SAND2012-4209C

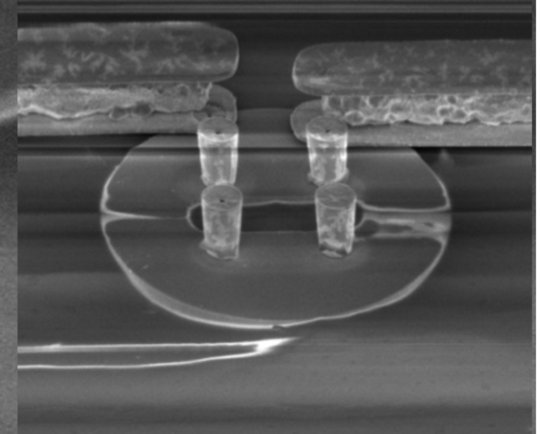
Active wavelength control of silicon microphotonic resonant modulators

Anthony L. Lentine, William. A. Zortman, Douglas. C. Trotter, and Michael R. Watts*

Sandia National Labs, Albuquerque, NM 87185,

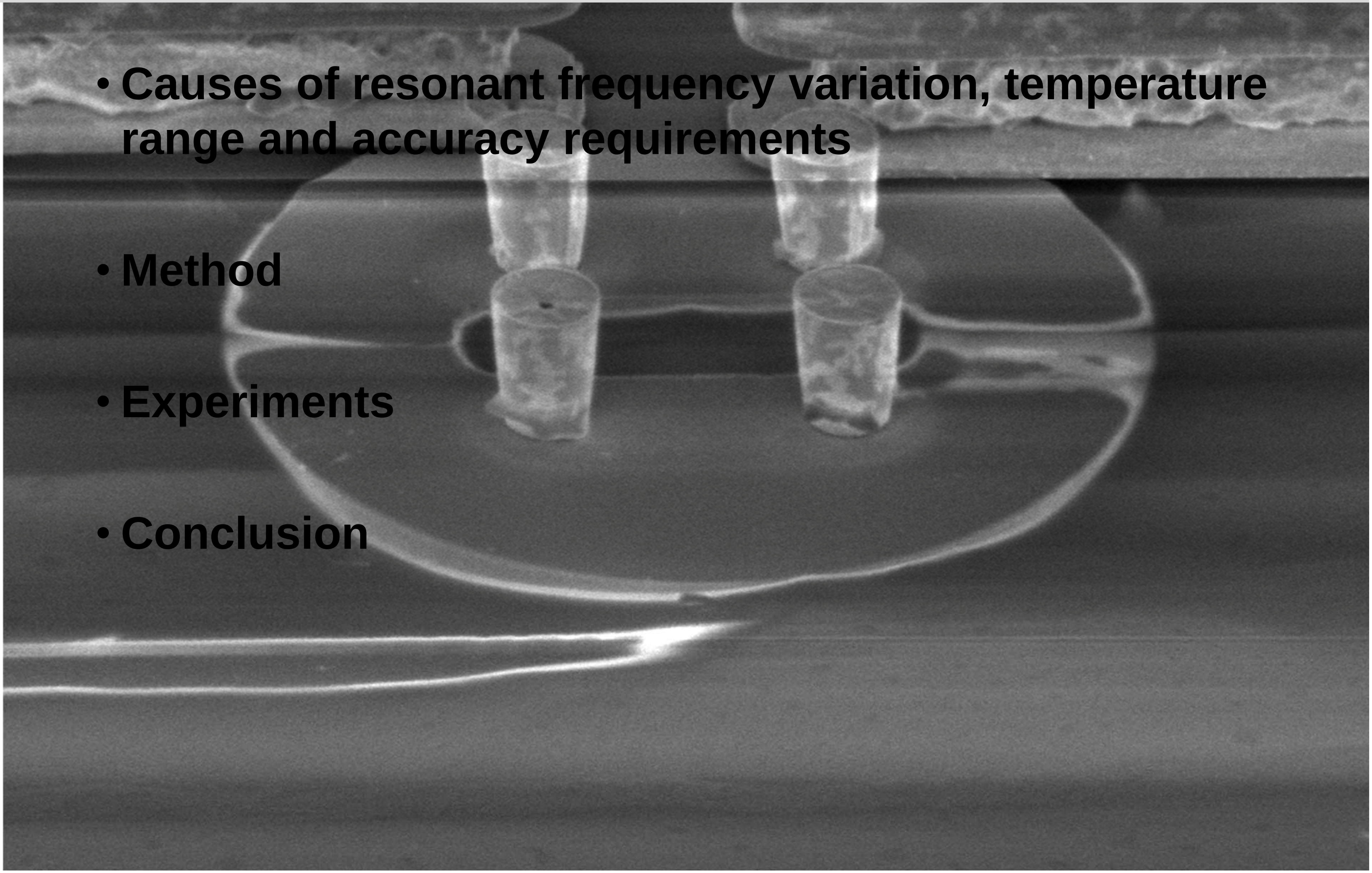
contact: alentine@sandia.gov

**** Now at MIT, Cambridge, MA 02139***



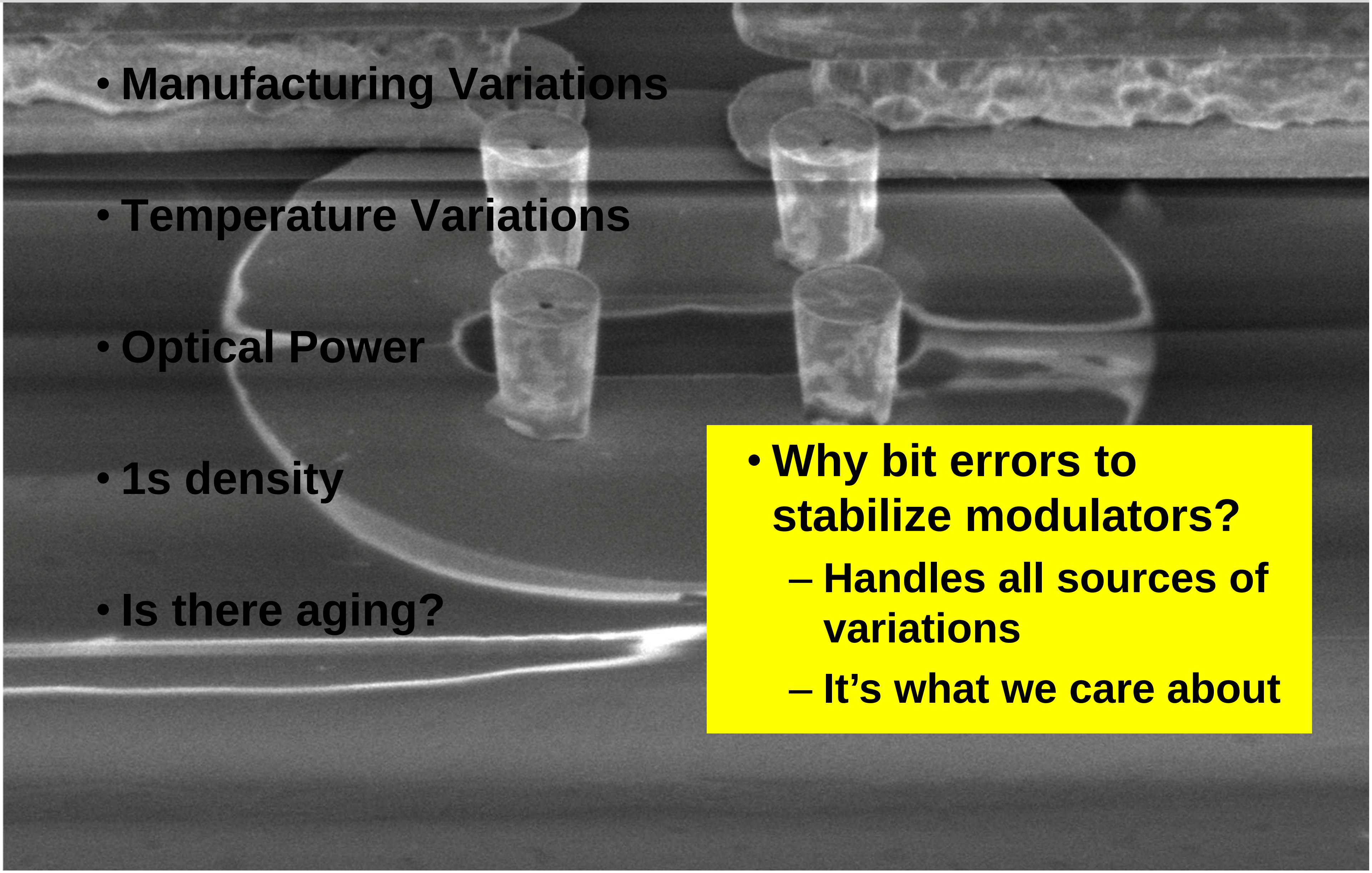
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline



- Causes of resonant frequency variation, temperature range and accuracy requirements
- Method
- Experiments
- Conclusion

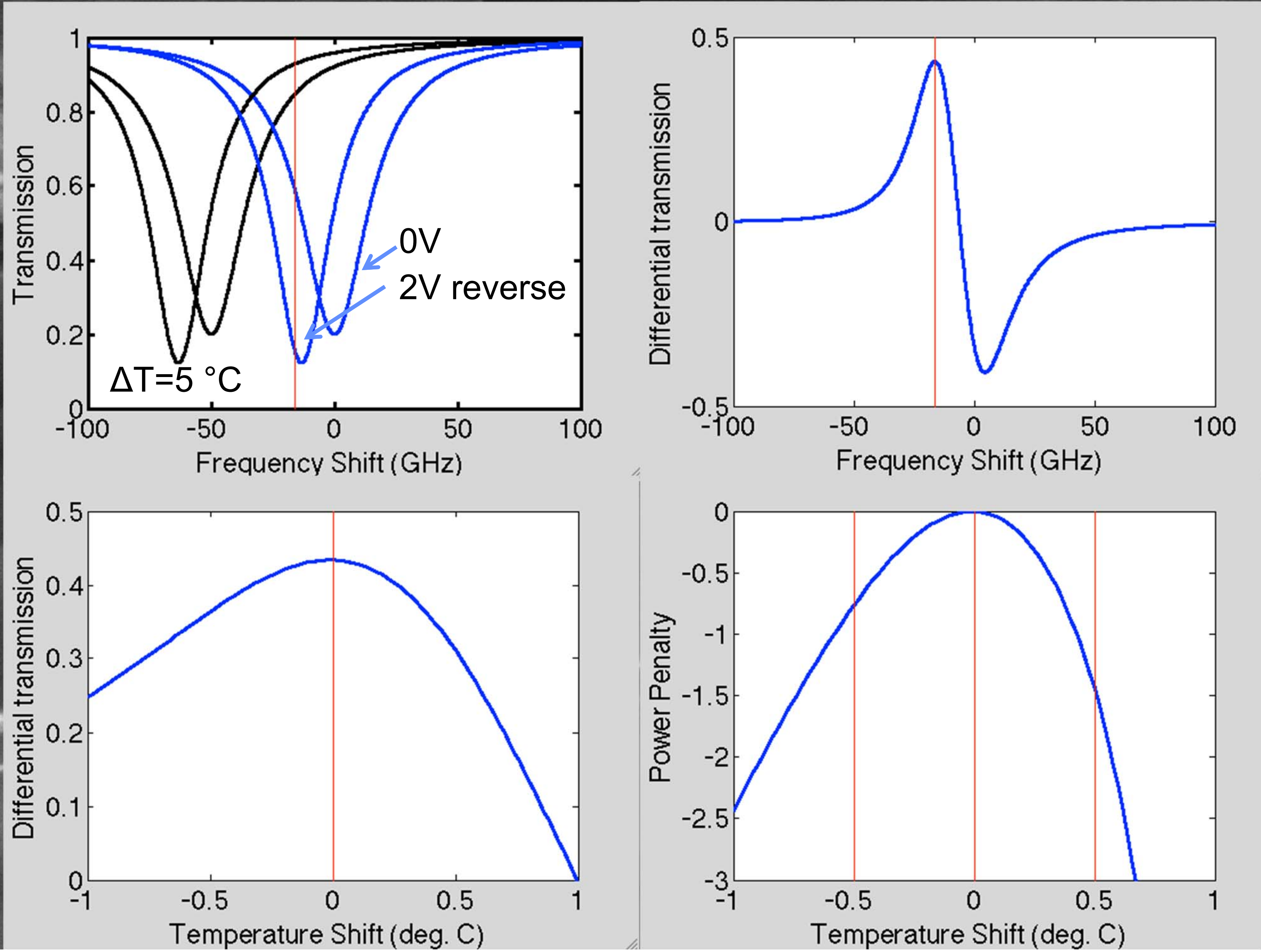
Causes of variations in resonant frequency



- Manufacturing Variations
- Temperature Variations
- Optical Power
- 1s density
- Is there aging?

- Why bit errors to stabilize modulators?
  - Handles all sources of variations
  - It’s what we care about

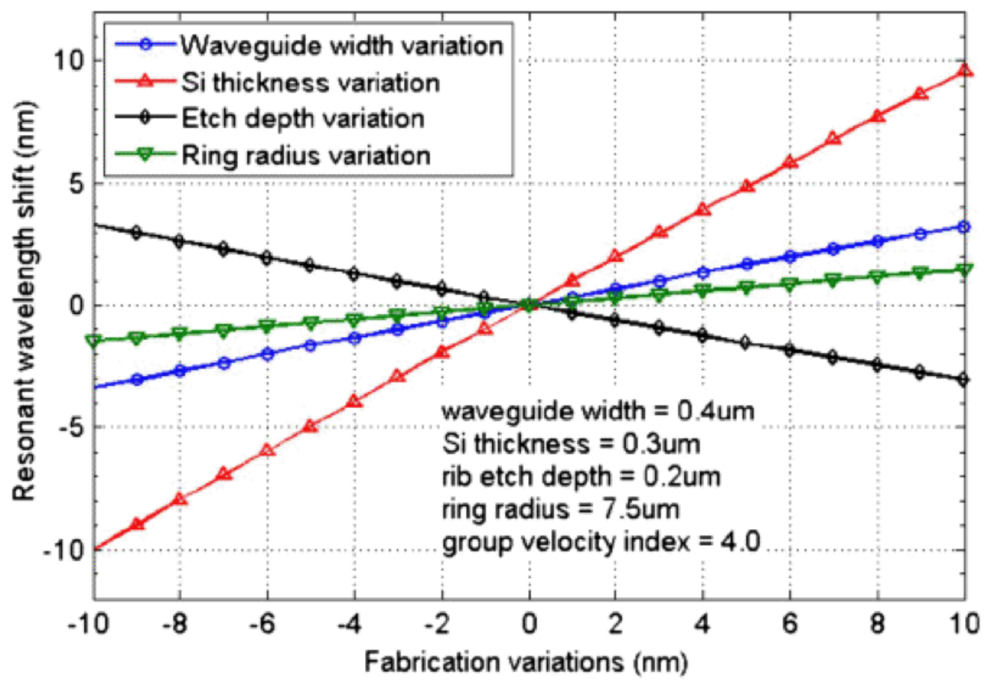
Optical Modulators: Effect on loss budget

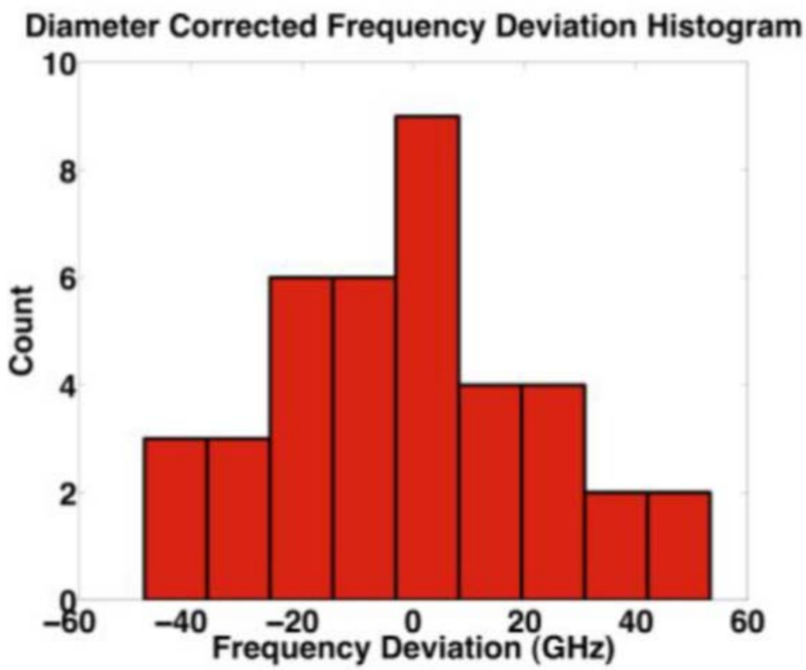


Resonant frequency manufacturing accuracy

- **Thickness variations of the silicon layer is dominant**
- **On-chip variation**

  < 100 GHz



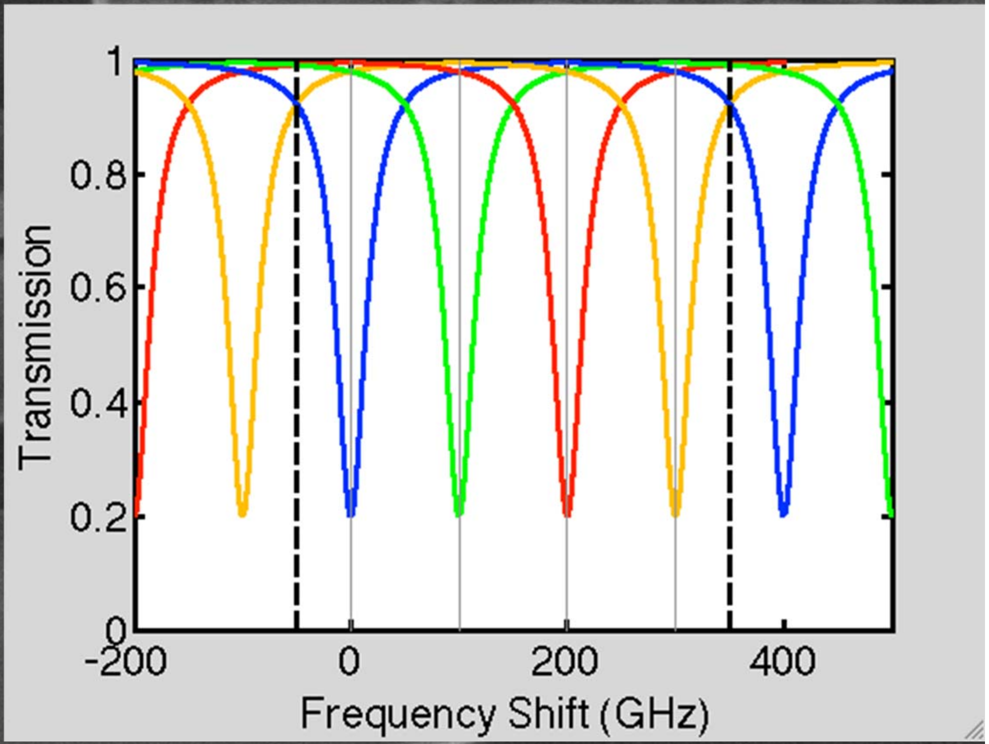


Krishnamoorthy et. al, IEEE Photonics J., 2011

Zortman et. al, Optics, Exp., 2011

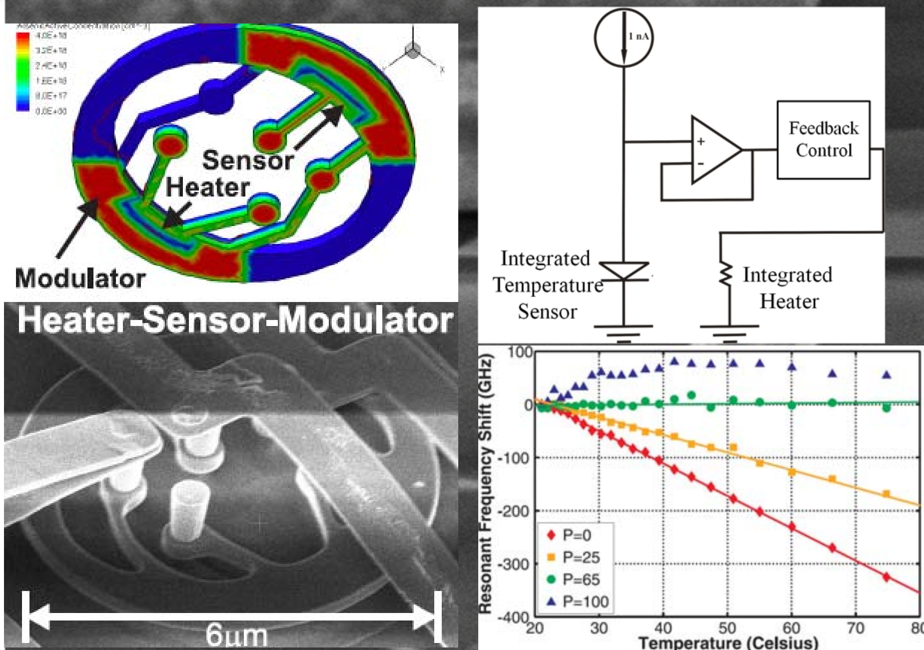
Cyclical Channels reduces tuning range

- **FSR=N x channel spacing**
- **Maximum heating = channel spacing**
  - **100GHz→ 10˚ C**
- **Manufacturing**
  - **100 GHz variation → 10C**
- **Total → 20C (worst case)**
- **Accuracy → 0.25C**

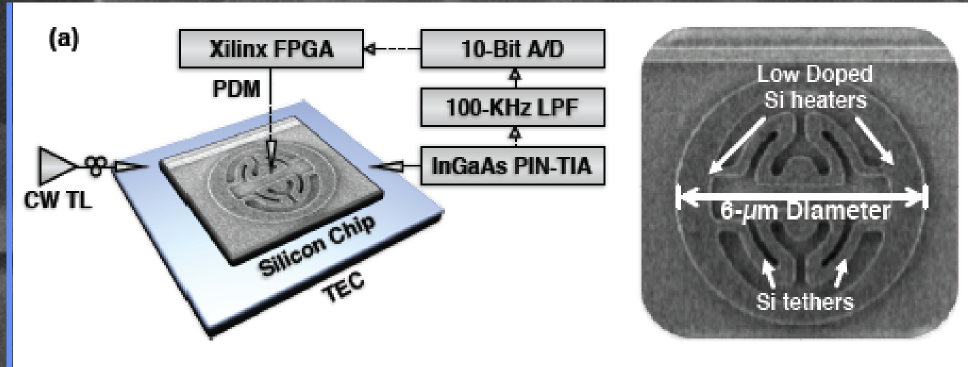


N. Binkert et al., ISCA 2011
A. V. Krishnamoorthy et. al., IEEE Photonics Journal, 2011
M. Gorgas et. al., IEEE CICC, 2011

Previous closed loop control experiments stabilizing the resonant frequency

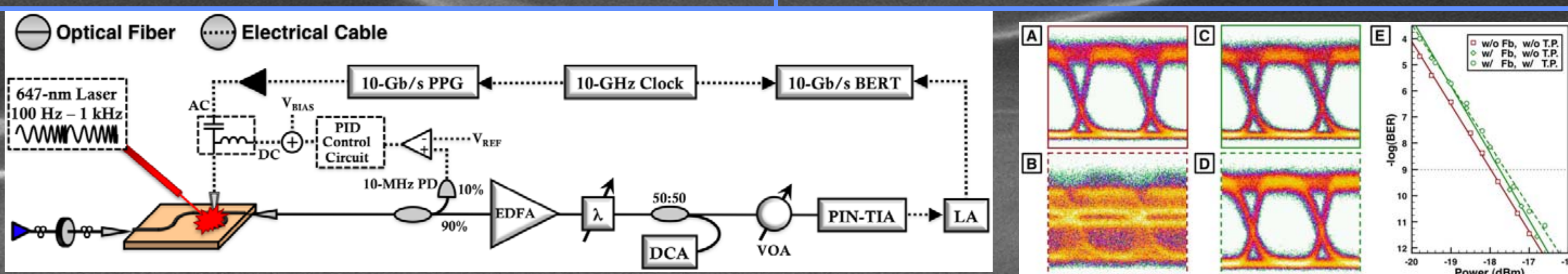


Resonator with temperature sensor, PID loop (DeRose CLEO2010)



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

External power measurement and feedback to lock wavelength

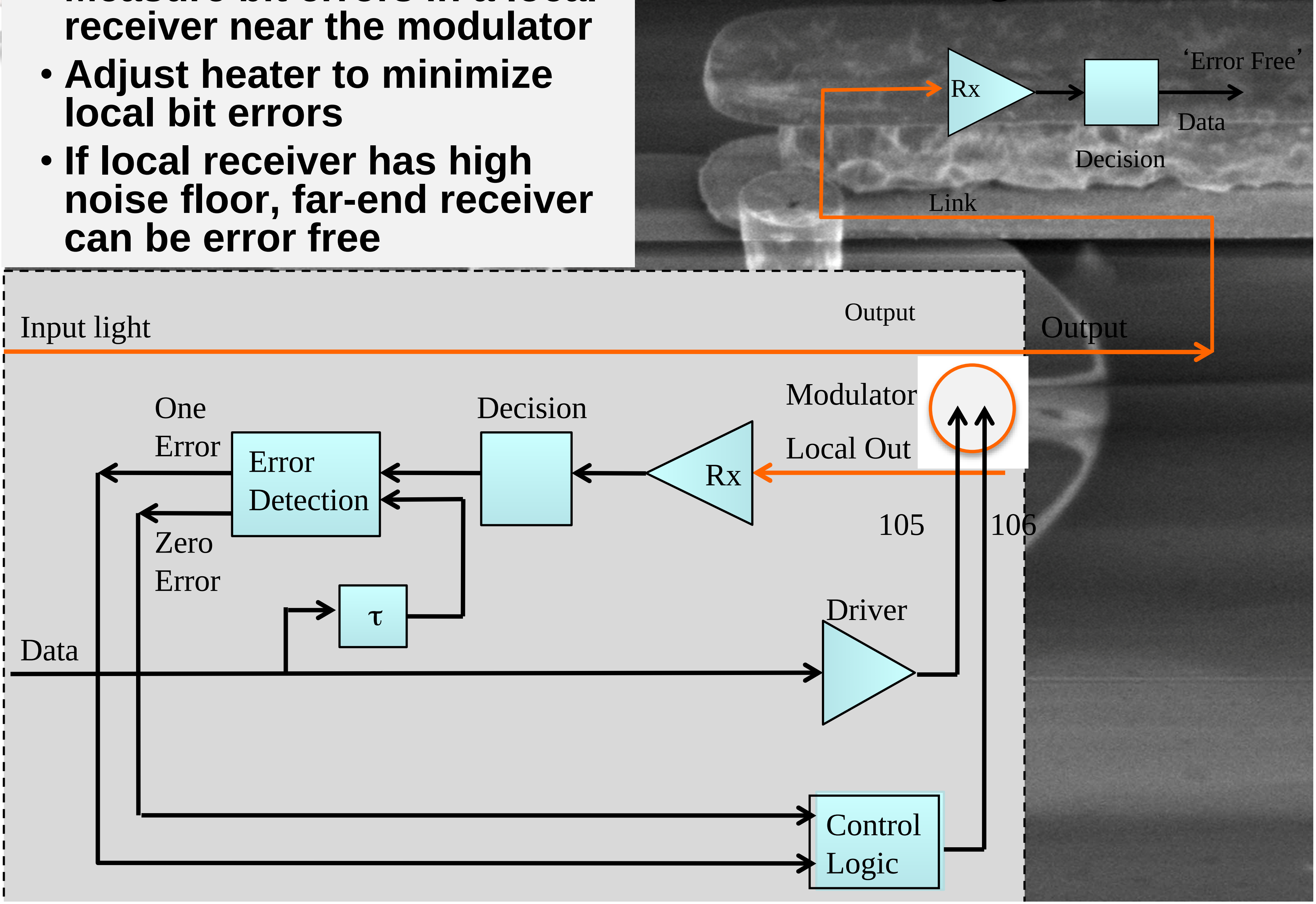


Modulator with bias induced temperature change monitoing mean optical power(Padmaraju, OFC 2012)

Method using bit errors

Idea

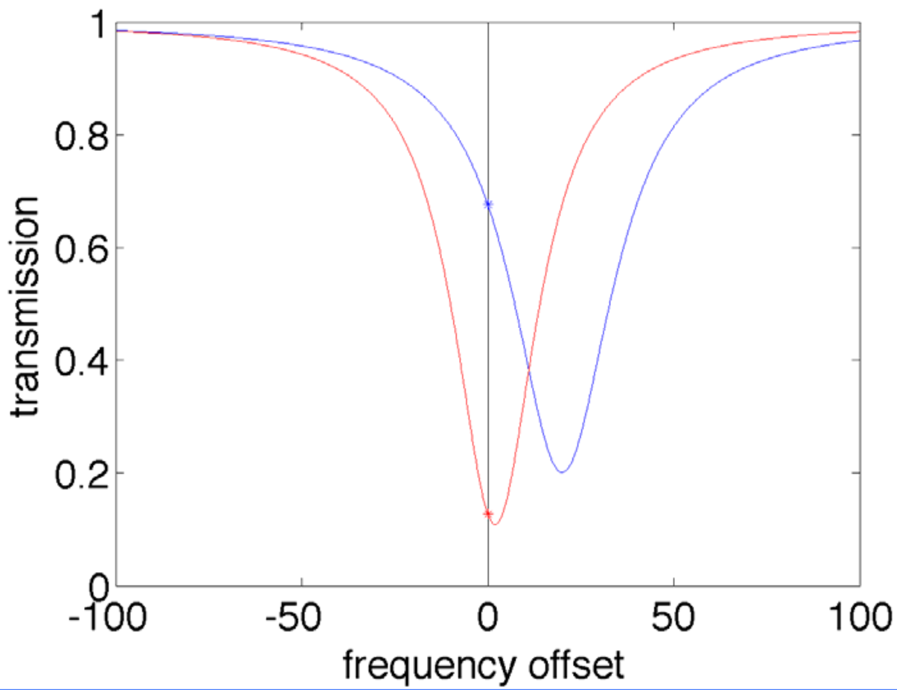
- **Measure bit errors in a local receiver near the modulator**
- **Adjust heater to minimize local bit errors**
- **If local receiver has high noise floor, far-end receiver can be error free**

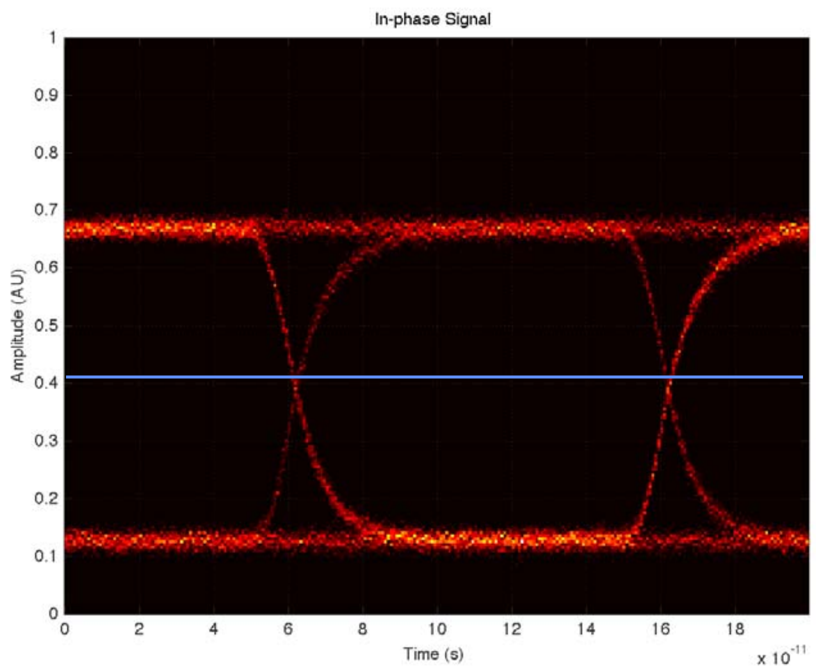


Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-2 °C



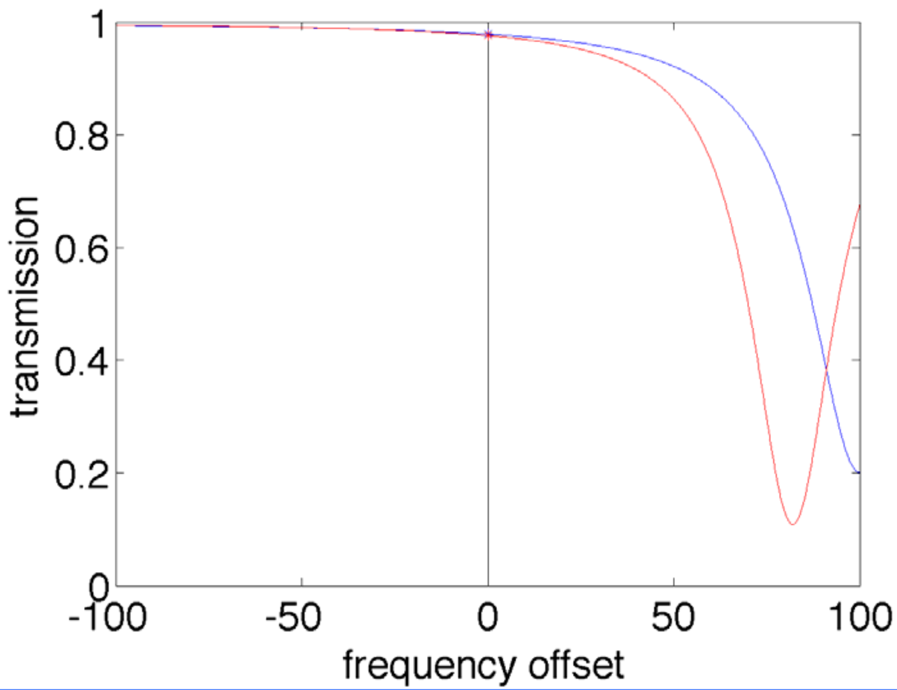


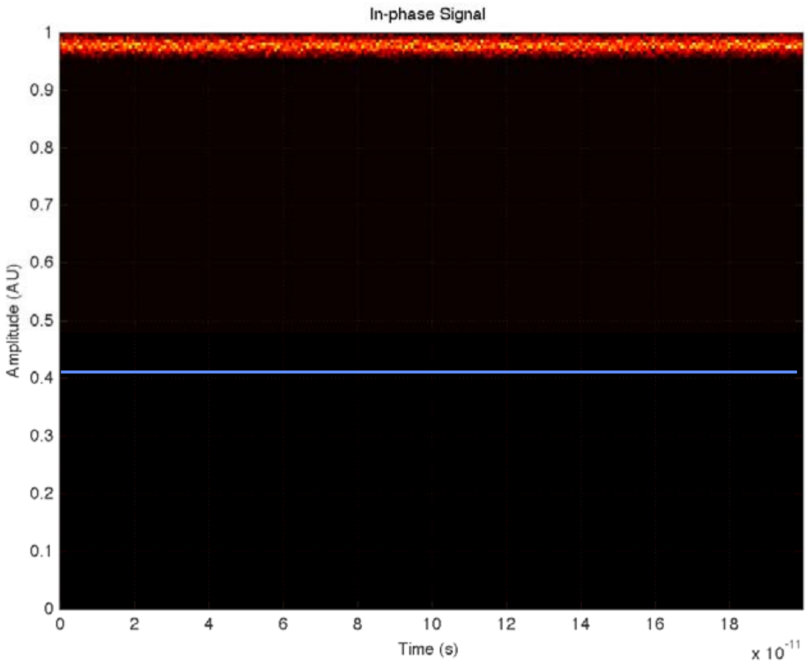
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

-10 °C





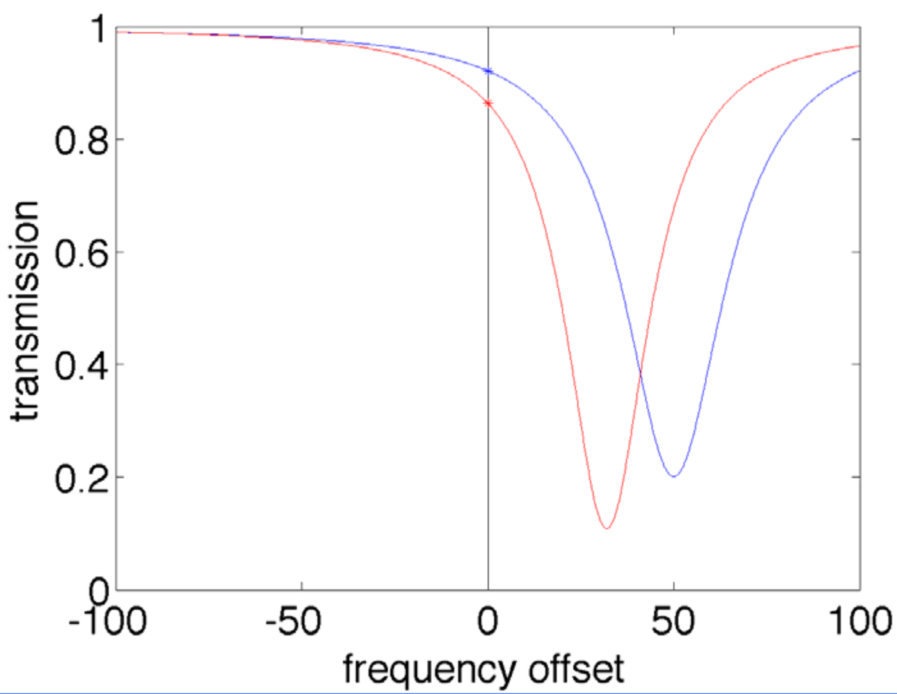
Red: Reverse Bias

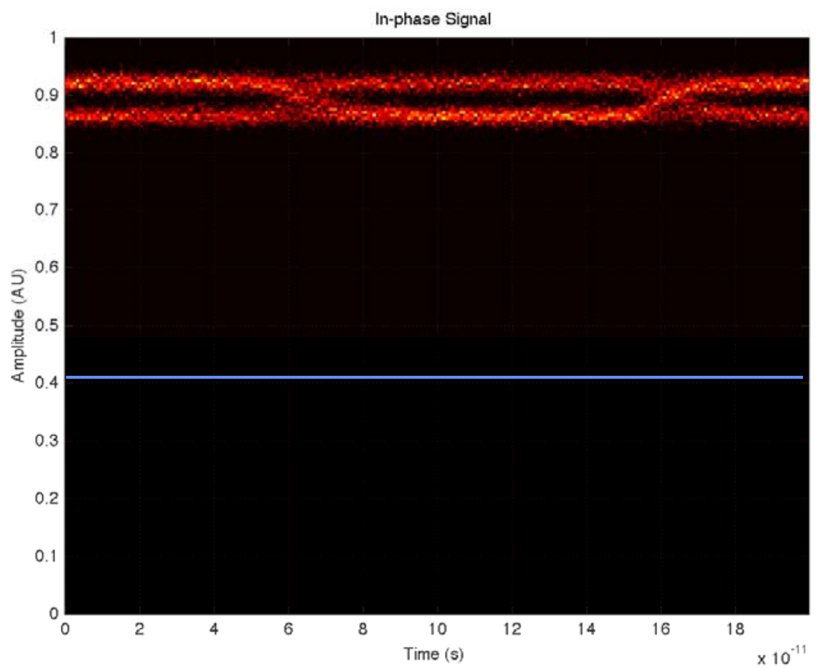
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-5 °C





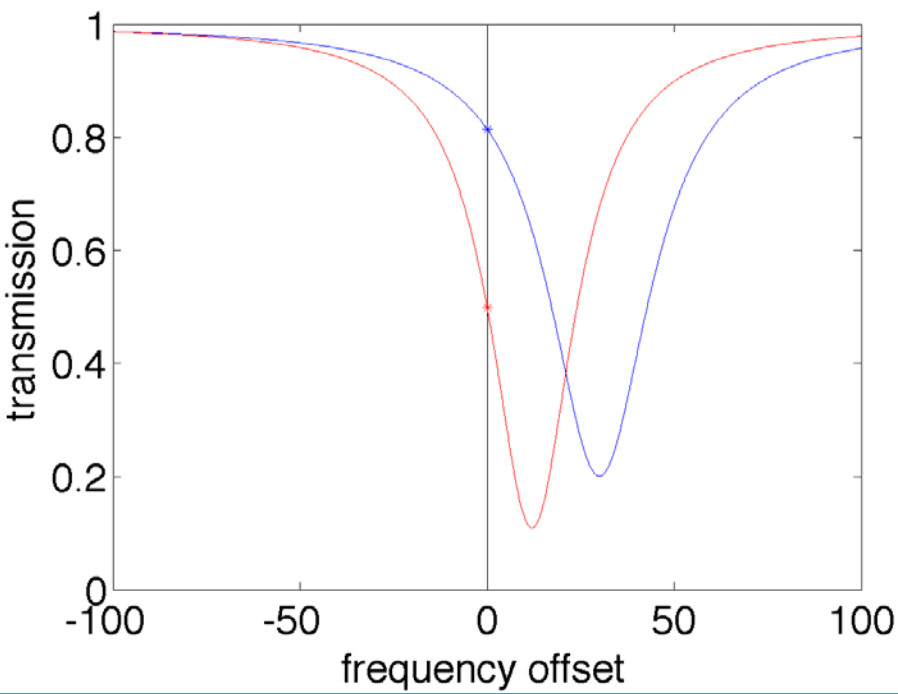
Red: Reverse Bias

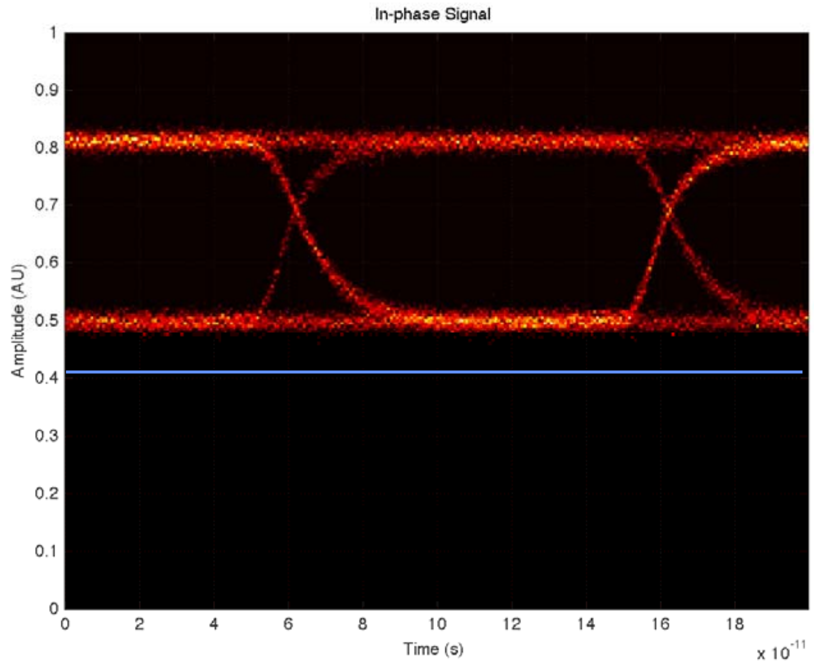
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

-3 °C





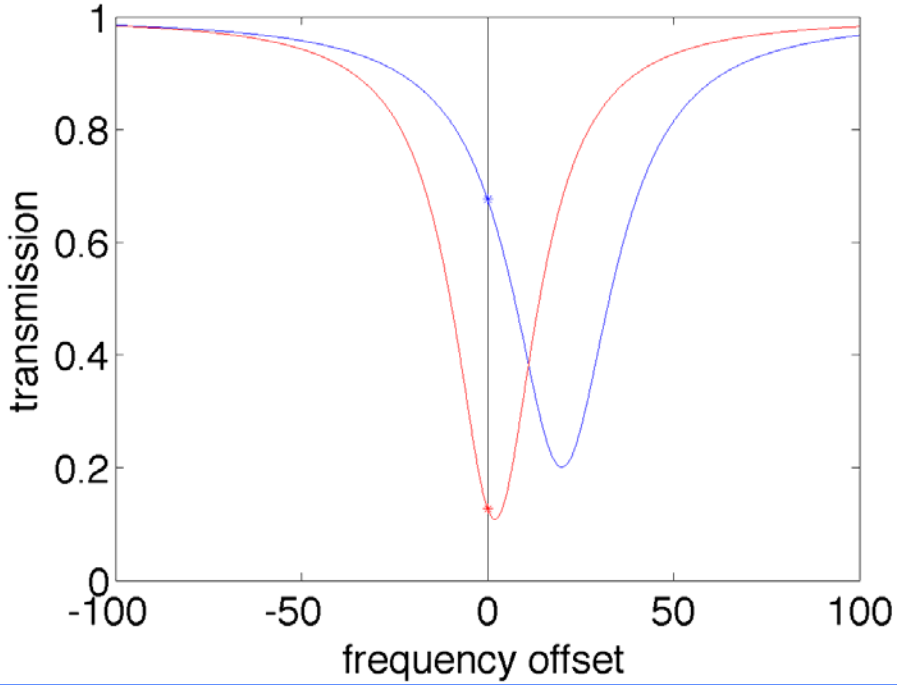
Red: Reverse Bias

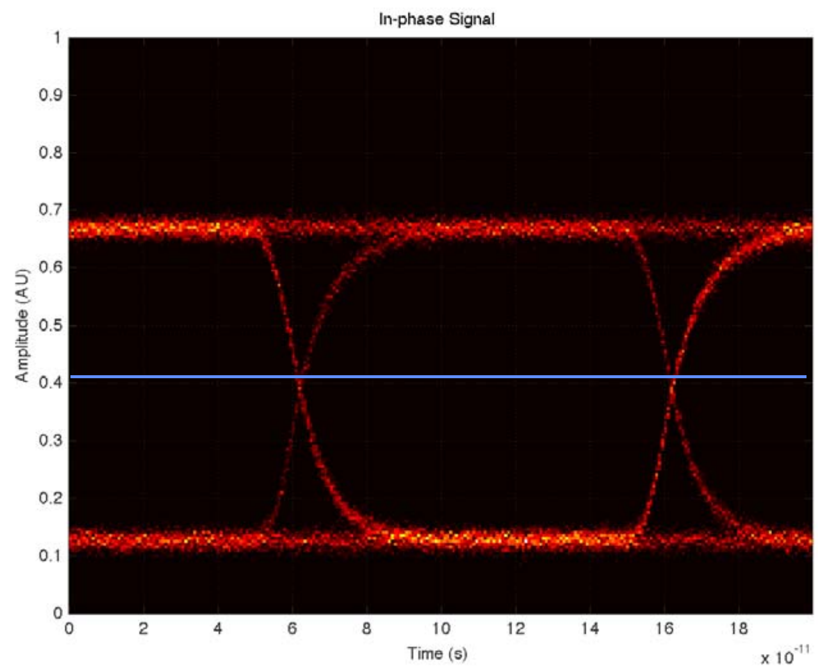
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-2 °C



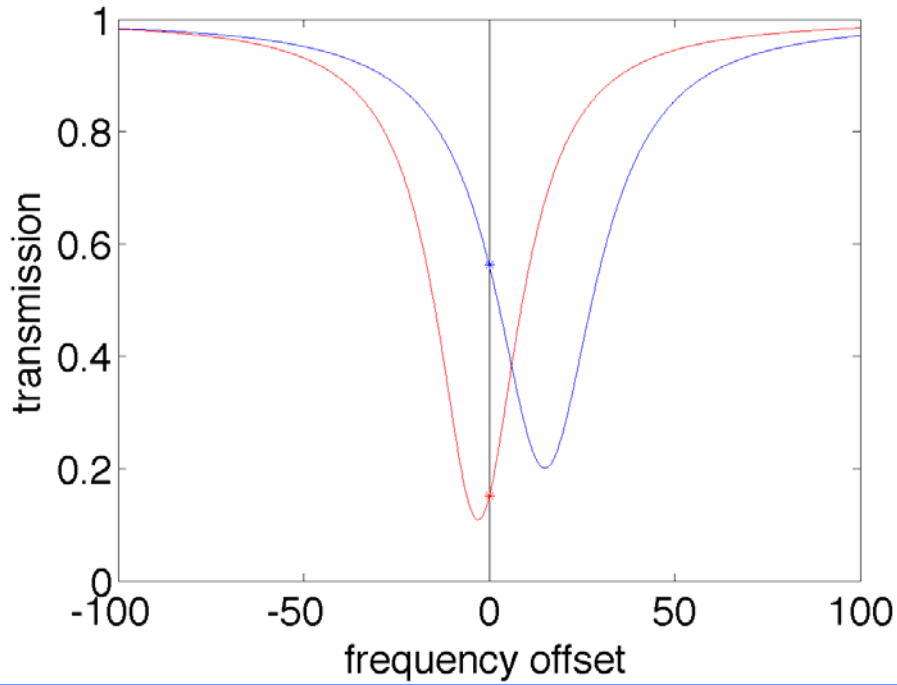


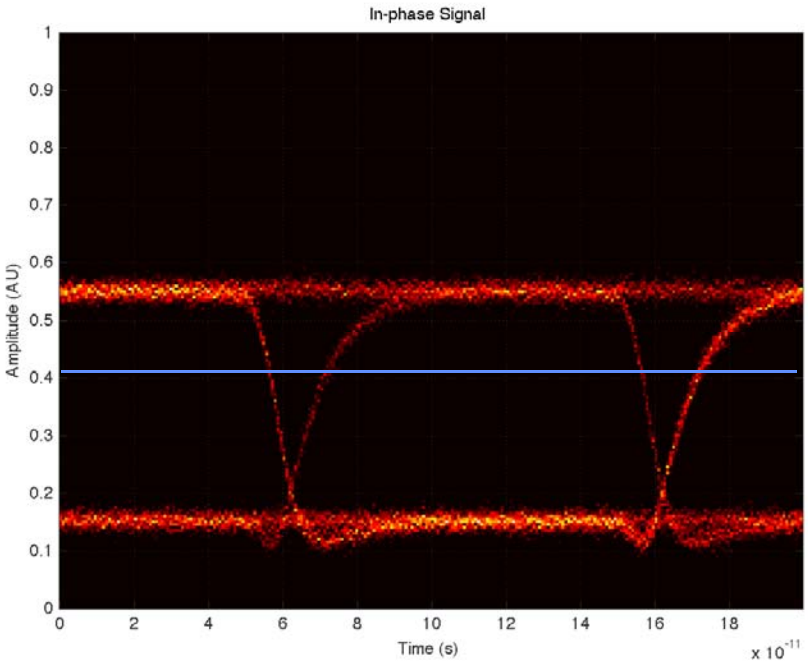
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-1.5 °C



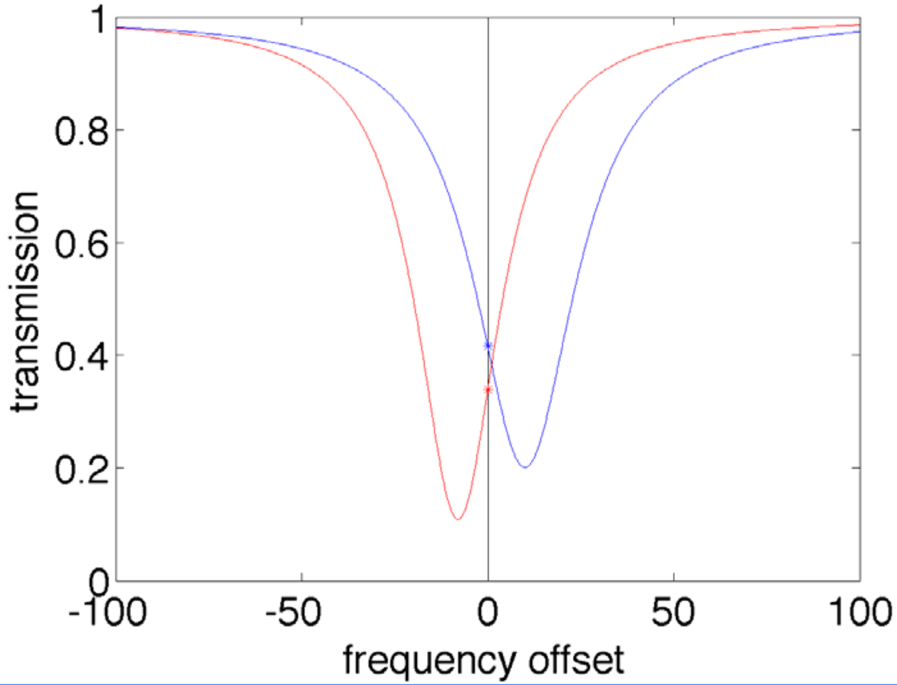


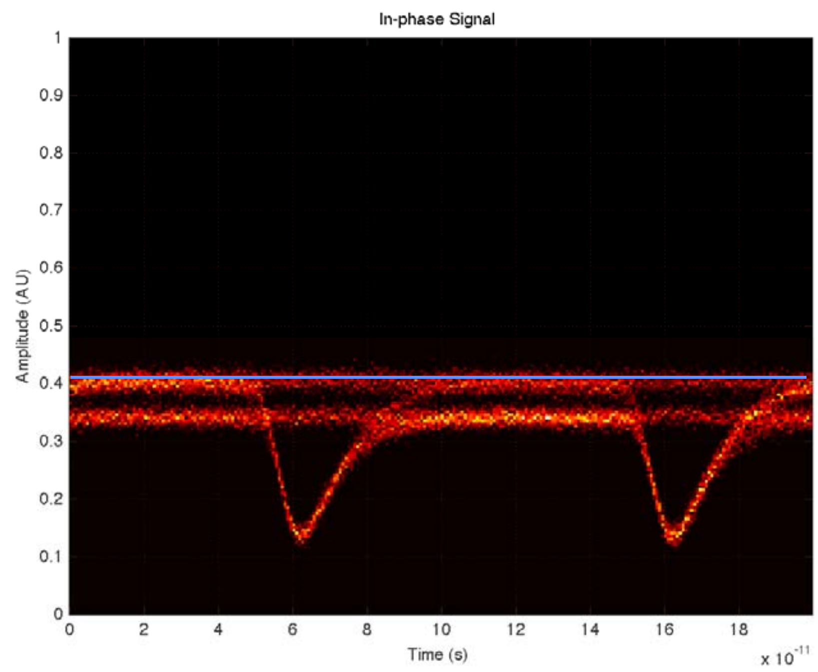
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-1.0 °C





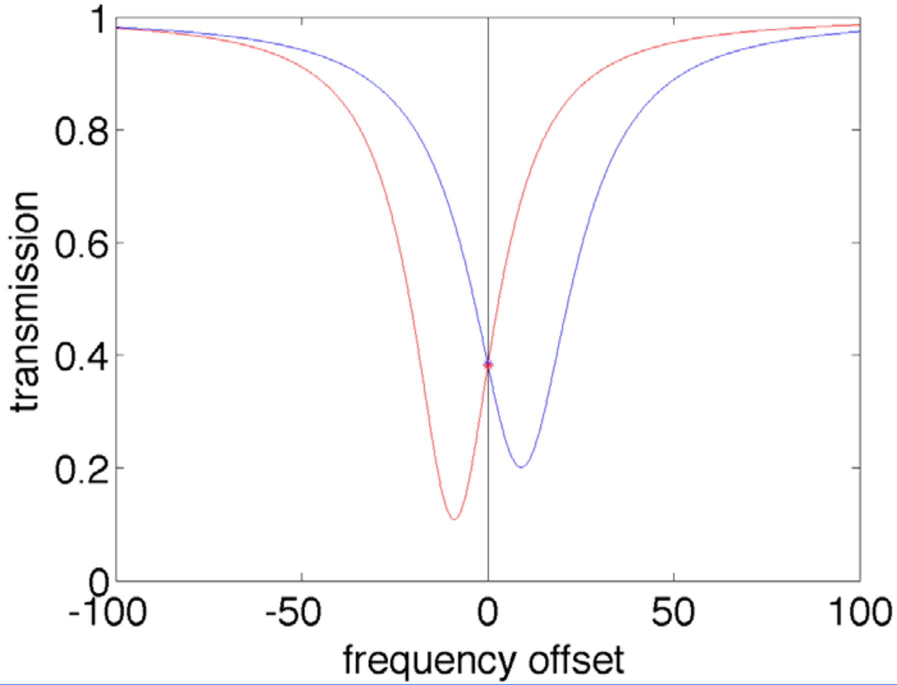
Red: Reverse Bias

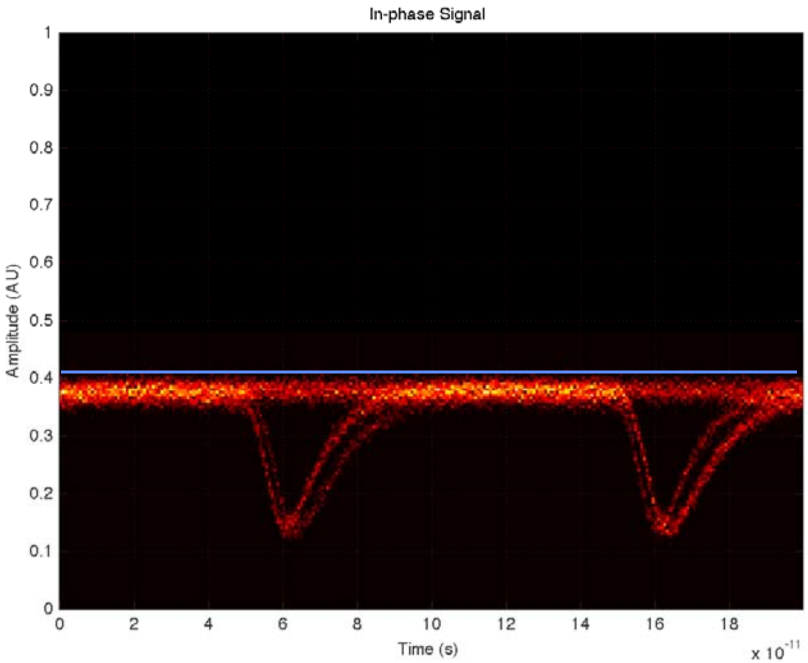
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

-0.9 °C



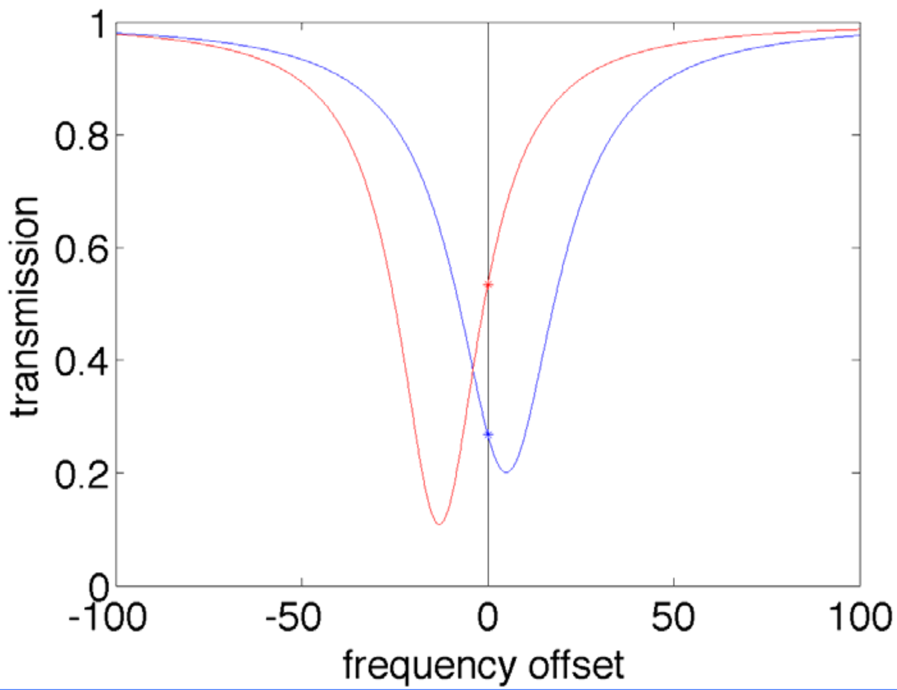


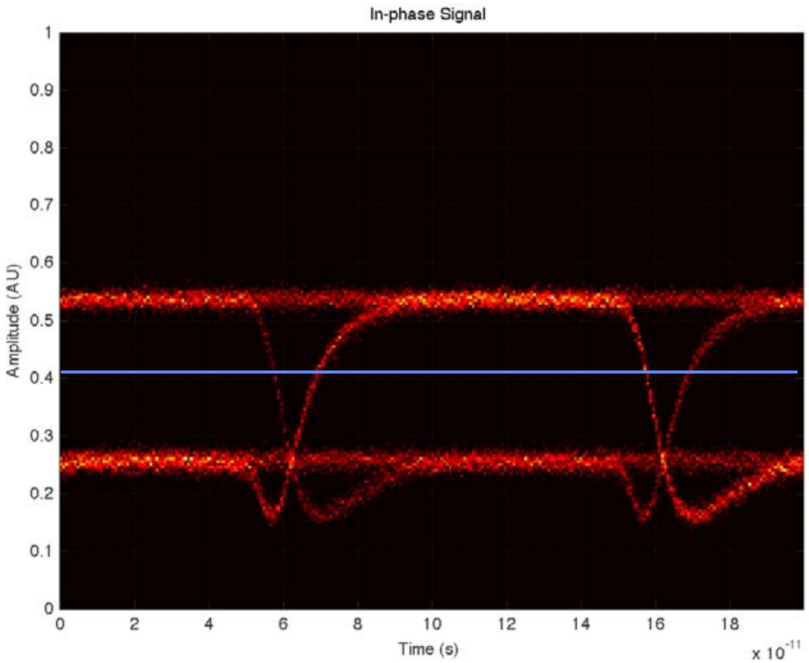
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

-0.5 °C





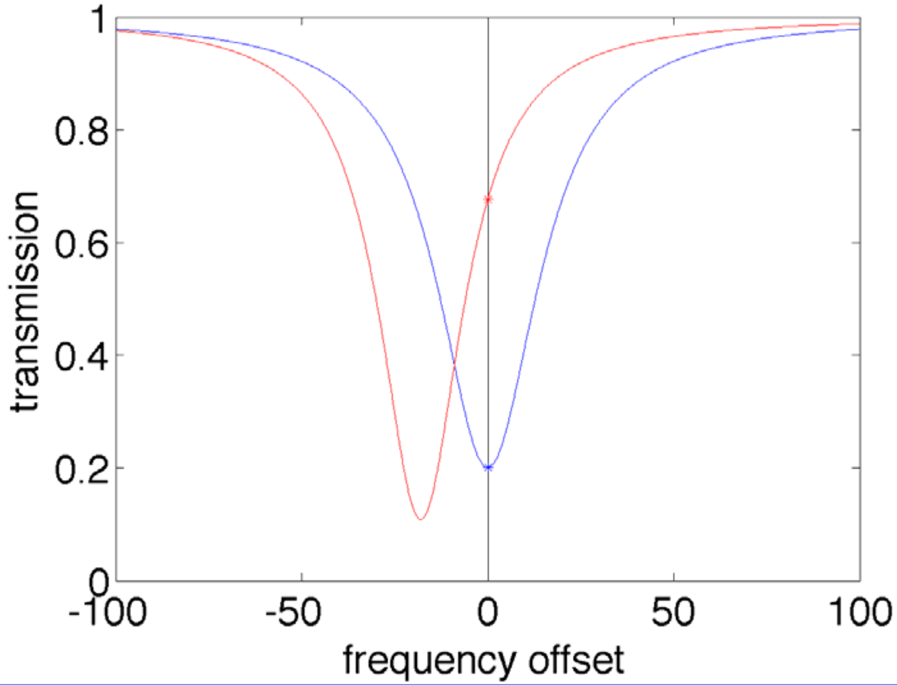
Red: Reverse Bias

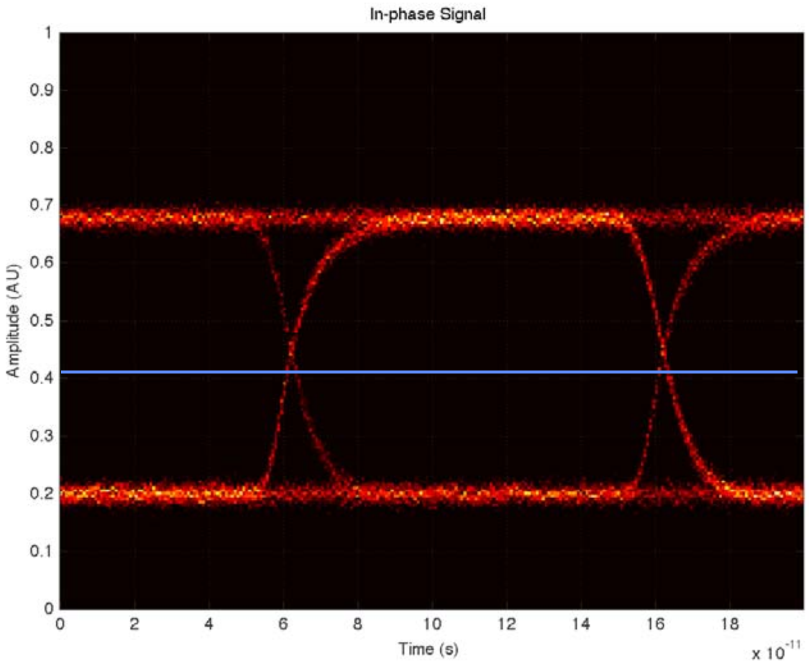
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

-0 °C





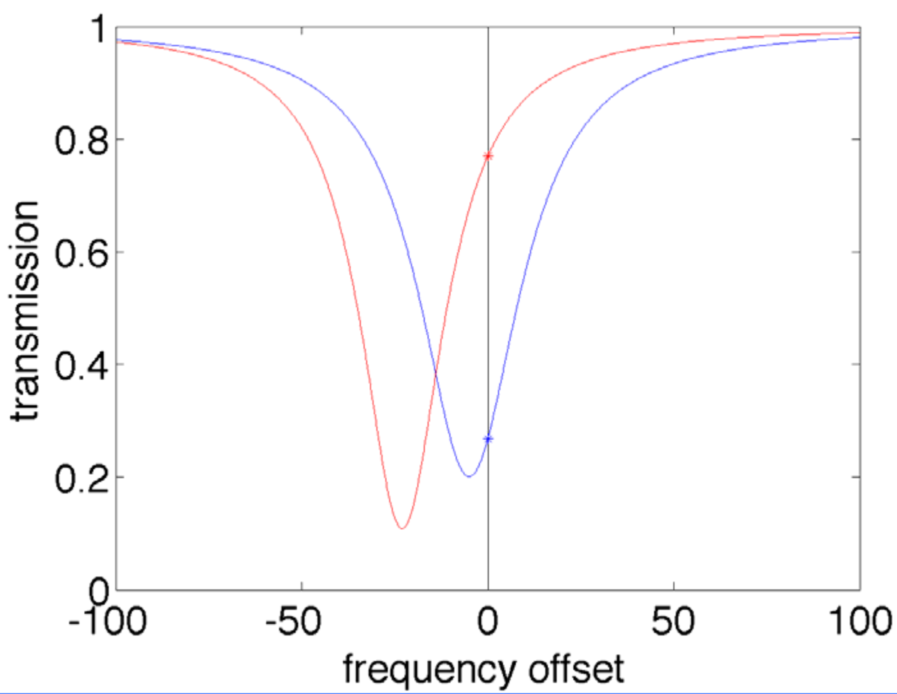
Red: Reverse Bias

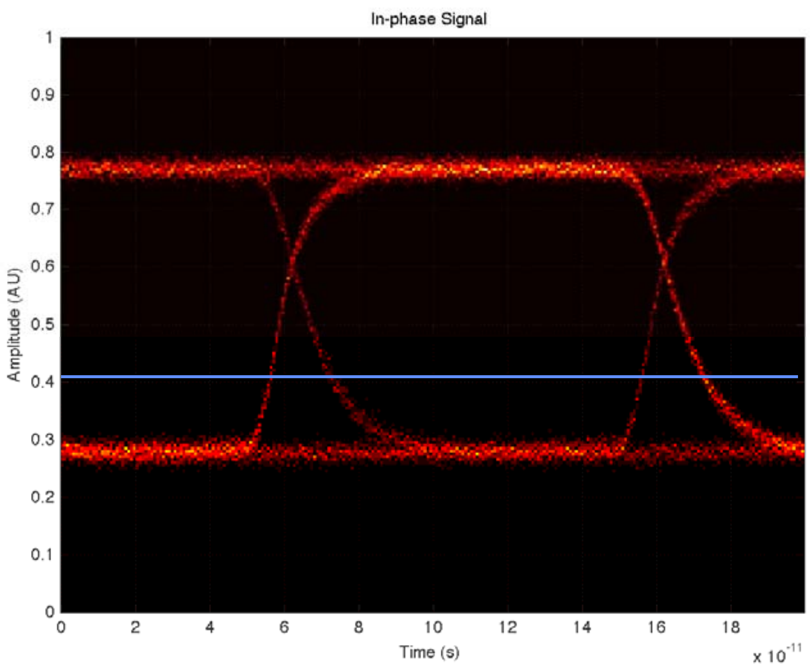
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

5 °C



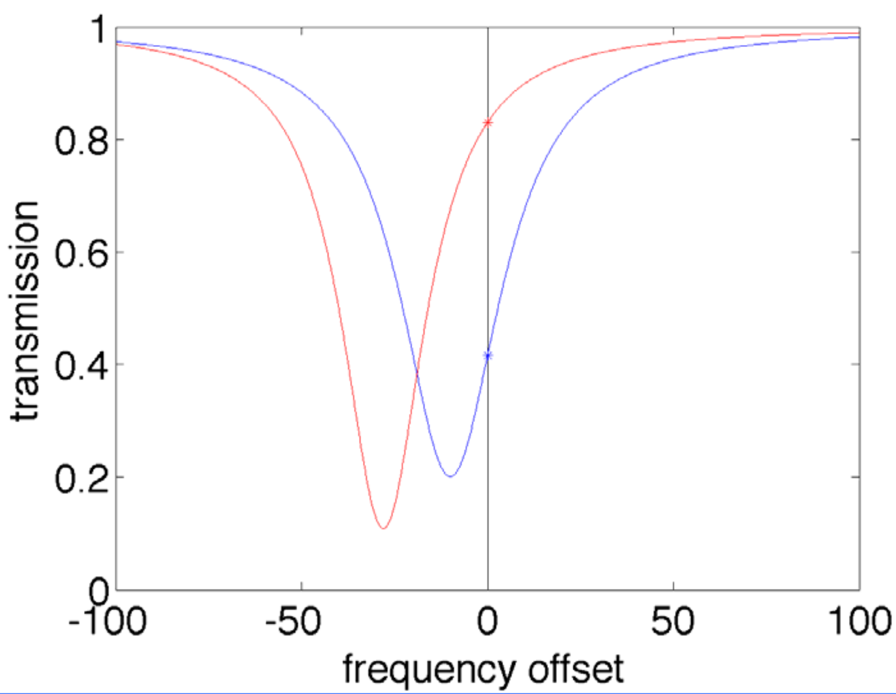


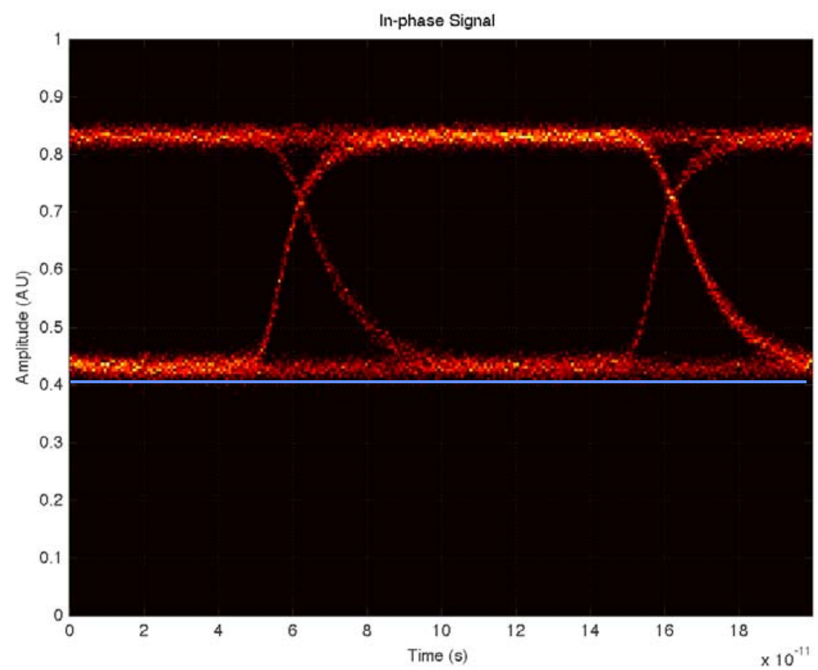
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

1 °C



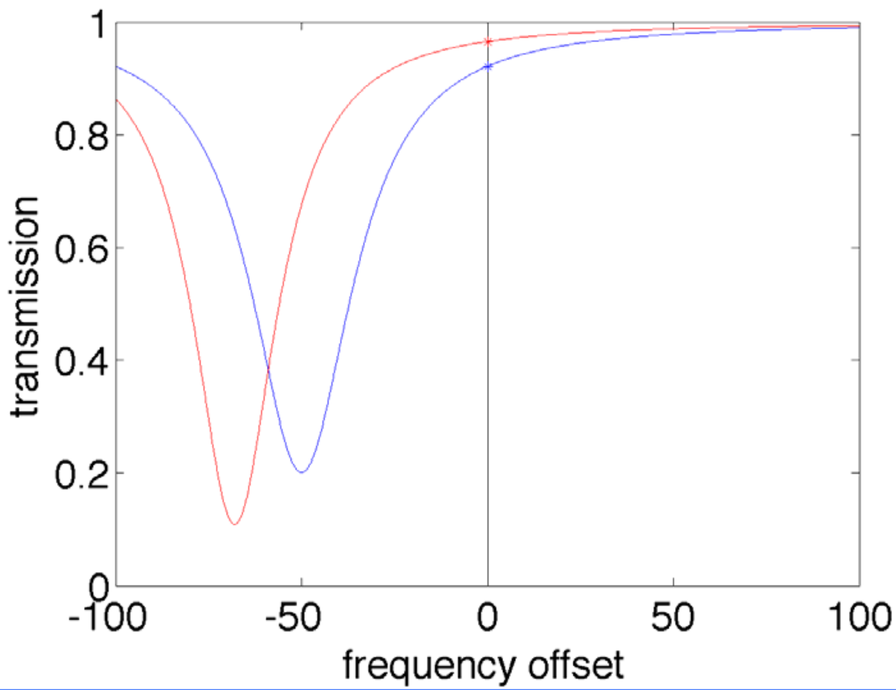


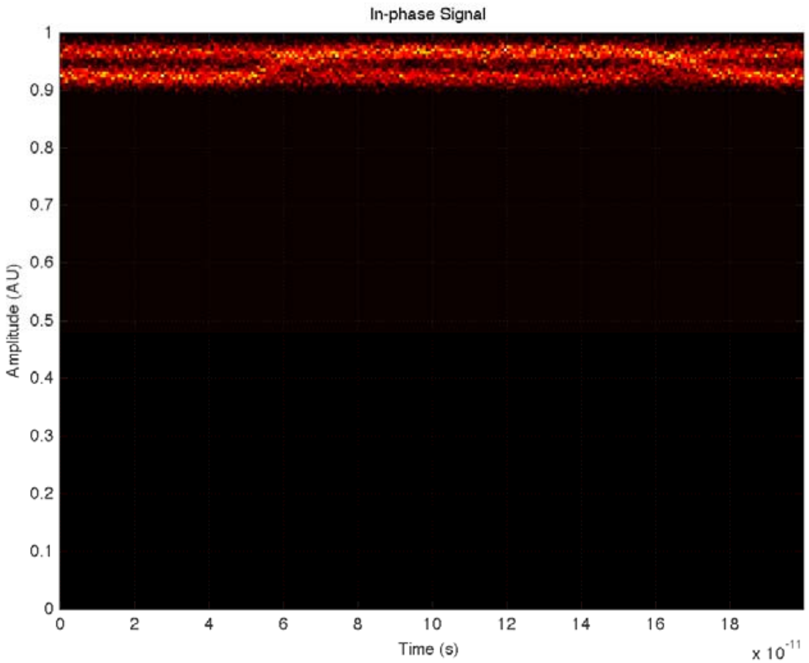
Red: Reverse Bias
Blue: Zero Bias

Resonant wavelength error

- **Progression of *simulated* eye diagram with heating for an initial position colder than optimum**

5 °C





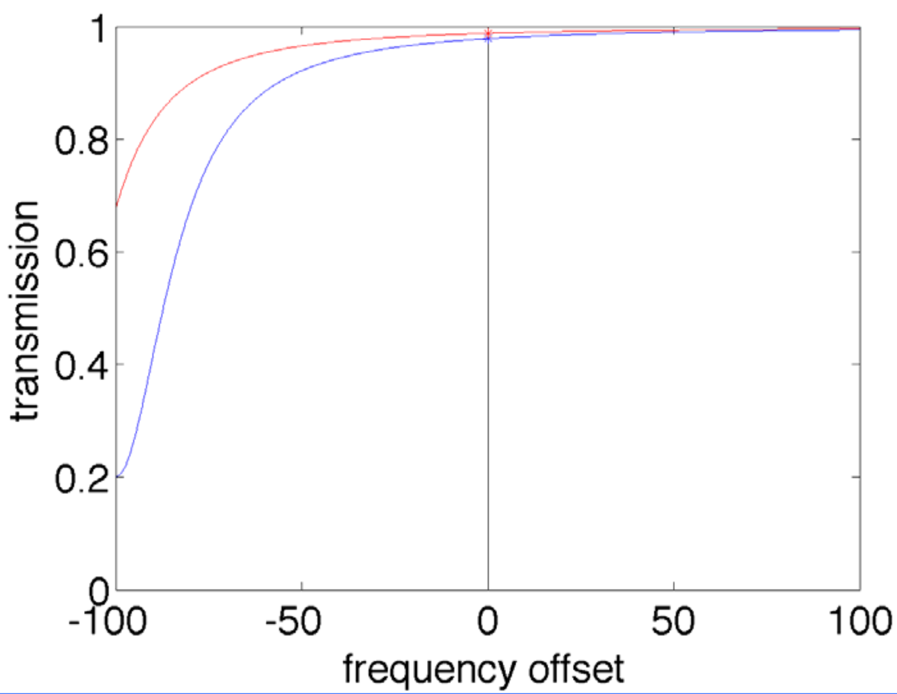
Red: Reverse Bias

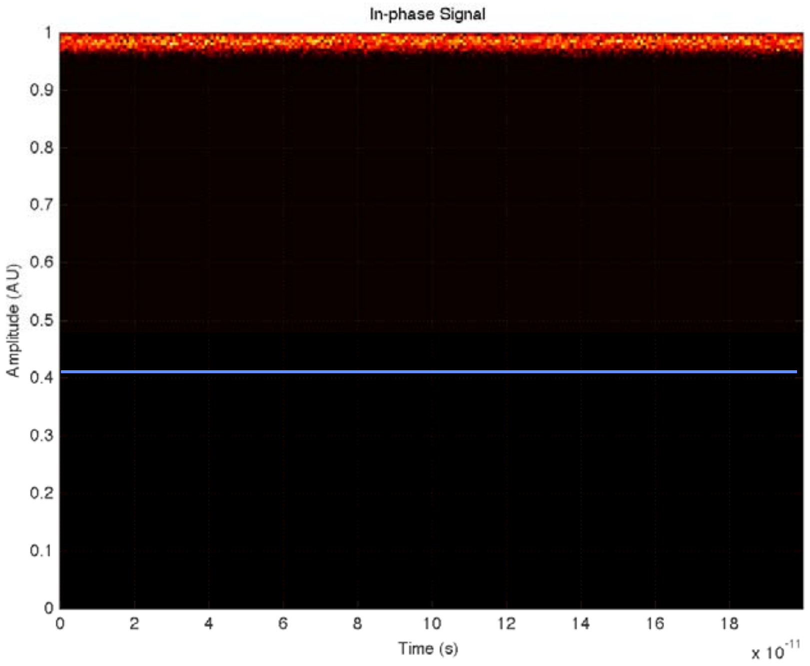
Blue: Zero Bias

Resonant wavelength error

- Progression of ***simulated*** eye diagram with heating for an initial position colder than optimum

10 °C



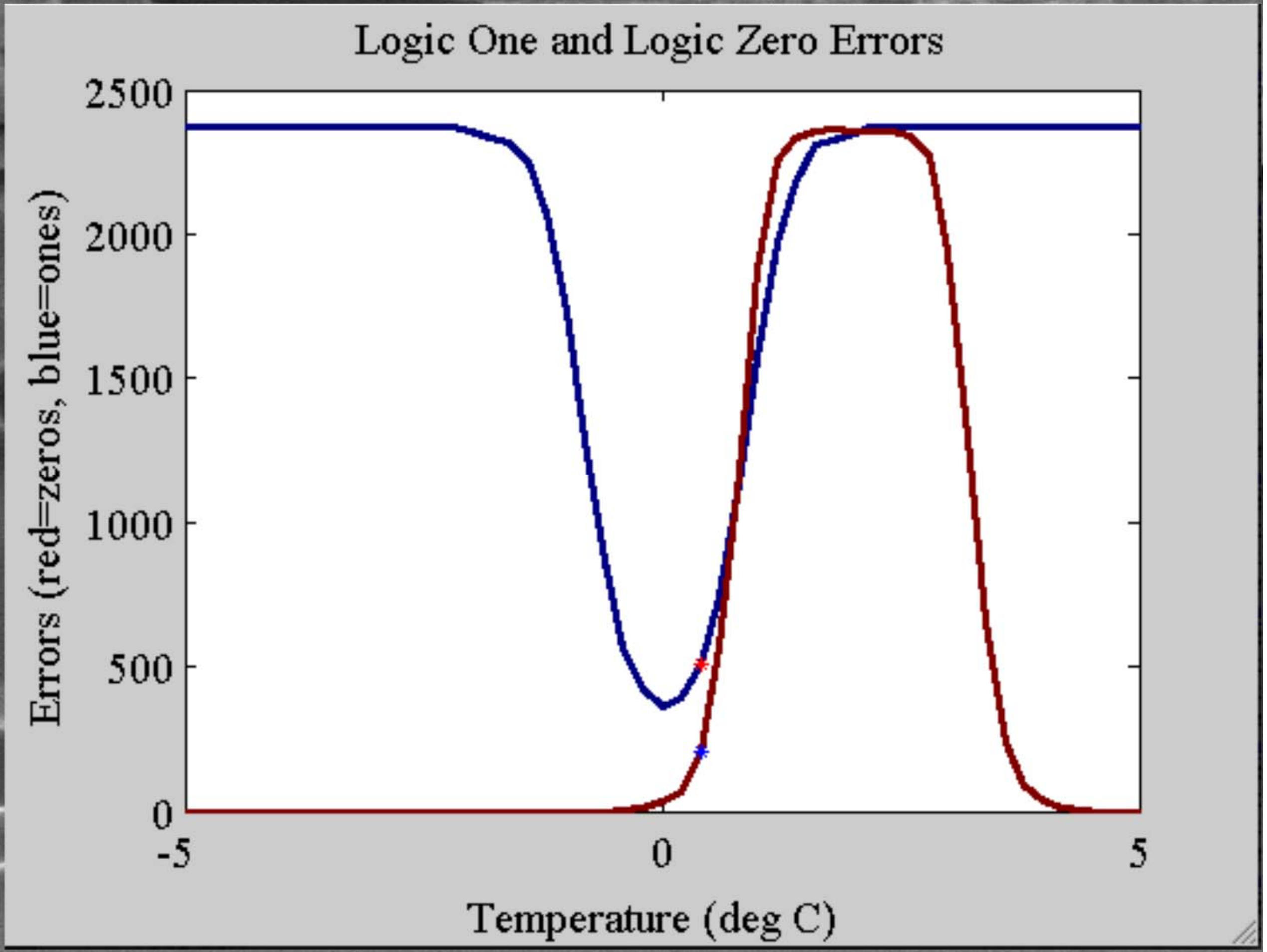


Red: Reverse Bias

Blue: Zero Bias

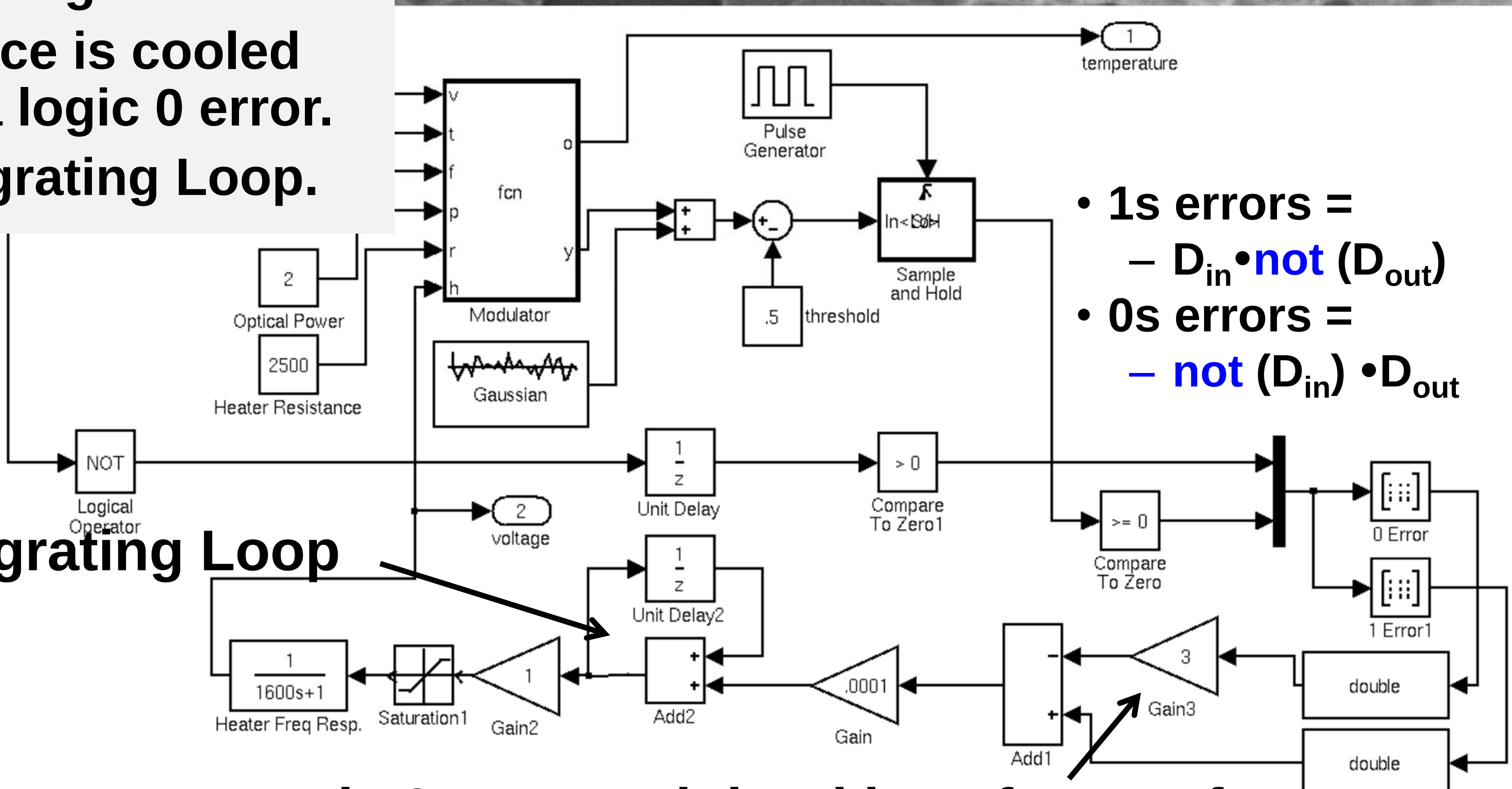
Logic one and logic zero errors

- **Operating point ends up slightly off of the optimum without extra offset**
- **Overshoot requires a reset**



Control logic (Simulink)

- **Device is heated for a logic 1 error**
- **Device is cooled for a logic 0 error.**
- **Integrating Loop.**

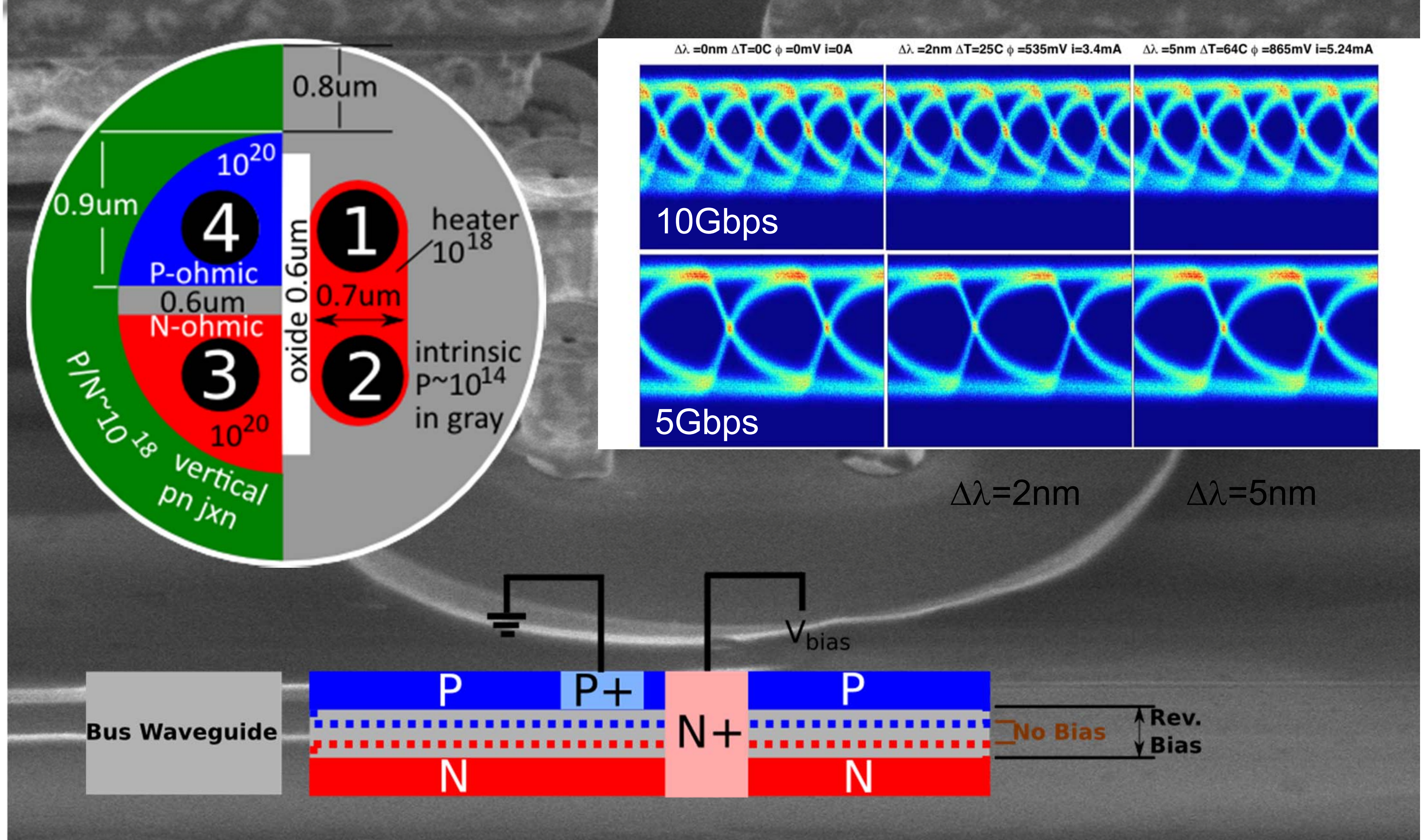


- **1s errors =**
  - **D_{in}•not (D_{out})**
- **0s errors =**
  - **not (D_{in}) •D_{out}**

- **Integrating Loop**

- **Logic 0 error weighted by a factor of 3 to arrive at operating point.**

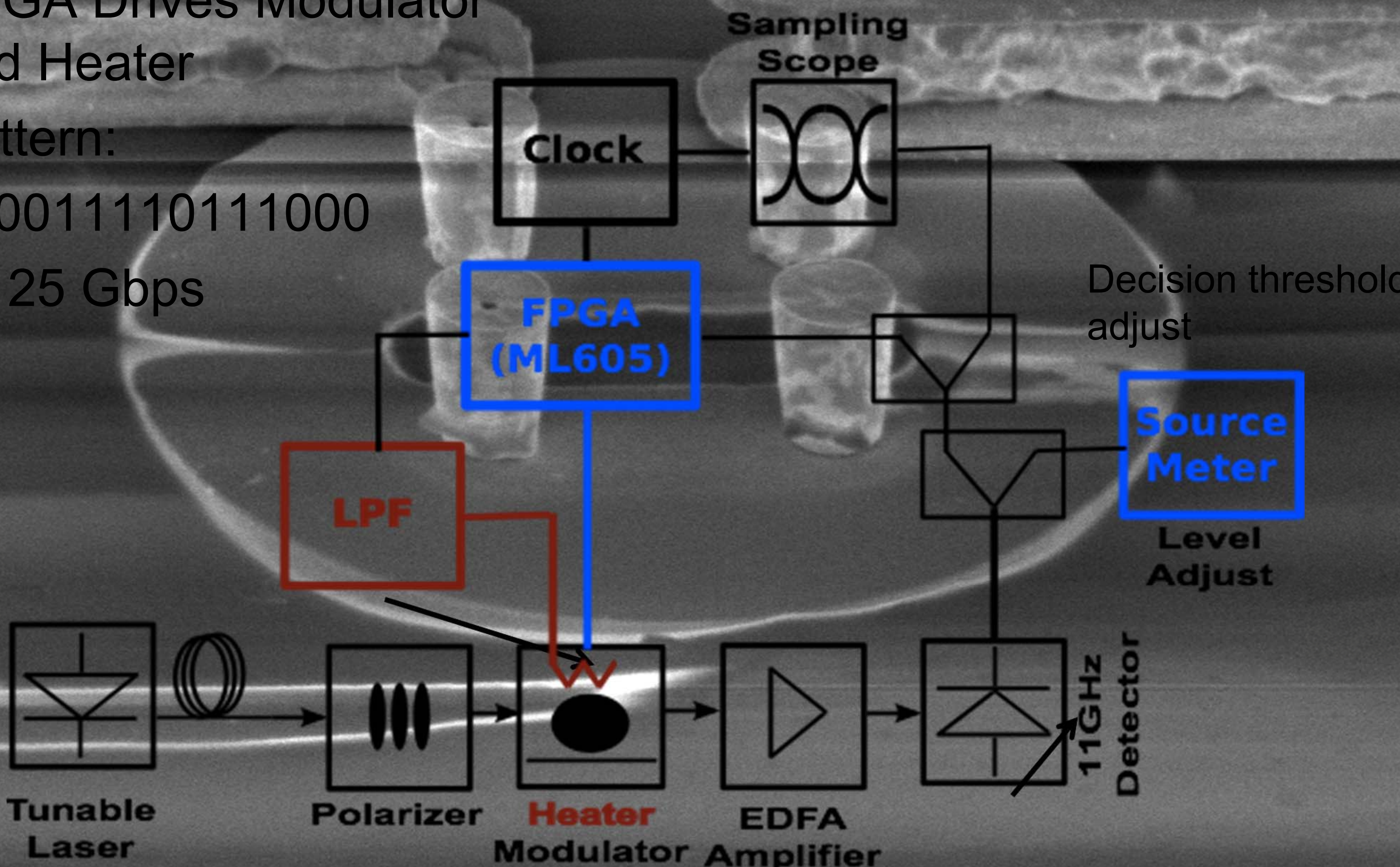
Heater-Modulator device



Zortman, Lentine, Trotter, Watts, OFC 2012

Experimental Set up

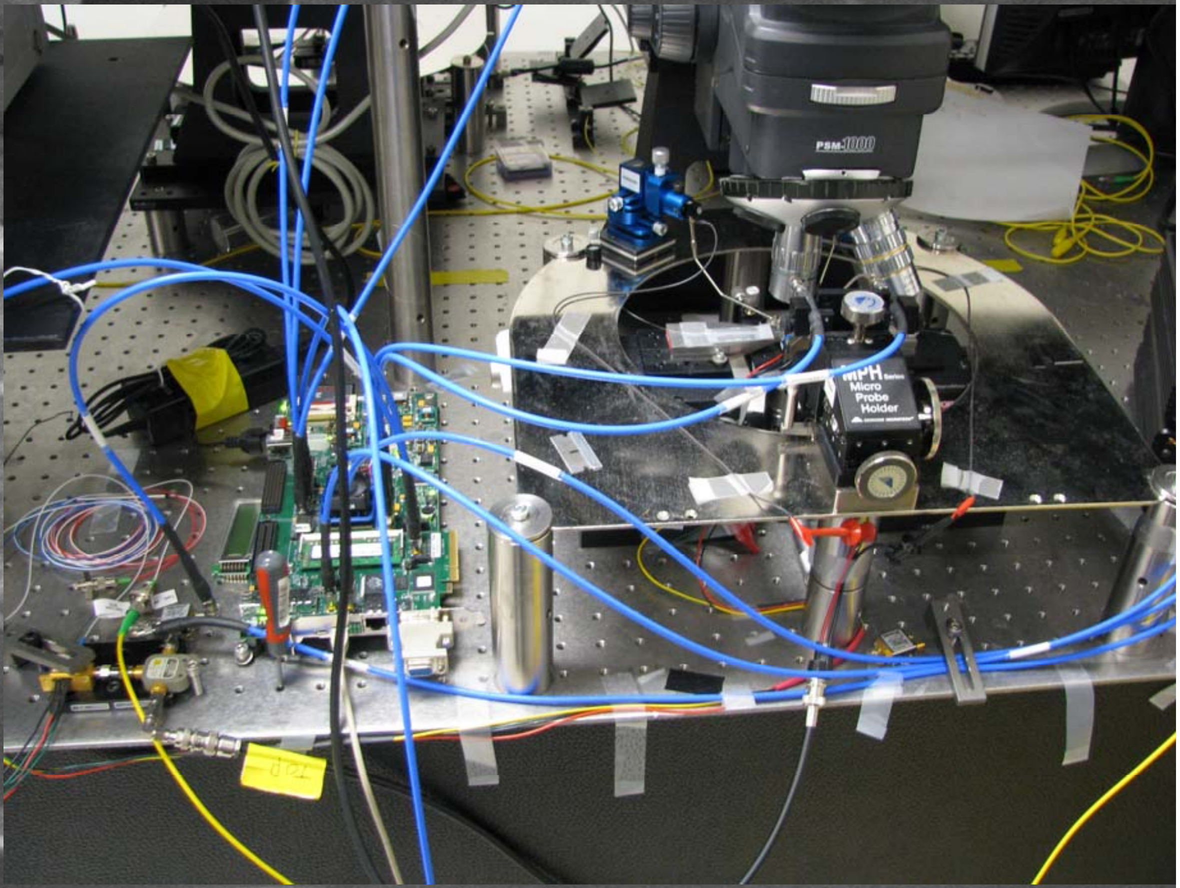
- FPGA Drives Modulator and Heater
- Pattern: 0100011110111000
- 3.125 Gbps



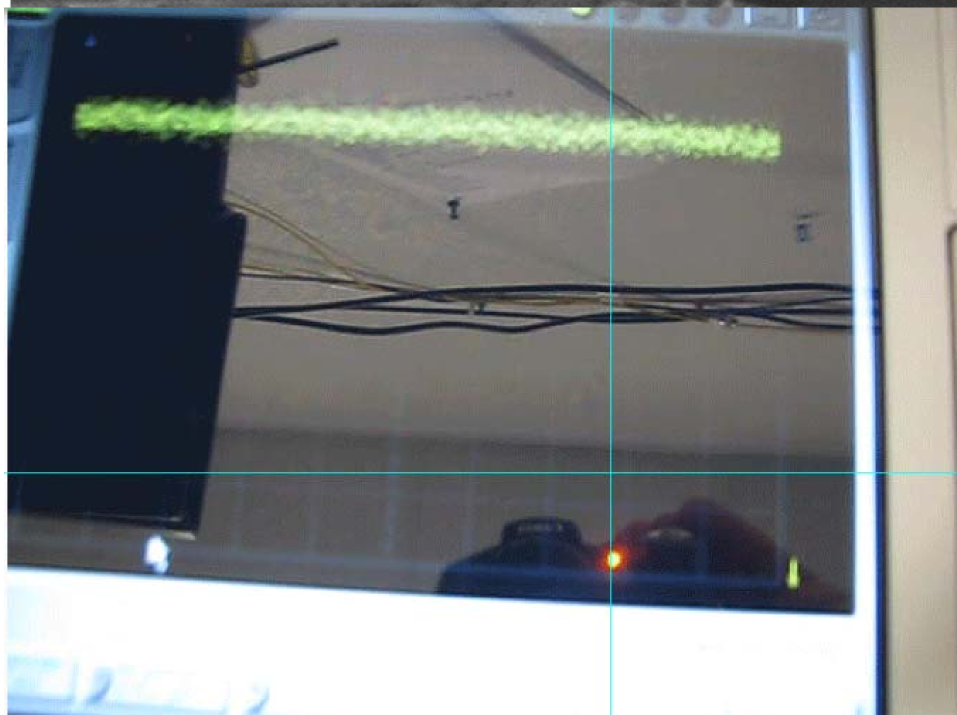
Experimental set up and results

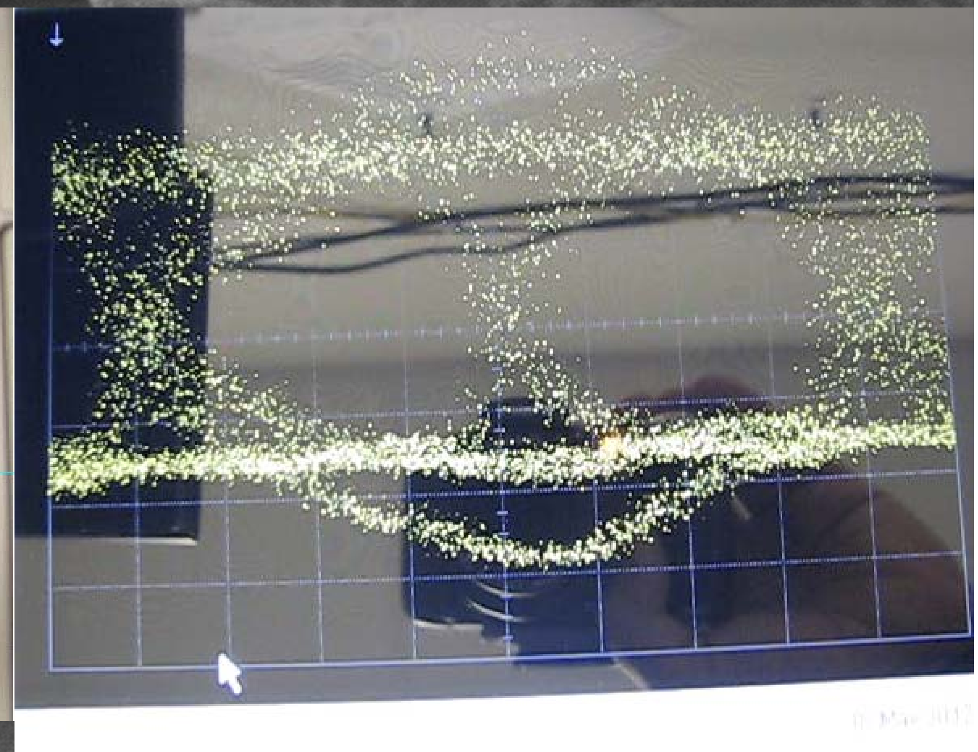
- **Case 1: Initial wavelength is lower than resonant wavelength**
  - **Tuning Range:**
  - **25C (> 2nm)**
  - **Capable of 10 – 100 us tuning time.**

- **Case 2: Device locked in the center of range**
  - **Device cooled by 16 C in 10pm steps**
  - **Device heated by 16C**
  - **Device remained locked**



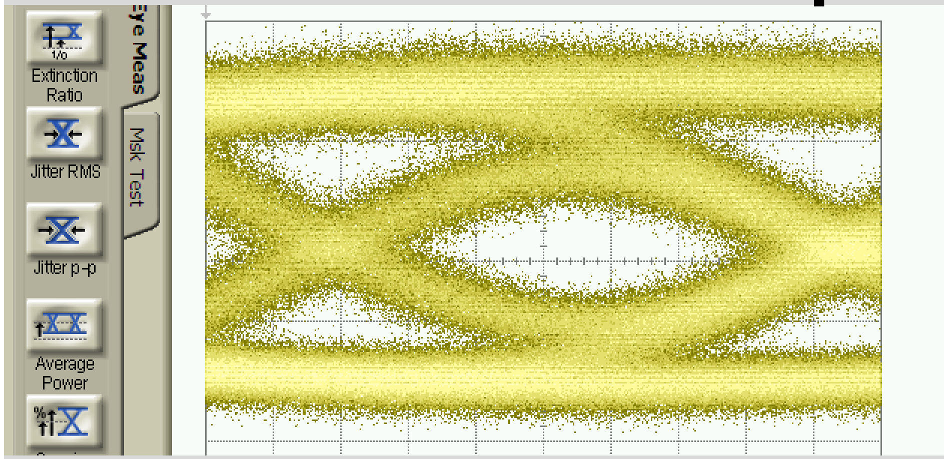
Experimental Results of Tuning

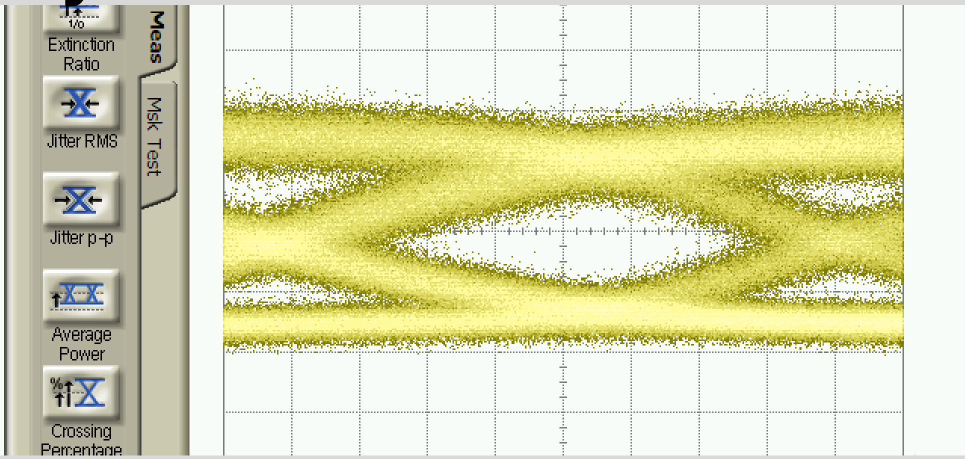




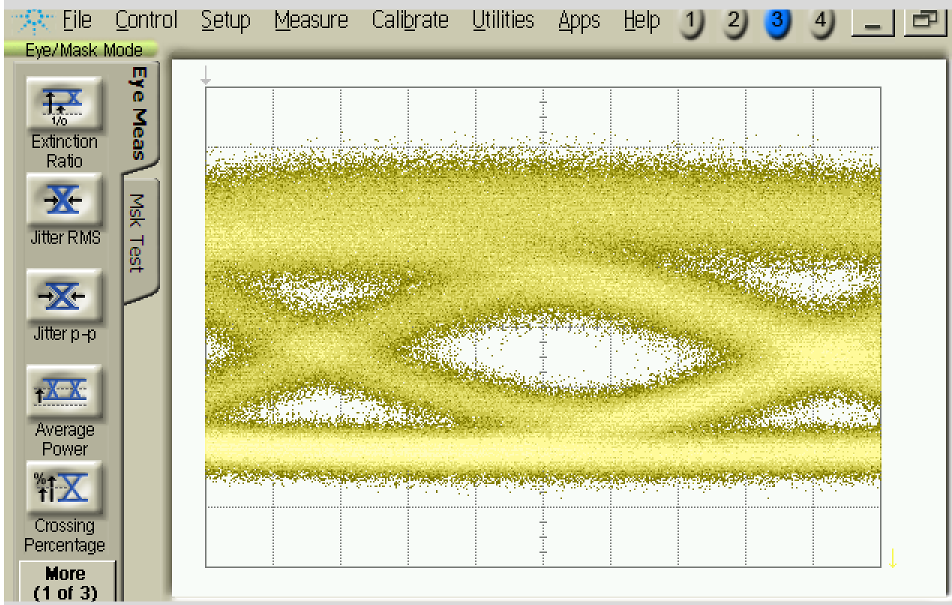
- Data rate = 3.125 Gbps
- Initial offset = 500 pm

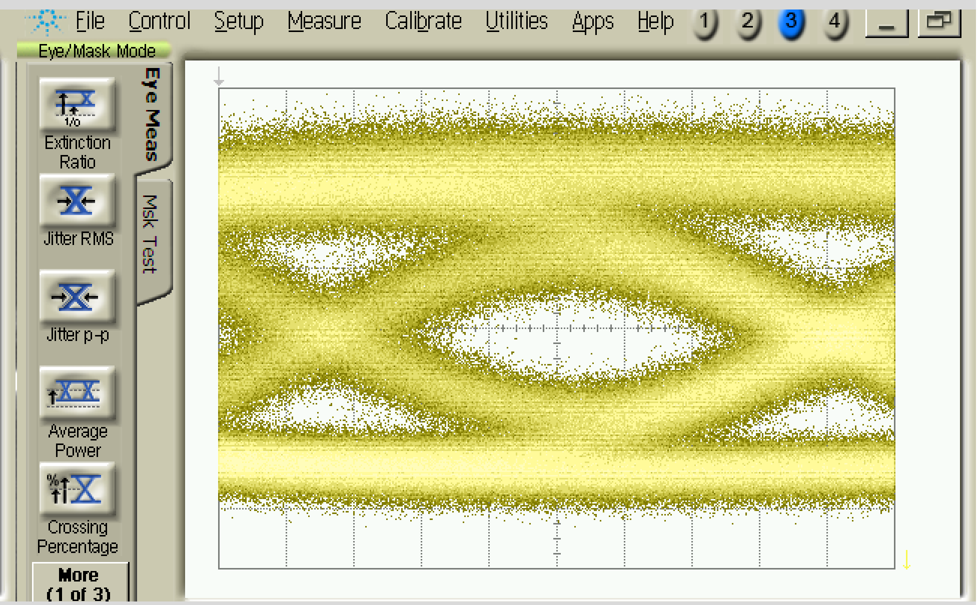
Experimental results: Tuned eye with initial resonant frequency error





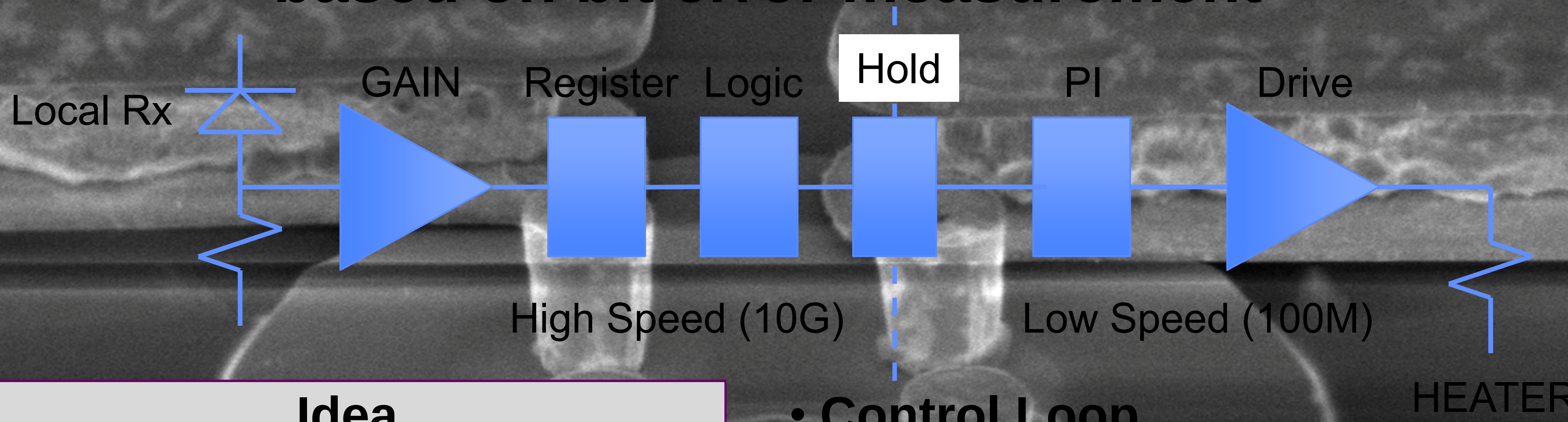
- 500 pm (62.5 GHz)
- 1000 pm (125 GHz)





- 1500 pm (187 GHz)
- 2000 pm (250 GHz)

Digital Wavelength Stabilization Electronics based on bit error measurement



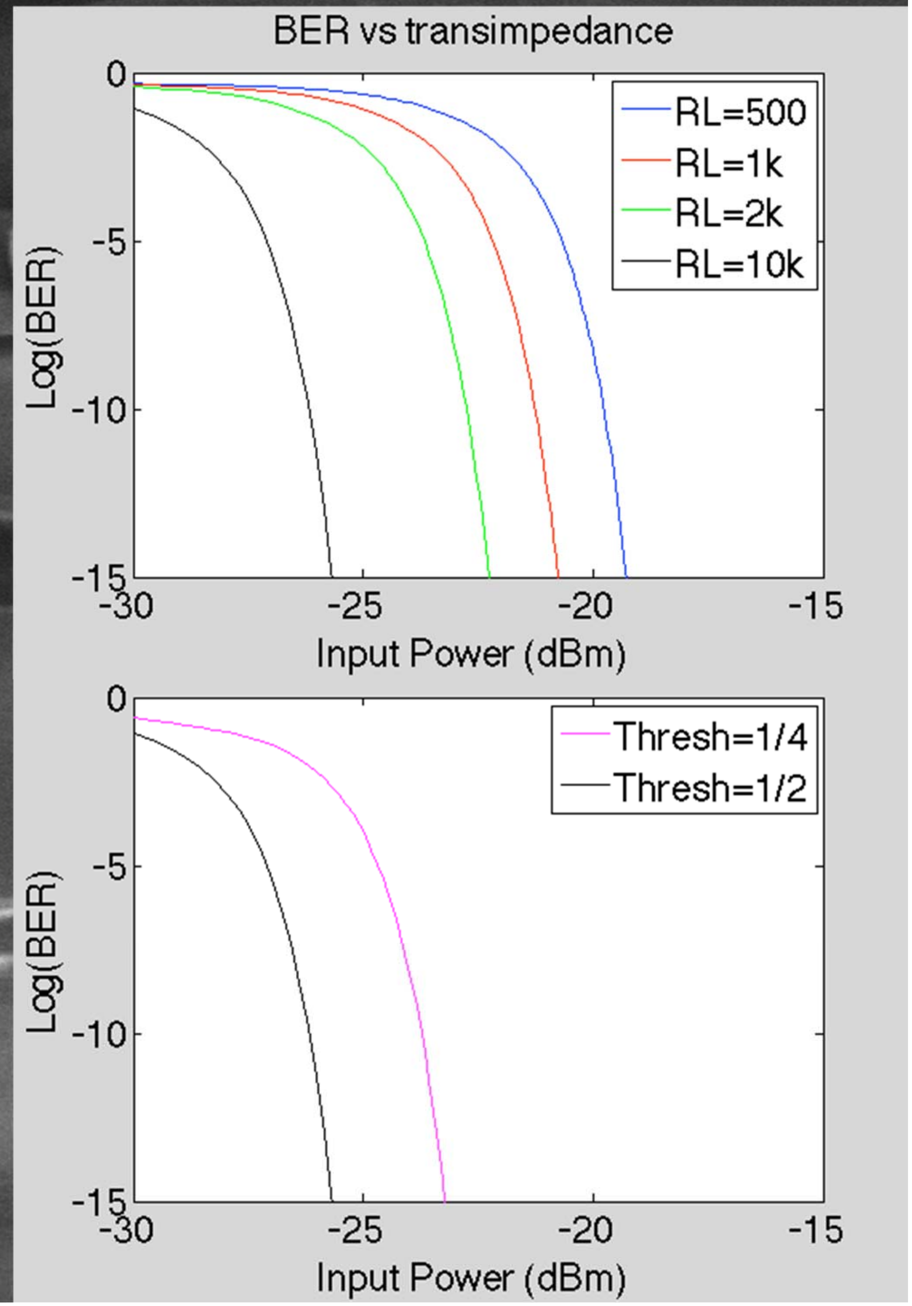
Idea

- **Measure bit errors in a local receiver near the modulator**
- **Adjust heater to minimize local bit errors**
- **If local receiver has high noise floor, far-end receiver can be error free**

- **Control Loop**
  - **Rx: 10 fJ/bit * [can we do this?]**
  - **Register (5 fJ/bit)**
  - **Logic (<10 gate eq. 5 fJ/bit)**
  - **Hold (~ 20fJ/bit est.)**
  - **PI: < 10 fJ/bit (100X slower)**
  - **Actuation (Heater power)**
- **Example**
  - **100G * 4.4μW/G = 44 fJ/bit @ 10Gbps + 50 fJ/bit = 90 fJ/bit**

Receiver Noise

- **How do we design a local receiver with higher noise than the remote receiver?**
  - **Lower transimpedence gain →**
    - **Higher power though**
  - **Different bias conditions**
  - **Different temperatures on resistors (micro-heaters)**
  - **Adaptive Threshold →**
    - **Different for ‘1’ and ‘0’**



Agrawal, ‘Fiber Optic Communications Systems,’ p. 171-172

Conclusion

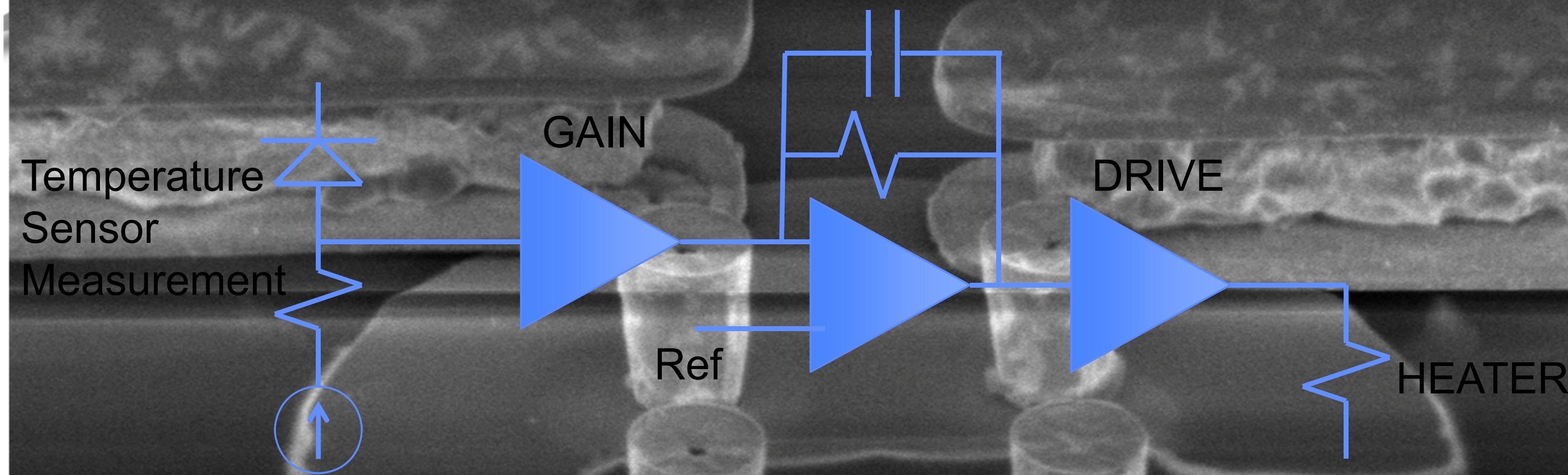
- **Preliminary demonstration of using bit errors from a local receiver to stabilize the resonant wavelength of a modulator**

- **Bit errors are what you really care about**
  - **Temperature, fabrication, aging, power, etc.**

- **Expect dissipation to be low in the circuit compared to the heater**

- **Still work to do**
  - **Full link showing error free operation at the receiver**
  - **Integration and _robust_ low power operation**

Analog Wavelength Stabilization Electronics

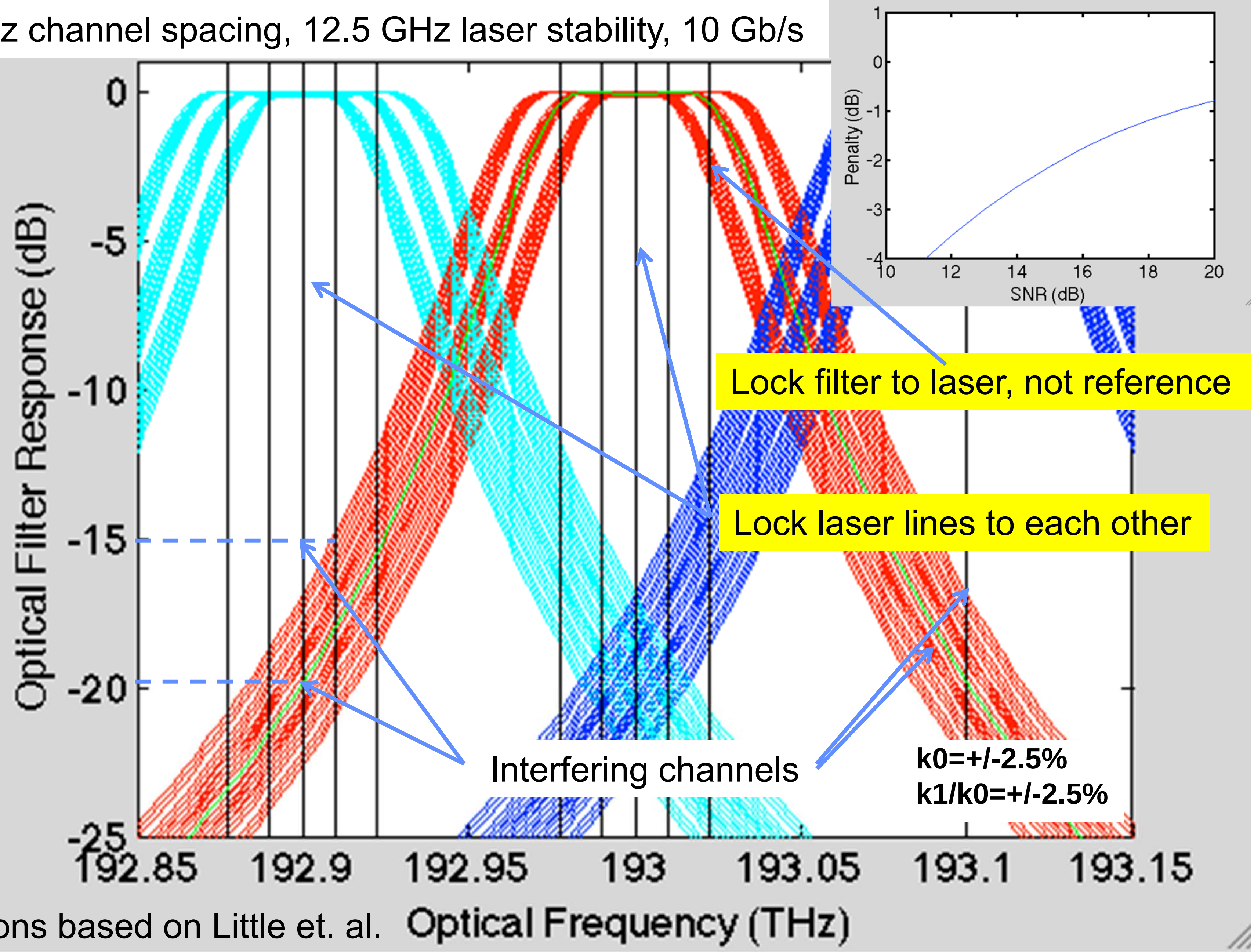


- Control Loop
  - Sensing & Gain (10μA 1V)
  - PID Loop Circuitry (10μA 1V)
  - Ref = 10μA 1V
  - Actuation (Heater power)
- Example
  - 100G * 4.4μW/G = 440 μW + 30μA = 47 fJ/bit @ 10Gbps

Based on C. T. DeRose et. al., CLEO 2010

Temperature Changes – 2nd order filter

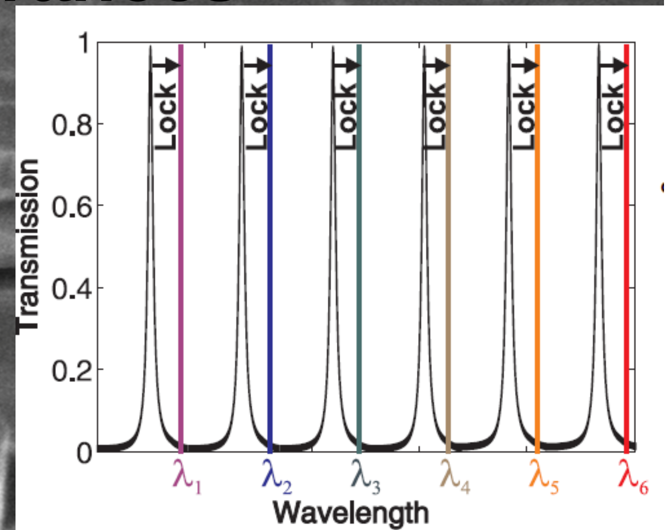
100 GHz channel spacing, 12.5 GHz laser stability, 10 Gb/s



Calculations based on Little et. al.

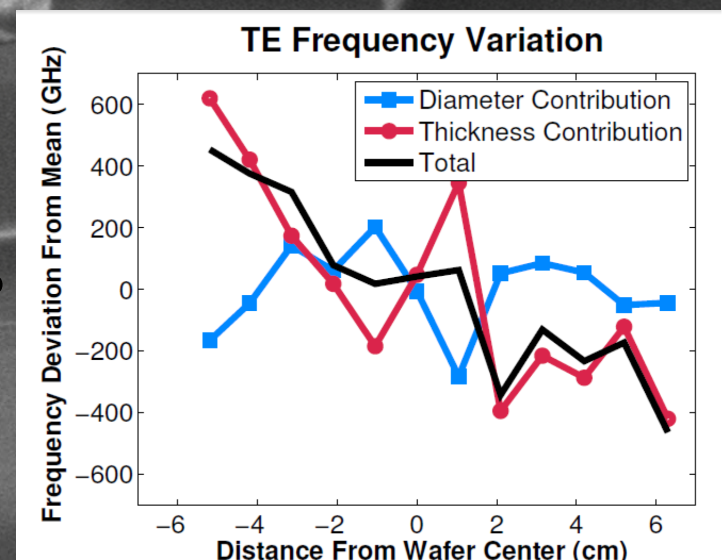
Wavelength Recovery and manufacturing tolerances

- **Thermal variations**
  - DWDM: alignment of resonators to specific lines, not quite as simple as single resonators



picture from M. Watts, HSD 2011

- **Manufacturing**
  - We think thickness is more of an issue than dimensions (for disks)
  - What is the ultimate limit of manufacturing wavelength variation?
  - Can it be post-processed?

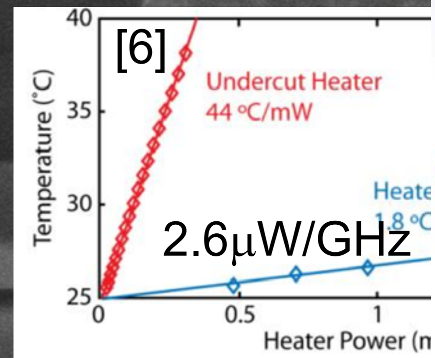


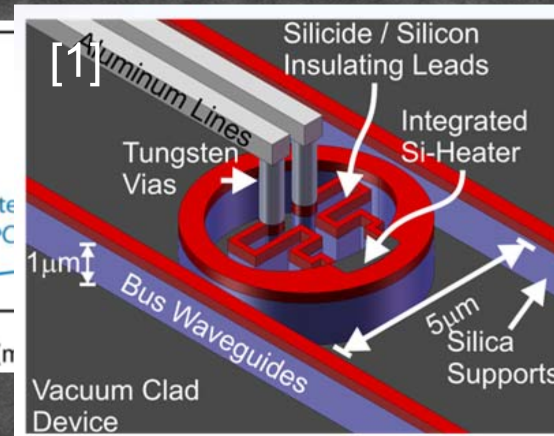
W. A. Zortman et. al., Optics Express (2010)

See also:
A. V. Krishnamoorthy et. al., IEEE Photonics Journal, 2011
M. Gorgas et. al., IEEE CICC, 2011

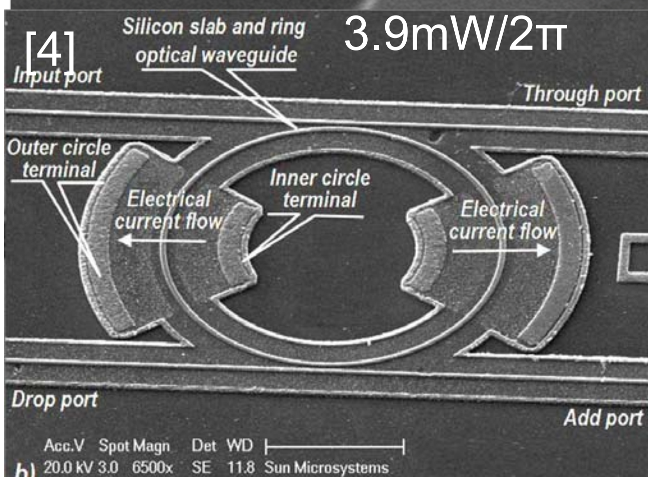
Wavelength Stabilization Devices

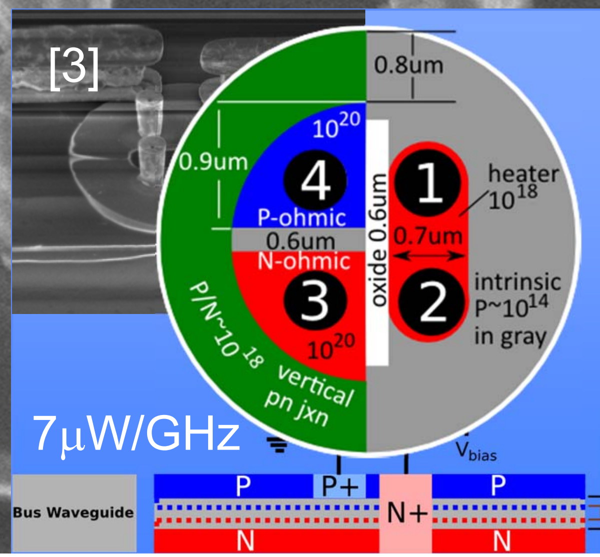
- Device Concepts
  - Heater-filters
  - Heater-modulators
  - Heater-sensor-modulators

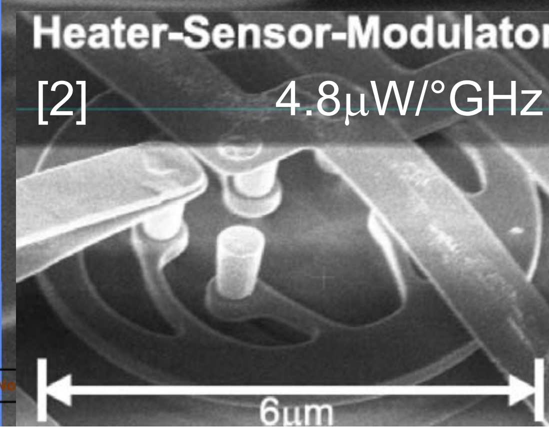


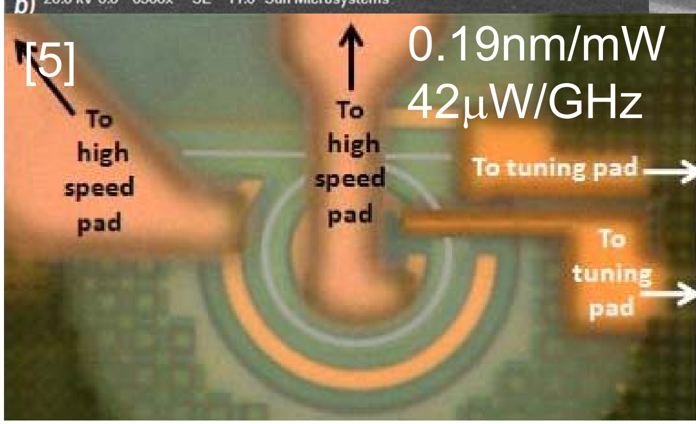


4.4µW/GHz









1. M. R. Watts et. al., CLEO 2009
2. C. T. DeRose et. al., CLEO 2010
3. W. A. Zortman et. al., OFC 2012
4. J. E. Cunningham et. al., Optics Express, 2010
5. G. Li et. al., Optics Express 2011
6. J. S. Orcott et. al., Optics Express 2011