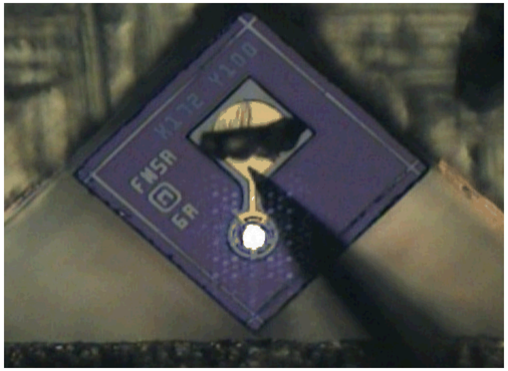
- Small-signal response
  - 17 GHz 3-dB frequency
  - 850-nm VCSEL compatible with datacomm standards
  - 980-nm VCSEL can achieve bandwidth > 30 GHz

S21 measurement of 850nm VCSEL



- Large-signal response





R.H. Johnson, D.K. Serkland, "17 G directly modulated datacom VCSELs", CLEO 2008.
Finisar VCSELs, tested at Sandia.

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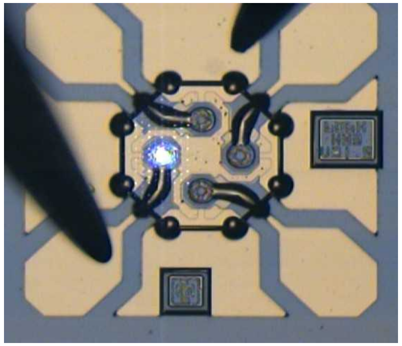
10Gb/s Low-Power VCSEL Transmitter

- Goals:
  - Threshold <= 0.2 mA
  - Bandwidth >= 8 GHz
  - Slope efficiency >= 50%
    - (photons out)/(electrons in)
  - Series resistance <= 100 Ω
    - ΔI=3mA → ΔV=0.3V
- Strategy:
  - Wavelength = 980nm
    - Low threshold
      - Optimum distributed Bragg reflectors (DBRs)
    - High bandwidth
      - InGaAs quantum wells provide high differential gain
  - Power = 3mW = 1.5mA*2V
    - Energy = 0.3pJ/bit

VCSEL

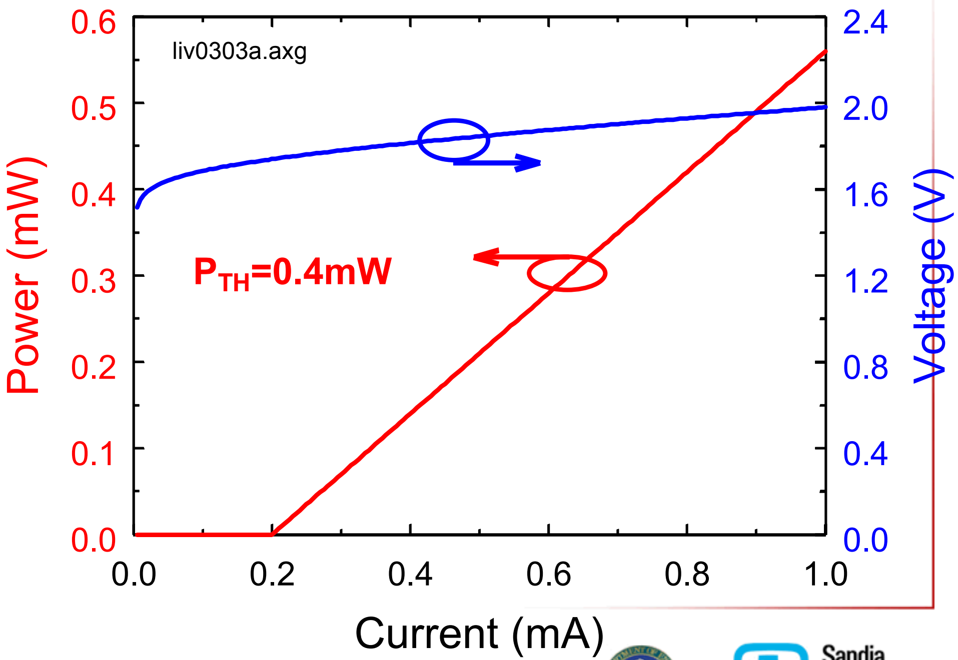


V_B=2.0V

Low-voltage CMOS (Vdd = 1V or less)

Drive: ΔV=0.3V ΔI=3mA

Output power and Voltage drop vs. Current



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