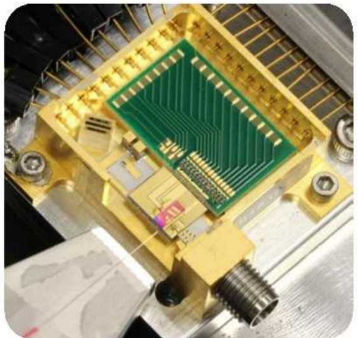
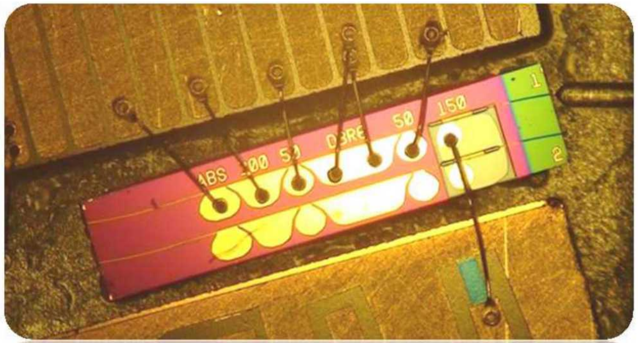
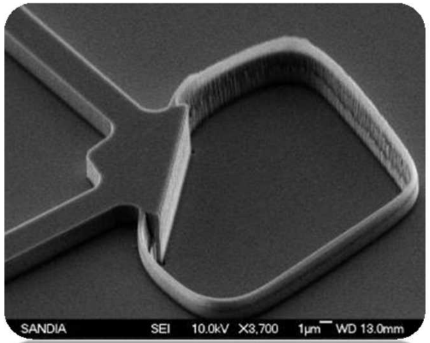
SAND2019-4727PE







Compound Semiconductor Photonic Integrated Circuits at Sandia National Laboratories

Erik Skogen, G. Allen Vawter, Anna Tauke-Pedretti

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

- Introduction to Integrated Photonics at Sandia National Laboratories
- InP-based Photonic Integrated Circuits (PICs)
- Sandia's InP-based PIC toolkit
- PIC examples
  - Electrical-to-optical transmitter
  - Optical heterodyne
  - Digital logic gates
  - RF channelized receiver
  - Coupled cavity lasers & Injection Locking
- Summary

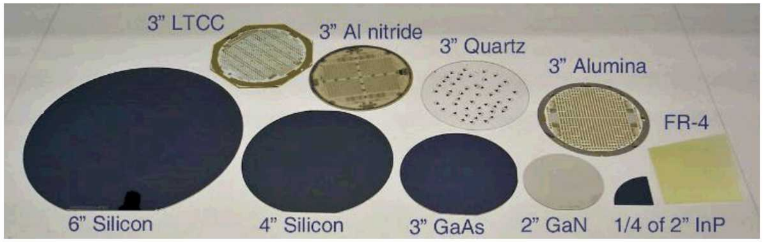
Outline

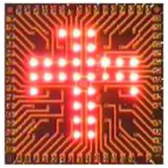
- Introduction to Integrated Photonics at Sandia National Laboratories
- InP-based Photonic Integrated Circuits (PICs)
- Sandia's InP-based PIC toolkit
- PIC examples
  - Electrical-to-optical transmitter
  - Optical heterodyne
  - Digital logic gates
  - RF channelized receiver
  - Coupled cavity lasers
- Summary

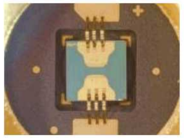
Sandia National Labs MESA Complex

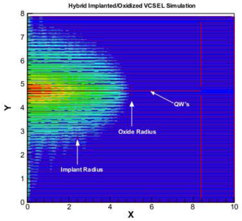
- Prove, Advance Technology Readiness Level, Productize
  - TRL1-6+: create, develop, prototype
  - Trusted
- Trusted, custom, low-volume, high-reliability products for harsh environments when industry is unwilling or unable to deliver
- Foundational Capabilities
  - III-V compound semiconductor epitaxy,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

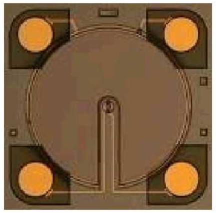
SiFab: 11,900 ft^2 Class 1
MicroFab: 14,230 ft^2 Class 10/100

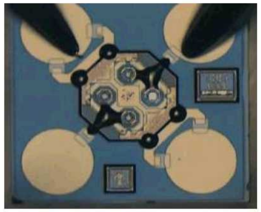


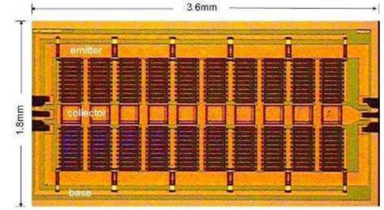


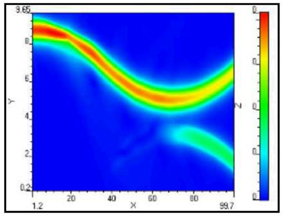


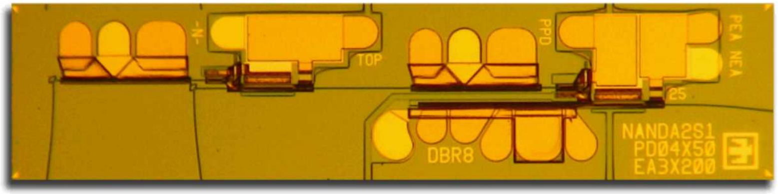


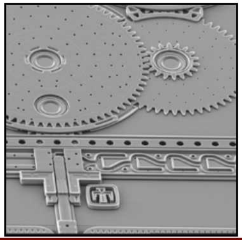


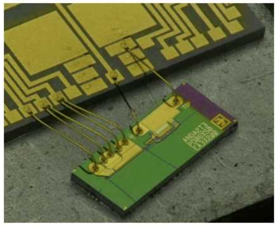






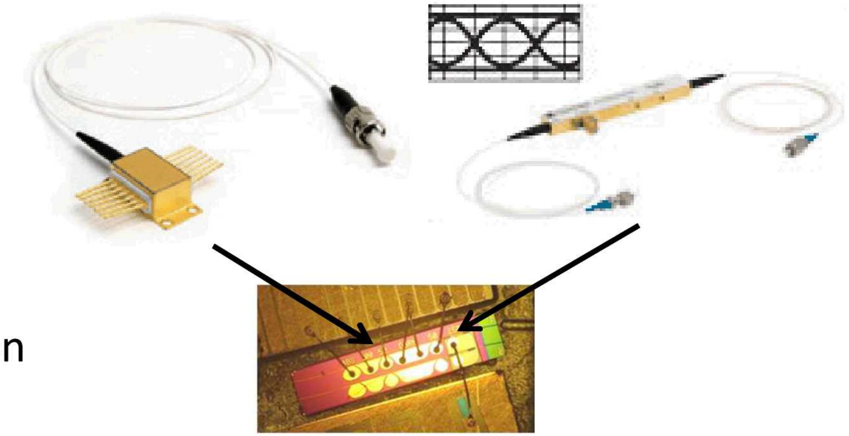






Photonic Integration

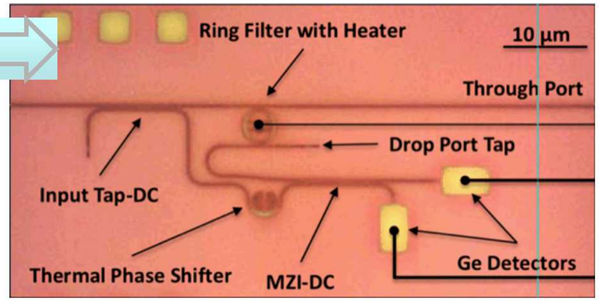
- Integration has been driven by the benefits of:
  - Smaller size
  - Lower power
  - Mechanical robustness
  - Simplified packaging
  - Lower costs
  - Optical interface coupling loss reduction
  - *More complex optical functions*

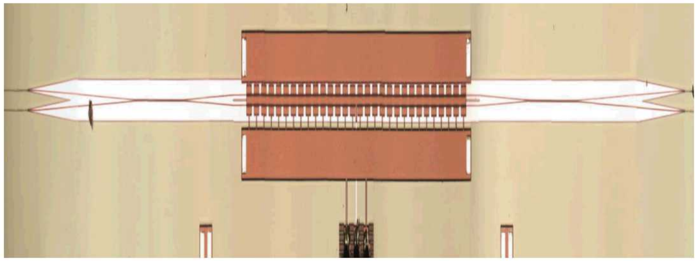


- Offers opportunities to make impacts in applications beyond telecommunications including:
  - Optical signal processing
  - Sensors
  - Applications where SWaP is important
  - Scientific research: lab on chip
  - *Significant innovation is possible on the circuit level*

Si Photonics at Sandia National Labs

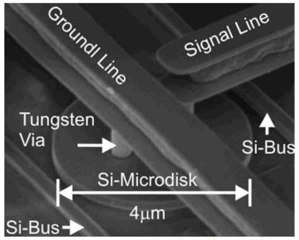
- **2014** balanced homodyne resonant wavelength stabilization > 55C
- **2013** Si Photonics MPW (CIAN NSF ERC)
- **2012** 24 GHz Si TW MZM
- **2011** 45 GHz Ge Detector
- **2010** 3 fJ/bit resonator modulator, 1V-cm MZM
- **2009** wavelength tunable rings over 35 nm
- **2008** 2.4 ns Wavelength selective switch
- **2007** MicroDisk resonator infrared detector
- **2005** Si_3N_4 low-loss waveguides
- **2000** SiON / SiO2 (Clarendon Photonics)
- **1990s** Si PhC & Optical MEMS



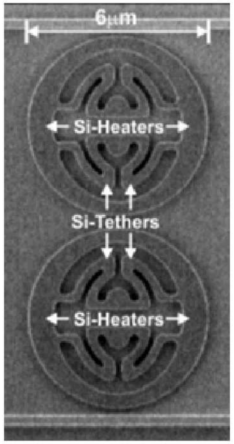


24 GHz 0.7V-cm Travelling Wave MZI Modulator

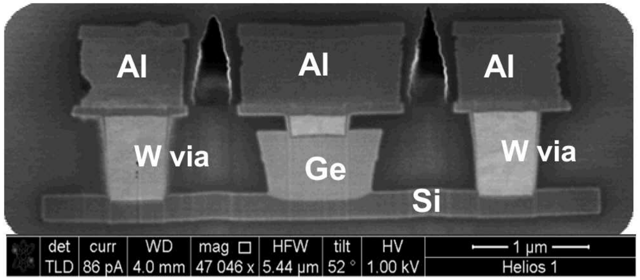
3.2fJ/bit at 12Gb/s



Resonant Optical Modulator/Filter

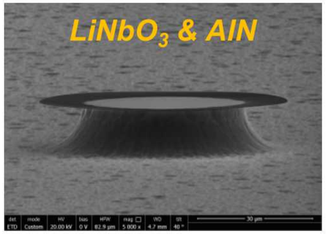


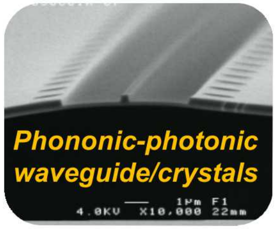
Tunable Resonant Filter



45 GHz High-speed Ge Detector on Si

MEMS process for additional capability

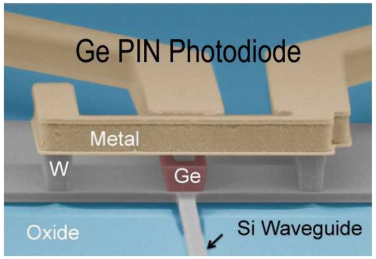


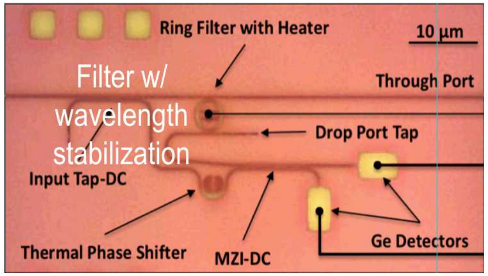


Si Photonics MPW

Silicon Photonics Platform

- Built on an SOI wafer with two waveguide interconnect layers, dopant implants for active p-n junctions and low resistance contacts, and metal interconnects with optical cladding layers.
- **Demonstrated Device & Circuit Examples**: Arrayed waveguide grating based RF channelizers, high-speed ultra-broadband amplitude modulators, avalanche photodiodes, optical phased arrays for chip-scale beam steering, micro-disk modulators for cryogenic temperature, Quantum Key Distribution transceivers, on-chip data links, optical active beam steering, resonant wavelength stabilization circuits for both modulators and filters, low noise oscillators, optical network add-drop node (CIAN), optical channel monitor (spectrum analyzer) (CIAN)
- **MPW Device Library**
  - 20 Active Components, 22 Passive components
  - 37 issued patents
  - PDK developed with Synopsis OptoDesigner (previously PhoeniX)
  - The next MPW will run on **our new 200 mm SOI platform**.
  - Typical block size: 4 mmx 26 mm
  - Three Deliverables: passive (Si+SiN), Passive+ Active, Passive+ Active+ Germanium
- **Unique Sandia SiPh MPW features**
  - Collaborative Research & Custom work possible within or outside MPW framework
  - Radiation Effects- Aware Designs
  - Harsh Environment & Cryogenic Photonics
  - Heterogeneous Integration of $LiNbO_3$ and III-V Lasers
  - Non-traditional materials such as Al_2O_3 and Epsilon-Near-Zero In_2O_3 and CdO

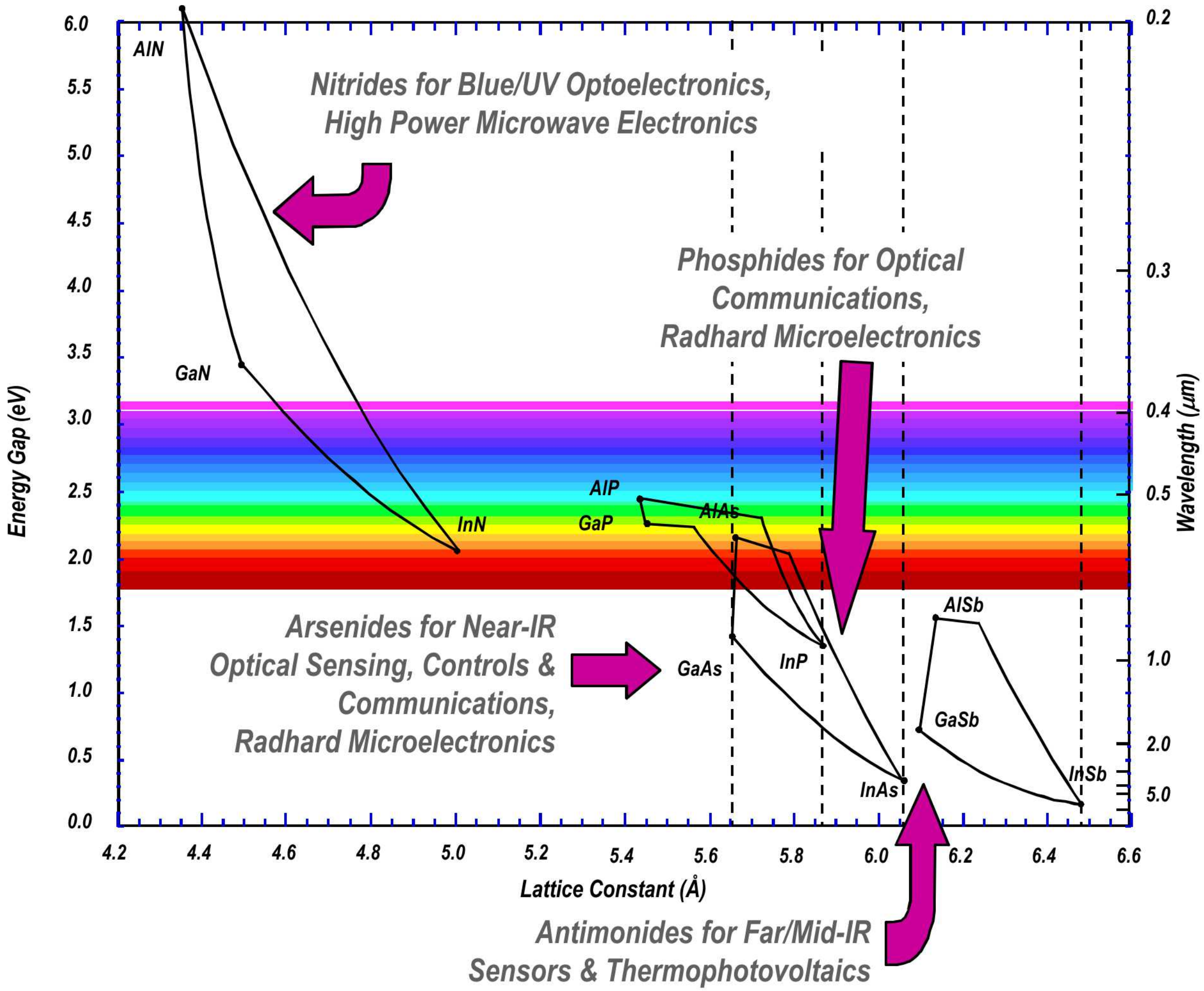


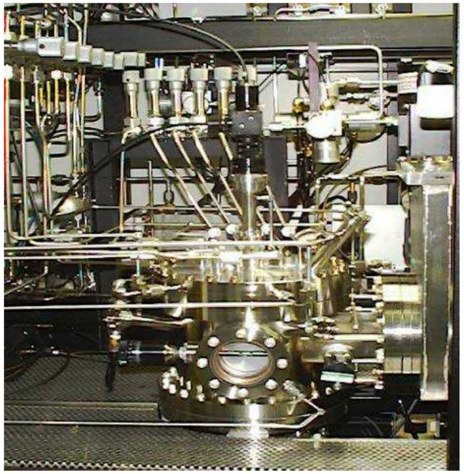


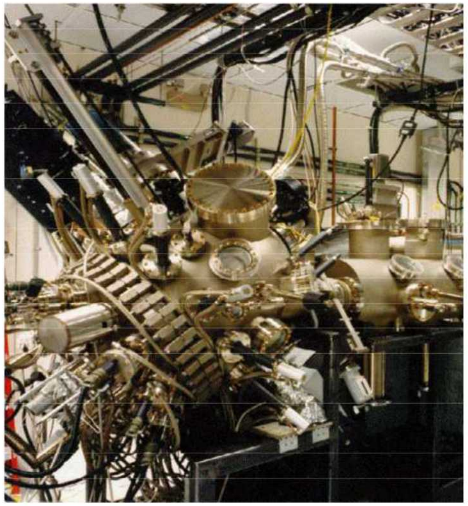
Group III-V Semiconductor Photonics at Sandia

Sandia Grows the Full Spectrum of III-V Materials

6 – MOCVD: As, P, Sb, N
4 – MBE: As, P, Sb

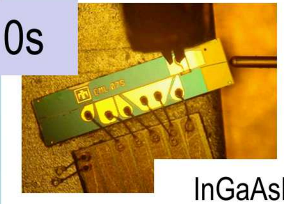




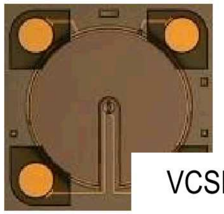


III-V Photonics at Sandia National Labs

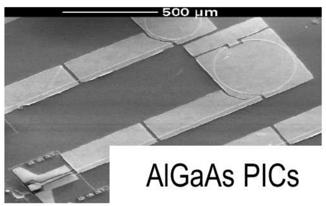
2010s



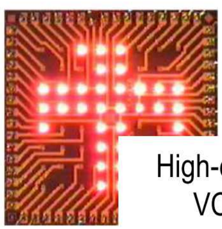
InGaAsP PICs



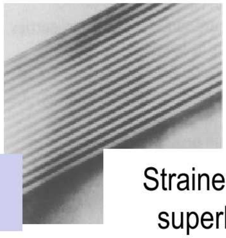
VCSEL+ PD



AlGaAs PICs

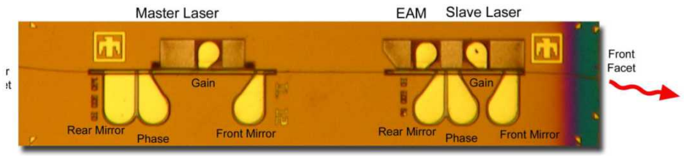


High-efficiency VCSELs

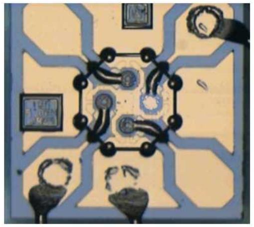


Strained-layer superlatices

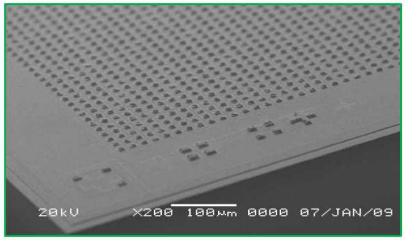
1980s



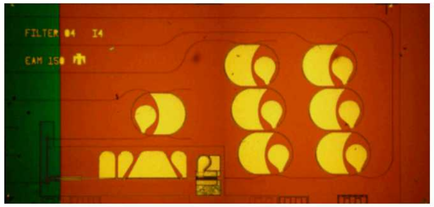
On-Chip Injection Locking
Enhanced Modulation > 50 GHz, C-Band



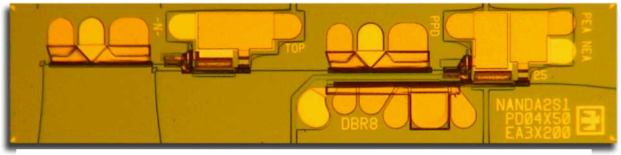
Single-Frequency Tunable VCSELs,
For atomic spectroscopy and sensors



nBn FPAs in the SWIR, MWIR and LWIR,
leveraging novel III-P and III-Sb materials



RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



All-Optical Logic at >40 Gb/s, C-Band

- **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, low-volume, high-reliability products for harsh environments**

InP ‘Design-Guided’ Multi-project Wafer Runs

Sandia National Laboratories

<u>3 tier offering at 1550 nm:</u>

- Tier 1: one regrowth
- Tier 2: 2 regrowths – adds High P_{sat} optical amplifier
- Tier 3: Full custom process – adds additional performance at 1550 nm, novel capabilities, mixed waveguide architectures, customized process, SME Design Guidance is included.

<u>Unique features of Sandia’s InP MPW runs</u>

- ITAR-Controlled, limited access (classified) facility
- Radiation-Effects aware designs and components
- Harsh Environment & Cryogenic Photonics

<u>Example InP PICs Demonstrated</u>

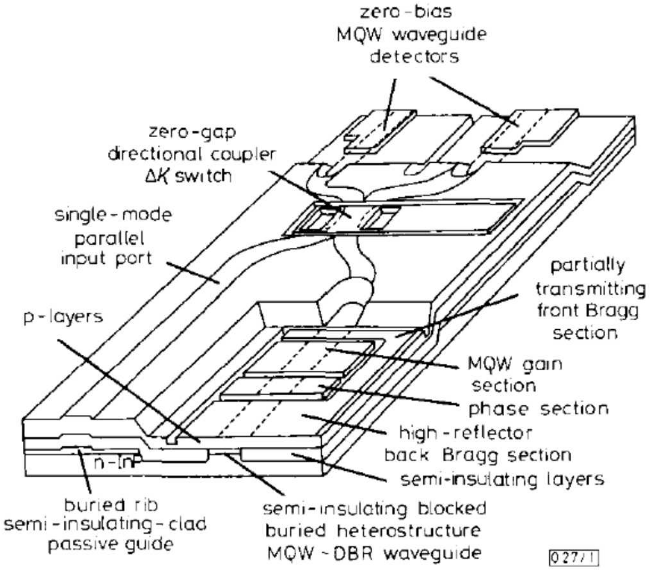
- RF Optical channelizing filters
- All-optical Logic (AND, NOT)
- Transceivers (tunable laser integrated modulators/amplified PD)
    - Modulator – electro-absorption or Mach-Zehnder
    - Receiver – optically amplified, high input saturation power
- Optical heterodyne
- Injection locked lasers
- AWG, TIR turning mirrors, low divergence waveguides

Process		Tier 1	Tier 2	Tier 3
Description		One MOCVD regrowth	Two MOCVD regrowths	Full custom process
Lasers	Tunable (~5 nm)	YES	YES	YES
	Tunable (~40 nm)	YES	YES	YES
SOA	High Gain (dB/cm)	400	400	400
	High P_{sat}	NO	YES	YES
Detectors	R (A/W)	0.8	0.8	0.8
	P_{in} saturation (dBm)	15	15	15
	Bandwidth (GHz)	> 20	> 40	> 40
Wave-guide	Propagation Loss (dB/cm)	< 2	< 2	< 2
	Turning mirror loss (dB)	N/A	< 0.5	< 0.5
EA-Modulator	Length (μm)	125	125	125
	Efficiency (dB/V/cm)	800	800	800
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	40	40
MZ-Modulator	Electrode Length (μm)	250	250	250
	Efficiency (V_π)	2	2	2
	Loss (dB)	~1	~1	~1
	Bandwidth (GHz)	> 20	> 20	> 40
Phase Modulator	Length (μm)	200	200	200
	Efficiency (°/V)	20	20	20
	Loss (dB)	< 1	< 1	< 1
	Bandwidth (GHz)	> 20	> 20	> 40

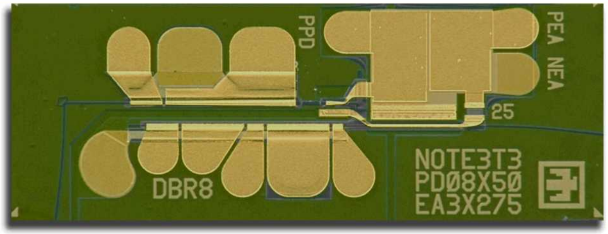
Inaugural Device Library

Compound Semiconductor PIC Features

- Generate and amplify light
  - All modulation functions of passive (e.g., Si) with
    - On-chip optical gain (SOAs)
    - Lasers and LEDs
  - Narrow linewidth, low noise lasers
- High absorption co-efficient if needed
  - Efficient and fast photodetectors
- On-chip gain
  - Offset waveguide and fiber coupling losses
    - Zero-insertion loss PICs
  - Active light switching
  - Ultra-fast nonlinearities
    - Cross-gain modulation
    - Cross-phase modulation
- Modulation >300 GHz
  - High speed, high extinction modulators
- Passive losses
  - 0.5 – 5 dB/cm
- Fiber coupling
  - Spot size transform or lensed fiber



Monolithic Optical Heterodyne Receiver
Koch, AT&T Bell Labs
Electronics Letters 25(24), 1989



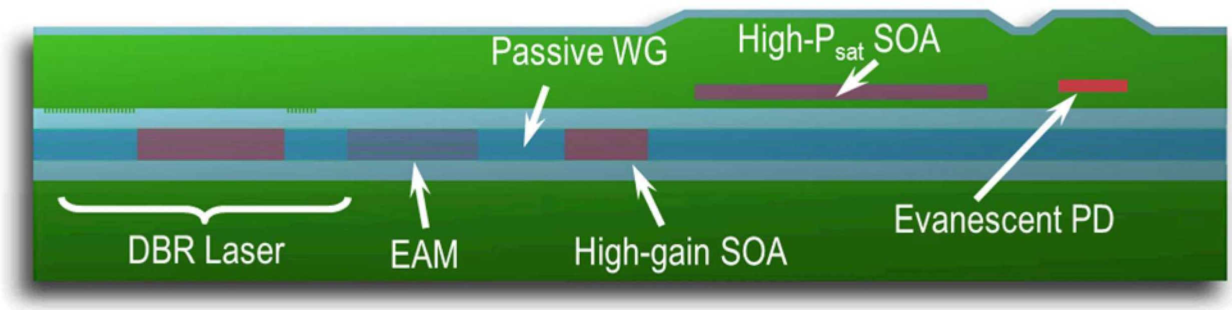
All-Optical Logic Gate, 40 Gb/s
Skogen, Sandia National Labs
Photonics in Switching Conf., 2010

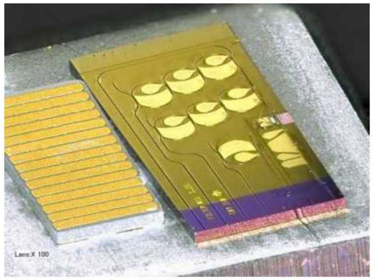
Outline

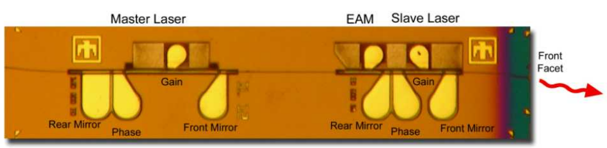
- Introduction to Integrated Photonics at Sandia National Laboratories
- InP-based Photonic Integrated Circuits (PICs)
- Sandia's InP-based PIC toolkit
- PIC examples
  - Electrical-to-optical transmitter
  - Optical heterodyne
  - Digital logic gates
  - RF channelized receiver
  - Coupled cavity lasers
- Summary

Monolithic Integration

- Sandia developed toolkit incorporating many components allows for new PICs with reduced overhead
  - Components: Lasers, EAMs, passive waveguides, high-gain SOAs, high-saturation power SOAs, evanescently-coupled photodetectors, quantum well photodetectors
  - Circuits: Optical logic gates, optical RF channelizers, transmitters, receivers, coupled-cavity lasers

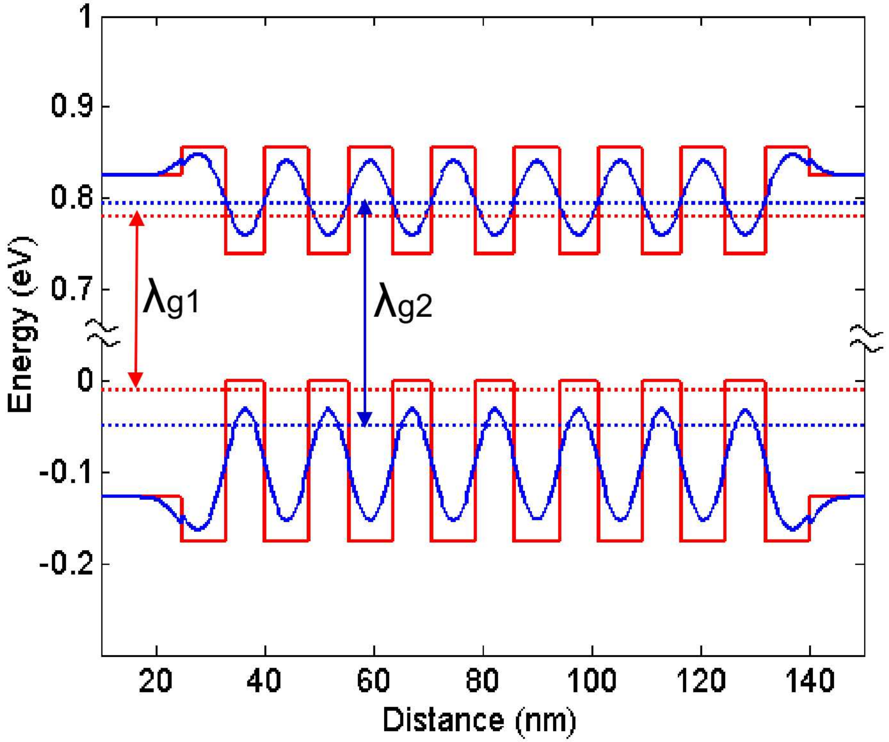




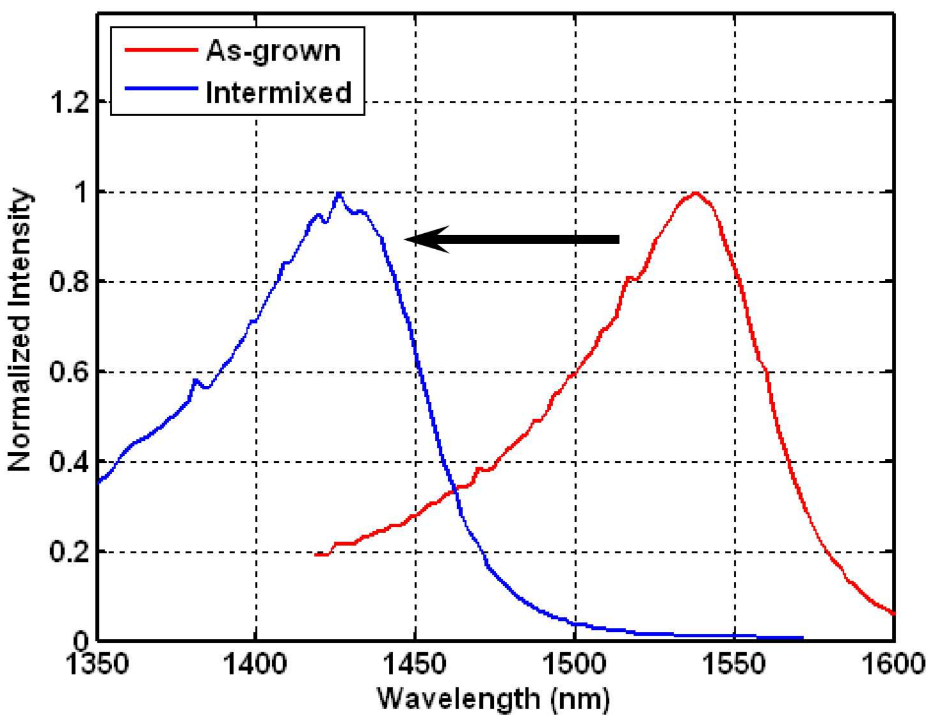


Monolithic Integration Platform

- Quantum well intermixing
  - Metastable interface between well/barrier
  - Add catalyst to enhance interdiffusion
  - Reshaping increases the energy level
    - Reduces the bandgap wavelength

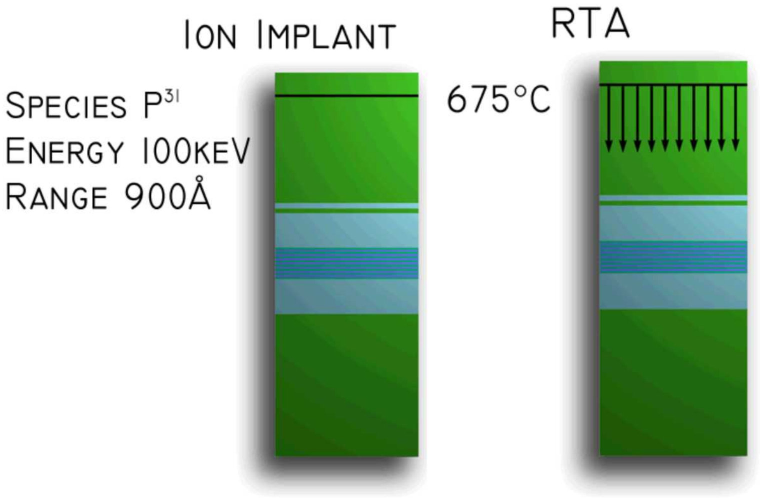


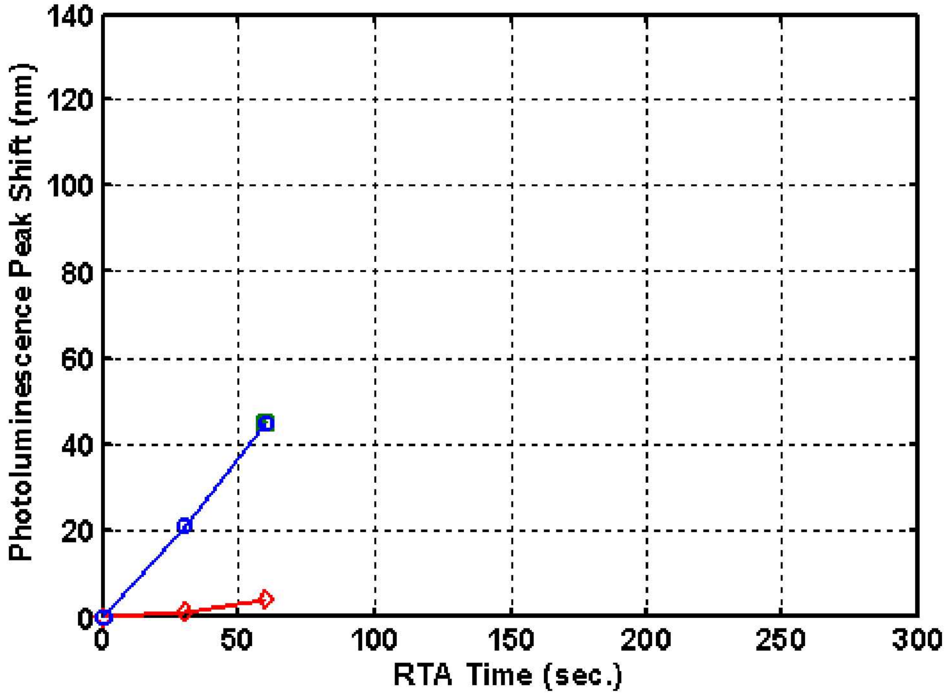
- Photoluminescence
  - Active =1540nm, Passive = 1425nm



Monolithic Integration Platform

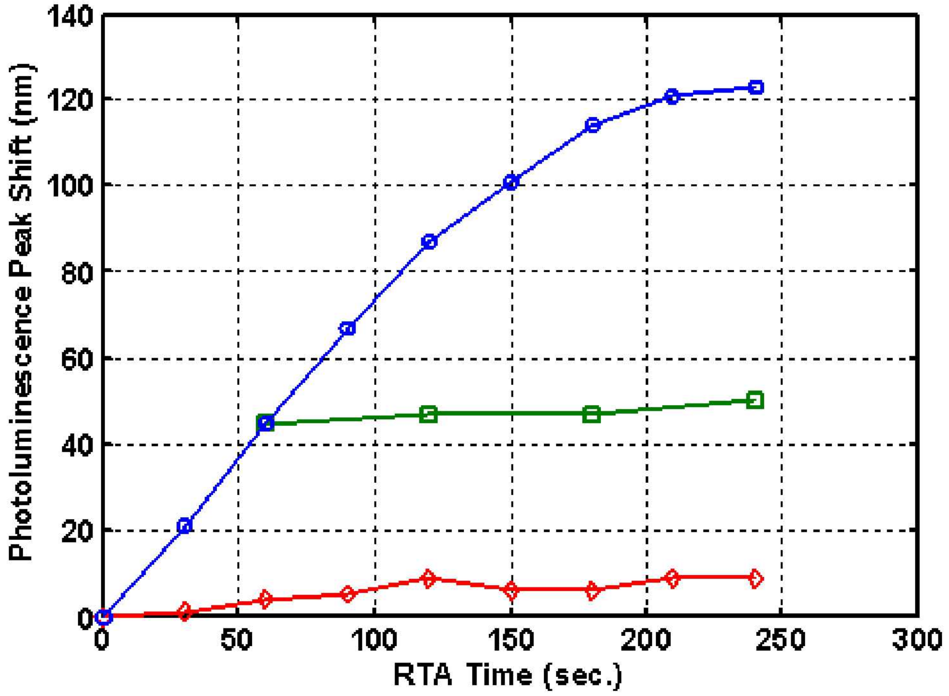
- Integrate devices with different functionalities
  - Ability to program QW bandgap wavelength
  - Non-shifted band-edge for lasers/SOAs/PDs
  - Intermediate band-edge for EAMs
  - Maximal shift for low loss waveguides

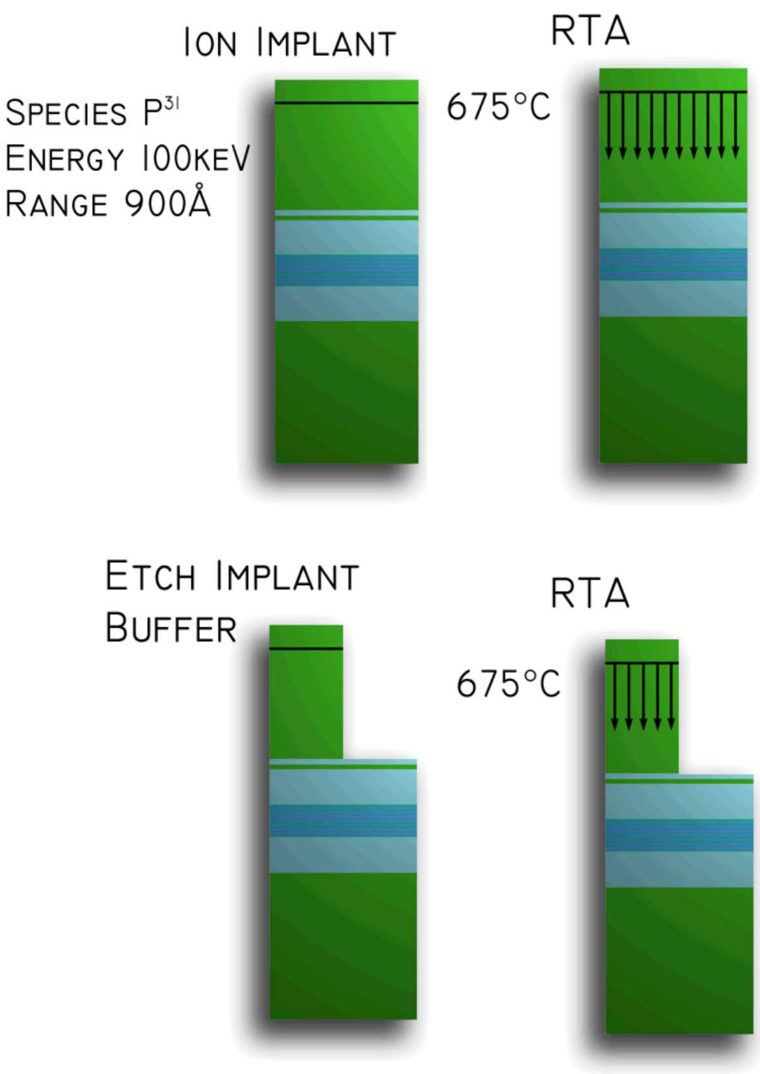




Monolithic Integration Platform

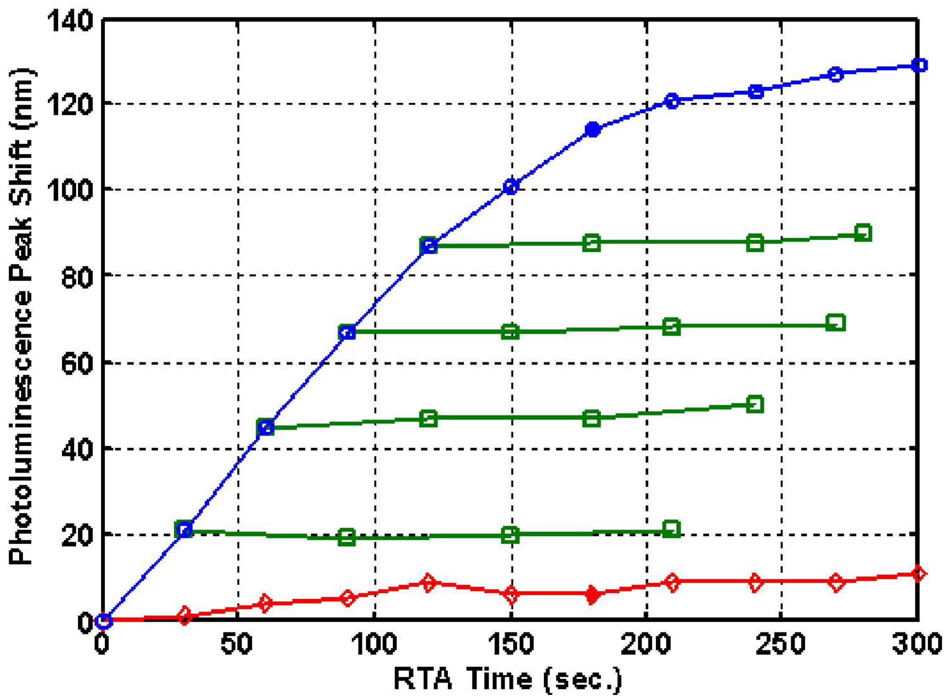
- Integrate devices with different functionalities
  - Ability to program QW bandgap wavelength
  - Non-shifted band-edge for lasers/SOAs/PDs
  - Intermediate band-edge for EAMs
  - Maximal shift for low loss waveguides

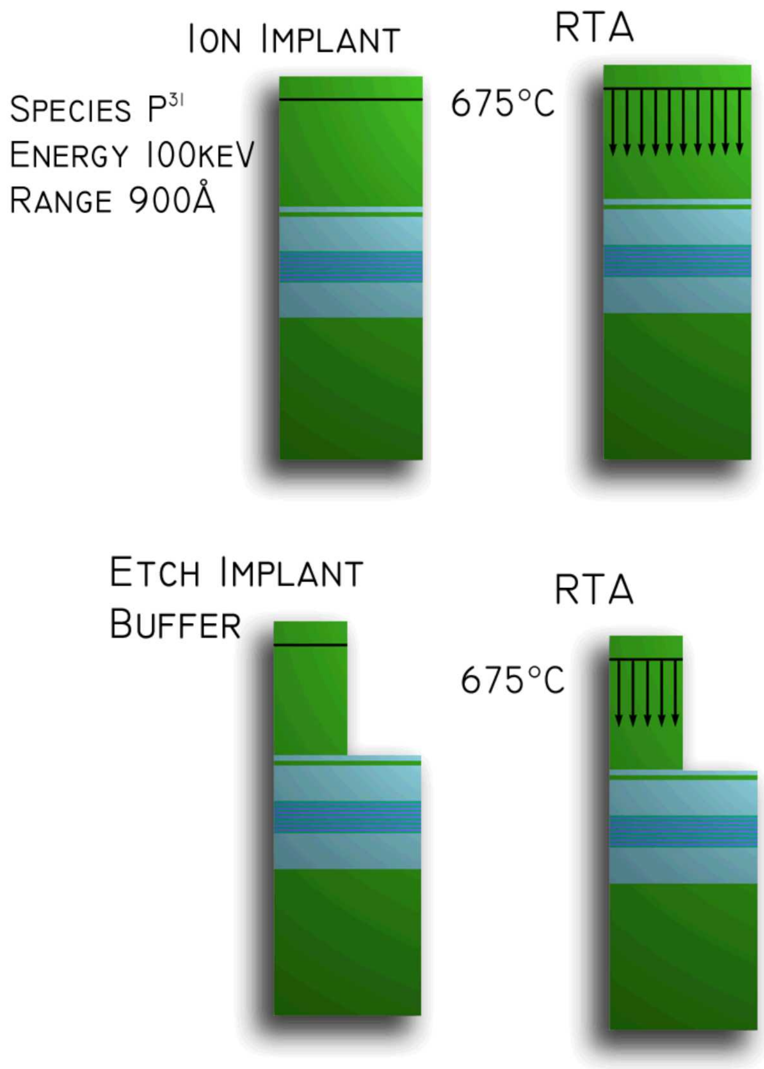




Monolithic Integration Platform

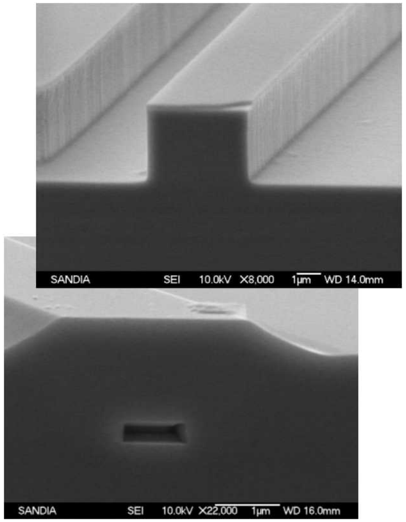
- Integrate devices with different functionalities
  - Ability to program QW bandgap wavelength
  - Non-shifted band-edge for lasers/SOAs/PDs
  - Intermediate band-edge for EAMs
  - Maximal shift for low loss waveguides



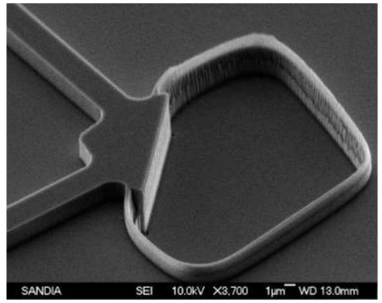


SNL Photonic Integrated Circuit Elements

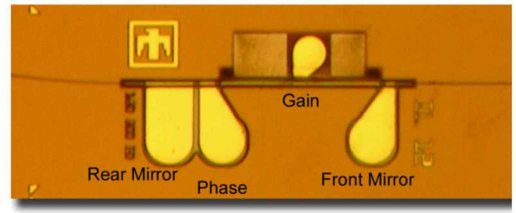
Sandia National Laboratories



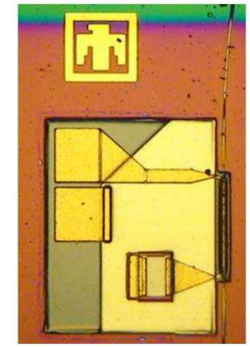
Waveguides



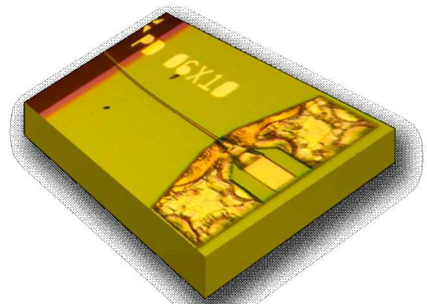
Turning Mirrors



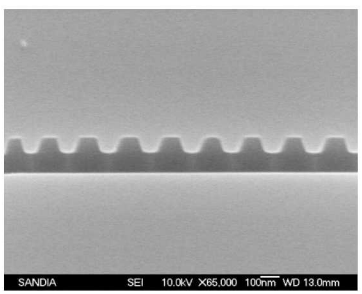
Lasers



Electro-Absorption Modulator (EAM)

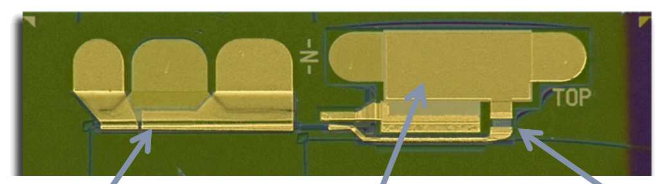


Photodiodes



Gratings

Ring Filters

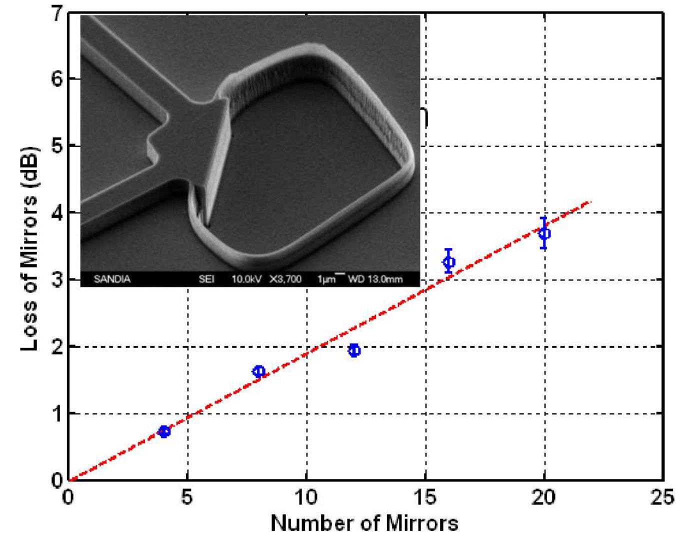


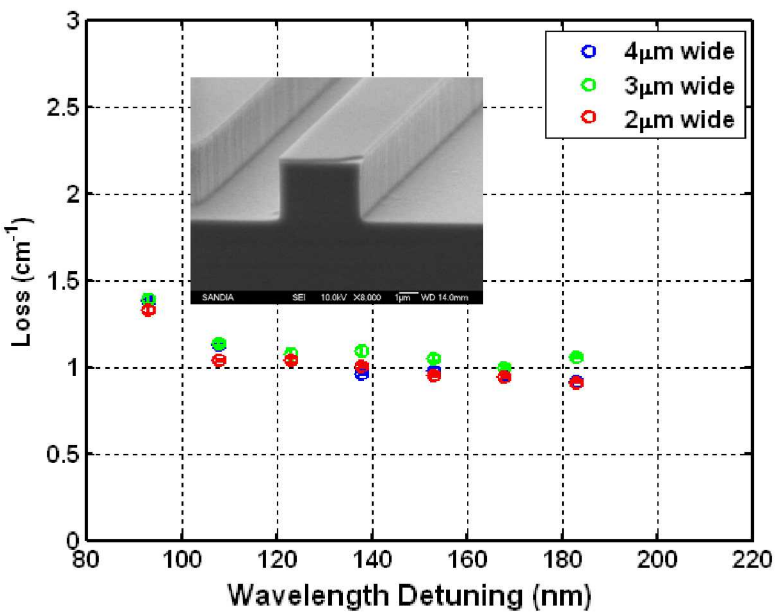
Optical Amplifiers Capacitors Resistors

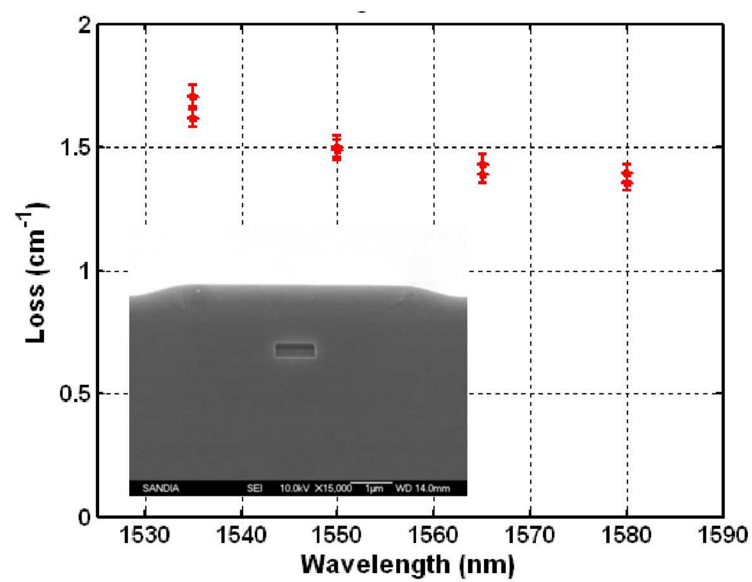
- State of the art – InP Photonic Integrated Circuits

Waveguides and Mirrors

- Ridge waveguide formed by dry etch
  - 1 cm^{-1} loss in doped waveguide
- Buried heterostructure waveguides
  - 1.5 cm^{-1} loss at 1550 nm in doped waveguides
- Total internal reflecting mirror
  - Deep etched mirror face
  - Low loss: 0.19 dB/turn (96% transmission)

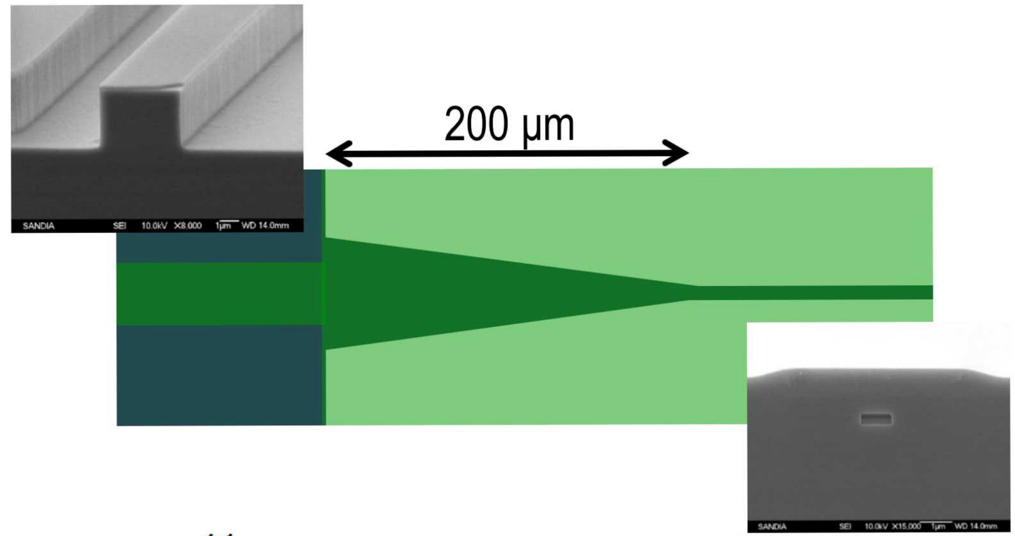


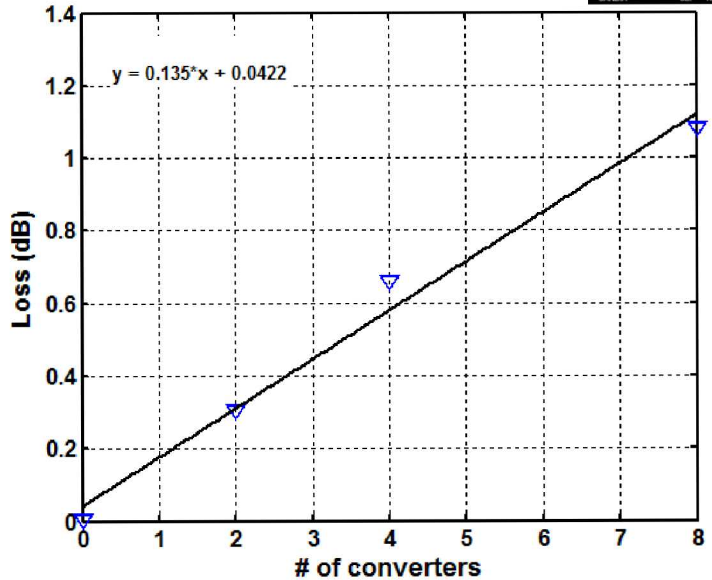




Ridge to Buried Heterostructure Coupler

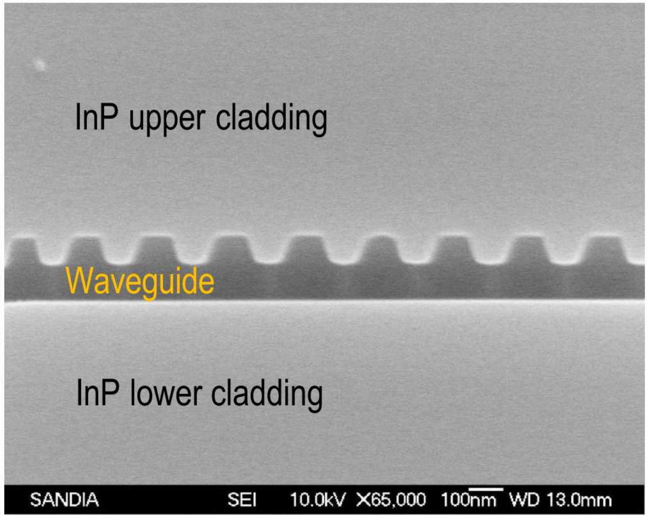
- Transition between the two waveguide types is done by tapering
- Experimental measurements show excess loss of 0.14 dB/transition
  - BPM simulation predicts 0.11 dB/transition

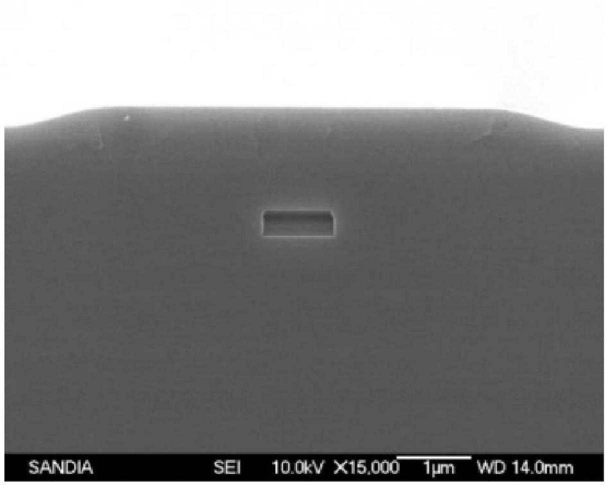


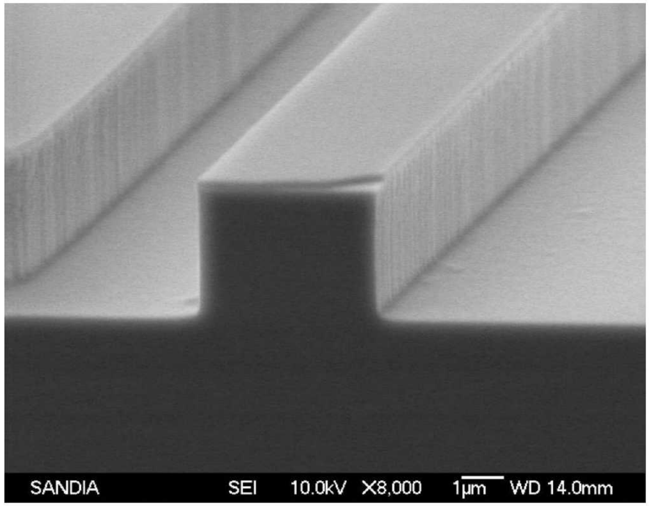


DBR Gratings and Regrowth

- Gratings
  - Used for laser mirrors
  - Defined with e-beam lithography
  - Etched into waveguide
- Single blanket regrowth
  - Fill in the gratings
  - Provide the upper p-contact
  - Form the upper cladding of waveguide



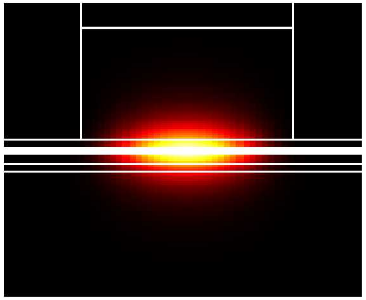




Simulation Enables PICs

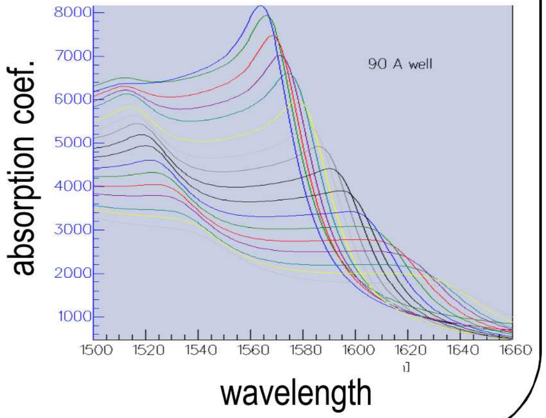
Waveguide

- Maxwell's equations
- Guided optical modes



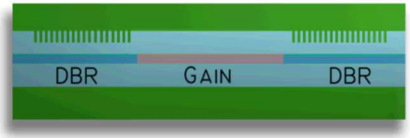
Modulator

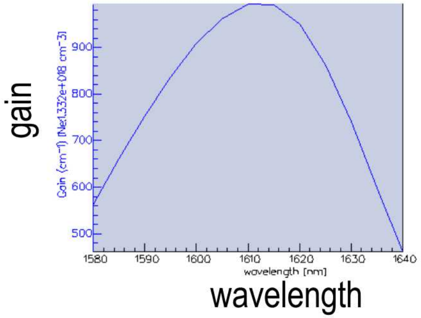
- Materials properties
- Schroedinger wavefunction
- Matrix element for absorption



Laser and SOA

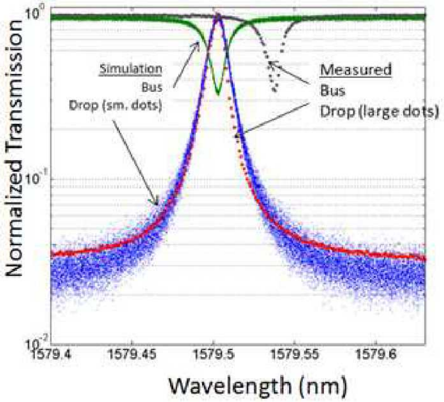
- Materials properties
- Schroedinger & Poisson Functions
- Matrix Element for Light Emission
- Traveling-wave optical solutions





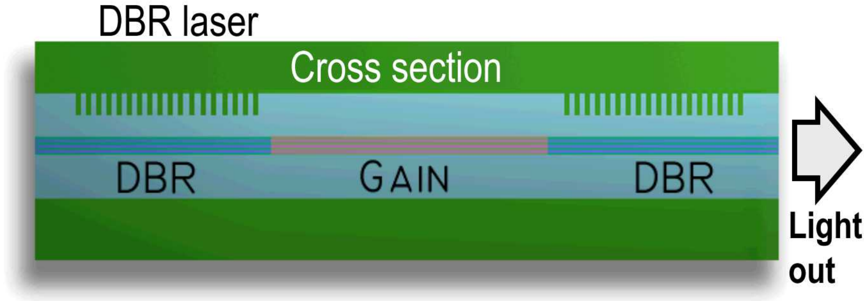
PIC

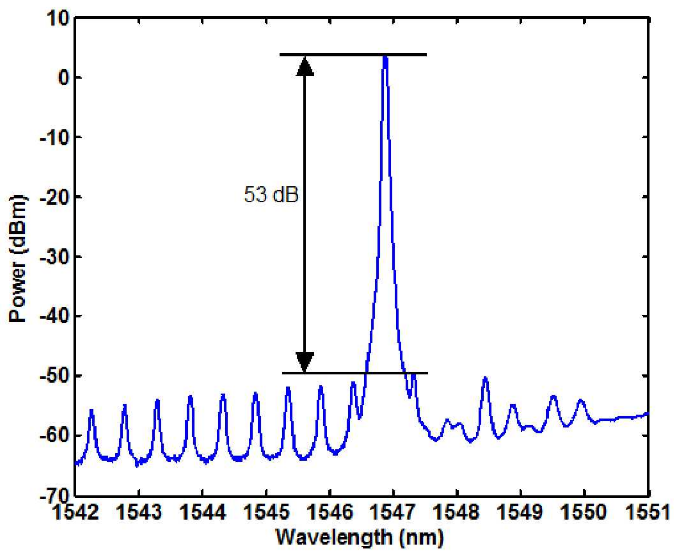
- Time dependent traveling wave solutions of optical modes
- Spontaneous and stimulated emission in diodes

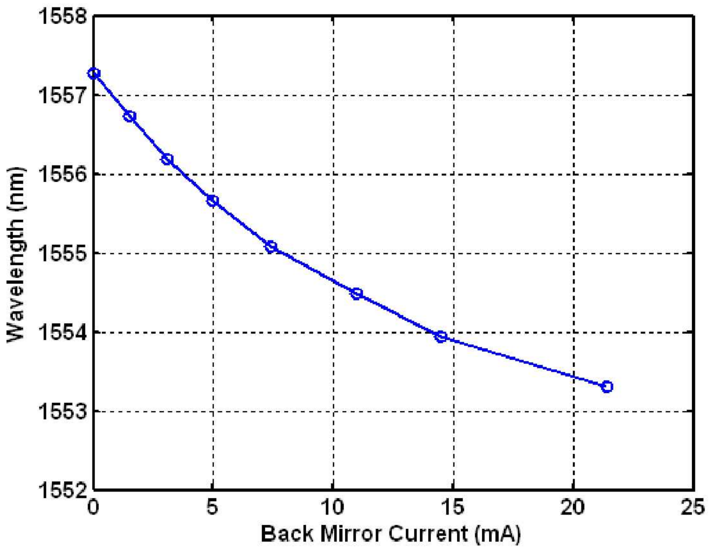


DBR Laser Technology

- DBR Laser Characteristics
  - Threshold: 10 mA
  - Output power: 20 mW
    - 6 mW fiber coupled
  - Side-mode suppression: >50 dB
  - Tuning: ~4 nm

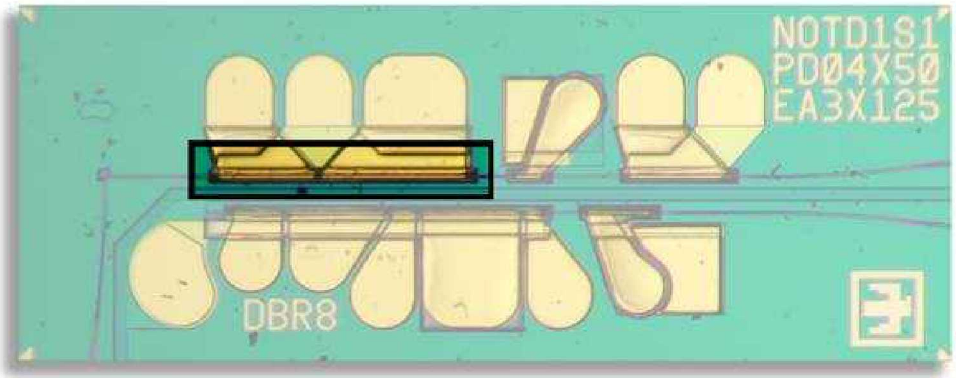


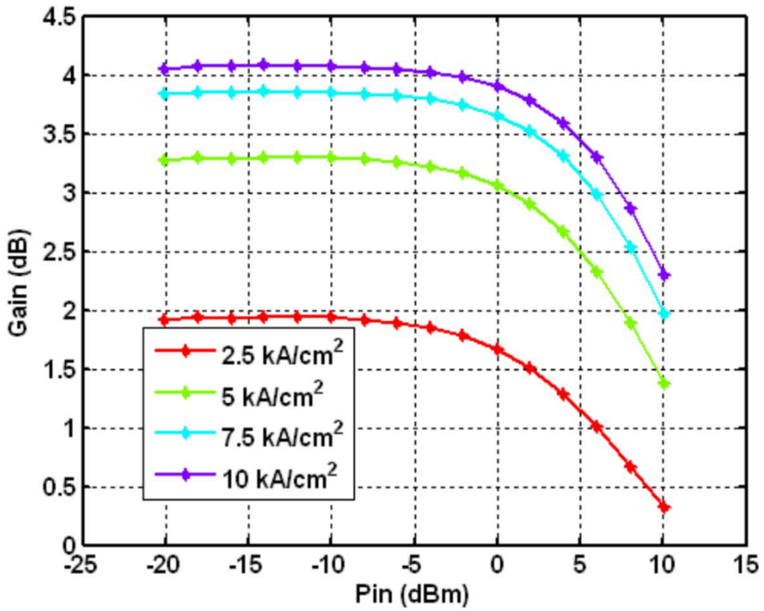




Semiconductor Optical Amplifiers

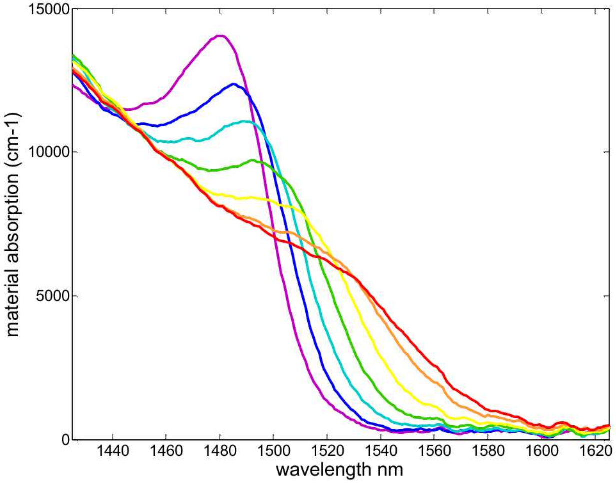
- Optimize for application
- High confinement factor
  - High gain
    - 8.7 dB gain in 200 um
- High saturation power
  - High confinement QWs
    - 10 dBm 1-dB saturation
  - Flaring to reduce power density
    - 13.2 dBm 1-dB saturation

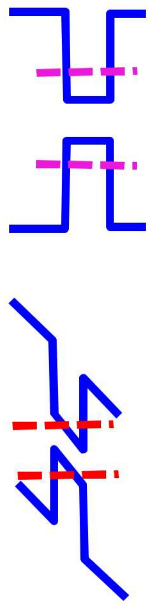




InP PICs: Modulation

- All the mechanisms of passive PLCs
  - Thermal
    - index modulation
  - Free carrier
    - Index modulation
    - Absorption modulation

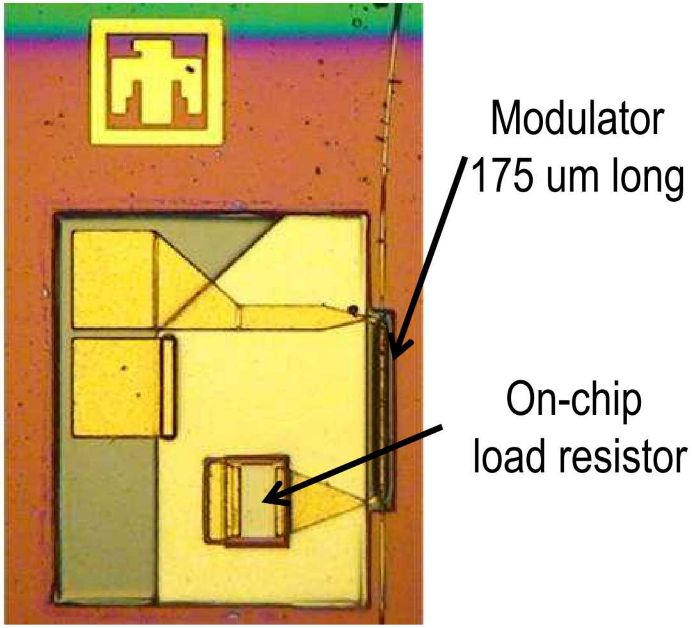




- Electro-optic effects
  - Electric field induced change
    - Linear (Pockels Effect)
    - Quadratic (Kerr Effect)
  - Very Fast
    - Instantaneous modulation with local field
    - Device modulation rate limited by RC time constants and RF design
- Quantum Confined Stark Effect
  - Applied electric field on thin layers supporting 2D transport and excitonic absorption
  - Field changes absorption energy of exciton
    - Refractive index is changed
  - Stronger effect than standard EO
    - Reduced drive voltage or power
  - Very fast

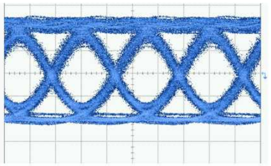
Electro-absorption Modulators

- Electro-absorption modulator
  - Utilize Stark shift in QWs
  - Compact footprint
    - 50-300 um long
  - High extinction efficiency
    - 19dB/V DC
  - High Speed
    - 40 GHz bandwidth
    - Integrated load resistor

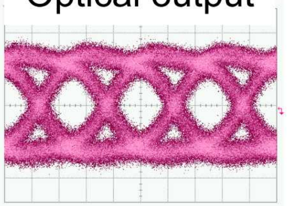


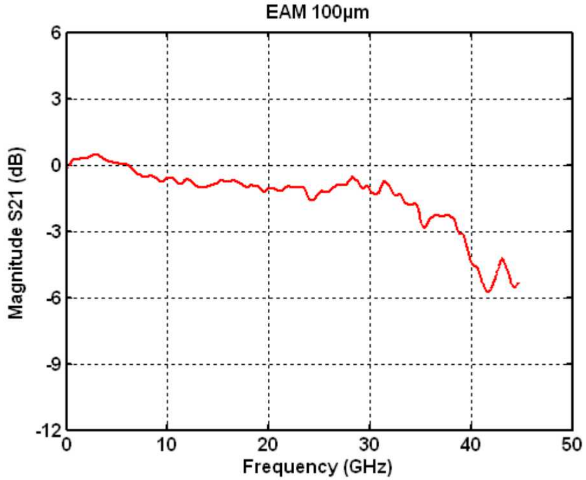
40 Gb/s eye patterns

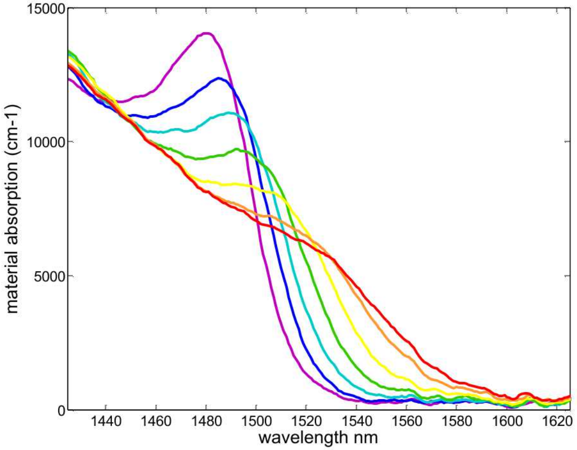
Electrical input



Optical output



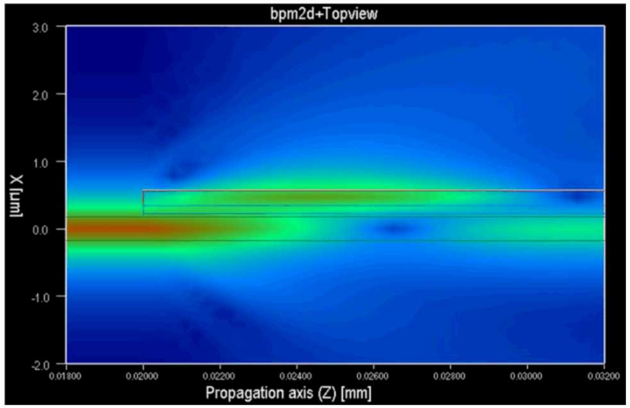


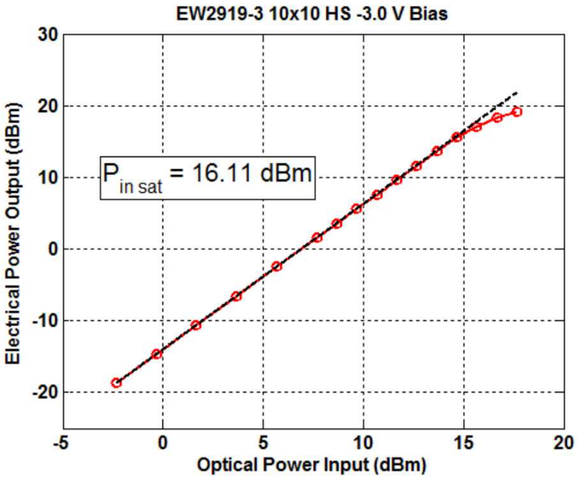


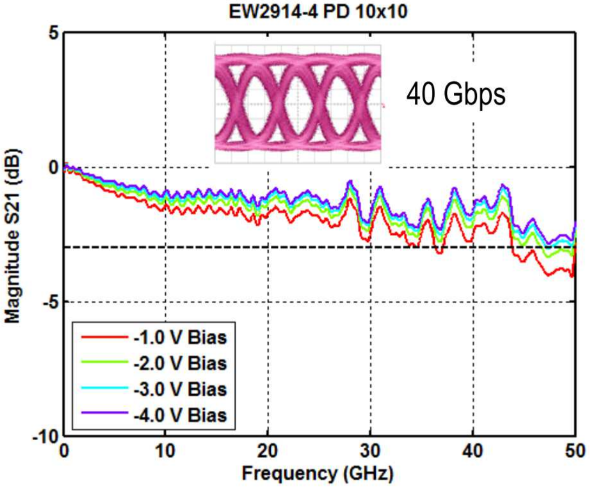
High-speed, High-power Photodetectors

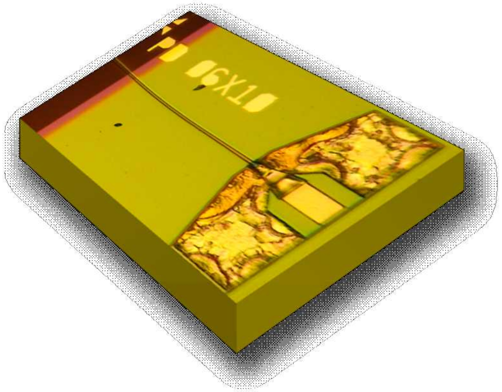
Sandia National Laboratories

- > 40 GHz bandwidth
- 90% quantum efficiency
- 16.11 dBm high input saturation power
- Solution – bulk, evanescently coupled photodiode with absorption near p-side







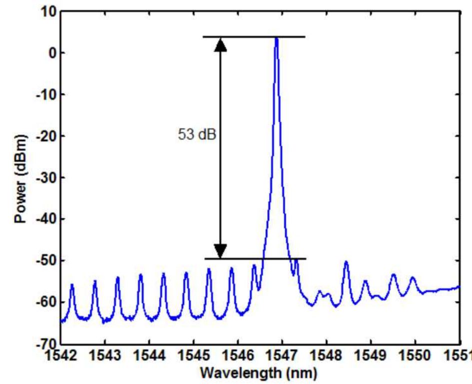


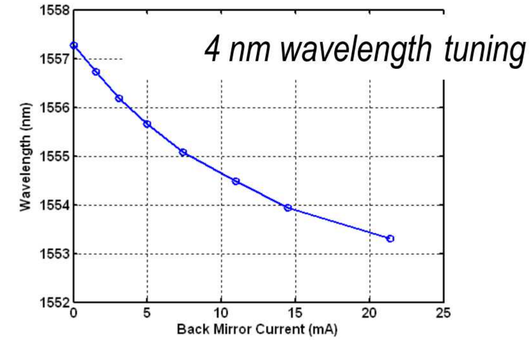
Outline

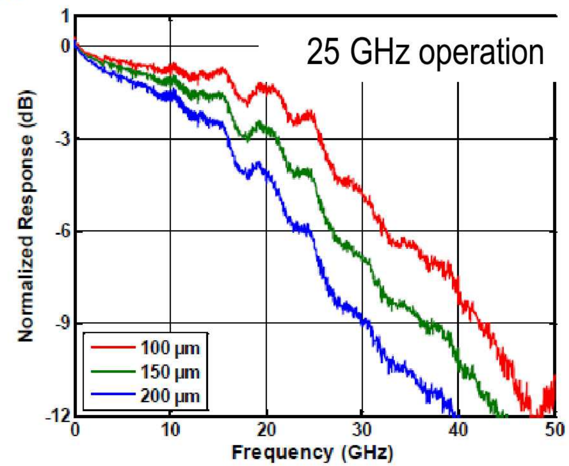
- Introduction to Integrated Photonics at Sandia National Laboratories
- InP-based Photonic Integrated Circuits (PICs)
- Sandia's InP-based PIC toolkit
- PIC examples
  - Electrical-to-optical transmitter
  - Optical heterodyne
  - Digital logic gates
  - RF channelized receiver
  - Coupled cavity lasers
- Summary

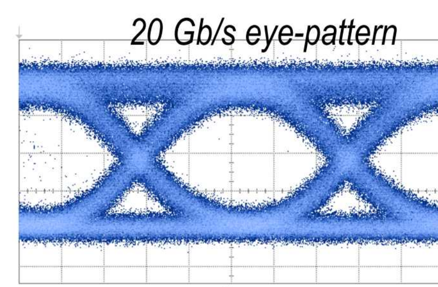
High-Speed Electrical-to-Optical Transmitter

Sandia National Laboratories









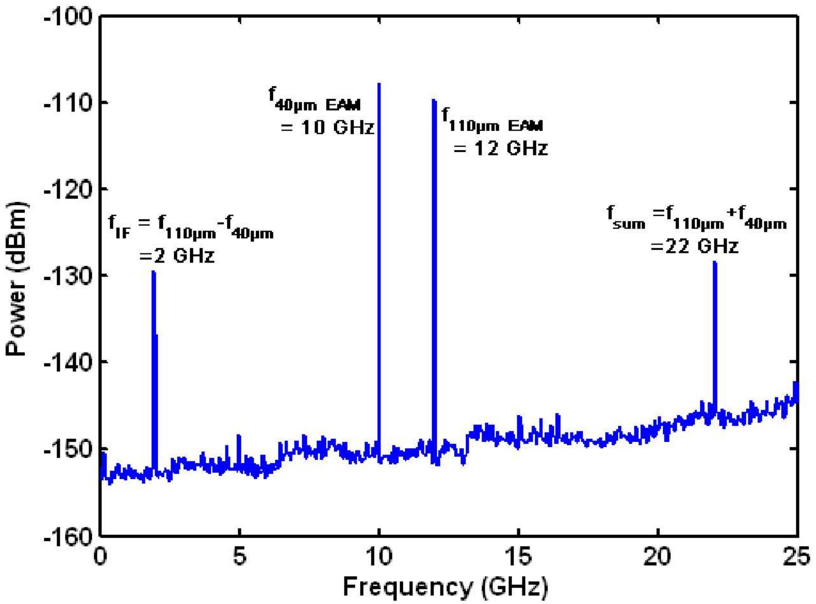
- InGaAsP Diode laser and modulator chip
  - DBR lasers
    - 6 mW fiber-coupled power
      - ~20 mW out from chip
    - 4 nm wavelength tuning
  - EAMs
    - Efficiency ~19dB/V DC
    - Bandwidth 20GHz
- Wavelength tuning
  - Track filter frequencies
  - Tune to WDM channels

Power for RF photonics

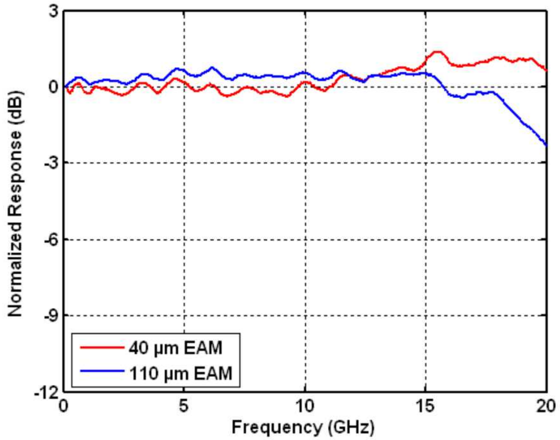
Wavelength agility

Scalable to mm-wave

Ultra-Compact Optical heterodyne



- DBR Laser with Dual EAMs
- f_{Mod1} = 10 GHz; f_{Mod2} = 12 GHz
  - $P_{electrical\ input}$ = 5 dBm for both EAMs
- 2 GHz IF signal (2 GHz) extracted

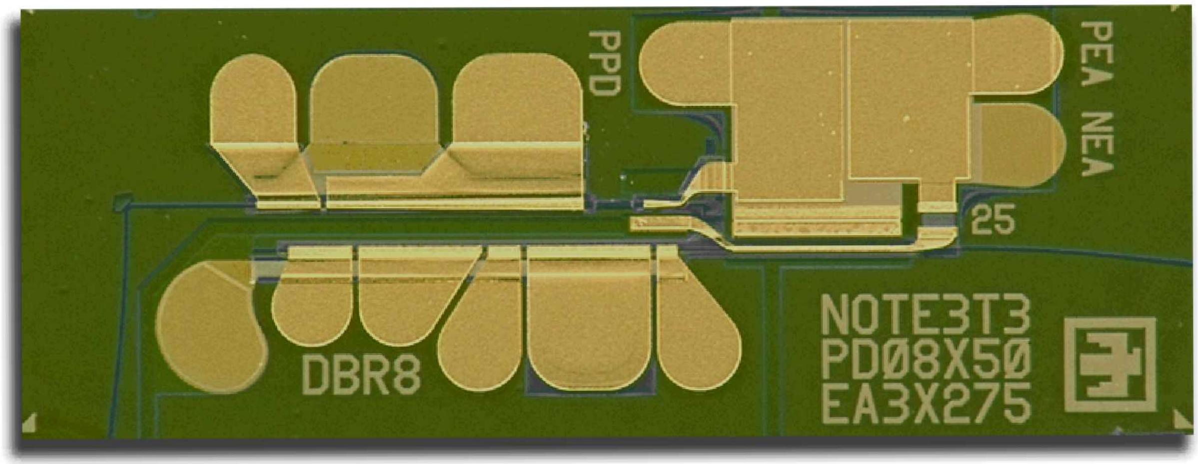


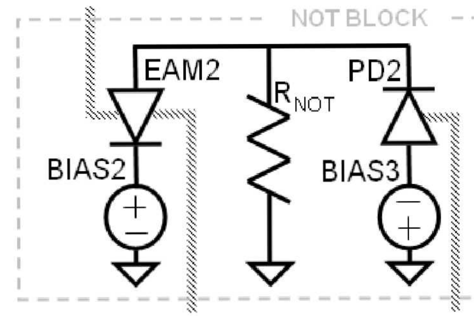
Optical Logic Gates: Motivation

- Optical logic enables high data rate networks with fewer O-E-O conversions
    - Header recognition, label swapping, parity checking, and data (de)encryption
- Logic Gate Requirements
    - Building-block framework for device and gate implementation
    - Boolean complete gate set which scales to LSI+ circuit complexity
    - Monolithically integrated to facilitate sophisticated multi-gate circuits
- Our Approach
  - Electro-absorption modulator (EAM) - Photodiode (PD) pair technology core
    - Use quantum well intermixing technology and epitaxial regrowth to…
      - Integrate devices with different functionalities
    - Assemble opto-electronic building blocks using discrete components that…
      - Share common growth and processing platform
    - These building blocks can be arranged in multiple configurations that…
      - Function as NOT, AND, NAND, NOR, XOR, latches and so on

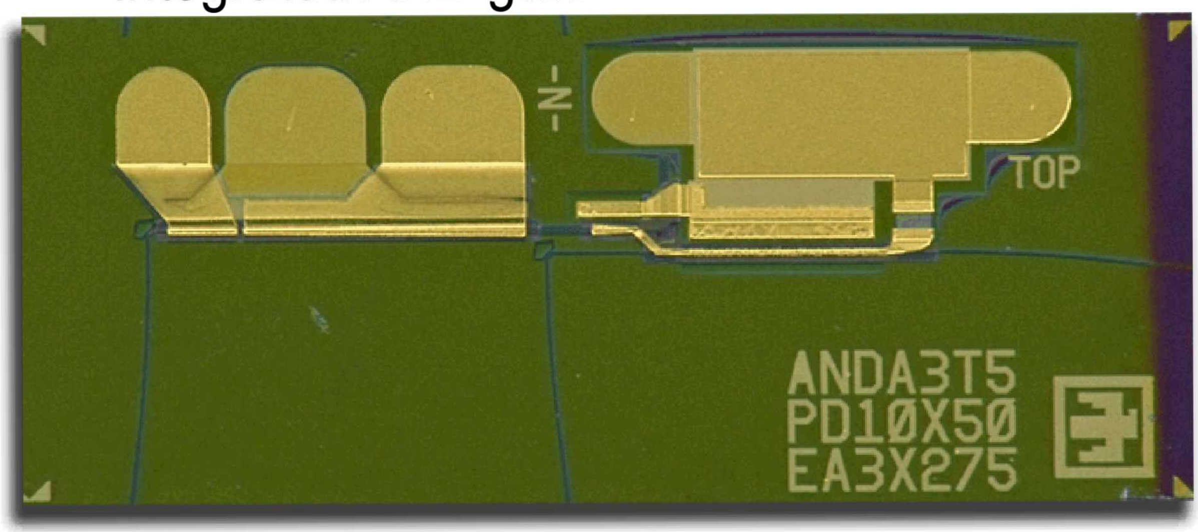
Optical Gate Layout

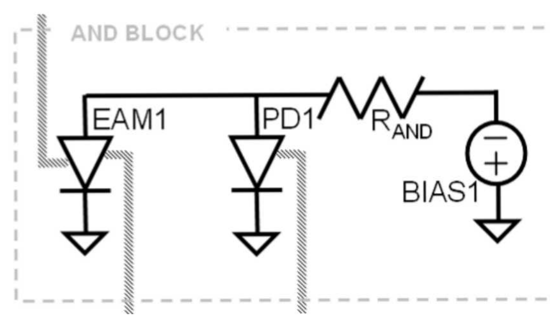
- Integrated NOT gate



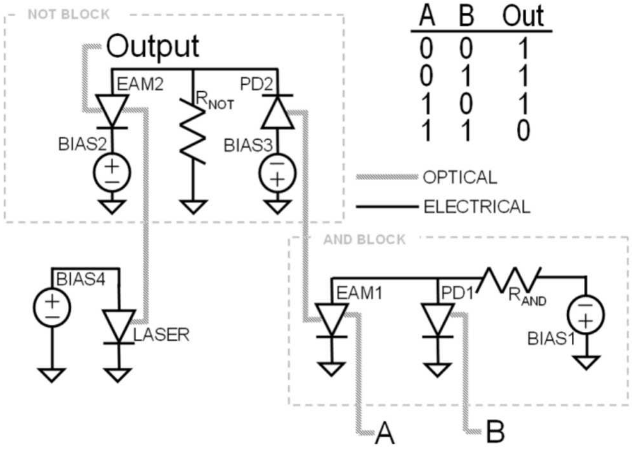


- Integrated AND gate





Circuit Designs



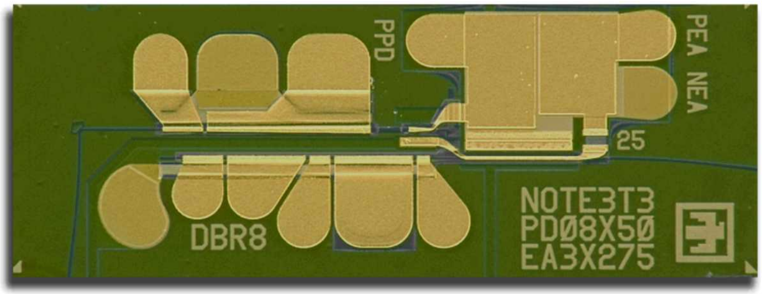
A	B	Out
0	0	1
0	1	1
1	0	1
1	1	0

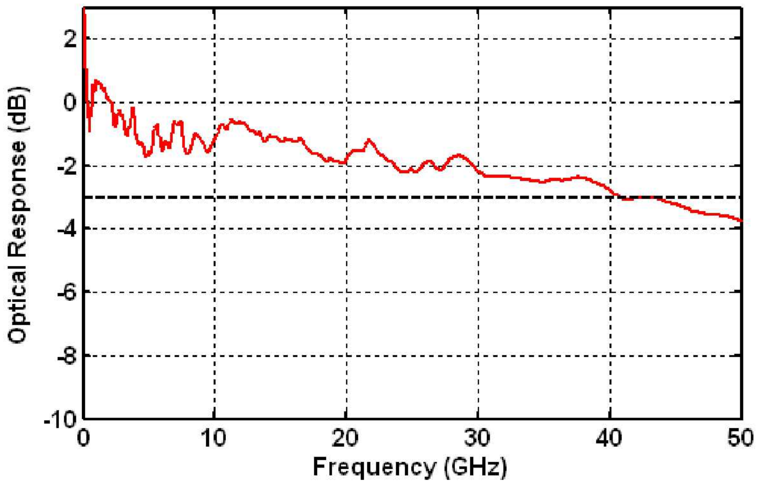
- Merits to this approach
  - Control signal is terminated at each EAM-PD pair
    - No need for complex filtering of wavelength
    - Can perform optical 2R, reamplification and reshaping
  - Integrated lasers are tunable
    - Each NOT gate can perform wavelength conversion
    - Enables built-in signal routing and dynamic re-configurability
  - Circuit is bit-rate independent
    - Can operate NRZ or RZ over various line rates
  - Components are resilient to modest changes in wavelength
    - PDs are quite broadband
    - EAMs have been shown to operate over full c-band

Patent Pending: 12/182,683 Skogen, Raring, Tauke-Pedretti, 'Optical NAND Gate'

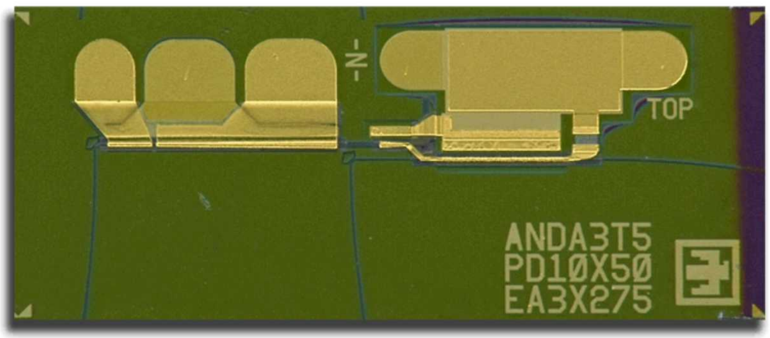
Gate Bandwidth

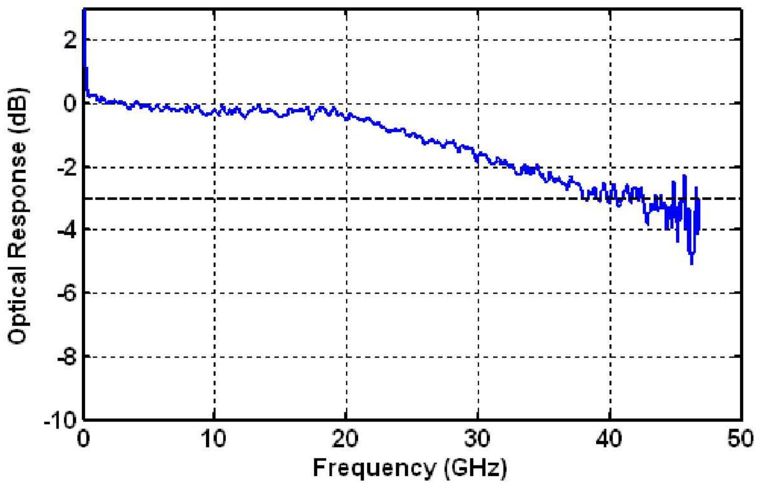
- NOT gate frequency response
  - 25 Ω load, 40 pF capacitors
  - 40 GHz optical 3 dB bandwidth





- AND gate frequency response
  - 25 Ω load, 51 pF capacitor
  - 40 GHz optical 3 dB bandwidth

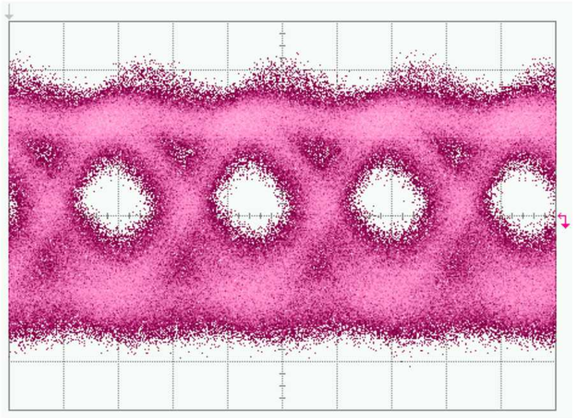


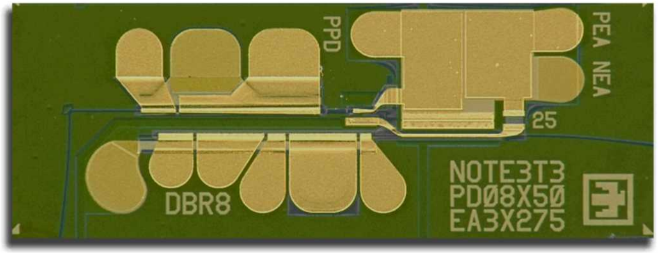


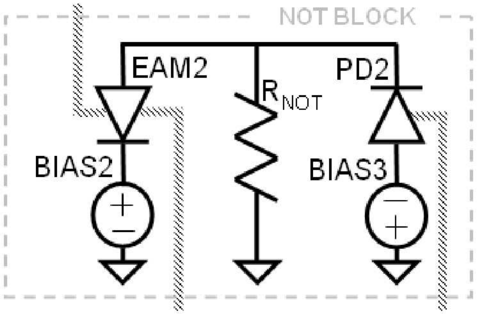
E. Skogen, *et al.*, Photonics in Switching. PWA6 (2010).

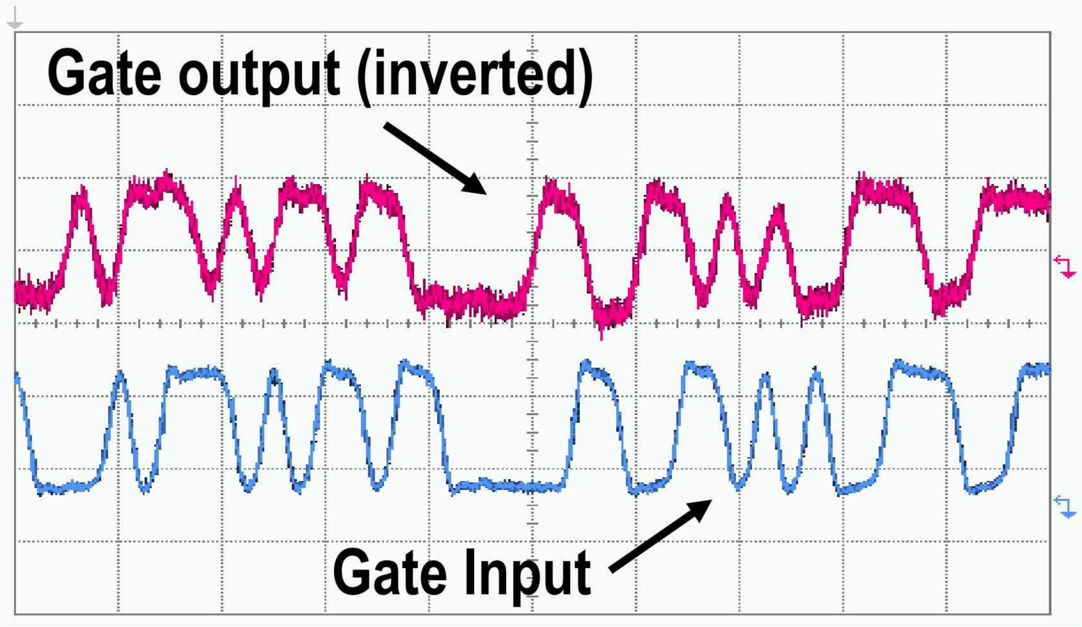
NOT Gate Waveforms

- Gate functionality
  - 40 Gb/s PRBS signal with 2^7-1 pattern length
    - Length could be increased with off-chip caps
  - Gate output detected using inverting receiver
    - Extinction ratio will improve with larger P_{sat}





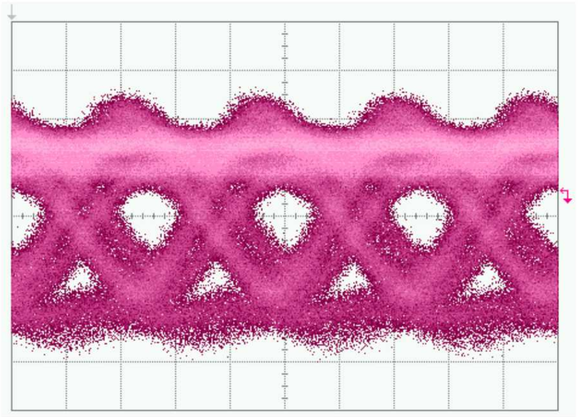


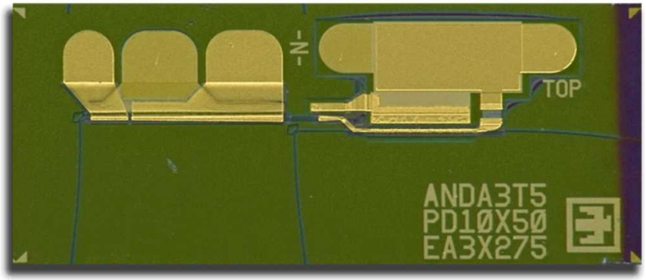


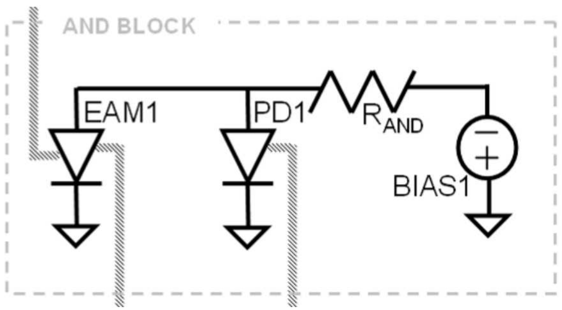
E. Skogen, *et al.*, Photonics in Switching. PWA6 (2010).

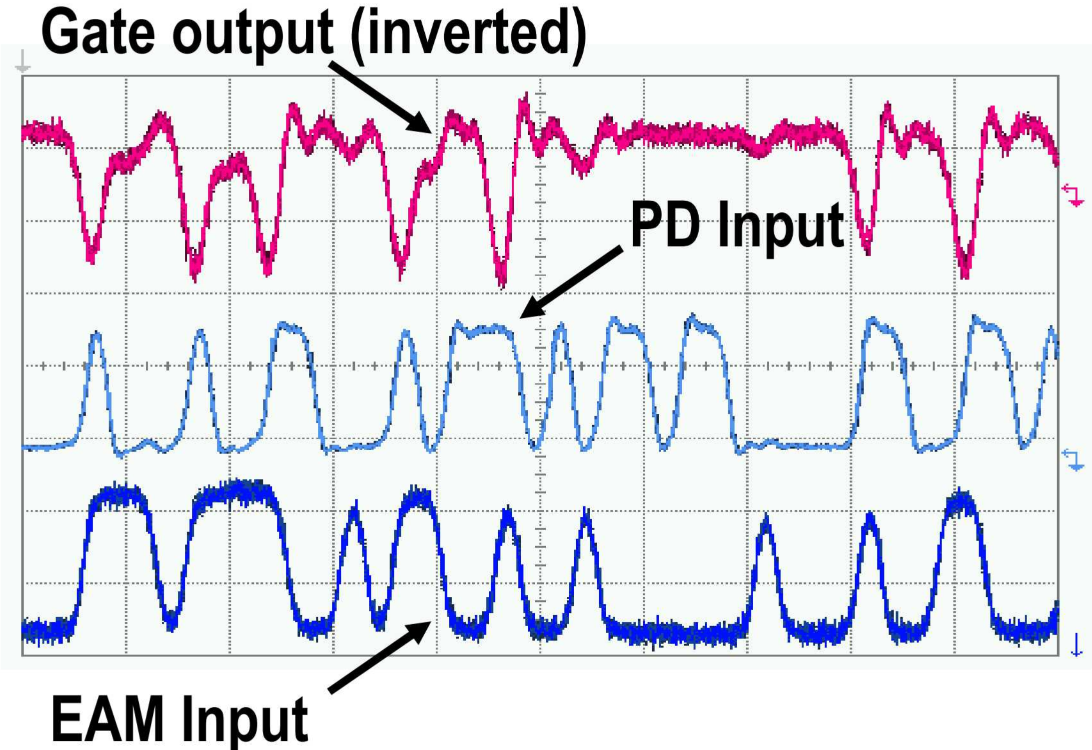
AND Gate Waveforms

- Gate functionality
  - 40 Gb/s PRBS signal with 2^7-1 pattern length
    - Length could be increased with off-chip caps
  - Gate output detected using inverting receiver
    - Extinction ratio will improve with larger P_{sat}







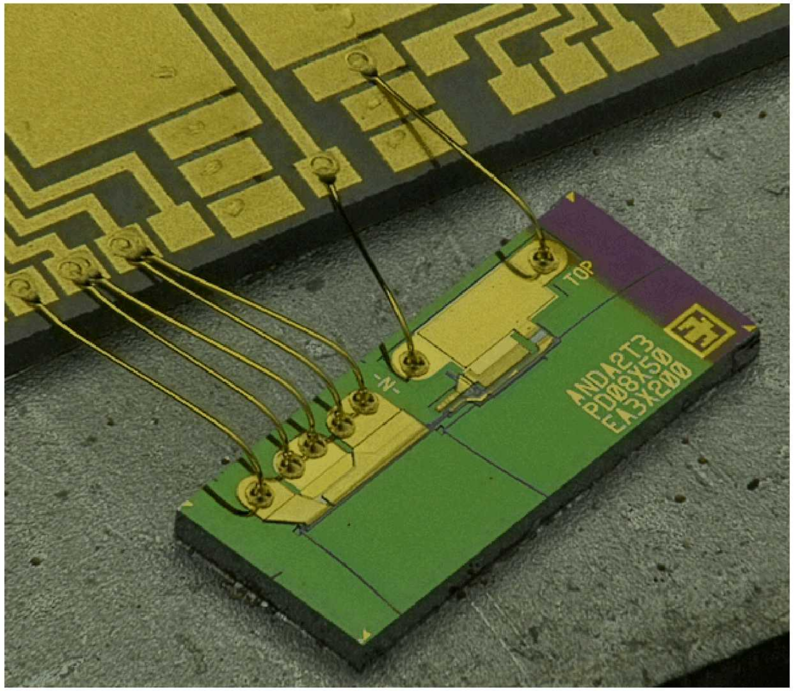


E. Skogen, *et al.*, Photonics in Switching. PWA6 (2010).

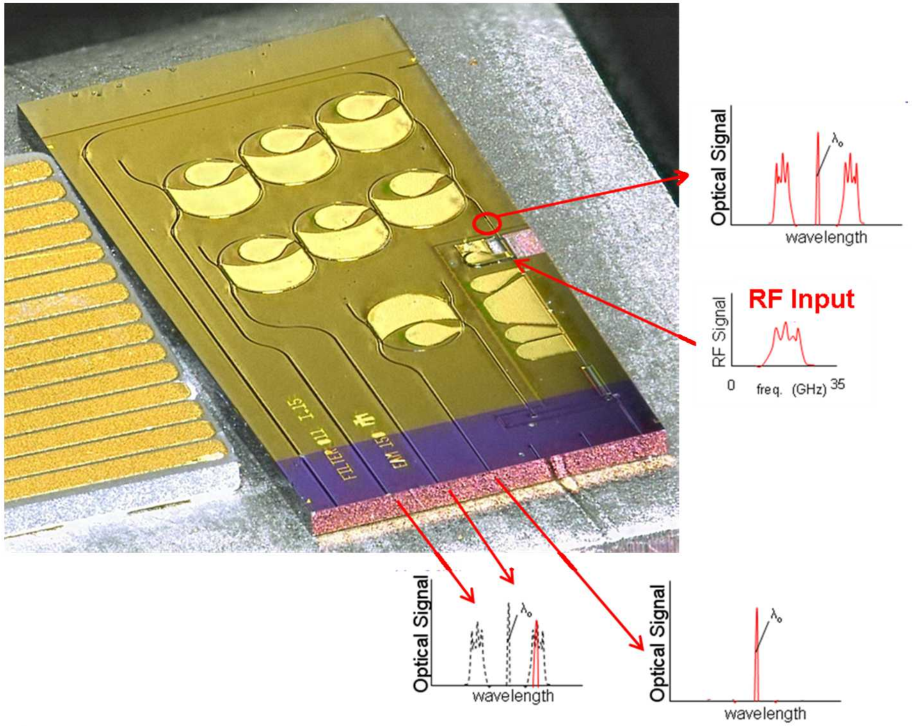
Optical Logic Gates: Summary

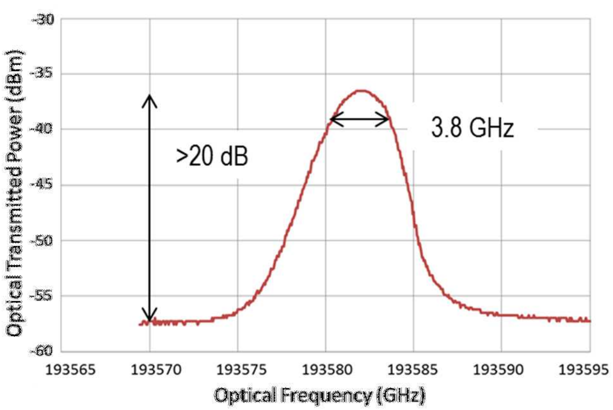
- We have extended EAM-PD structures into the photonic logic application space

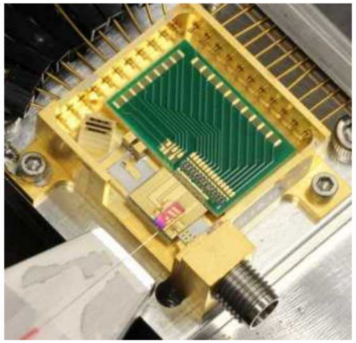
  - NOT and AND gates demonstrated at 40 Gb/s using a flexible processing platform for monolithic integration



Optical RF Channelized Receiver

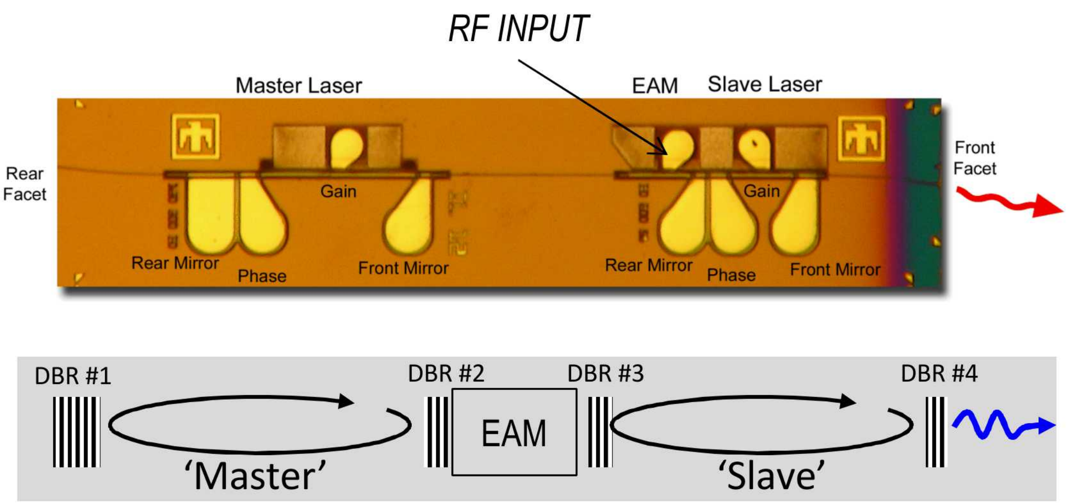


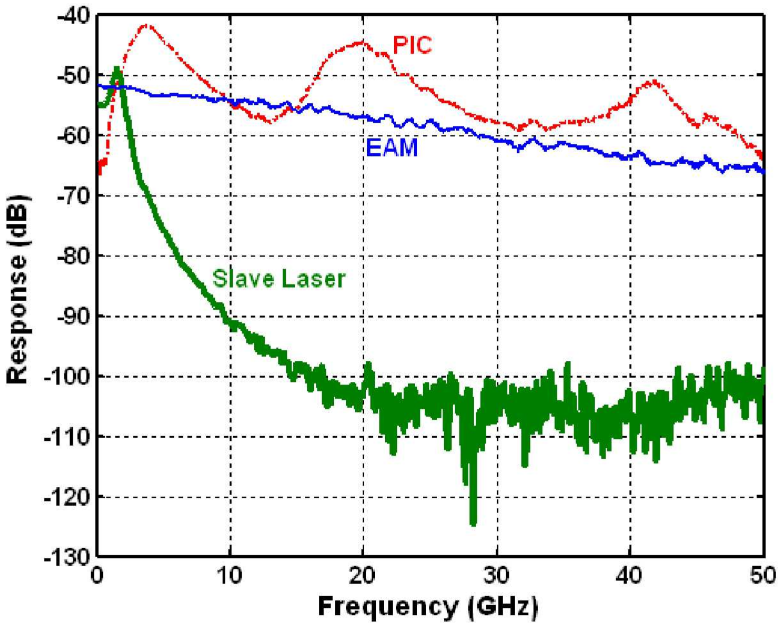




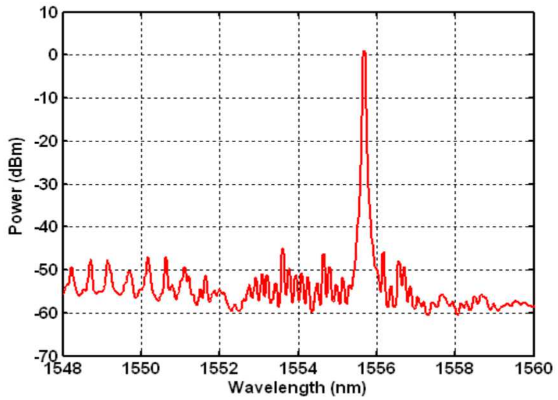
- Analyze an RF signal for frequency content
  - Filter outputs are spectral power density integrated over the filter bandwidth
- Compact, highly functional photonic integrated circuits (PICs) features:
  - 3-pole ring resonator filters
    - Tunable over 10’s GHz
    - GHz-class pass bands
    - 65 GHz free spectral range
  - Integrated laser-modulator
    - Signal to EAM provides the RF input
  - Integrated extra filter for wavelength monitoring

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



Summary

- Sandia has created a wide array of PICs using a common toolkit
- PICs continue to evolve and impact applications outside of telecommunications and datacom including:
  - optical signal processing, sensors, fundamental device research, RF photonics
- InP PICs offer unique capabilities as standalone circuits and can be complementary to other platforms
- Performance of individual components rival discrete counterparts

Thank You

ejskoge@sandia.gov