SAND2014-16118PE

Exceptional service in the national interest

Sandia National Laboratories

Very large scale integrated optical interconnects: Coherent optical control systems with 3D integration

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2014 Integrated Photonics Research IMA2A.1 Monday (10:30-11:00)

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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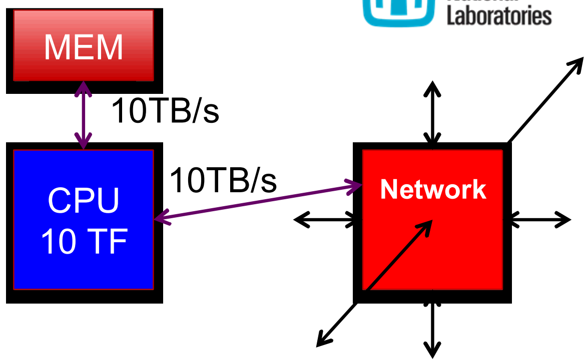
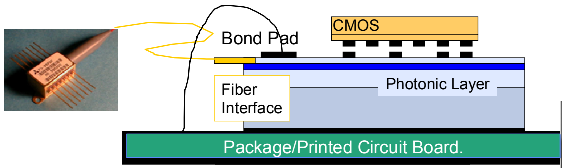
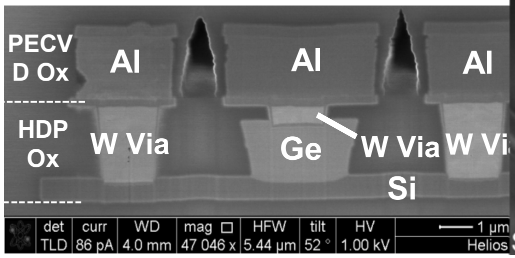
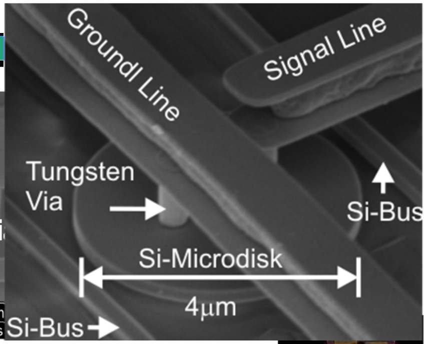
A new approach to high performance computing

- ***Instead of … Evolutionary architecture approach***:
  - Design around limited (network and memory) interconnect bandwidth (<< 1 bit per second/flop)
- ***Pursue … Revolutionary approach***:
  - Small silicon micro-photonic devices intimately integrated with network and processor ICs
  - Chip-scale 100s Tbps IO
  - <100 femtojoule/bit → <10sW IO

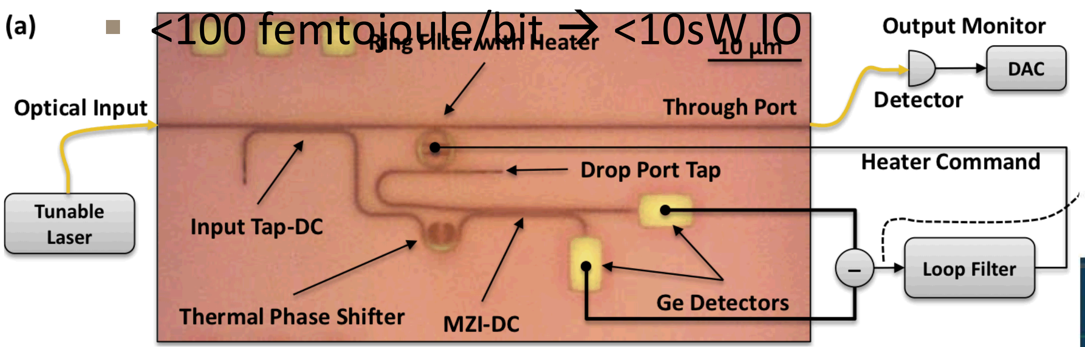


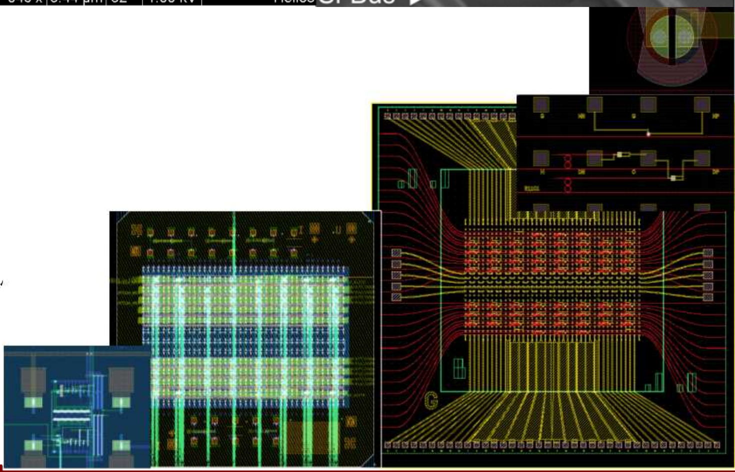






(a)





Resonant silicon micro-photonics

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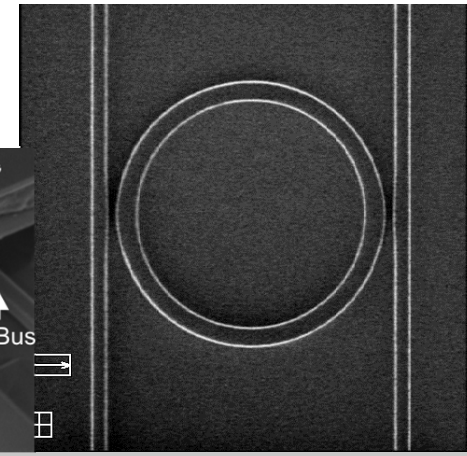
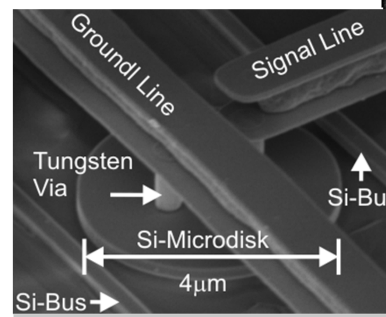
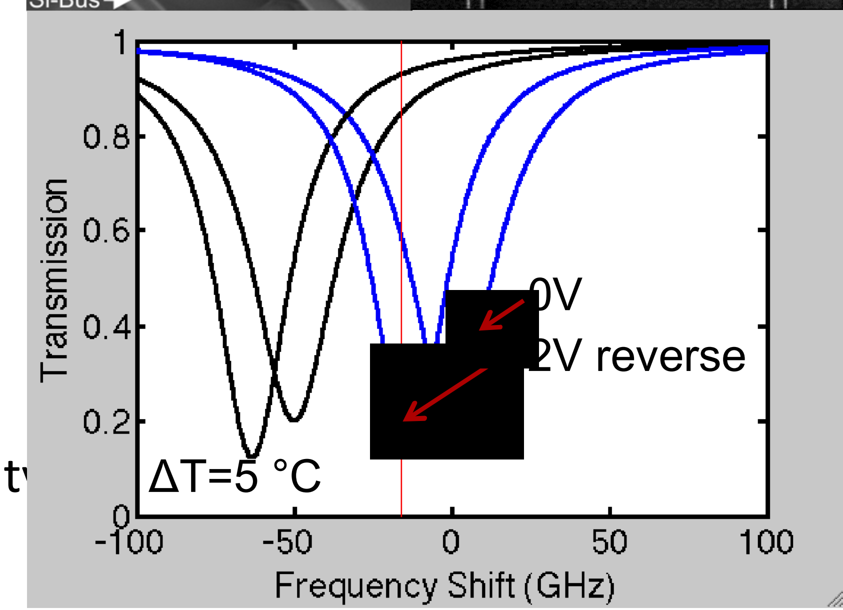
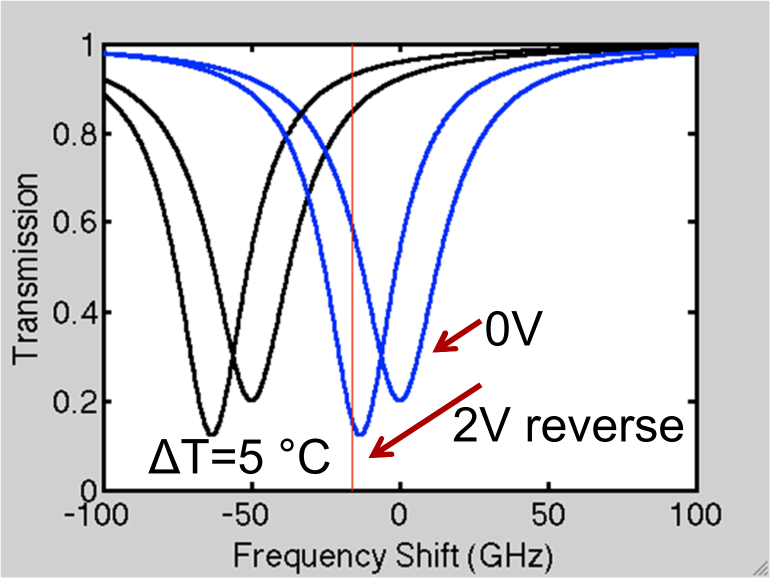
- Why resonant silicon photonics?
  - Small size (<4 um dia.)
  - Resonant frequency → DWDM modulators & mux/demux
- Benefits
  - Low energy (→ 1 fJ/bit)
  - High bandwidth density (→ 1 Tb/s/line)
- Resonant Variations
  - Manufacturing Variations
  - Temperature Variations
  - Optical Power (1s density)
  - Aging?
- Requirements:
  - Resolution: +/- 0.25 ° C (1 dB Laser penalty
  - Range: 0 – 85 ° C (depending)

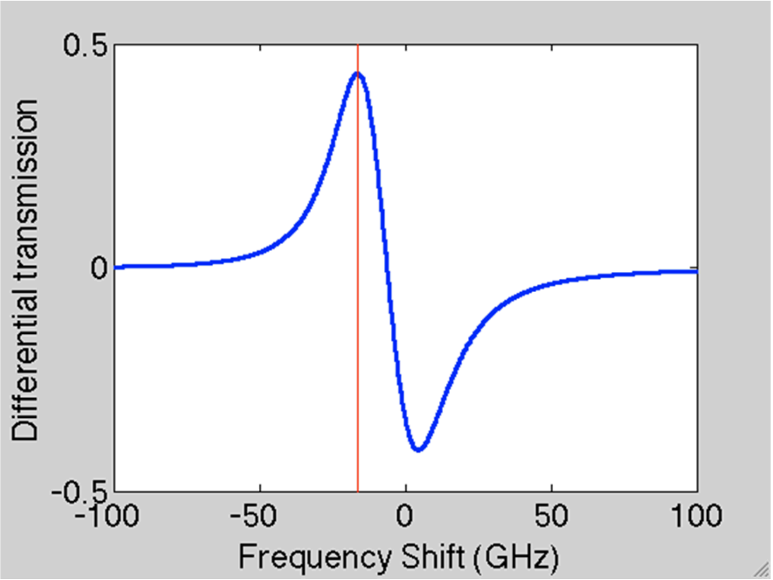


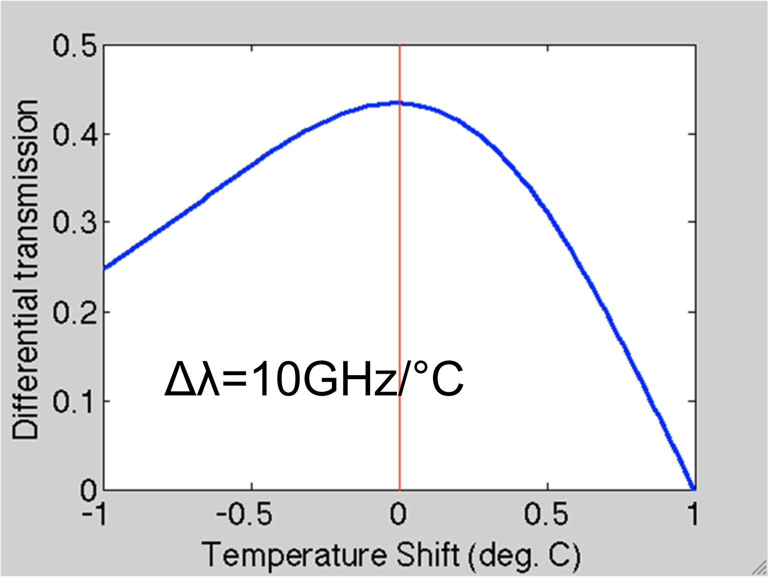


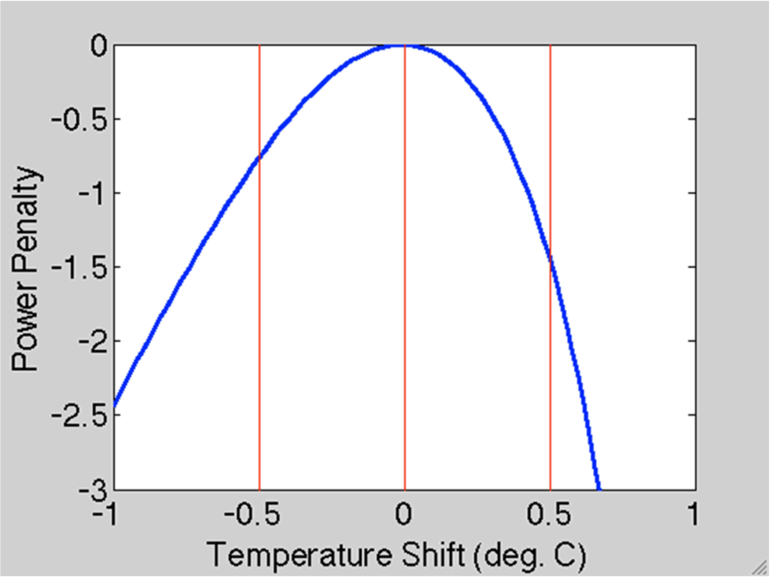


Effect of temperature on loss budget

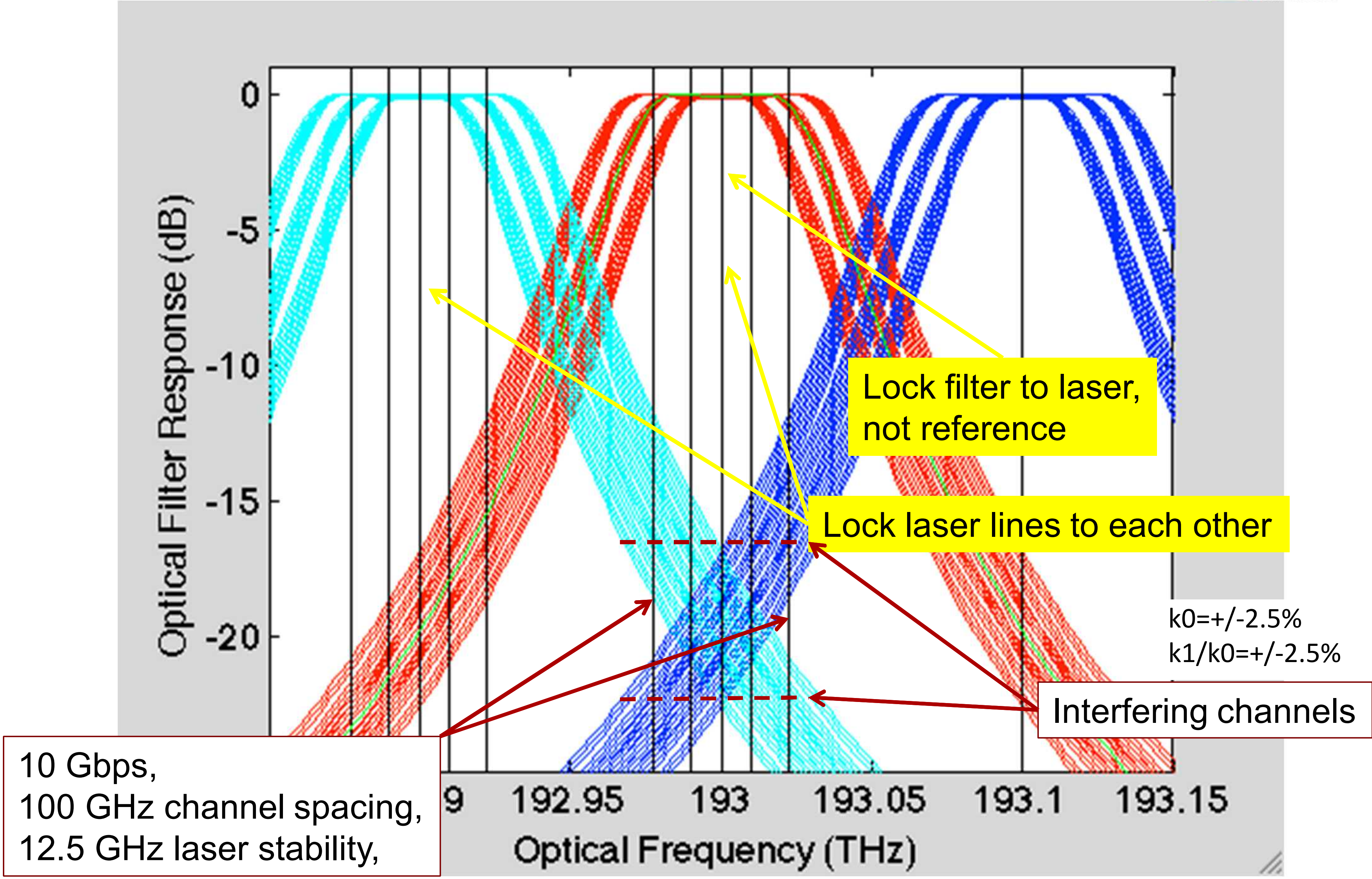








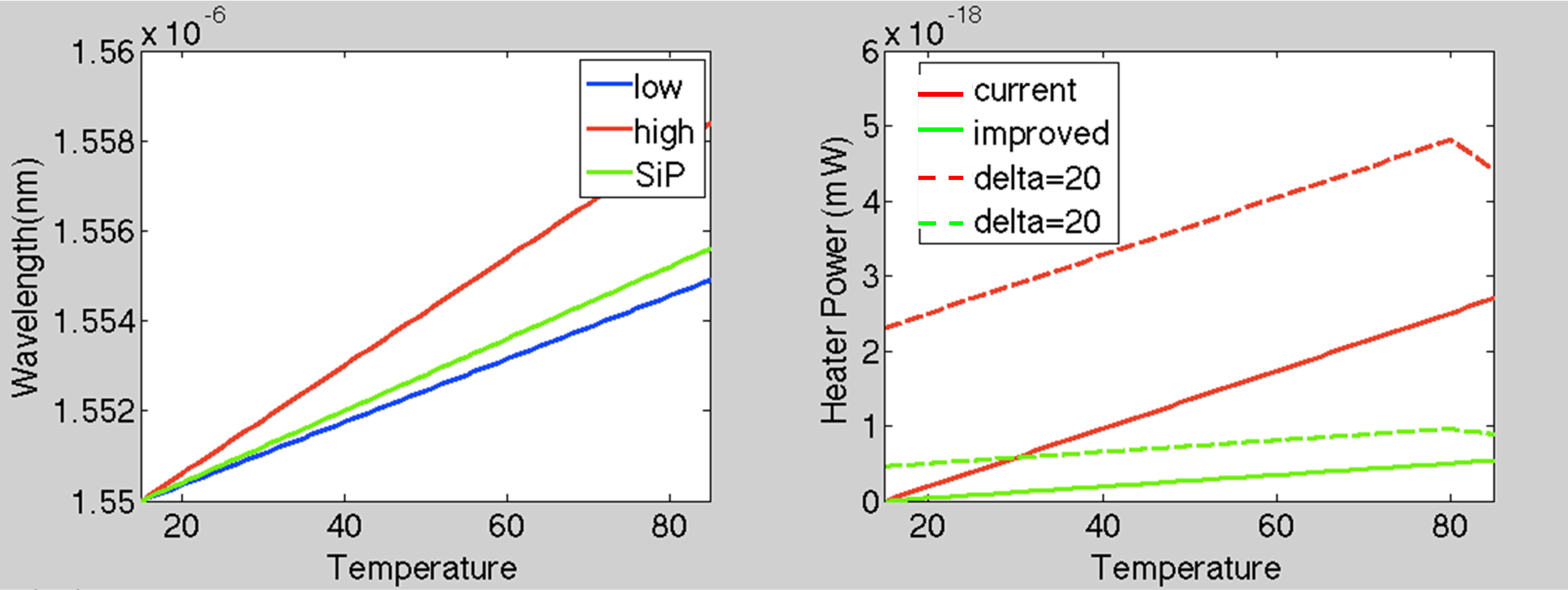
Filter allowable temperature drift.



Calculations based on Little et. al. JLT, 1997

λ Stability: Differential temperature differences

- Should we let the laser wavelength drift with temperature?
  - **Range requirements 0 – 85 ° C**
  - CWDM lasers (up to 10% efficient (0.7 – 1.2 nm/ ° C) SiP ~ 0.8 nm/° C)
  - Lock laser to resonator (Oracle 2.5% - 5% efficient)



Cyclical Channels

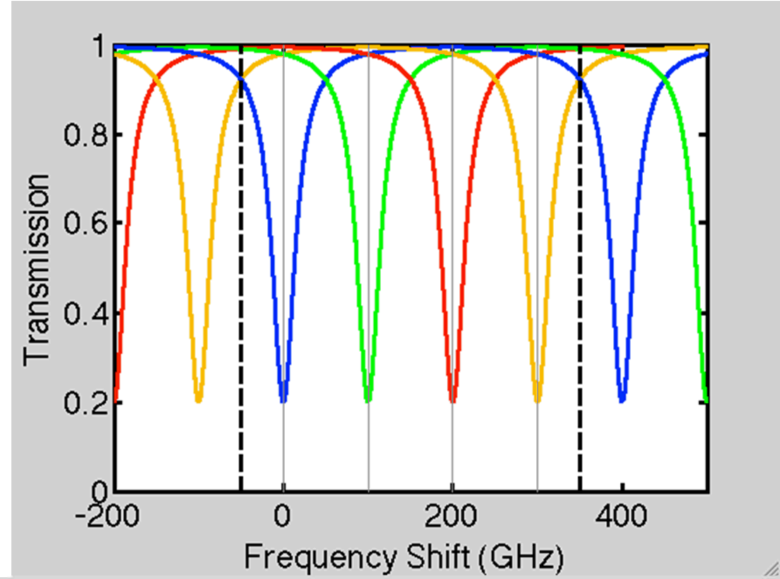
Example: 4 × 100GHz channel spacing

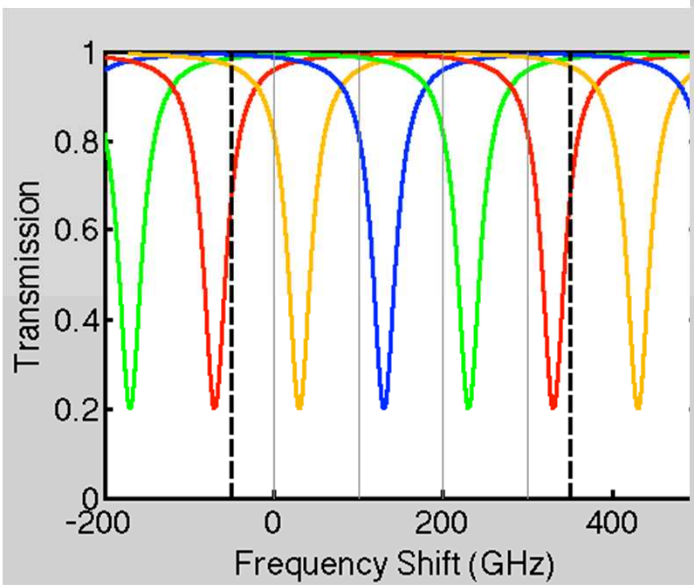
a) Designed alignment

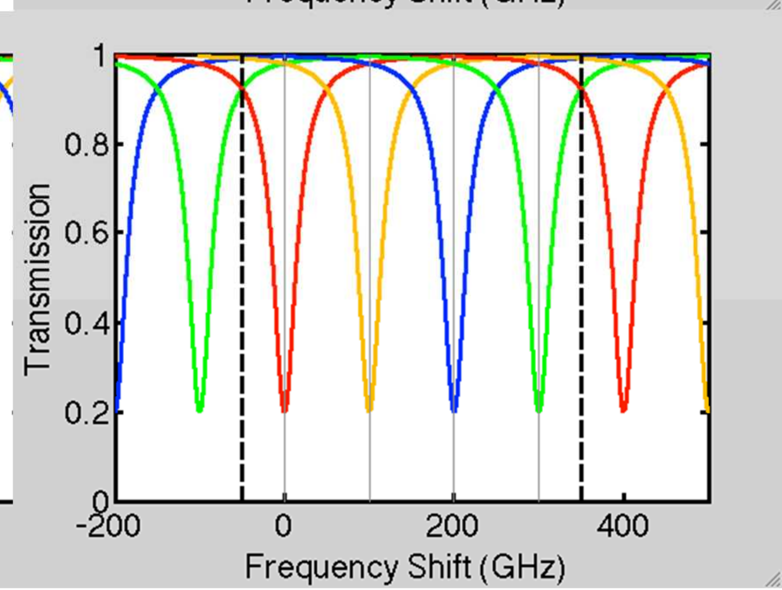
b) 13 ° C heating – 130 GHz shift

c) 7 ° C controlled heating to 200 GHz shift

Maximum heating = channel spacing / df/dT:
100GHz/10GHz/° C = 10° C







N. Binkert et al., ISCA 2011;

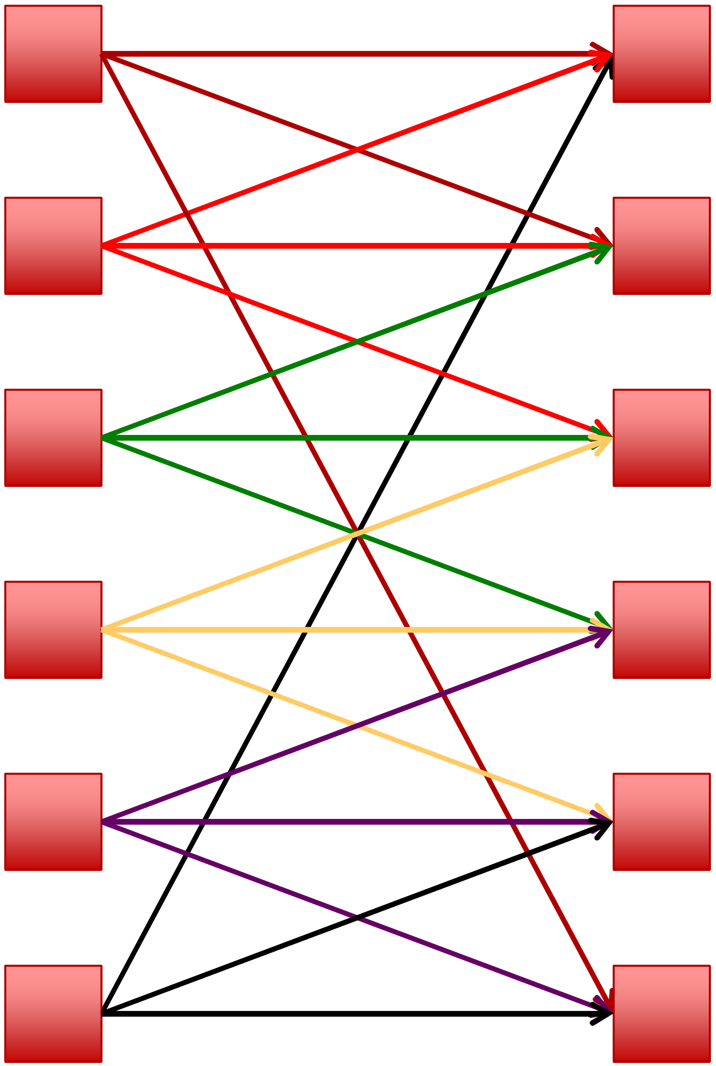
M. Gorgas et. al., IEEE CICC, 2011

A. Krishnamoorthy et. al., IEEE Photonics J., 2011

Circuit for DWDM channel alignment

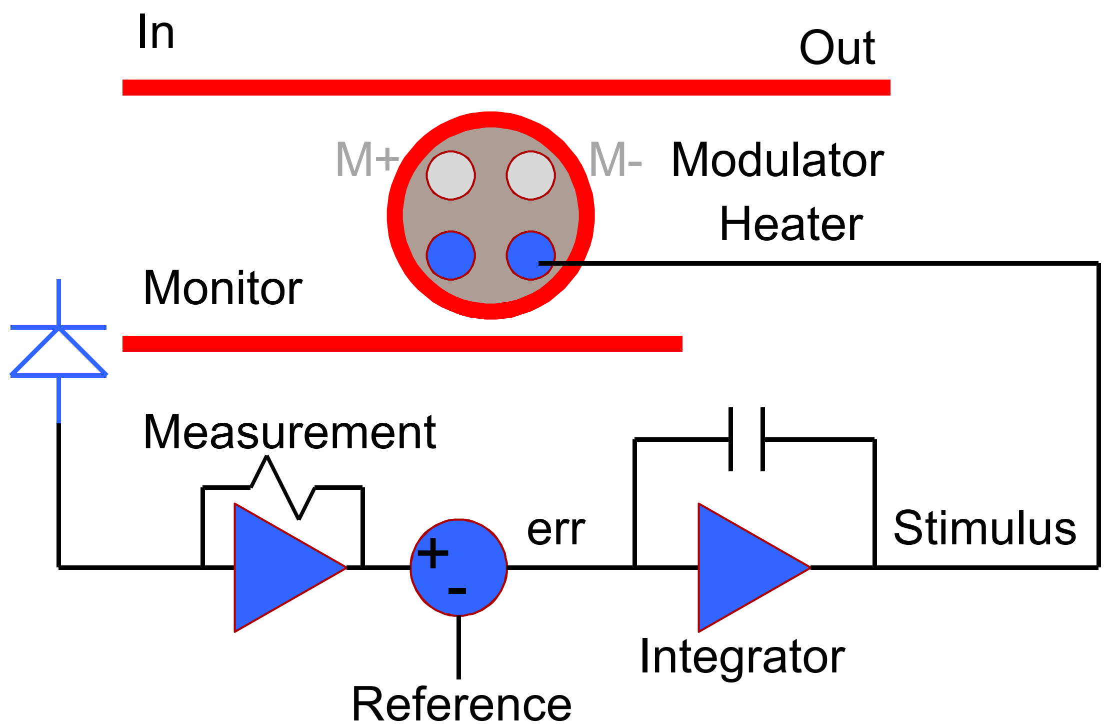
- MOSIS: Ring Oscillator 1.21 nW/MHz/gate → 0.3 fJ/bit (45 nm)
- Inverter, I = 0.25 fJ/bit (1 fF/1V)
- Logic Gate, L = 0.5 fJ/bit (2 fF/1V)
- Mux, M = (Sc-1)*L; Sc= S↑ power of 2
- Register, R = 10•L = 5 fJ/bit
- Buffer fan-out, F=S•I

- Back of envelope example: N=40, S=6
  - 2N registers (number of channels)
    - 80 * 5 fJ/bit = 400 fJ/'word'
  - Fan out of S
    - 40 * 6 * 0.25fJ/bit = 60 fJ/'word'
  - N S:1 multiplexers
    - 40 * (7) * 0.5fJ/bit = 140 fJ/'word'
  - Sum = 600 fJ/'word' = **15 fJ/bit**
  - SLOW circuitry
    - Control of the shifter
    - Extra laser channel

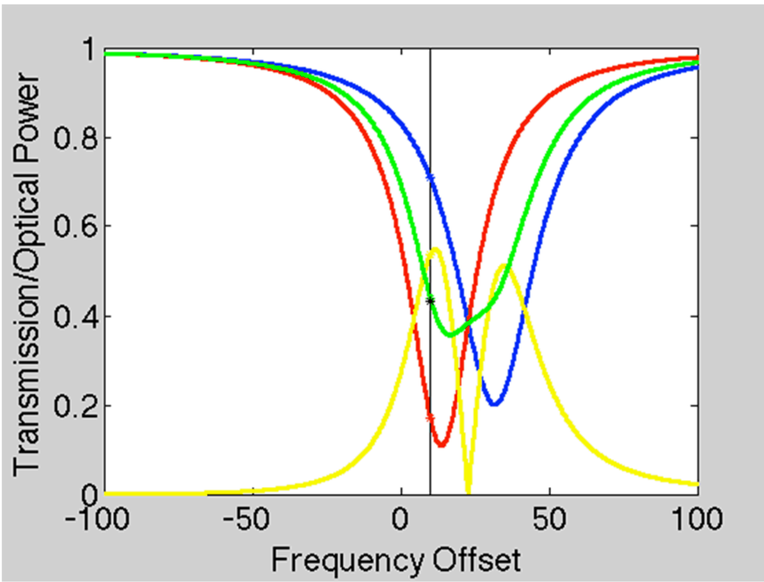


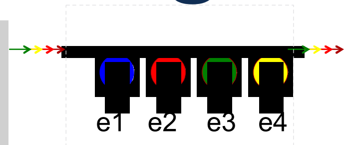
Resonant Wavelength Closed Loop Control

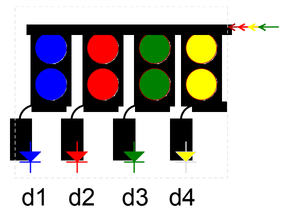
- Control Loop
  - Measurement
    - Temperature
    - Power (shown)
    - Phase (BHD, PDH)
    - Bit errors
  - Integration (PI Loop)
  - Stimulus
    - Integral Heater (shown)
    - Forward bias (heater/carriers)
    - Reverse bias (carriers)

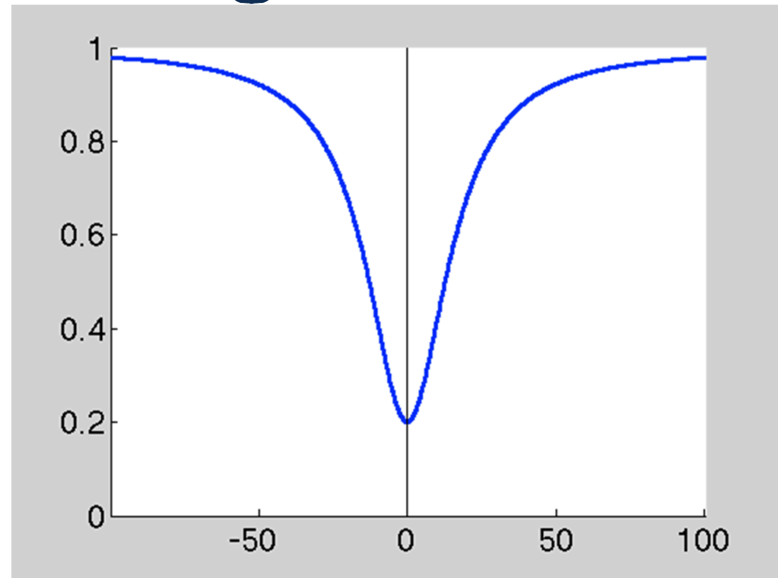


Resonant Wavelength Locking









Modulator

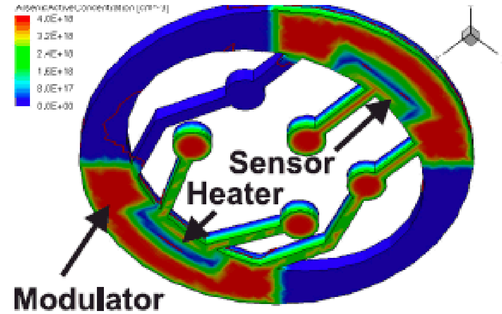
- Lock on side of resonance
- Accuracy depends modulation slope with wavelength
  - Independent of Wavelength spacing
  - Number of channels –
- Inaccurate lock leads to power penalty

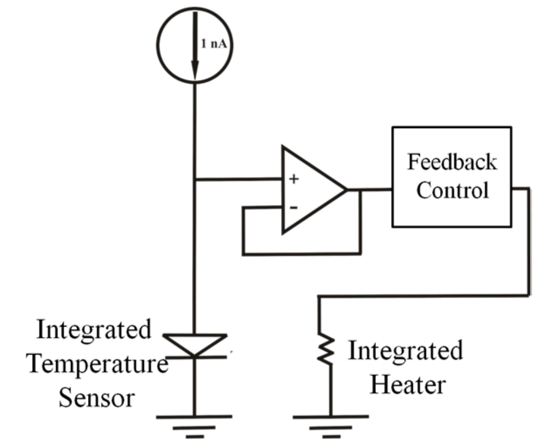
Filter (DeMux)

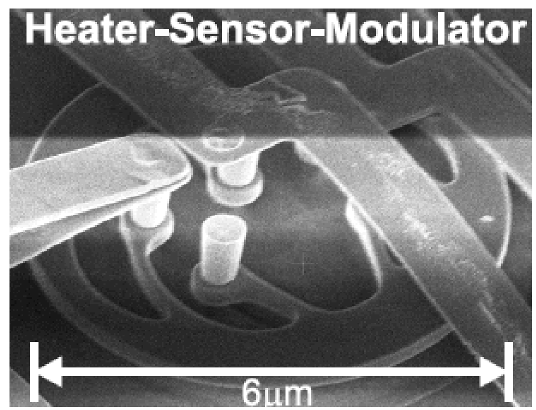
- Lock at minimum power
- Accuracy depends on bandwidth of filter (0.25° C – 1° C)
  - Wavelength spacing
  - Number of channels
- Inaccurate lock leads to crosstalk and power penalty

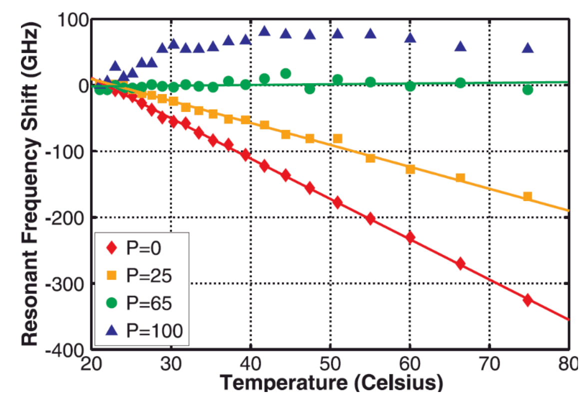
Temperature Sensor (Sandia)

- First attempt at resonant wavelength control
- Integral temperature sensors (diode)
- Sensor not independent of background temperature
- More complex device
- Not measuring other wavelength shifting affects
- Simple electronics (PI loop with P=k, I=0)









C. T. DeRose, et. al., CLEO 2011

Locking using Power Sensors (MIT, Columbia, Rice, Oracle)

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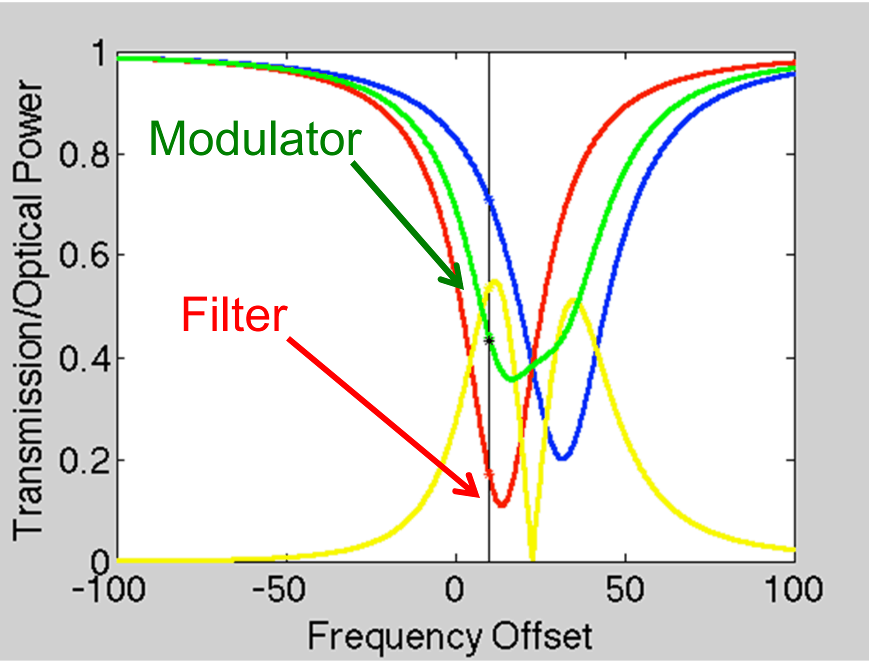
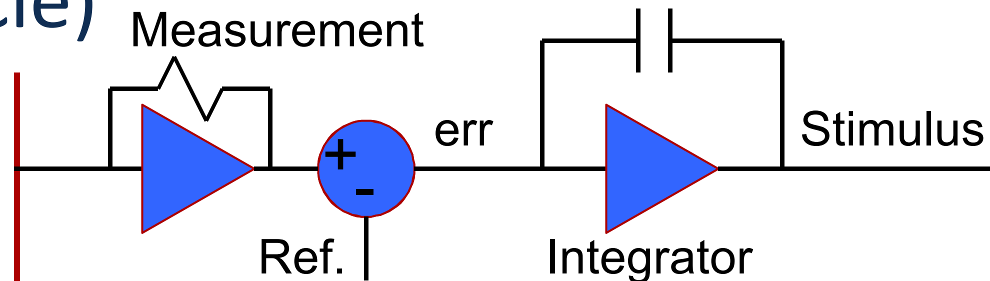
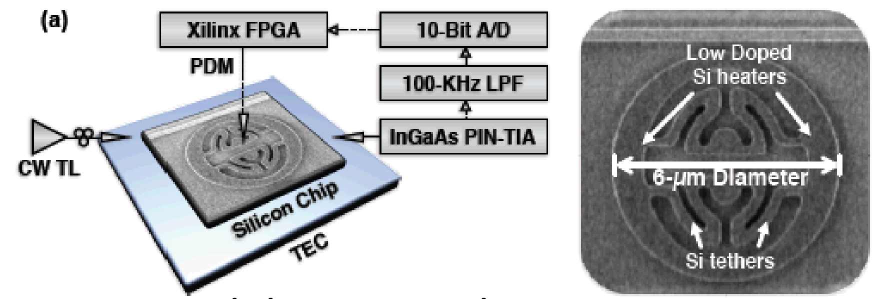
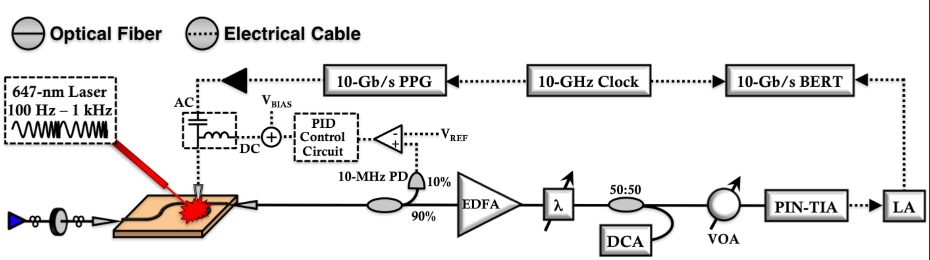


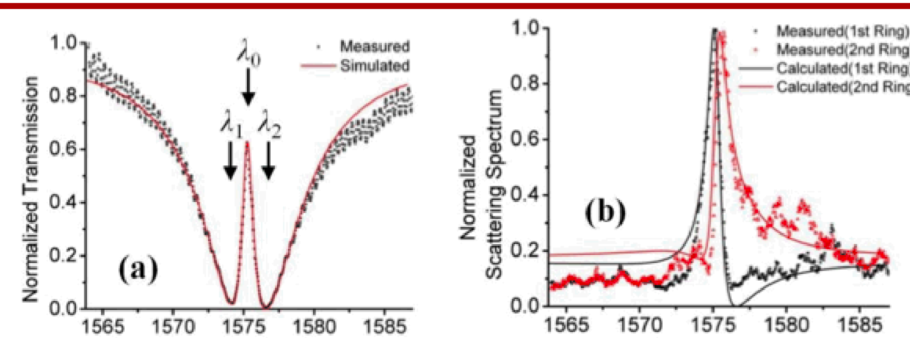




Resonator with heater, without sensor (Timurdogan et. al., CLEO 2012)



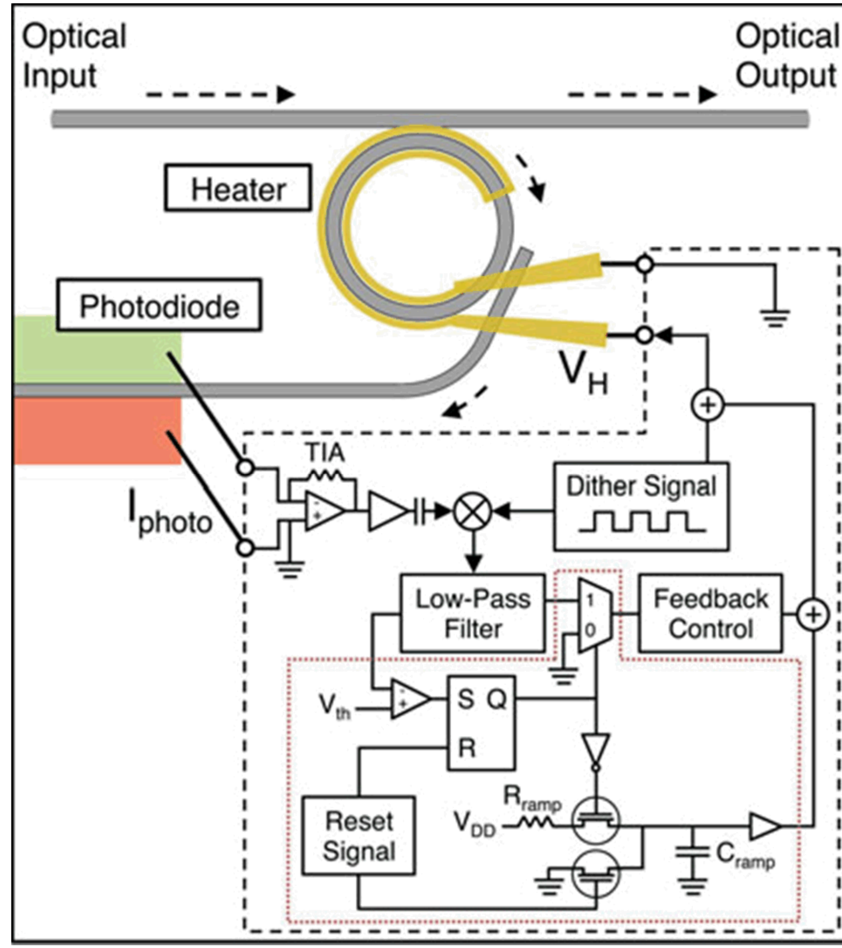
Modulator with bias induced temperature change (Padmaraju, OFC 2012)



Scattering from a dual-ring modulator (Qui et. al. Opt. Exp., 2011)

Locking using a dither signal (Columbia)

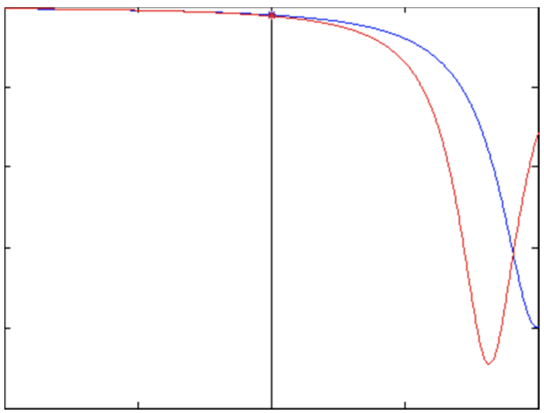
- Creates a signal that is anti-symmetric (lock at zero)
- More complex electrically
- Simple optically
- Some small degradation in the optical performance with dither
- Best for filter locking

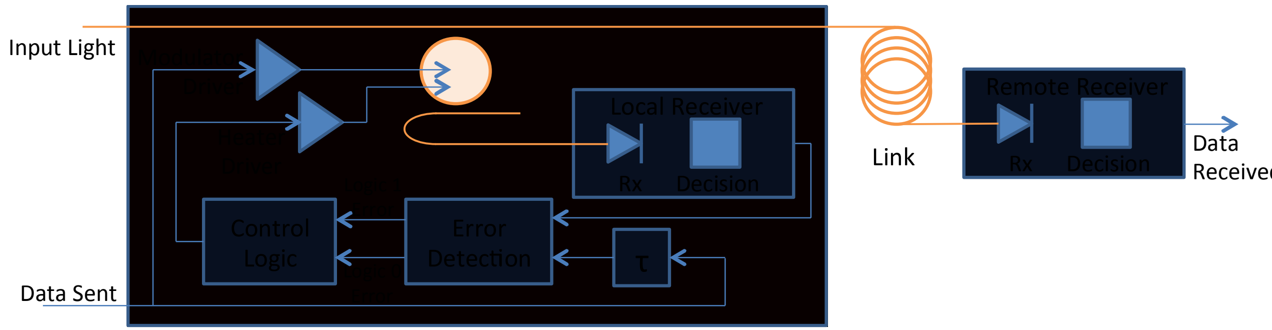


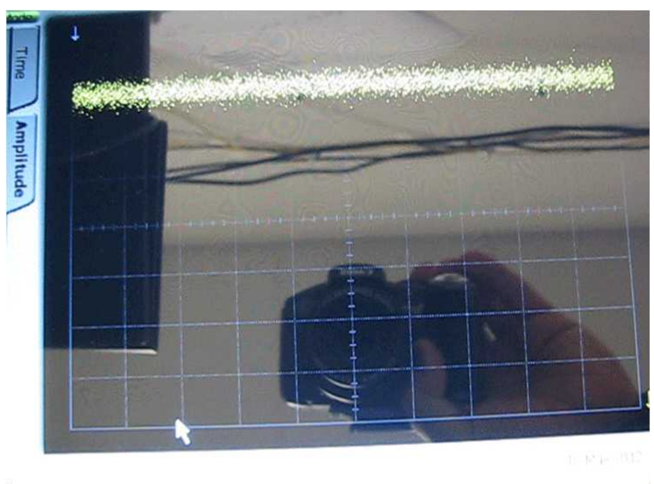
K. Padmaraju, et. al. JLT 32 (3) (2014)

Modulator wavelength stabilization using bit errors (Sandia)

- Direct measurement of the bit errors
- Requires high speed circuitry
- Most compact solution (no low pass filtering)

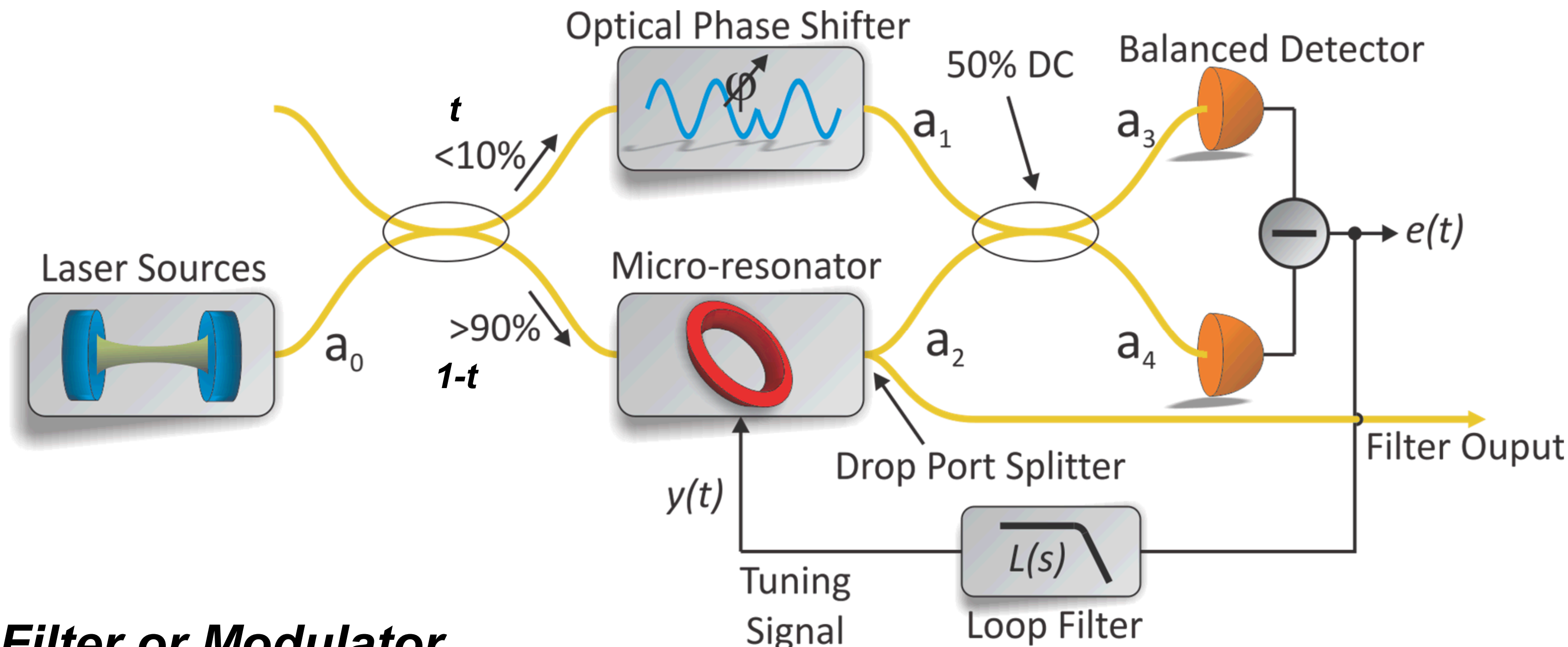






W. A. Zortman et. al., IEEE Micro (2012)

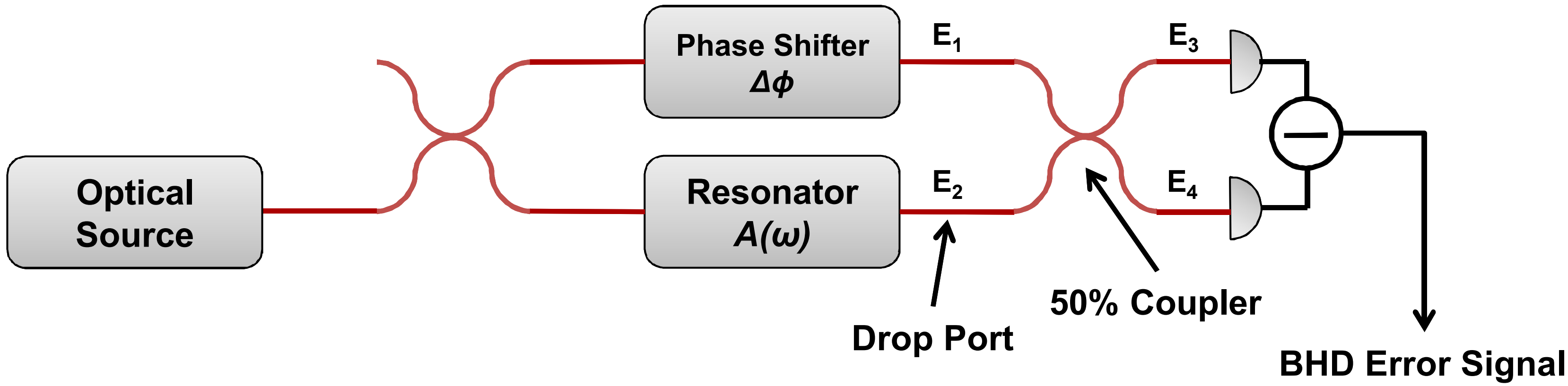
Balanced Homodyne Detection

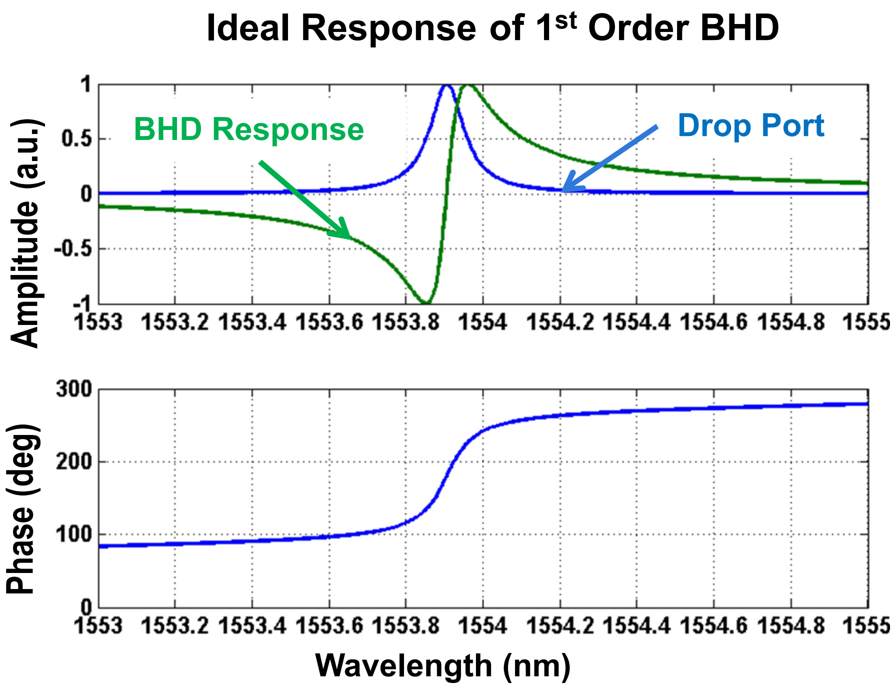


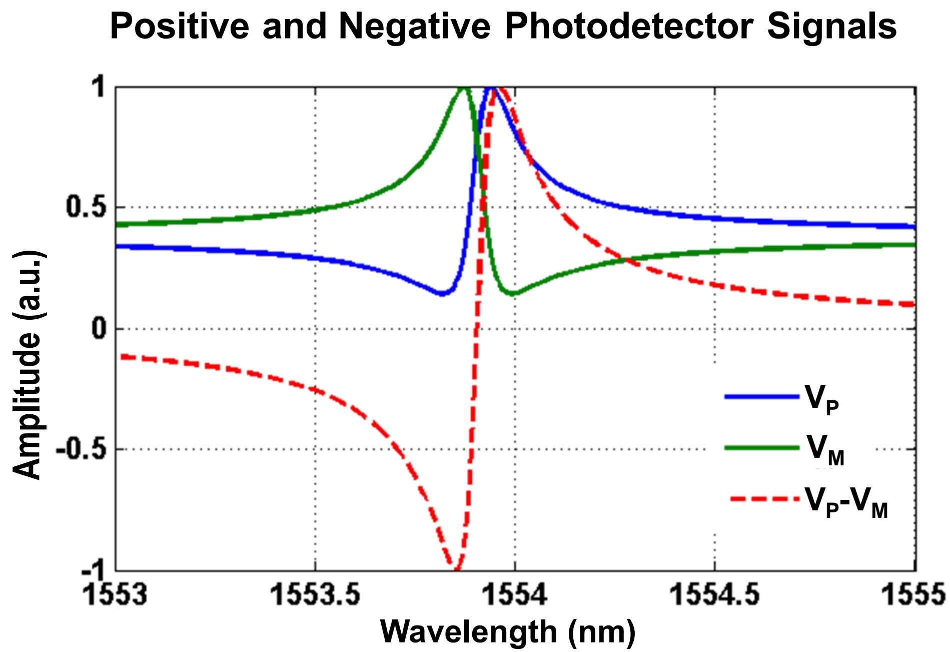
- ***Filter or Modulator***
- ***Lock to zero:*** No calibration or reference level needed for locking
- ***Amplitude insensitive:*** Locking point not influenced by optical intensity
- ***Precision locking:*** Resonator is not disturbed
- ***Minimum circuit complexity:*** Power and area consumption of control electronics is minimized

J.A. Cox, A.L. Lentine, D.C. Trotter and A.L. Starbuck, "Control of integrated micro-resonator wavelength via balanced homodyne locking," ***Opt. Express*** **Vol. 22(9) (2014)**

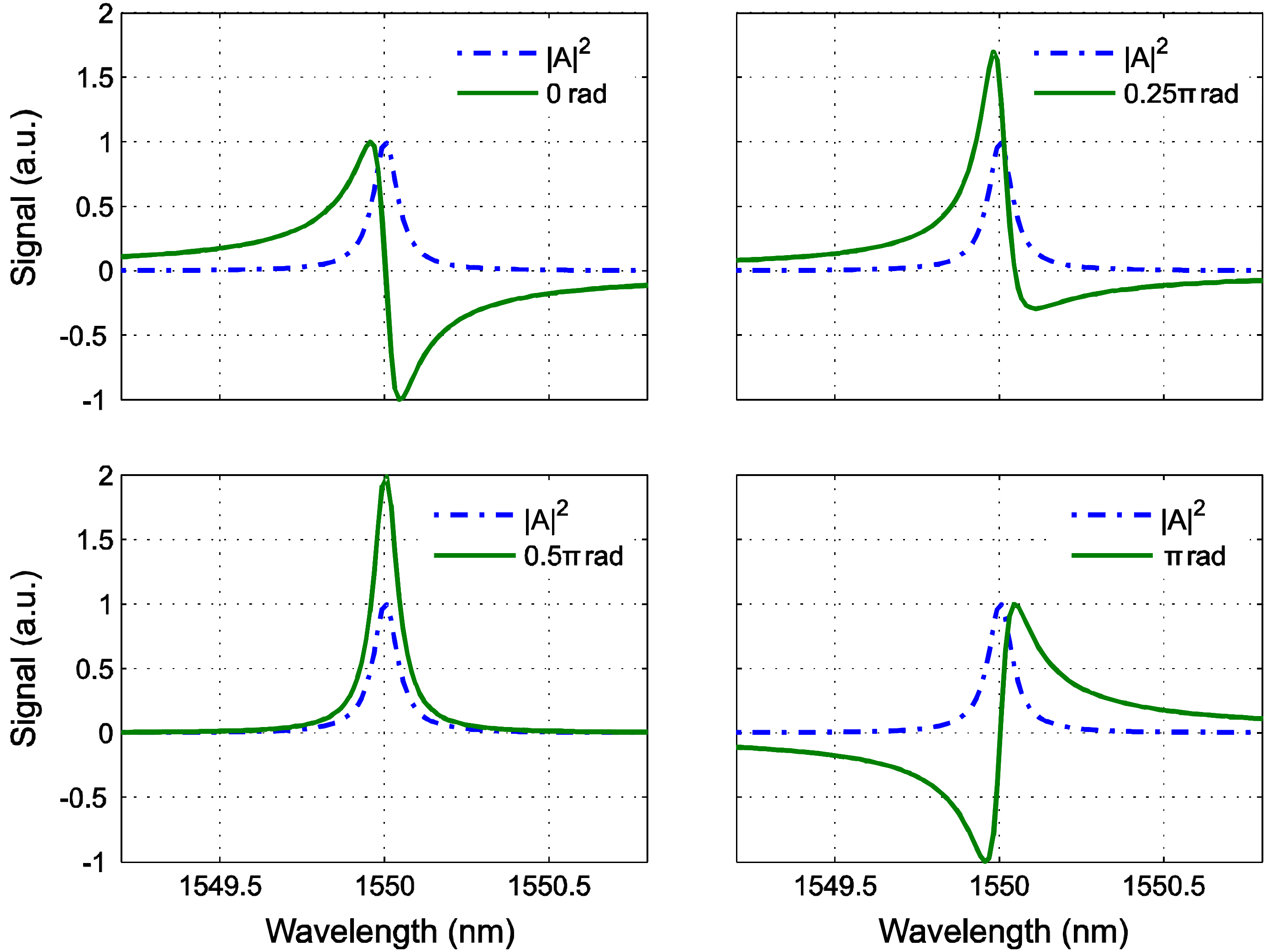
BHD Transfer Function





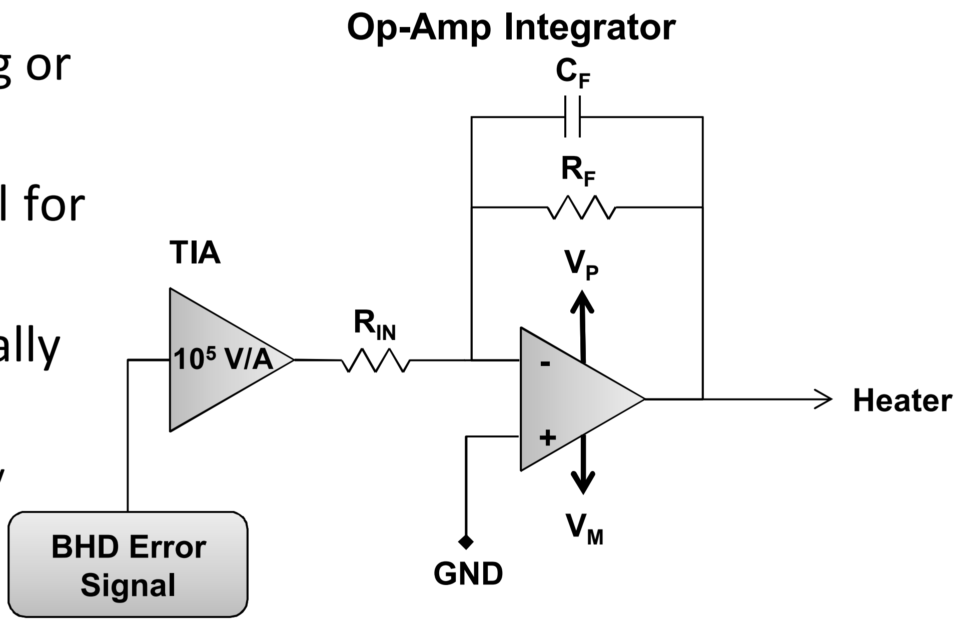


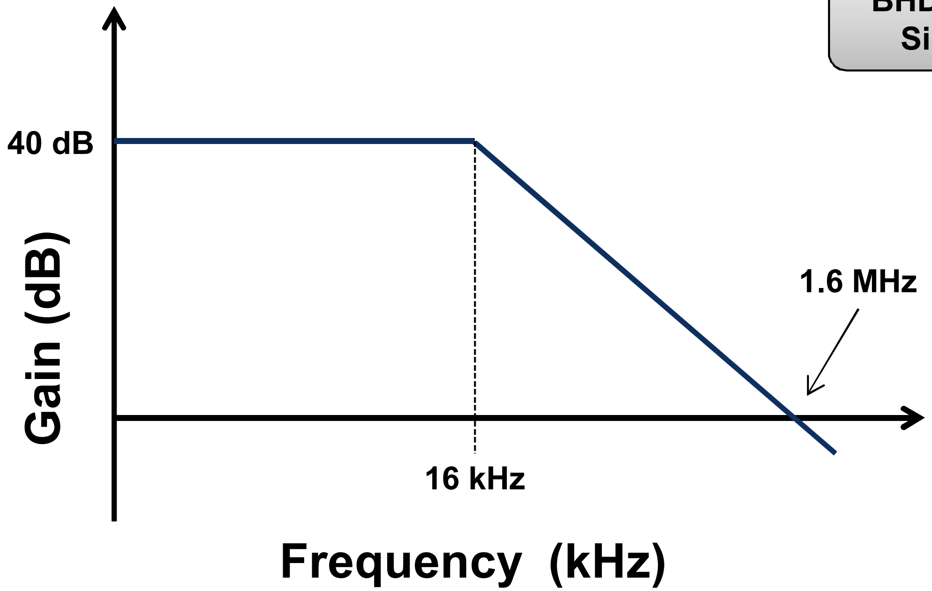
Effect of Phase Imbalance



Control Loop

- Simplest possible circuit for analog or digital implementation on-chip
- Smallest component values critical for analog design on ASIC
- Dual voltage operation automatically provides inverted feedback
  - Loop stable regardless of BHD polarity

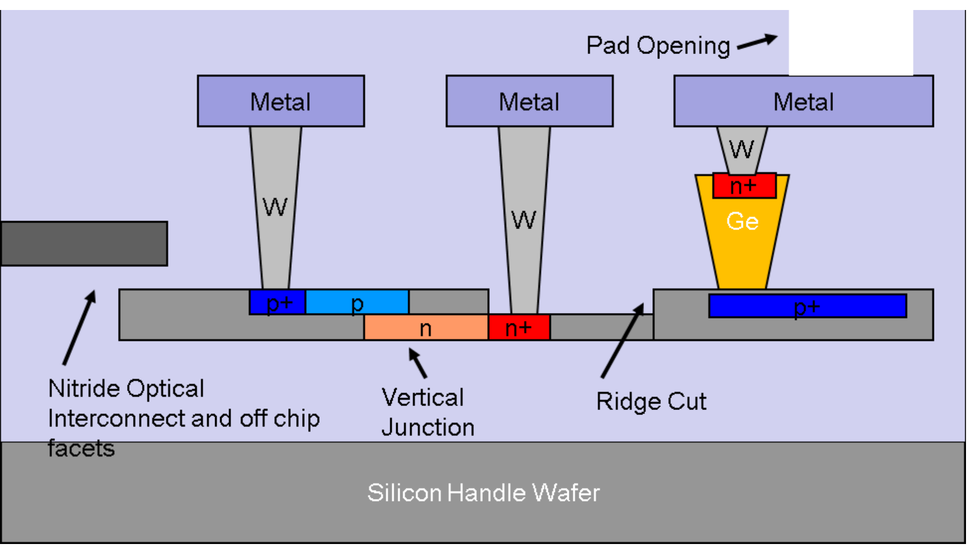


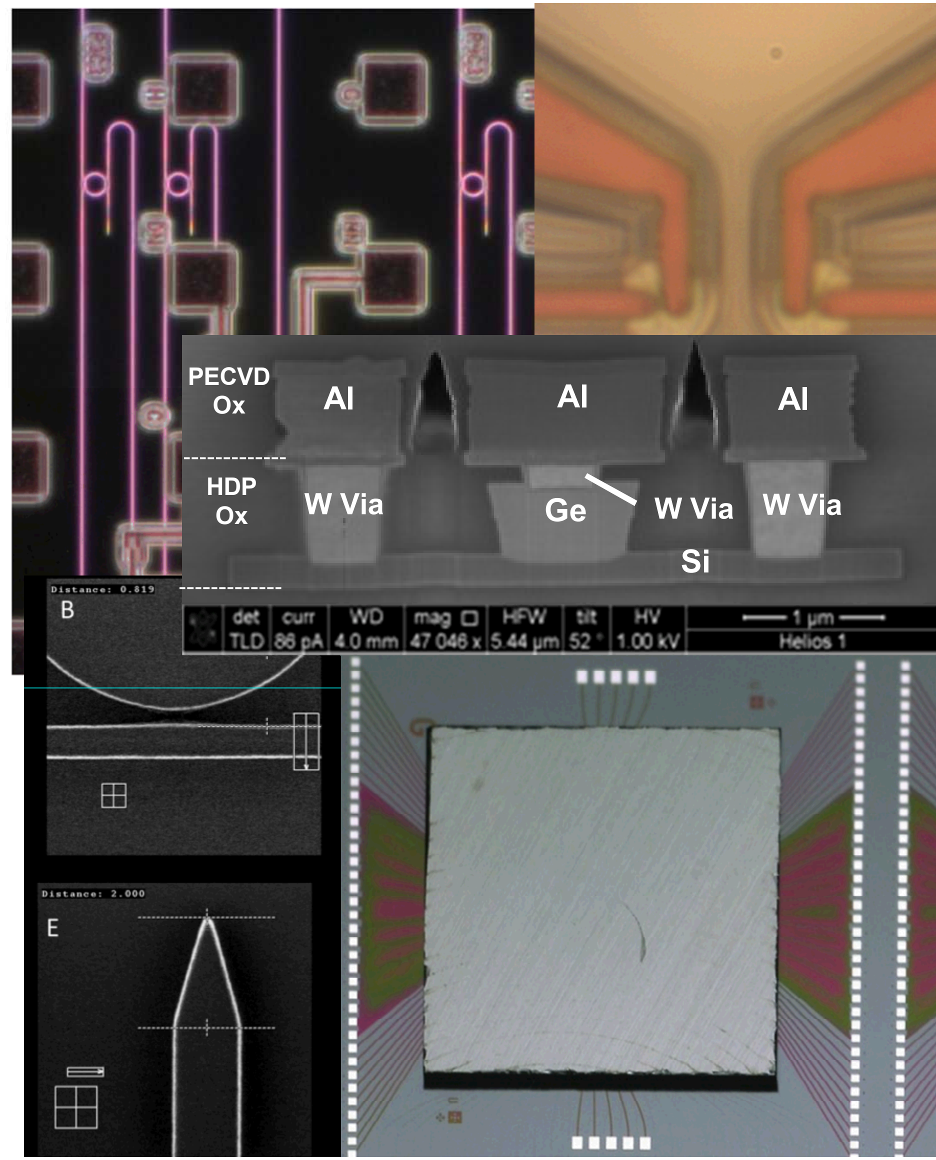


Element	Value
C_F	10 pF
R_F	1 MΩ
R_{IN}	10 kΩ

Sandia's Silicon Photonics Process

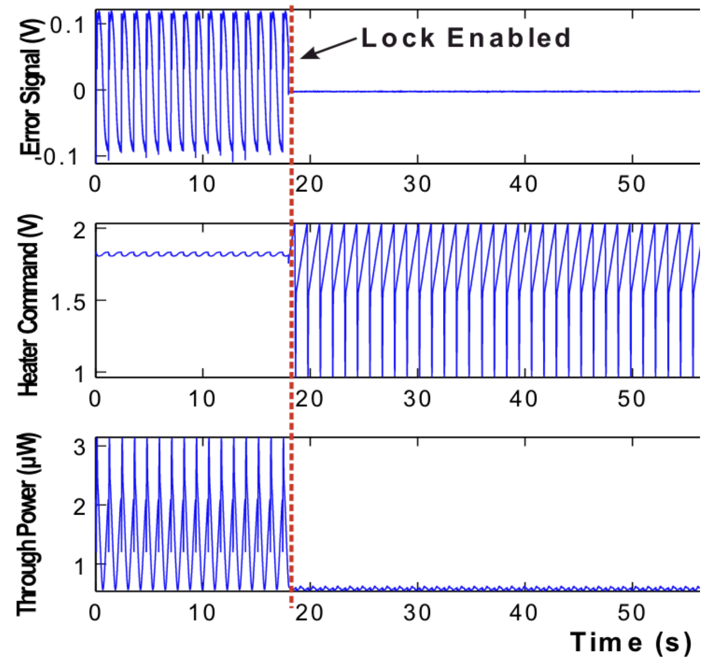
- Low energy modulators
- Fast (45 GHz) detectors
- Compact switch elements
- Wavelength tunable devices
- Si, Si ridge, SiN guides

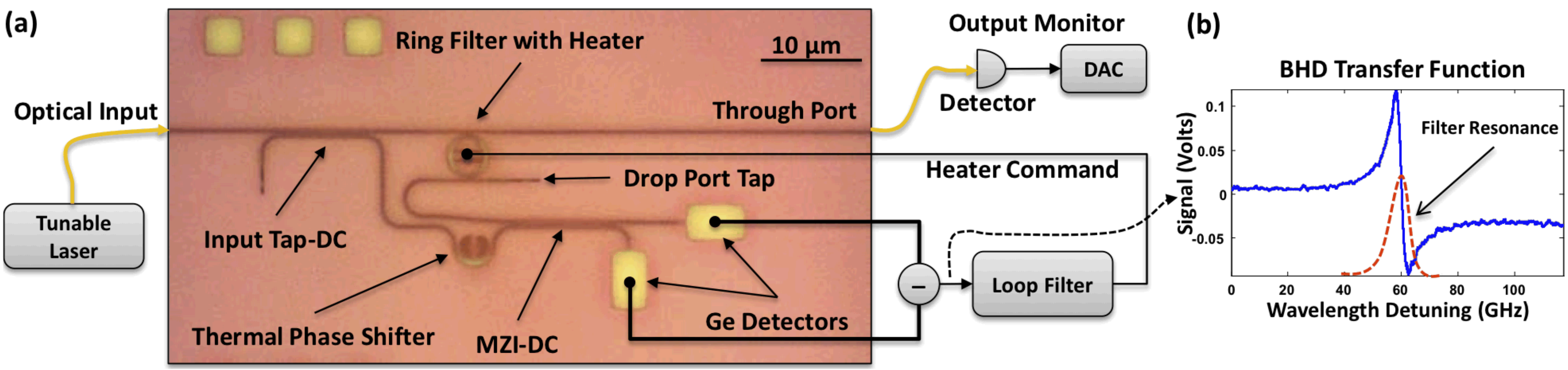




Resonant locking of a DWDM filter

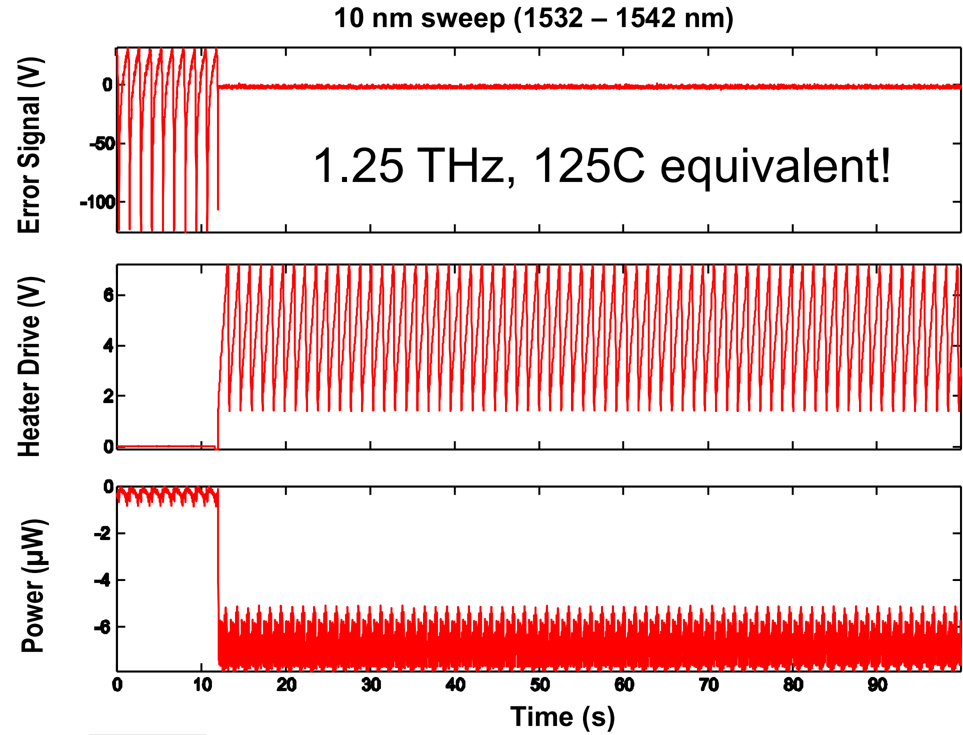
- Problem: locking on minimum power level does not lend itself to a simple control loop
- Solution: Homodyne detection with balanced detection gives optimal locking solution

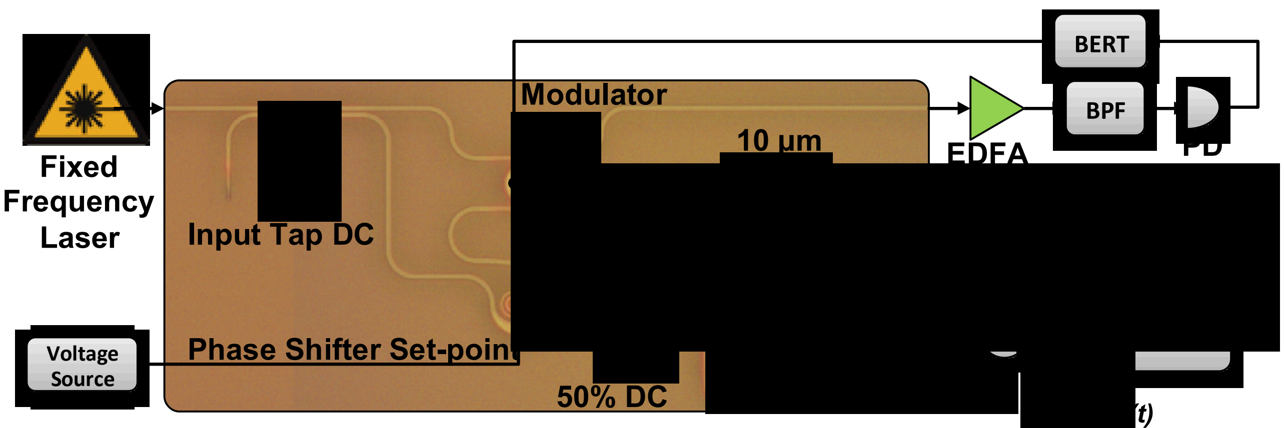


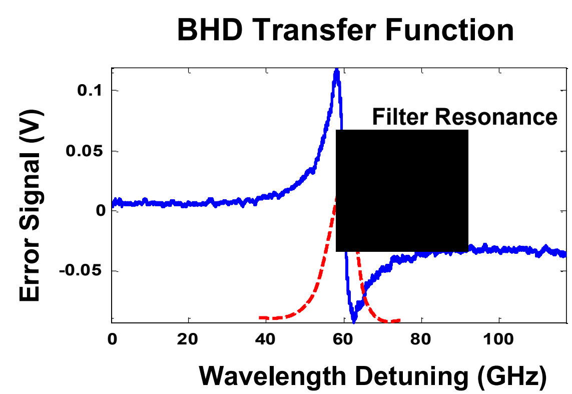


Modulator Stabilization System

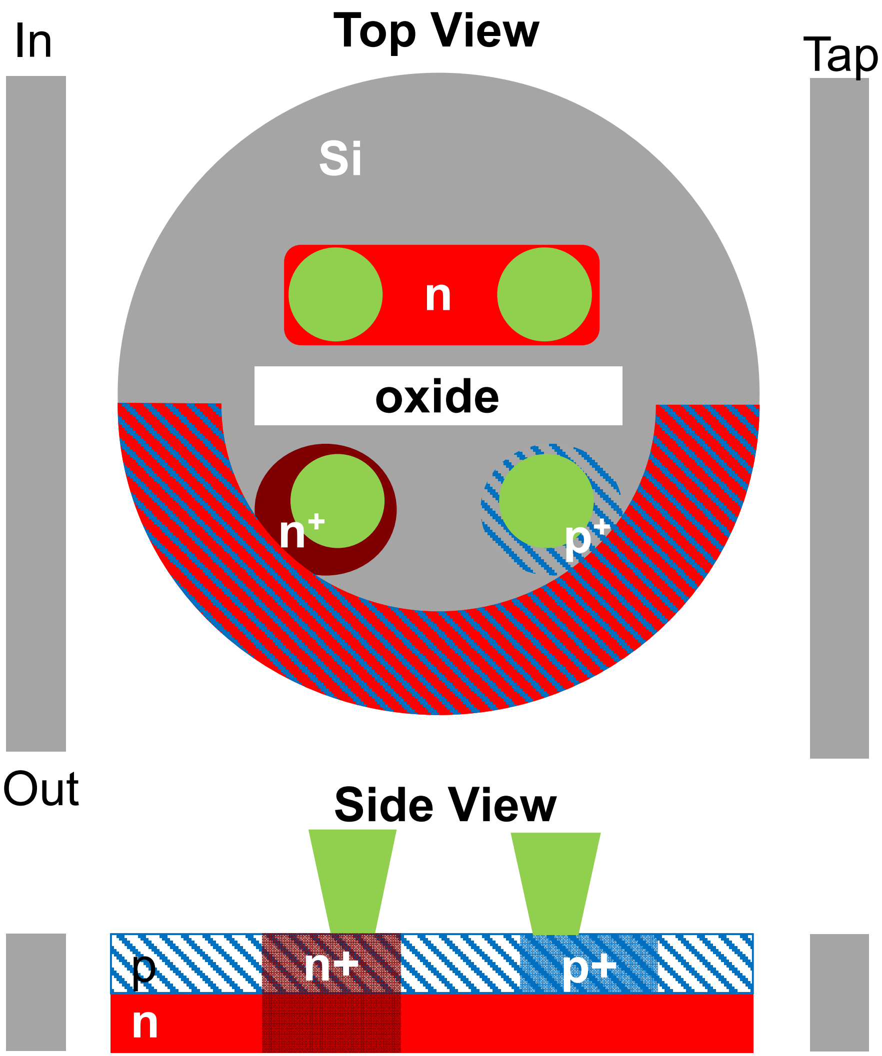
- ***Lock to zero:*** No calibration or reference level needed for locking
- ***Amplitude insensitive:*** Locking point not influenced by optical intensity
- ***Precision locking:*** Resonator is not disturbed
- ***Minimum circuit complexity:*** Power and area consumption of control electronics is minimized

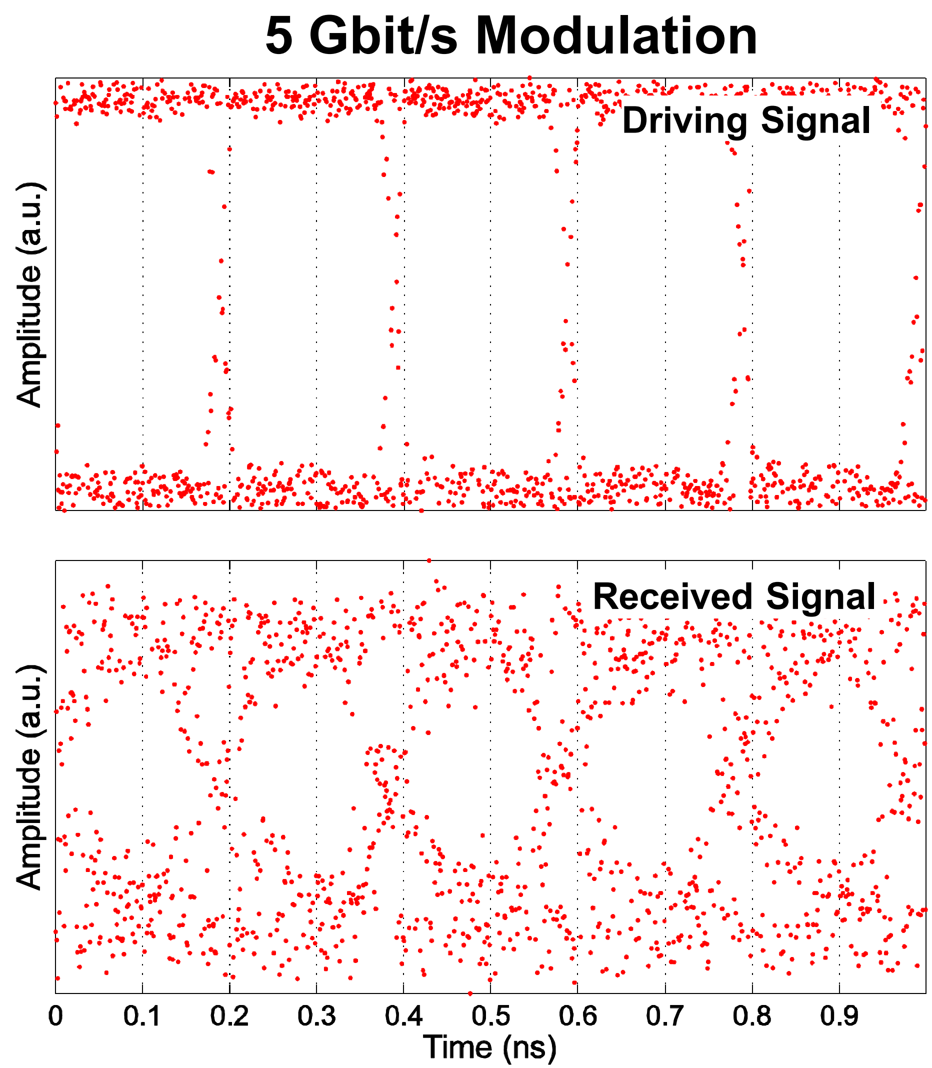






Modulator Design and Performance





W. Zortman, A. Lentine, D. Trotter, and M. Watts, "Integrated CMOS Compatible Low Power 10Gbps Silicon Photonic Heater Modulator," in *Optical Fiber Communication Conference,* OW4I.5. (2012)

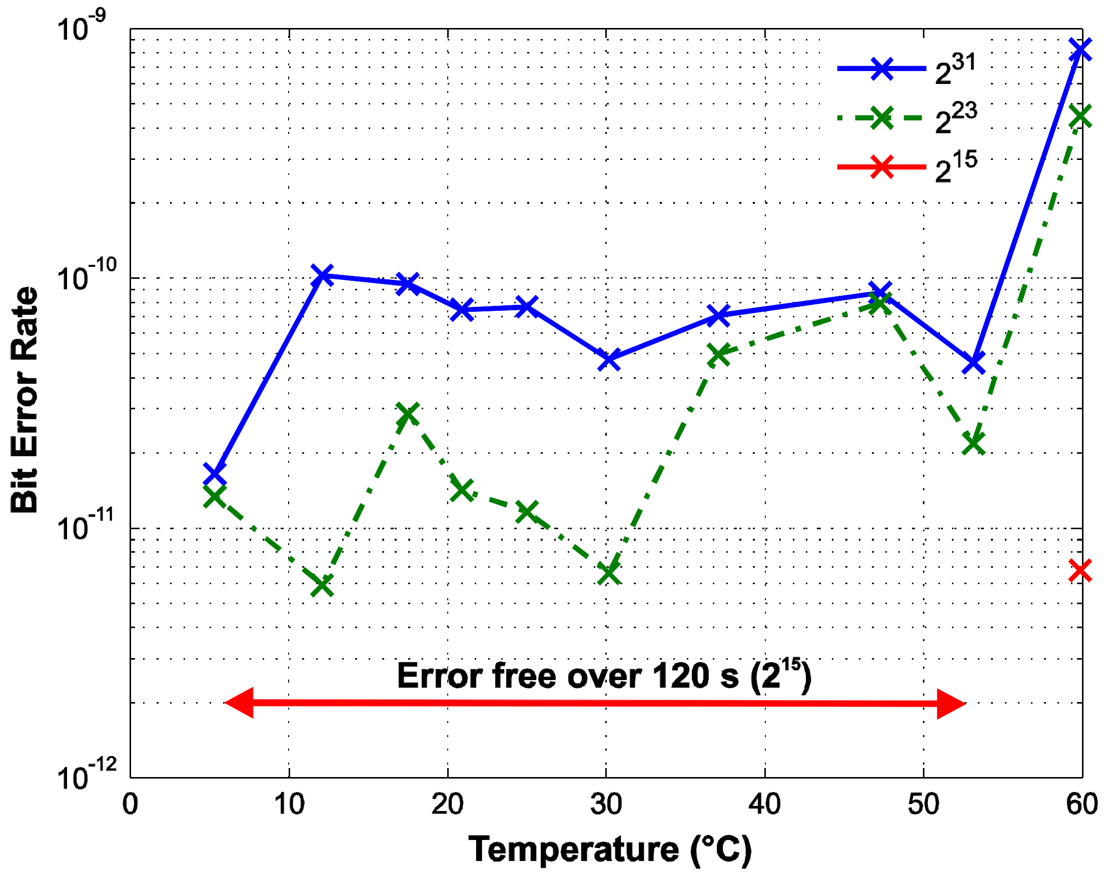
Error Rate vs. Temperature

- 5 GHz modulation applied
- Modulator locked, and phase shifter adjusted ***once*** for lowest BER.

- **Wavelength held constant. Chip temperature varied** from 5—60° C while locked.

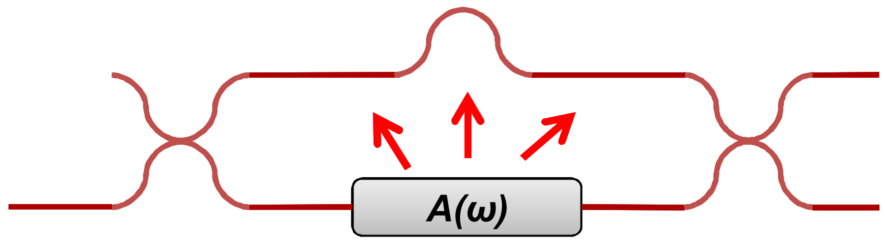
- Error free from 5—55° C (2^{15}-1 bits)

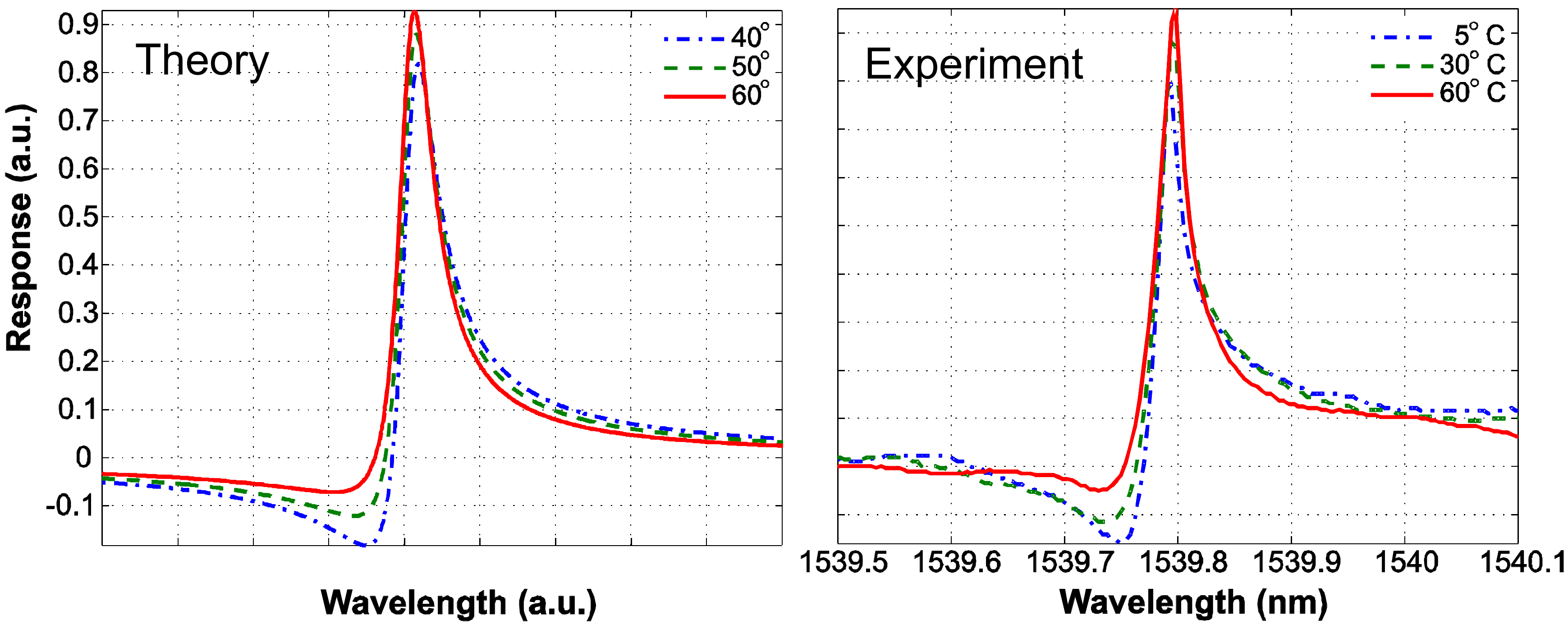
- Error rate rises at 60° C due to thermal phase imbalance in interferometer



Design Considerations

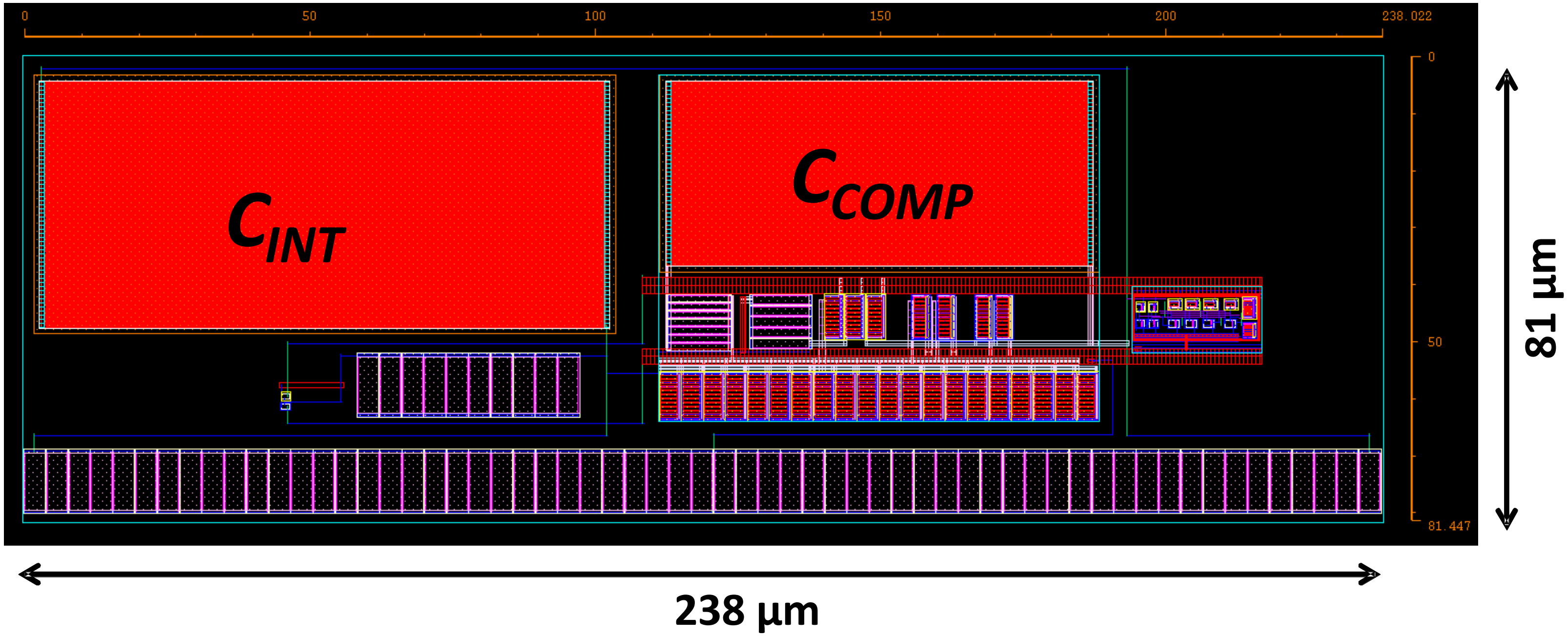
- ***Hypothesis:*** Path length imbalance and thermal gradients from modulator heater cause shift in locking point
- **Test:** Vary chip temperature while tuning heater to hold resonant wavelength constant





CMOS ASIC Design (currently in fab)

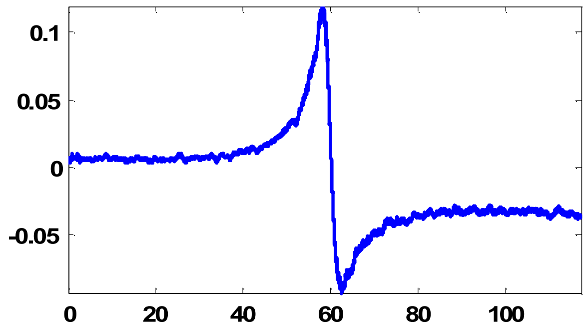
- **IBM 45 nm CMOS** ASIC designed at Sandia
- **Power consumption:** 1.07 mW (steady-state); 0.27 mW (TIA) and 0.8 mW (integrator) (30 – 100 fJ/bit @ 30Gbps-10Gbps) [1]
- **Heater time constant** → large integrator resistor and capacitor in loop filter
- **Heater driver:** Class-B "push-pull"
- **Inverter** implemented with analog switch network

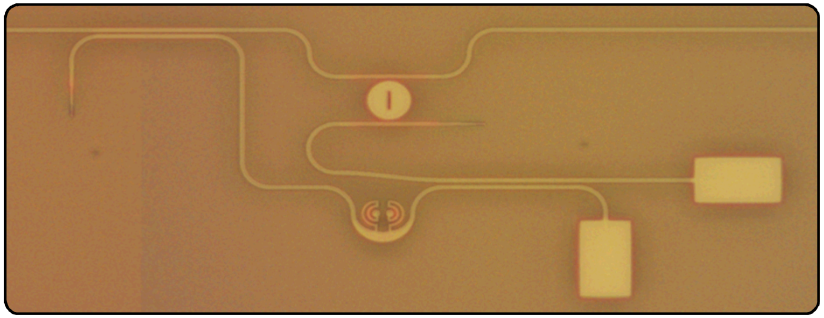


[1] recent result by X. Zheng (OpX 2014) 200µW, 2600 um^2 for 'power meter' control

Summary

- BHD provides a scalable, robust method for resonant modulator and filter wavelength stabilization
- Advantages
  - Suitable for DWDM networks
  - Insensitive to laser intensity noise
  - Arbitrary locking reference not required (lock to zero)
  - Simple control circuitry for dense on-chip integration
  - Precision locking for other micro-resonators application



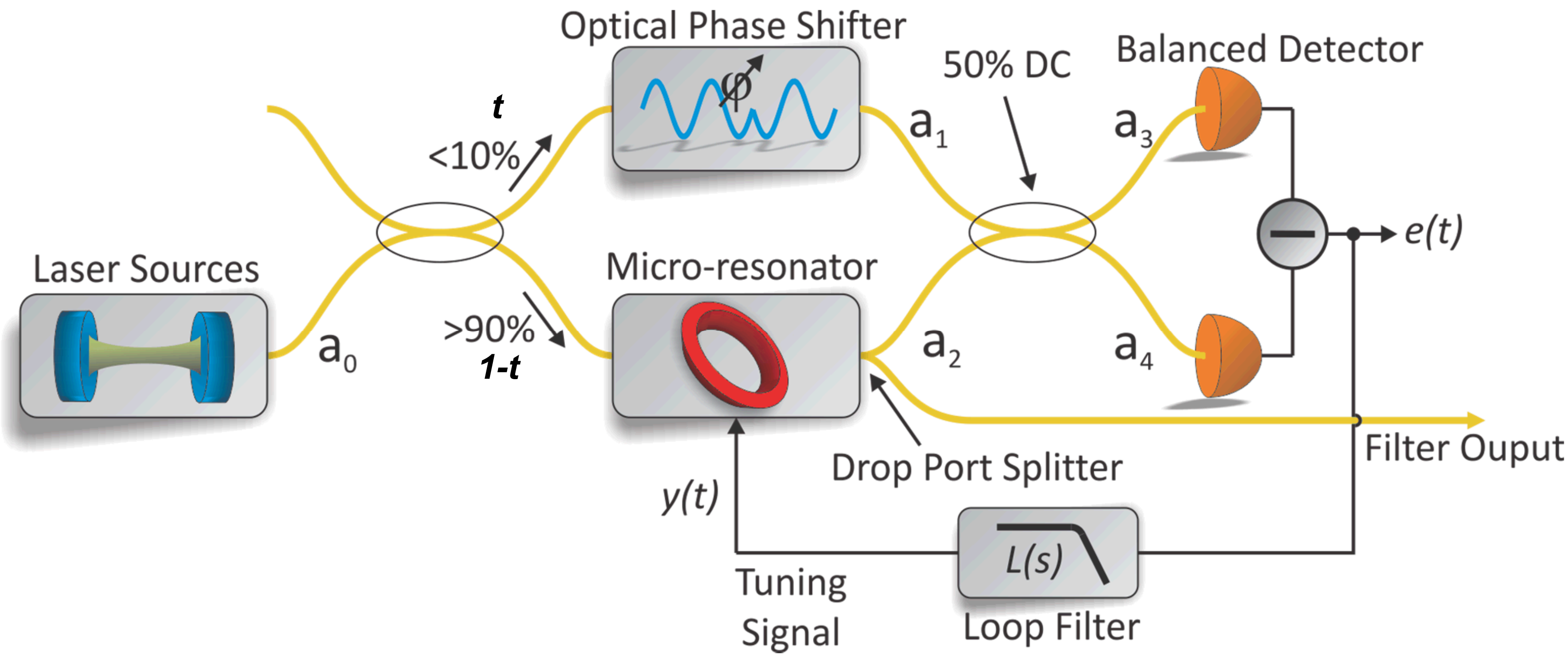


J.A. Cox, A.L. Lentine, D.C. Trotter and A.L. Starbuck, "Control of integrated micro-resonator wavelength via balanced homodyne locking," ***Opt. Express*** **Vol. 22(9) (2014)**

Backup Slides

Sandia National Laboratories

Balanced Homodyne Detection



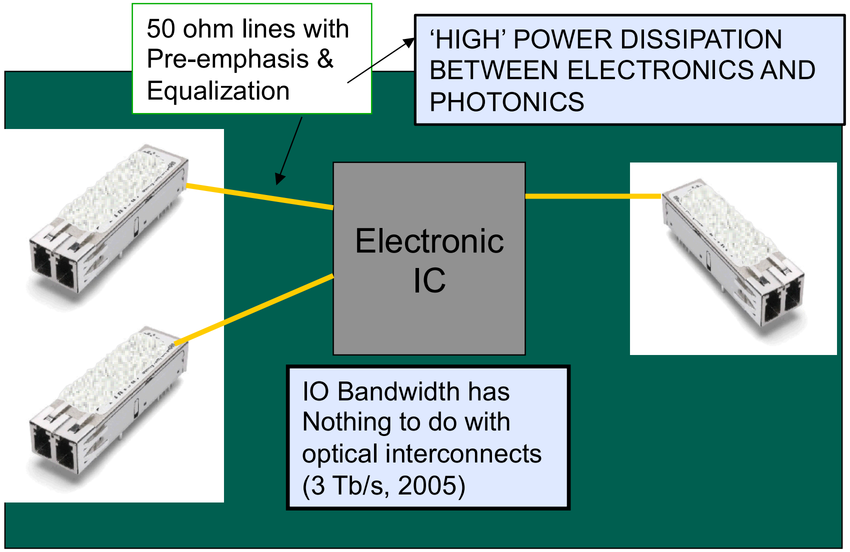
BHD Transfer Function

$$Y(\beta) = -\alpha G a_0^2 |\kappa|^4 \frac{a_m n}{Z_0} \sqrt{t - t^2} \left(\frac{e^{i\phi}}{\overline{\kappa^2}} \frac{e^{-i2\pi R\beta}}{e^{-i4\pi R\beta} + |\kappa|^2 - 1} + \frac{e^{-i\phi}}{\kappa^2} \frac{e^{i2\pi R\beta}}{e^{i4\pi R\beta} + |\kappa|^2 - 1} \right)$$

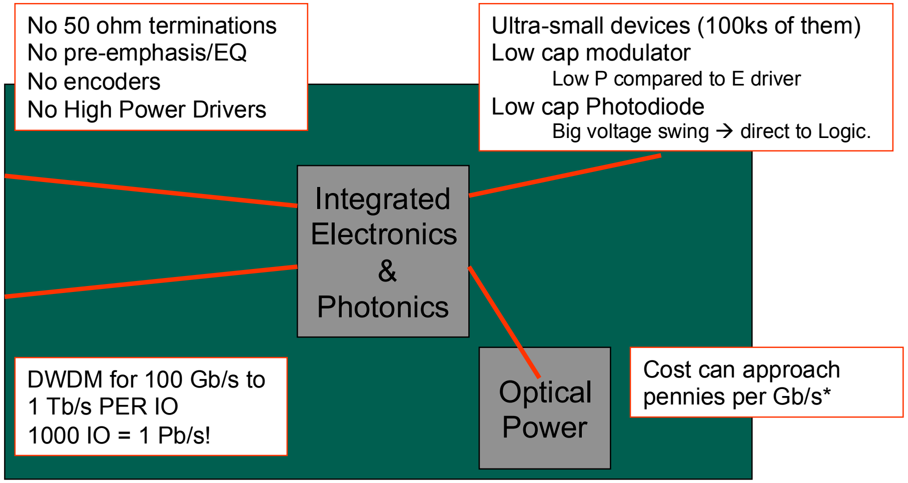
Optical Interconnects

- Evolutionary (Modules)
  - GbE and 10GbE Products
  - 100 GbE modules soon w/ VCSELs and Si Photonics
  - TbE modules on the horizon

- **Revolutionary (3DI)**
  - **Higher bandwidth density**
    - **DWDM is required!!**
  - **Drastic *potential* power reduction**
    - **No 50 Ω lines, pre-emphasis or equalization**
    - **Receiver has high transimpedance, few gain stages**
    - **Shared CDR (less delay variation and jitter)**



OPTICS FOR DISTANCE



OPTICS FOR *LOW POWER*, *HIGH BANDWIDTH DENSITY*, COST, SIZE, WEIGHT, DISTANCE