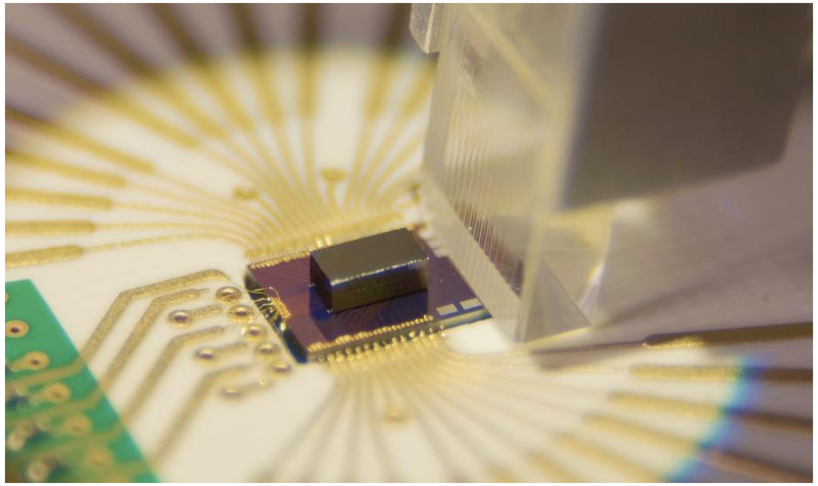


THERMALLY-TUNED PHOTONIC LINKS TOWARD OPTICAL NETWORKS ON INTERPOSER

Optics workshop – DATE 2018 | Yvain Thonnart

SILICON PHOTONICS FOR SHORT-RANGE COMMUNICATION

Silicon Photonics moves forward for long distance optical wireline transceiver

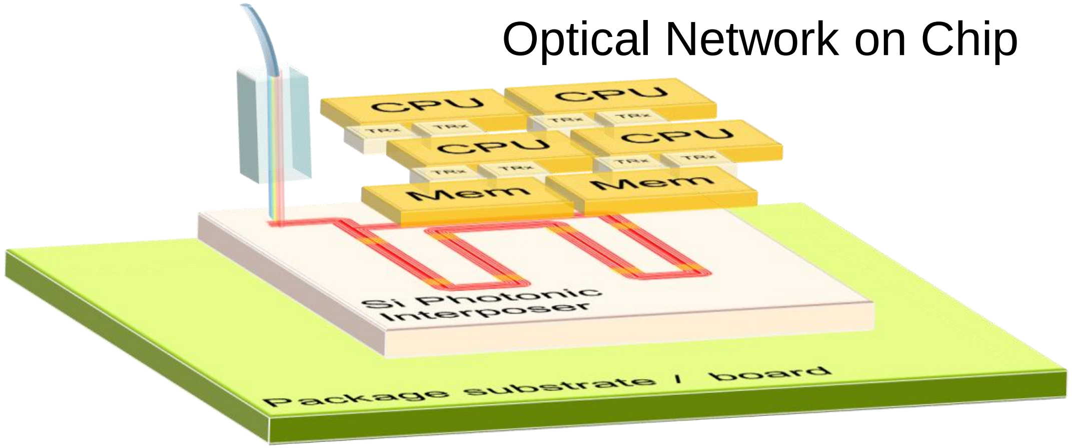
- 100 / 400 Gigabit Ethernet

Large-scale electronics longs for low-latency low-energy dense communication

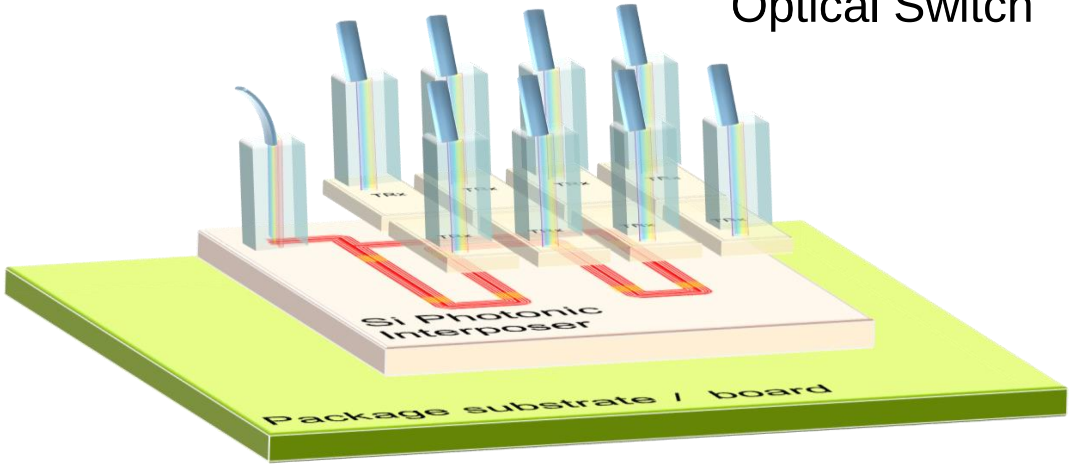
Optical short-range communication has been a long-term target for years

- Needs compact optical devices to maximize bandwidth per mm²
  ➔ **Microring optical resonators**

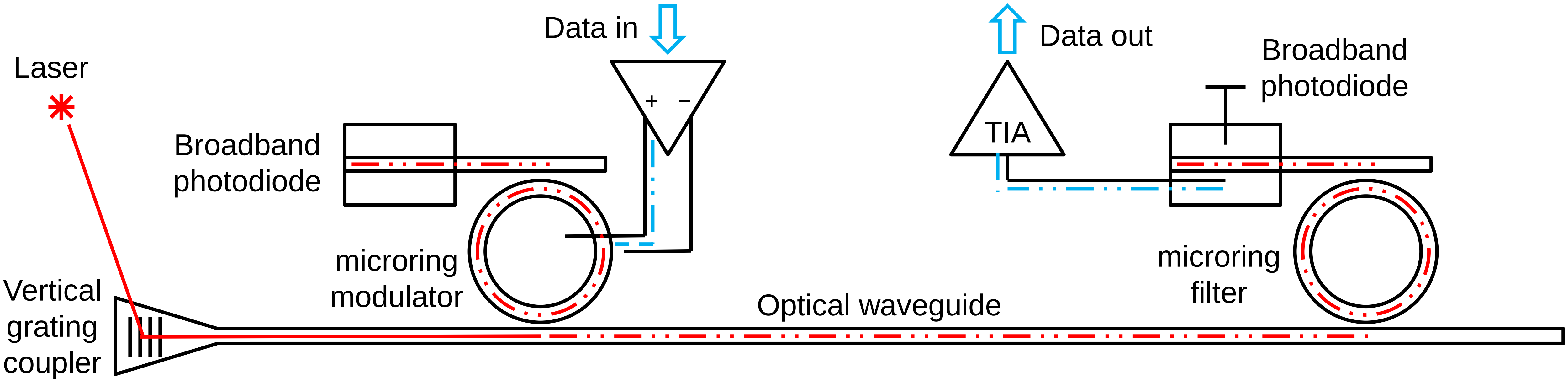
Optical Network on Chip



Optical Switch



MICRORING MODULATOR BASED LINK



Microrings & Photodiodes are compact & fast

- Area < 100µm×100µm – Bandwidth > 10 GHz

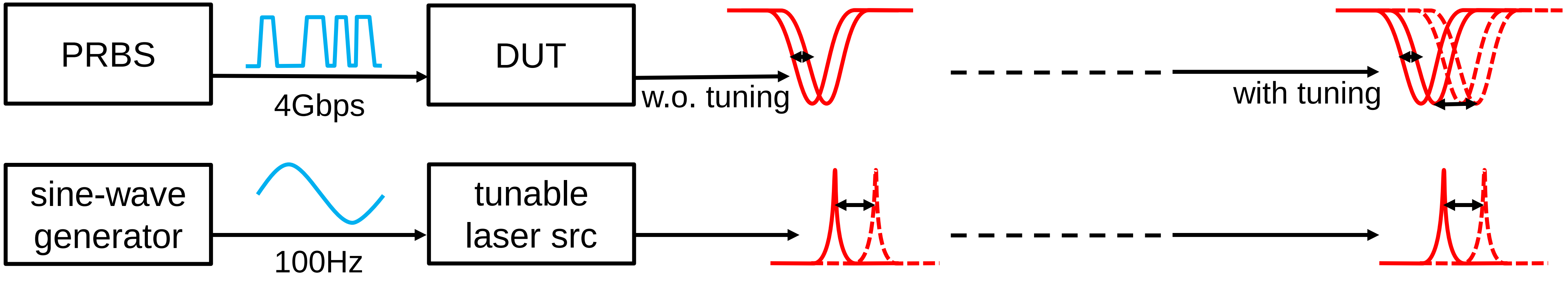
Waveguides have low latency & low losses

- Propagation ~ 10cm/ns – Losses ~ 0.1dB/cm

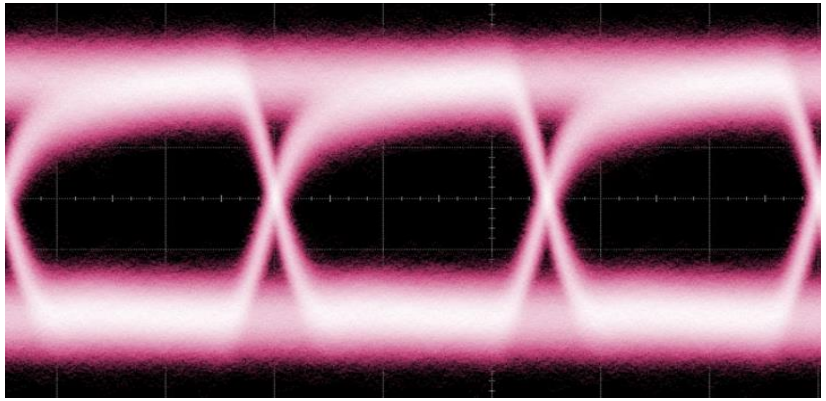
But Chip activity creates temperature changes ➔ disturbs the microrings

CIRCUIT OBJECTIVE: PRESERVE COMMUNICATION DESPITE ENVIRONMENTAL PERTURBATION

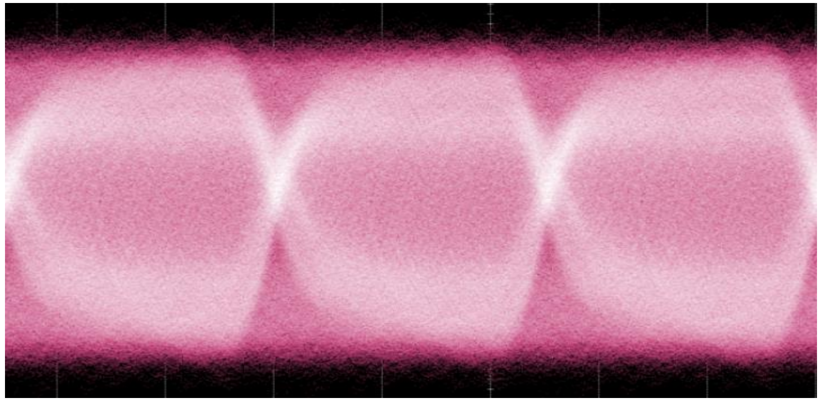
Experiment: 4Gbps modulation under laser wavelength wobulation 30pm$_{pp}$ at 100Hz
➔ Simulate thermal effect of workload changes on package (~1-10ms time constant)



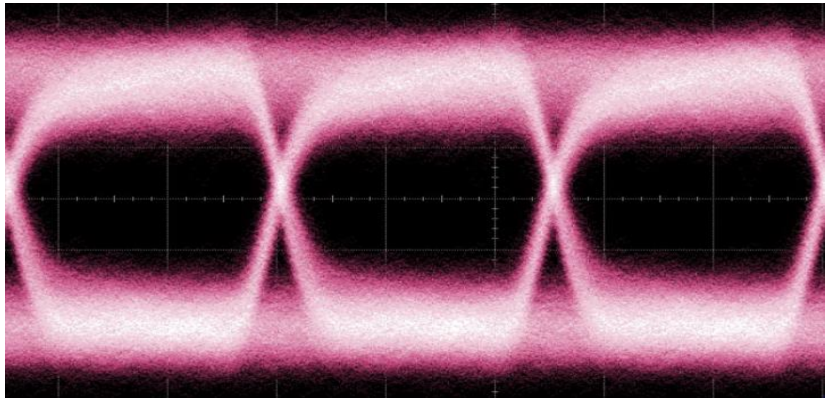
No wobulation



Wob+Thermal tuning deactivated



Wob.+Thermal tuning activated



OUTLINE

Context: Silicon photonics for short-range communication

Silicon-photonic devices

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TOWARD demonstrator

Measurements & benchmarking

$$\lambda_{res} = \frac{P\, n_{eff}}{k}$$

Compact optical devices

- Highly resonant: Q-factor 10,000–30,000

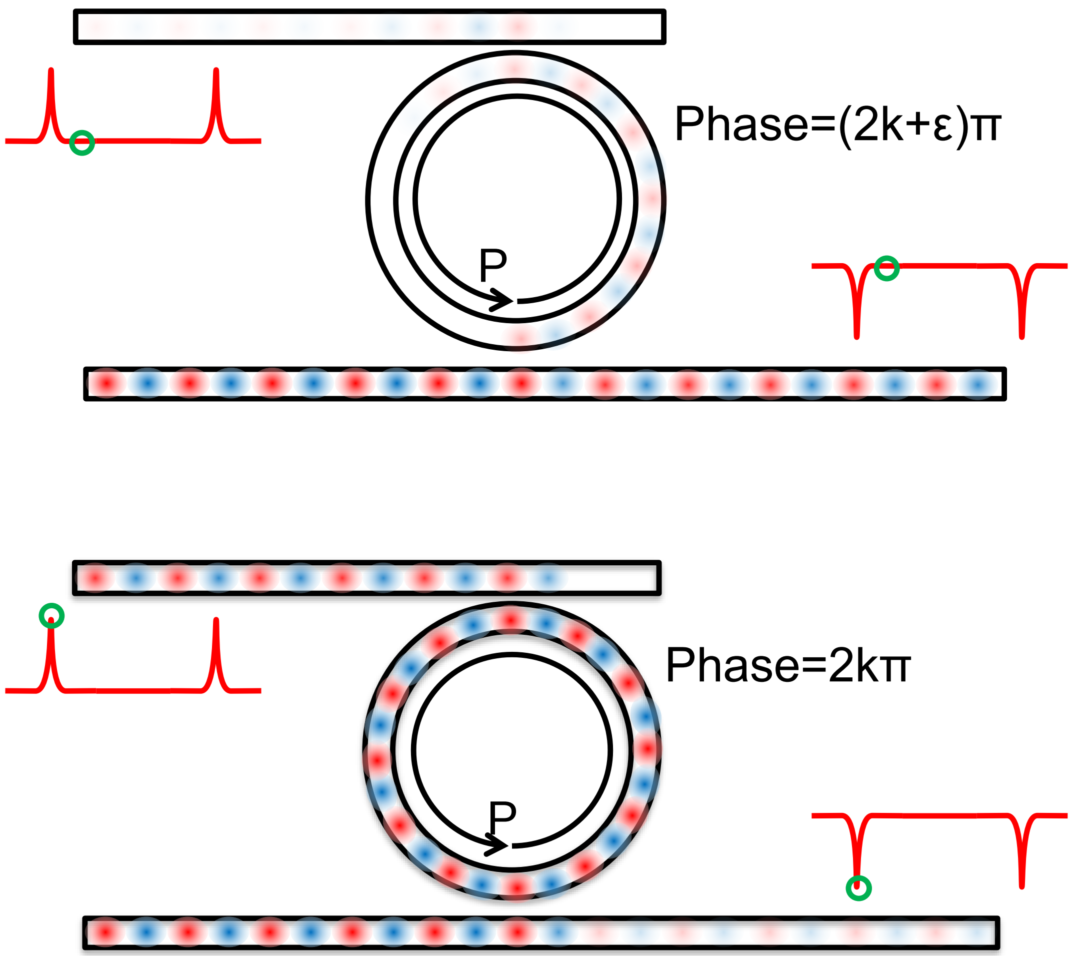
Any refractive index change shifts the resonant wavelength

PN or PIN diode junction can be created inside the ring for electrical control

- Different uses depending on diode
  - PN rings can be used as modulators (> 10 Gbps)
  - PIN rings can be used as filters (<500 MHz) for routing and wavelength demultiplexing

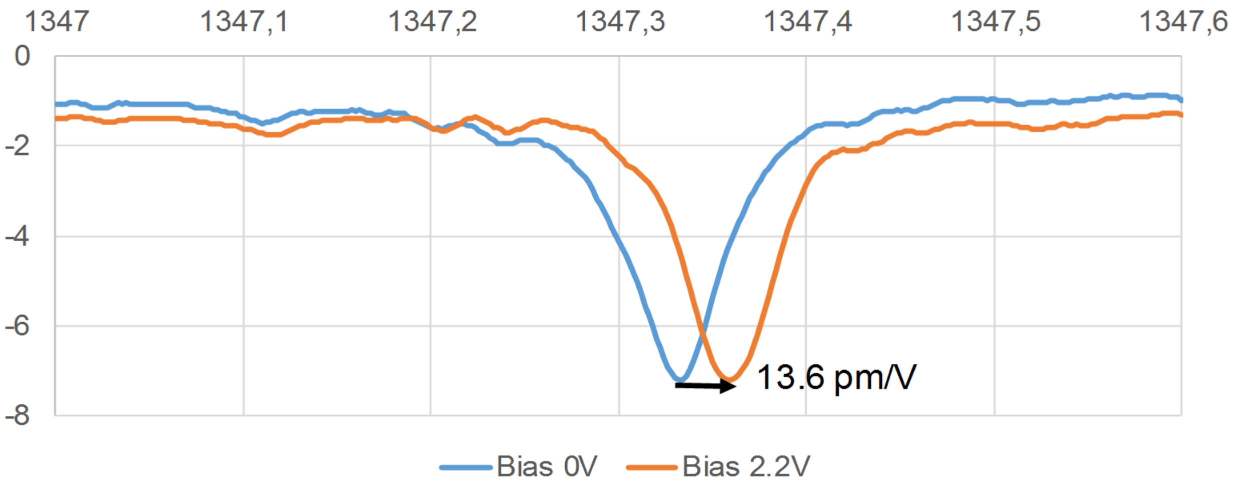
<u>But</u> Subject to Temperature variations

➔ Low-frequency resonance shift

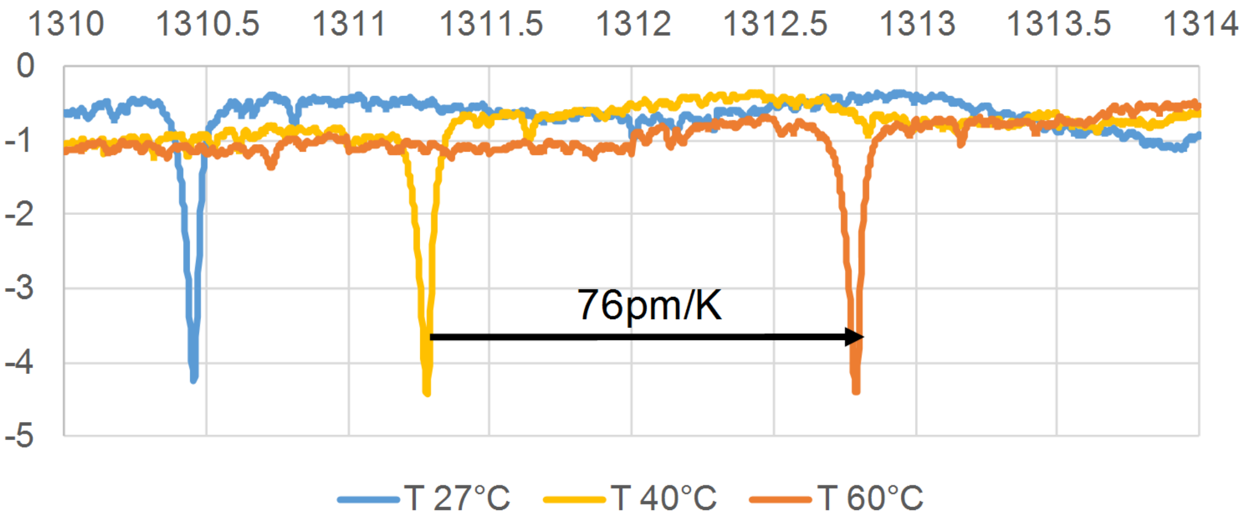


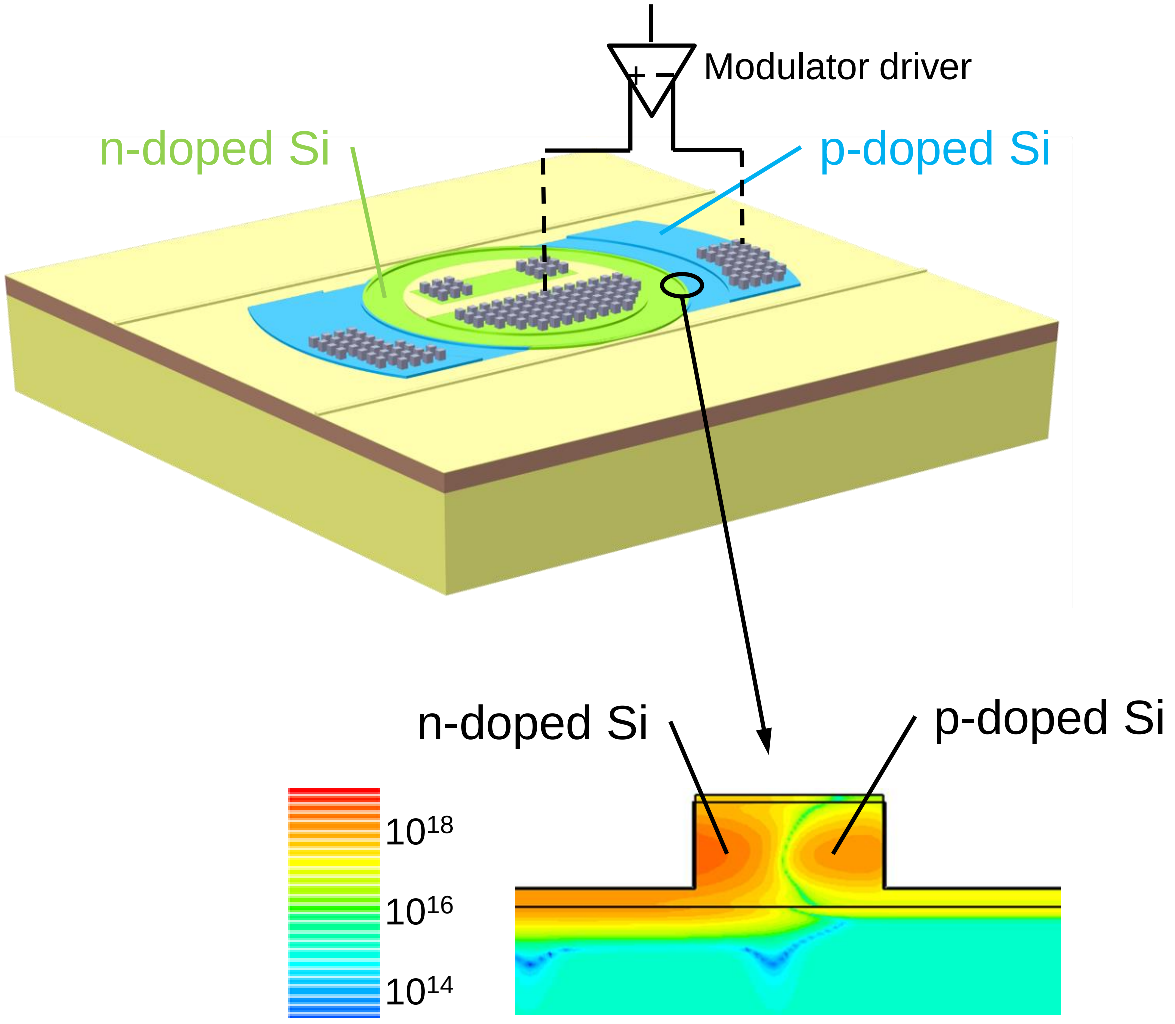
MODULATOR PRINCIPLE, THERMAL SENSITIVITY DΛ/DV & DΛ/DT MEASUREMENTS

13.6 pm/V modulation efficiency



76 pm/K thermal sensitivity





HEATER EFFICIENCY & DΛ/DP MEASUREMENTS

Heating using doped Silicon

- Resistive path inside the ring

Average ring temperature increase:

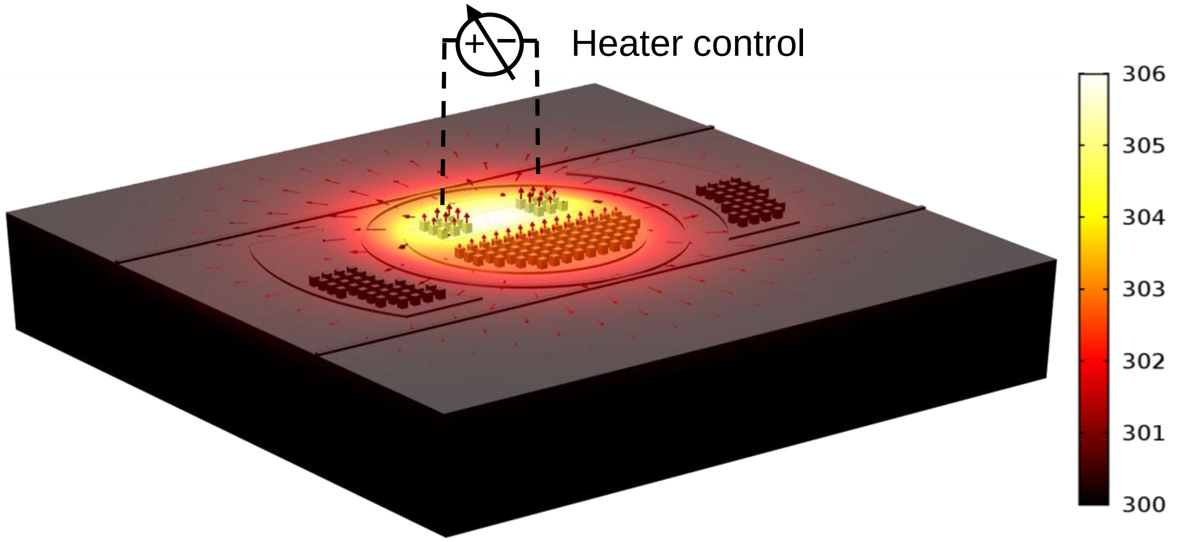
- Simulation: dT/dP ~ 2K/mW
- Measurements: dλ/dP ~ 40pm/mW

70nm Silicon film to preserve electrical connectivity for modulation

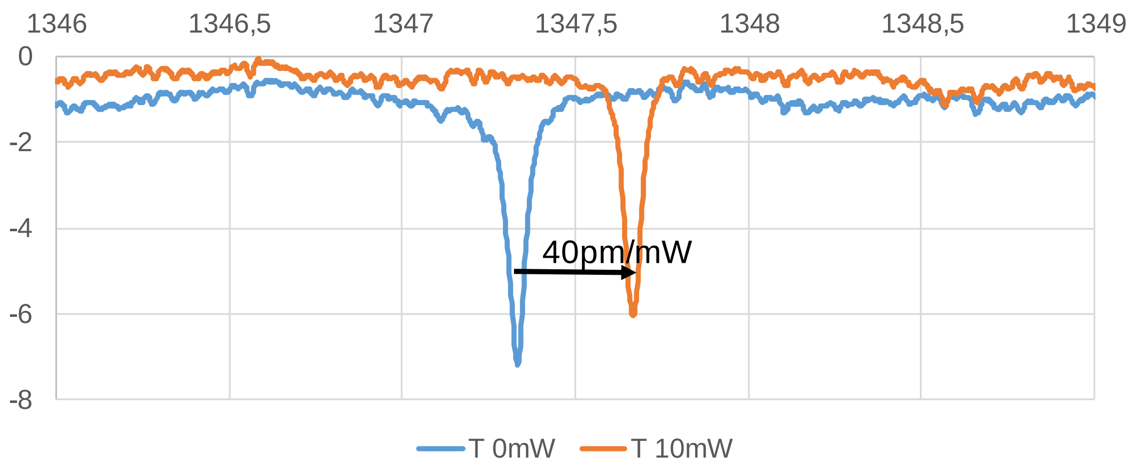
Could be improved by 10×

- Ti heater
- Back-side selective substrate removal

Temperature (K) and Heat Flux under 1mW heating



Resonance shift under 10mW heating

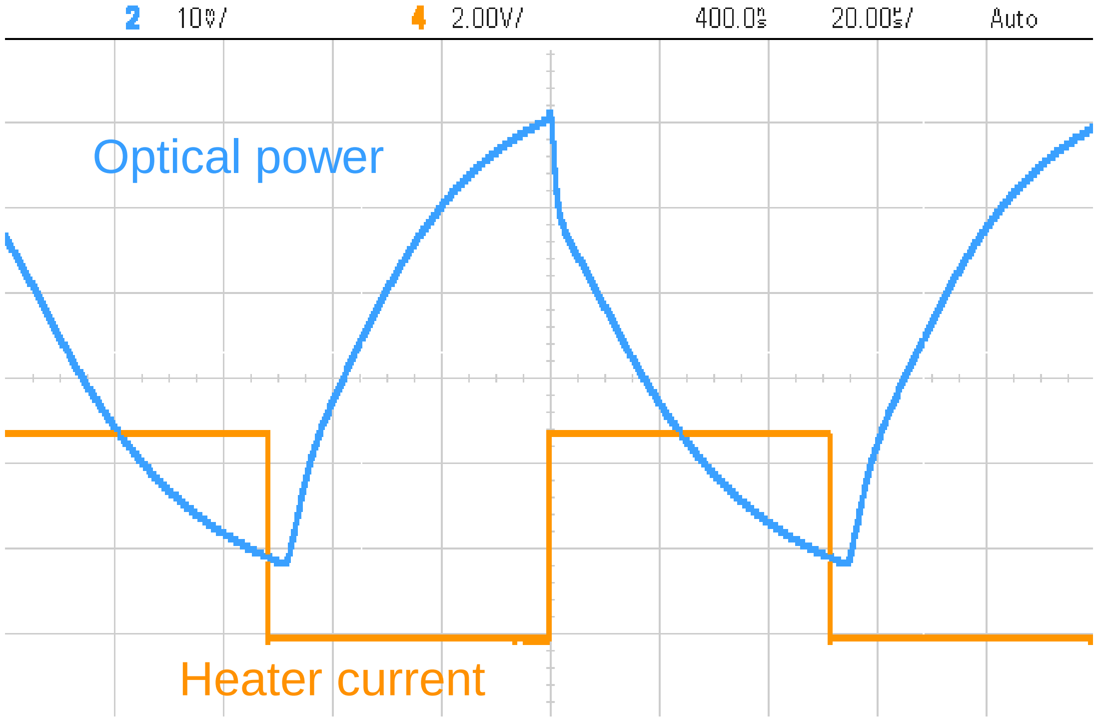


Optical measurements

- square wave on heater
- Test probes on Photonic die

Exhibits a 2nd order response

- distorsted due to lorentzian λ response
- local heating around 4µs
- heat diffusion around 25µs



Response modeled as a laplace transform

- Heat diffusion: dominant pole at 25µs
- Local heating: zero at 5µs, secondary pole at 2µs

$$H(s) = k \cdot \frac{1 + 5\mu s \cdot s}{(1 + 25\mu s \cdot s)(1 + 2\mu s \cdot s)}$$

RING MODULATOR OPERATION (TUNING+MODULATION)

Ring resonant wavelength unpredictible at design time

- 1 nm thickness variation
  ≈ 1 nm resonance shift

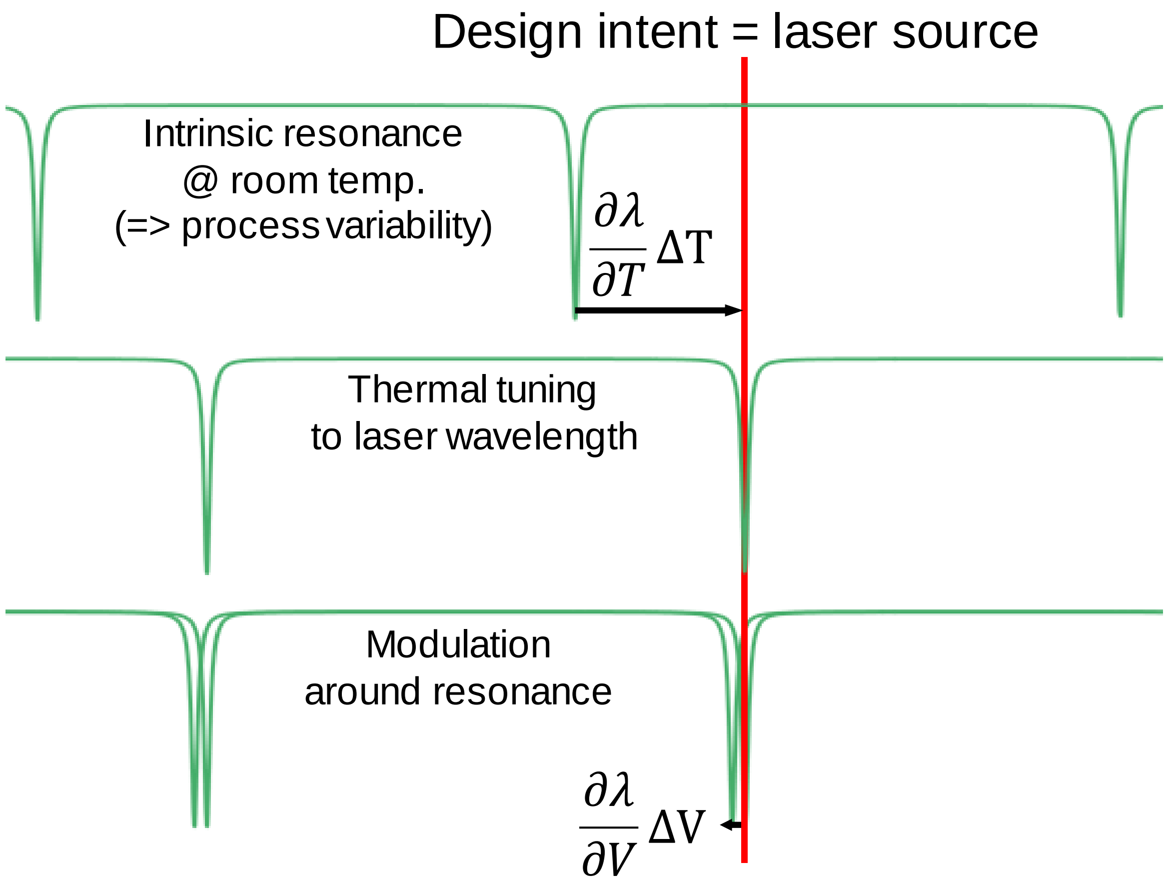
But finesse, free-spectral-range & amplitudes are well-controlled

Thermal tuning is used to align ring resonance on laser source

- Low-frequency control

Voltage is used to modulate light

- High frequency modulation

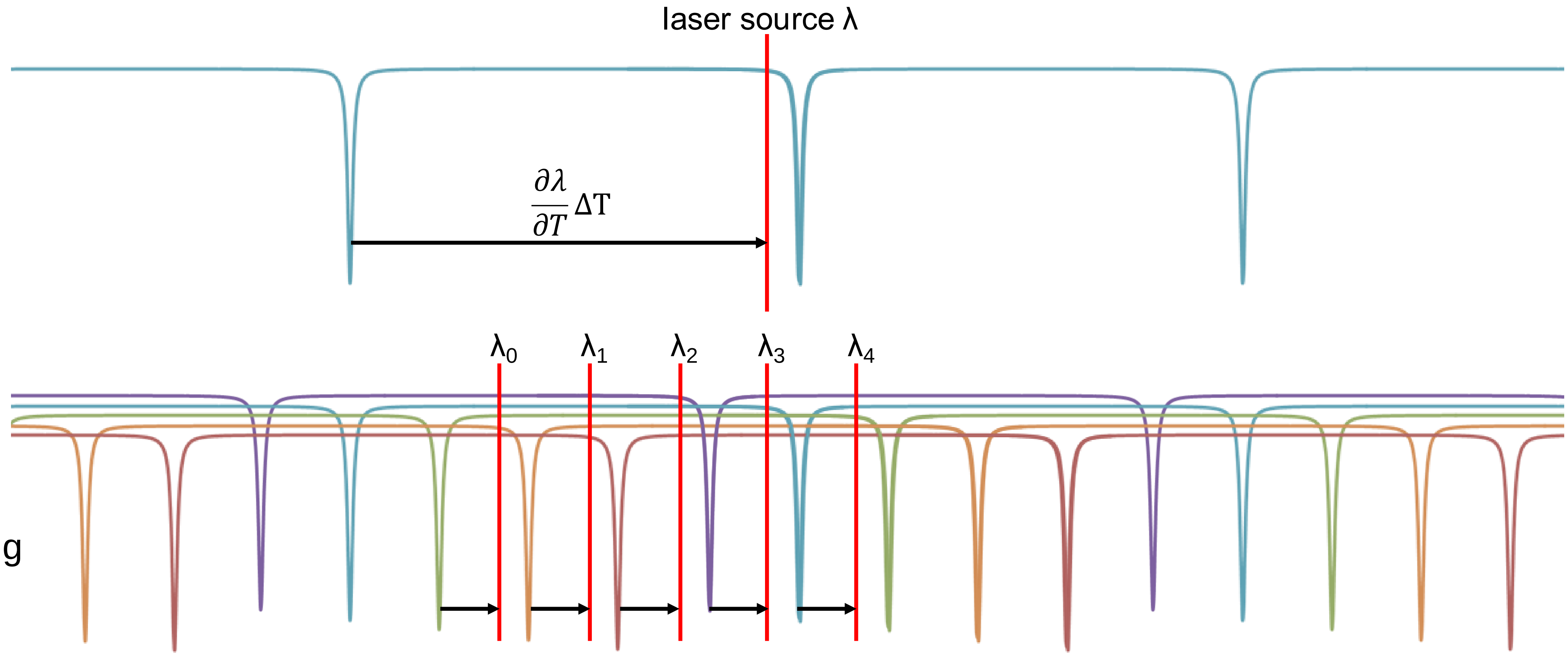


When total data throughput is sufficient: use several wavelengths

- Reduces the required shift for thermal tuning
  - From at most 1 FSR to at most 1/n FSR

Single wavelength

With wavelength-division-multiplexing



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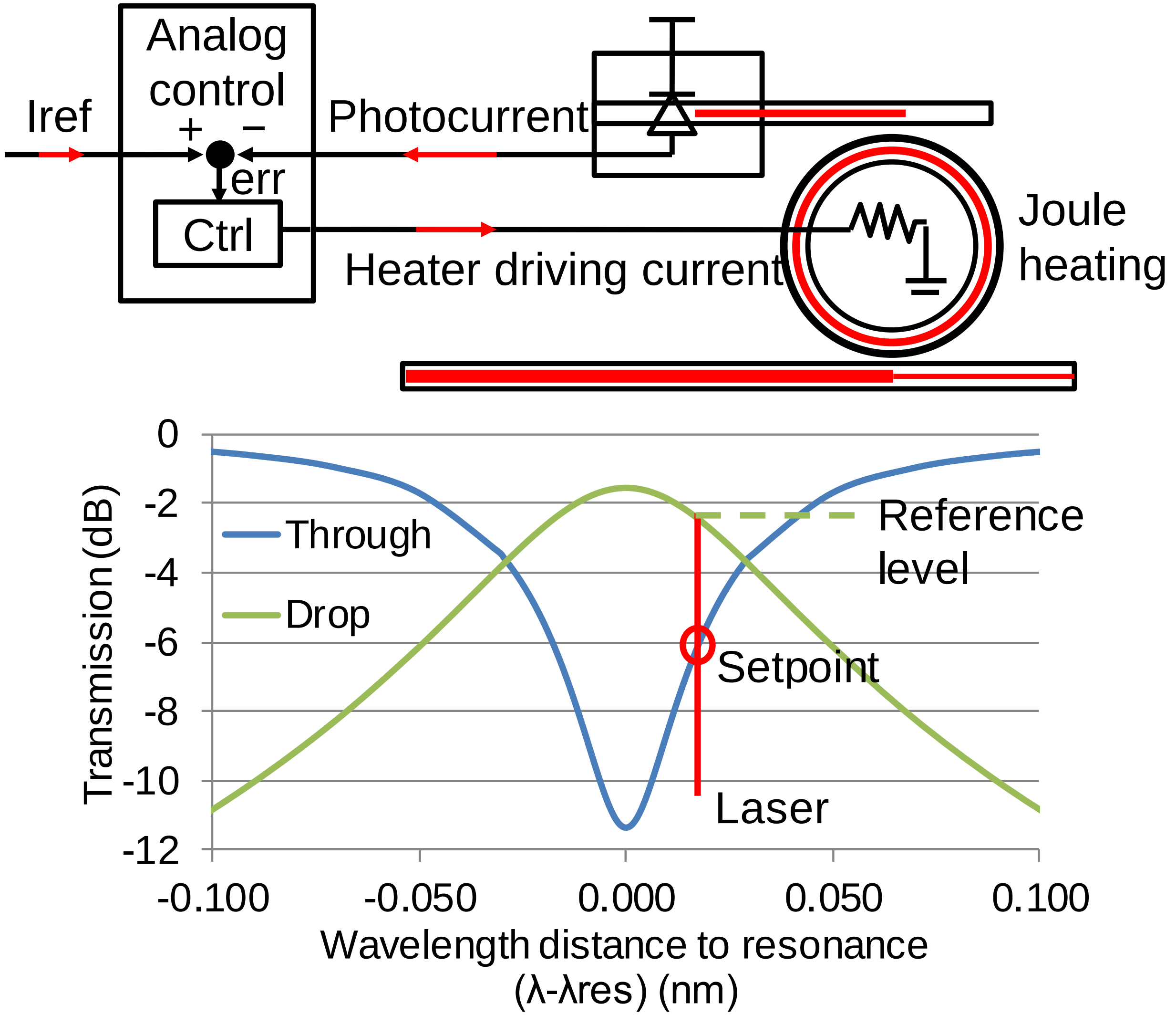
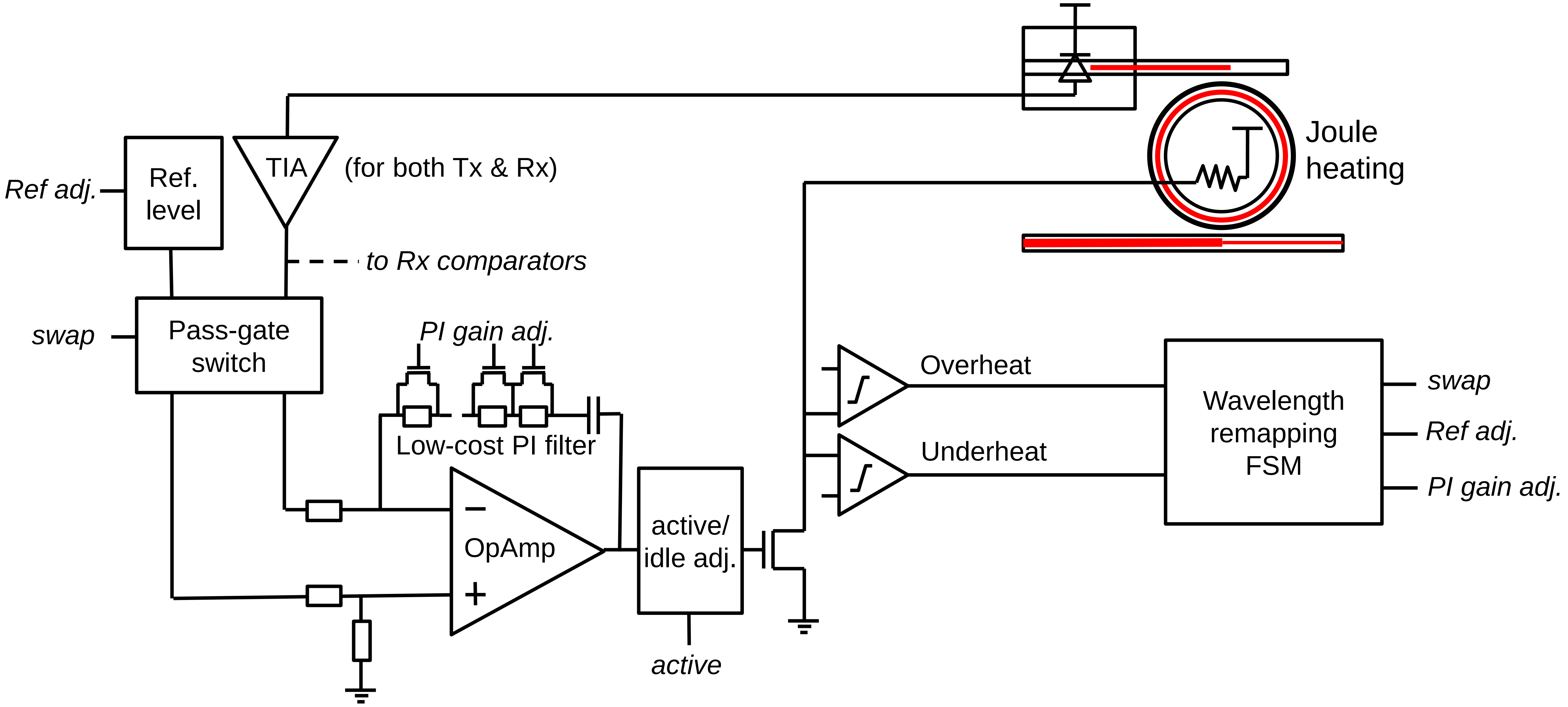
LOCKING ON REFERENCE CURRENT LEVEL VIA USE OF DROP PORT & PHOTODIODE

Ring resonance can be tracked by transmission on drop port

- Setpoint on through port corresponds to a power value on drop port
- Photodiode converts this to photocurrent
- Analog control used to match photocurrent with reference
- Joule heating by resulting heater driver current



COMPLETE CONTROL CIRCUIT



OVERHEAT/UNDERHEAT LIMITS & HYSTERESIS

Track heater command
for minimum and maximum heating

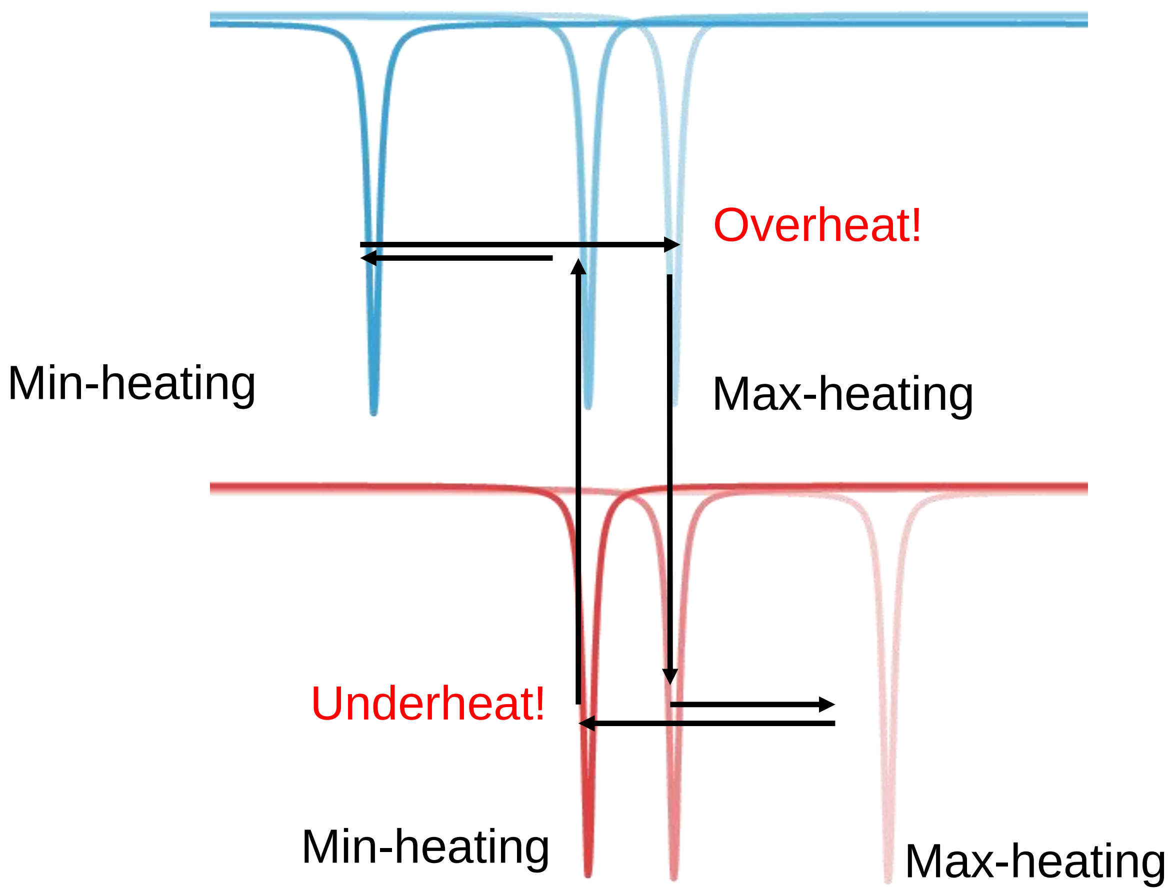
- Allow for 20% overlap

When overheat is reached

- better switch to a higher wavelength
  ➔Cool down

& Vice-versa for underheat

Use analog comparators
on heater voltage



DIGITAL FSM TO FIX SET-POINTS

Peak edges have different signs for dP/dT

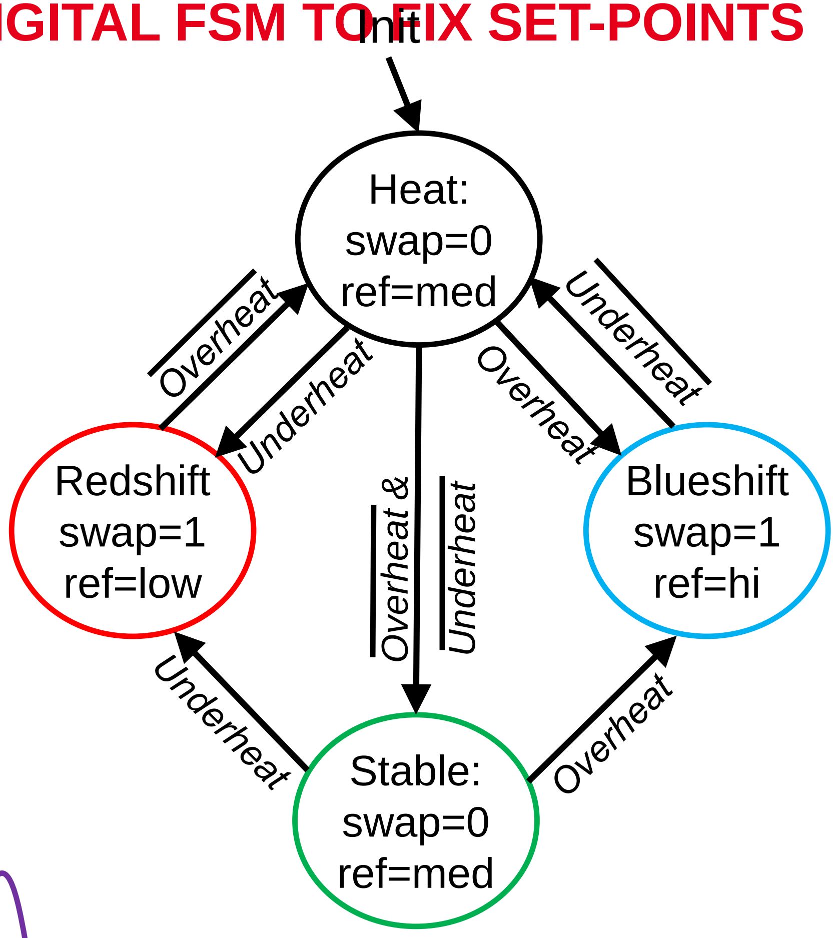
- One side is stable and the other is not

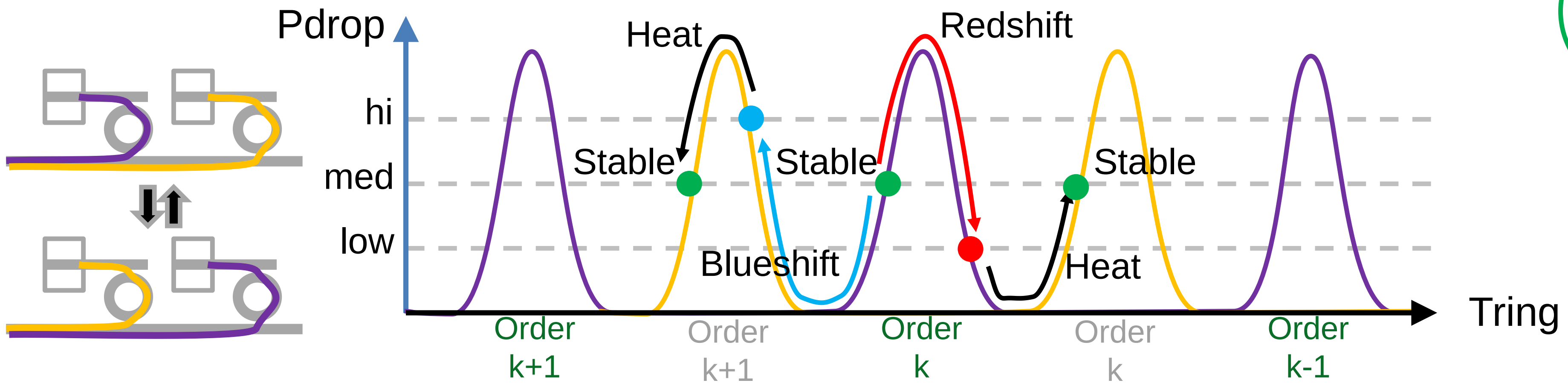
Swapping signal & reference in control loop allows switching stable edges

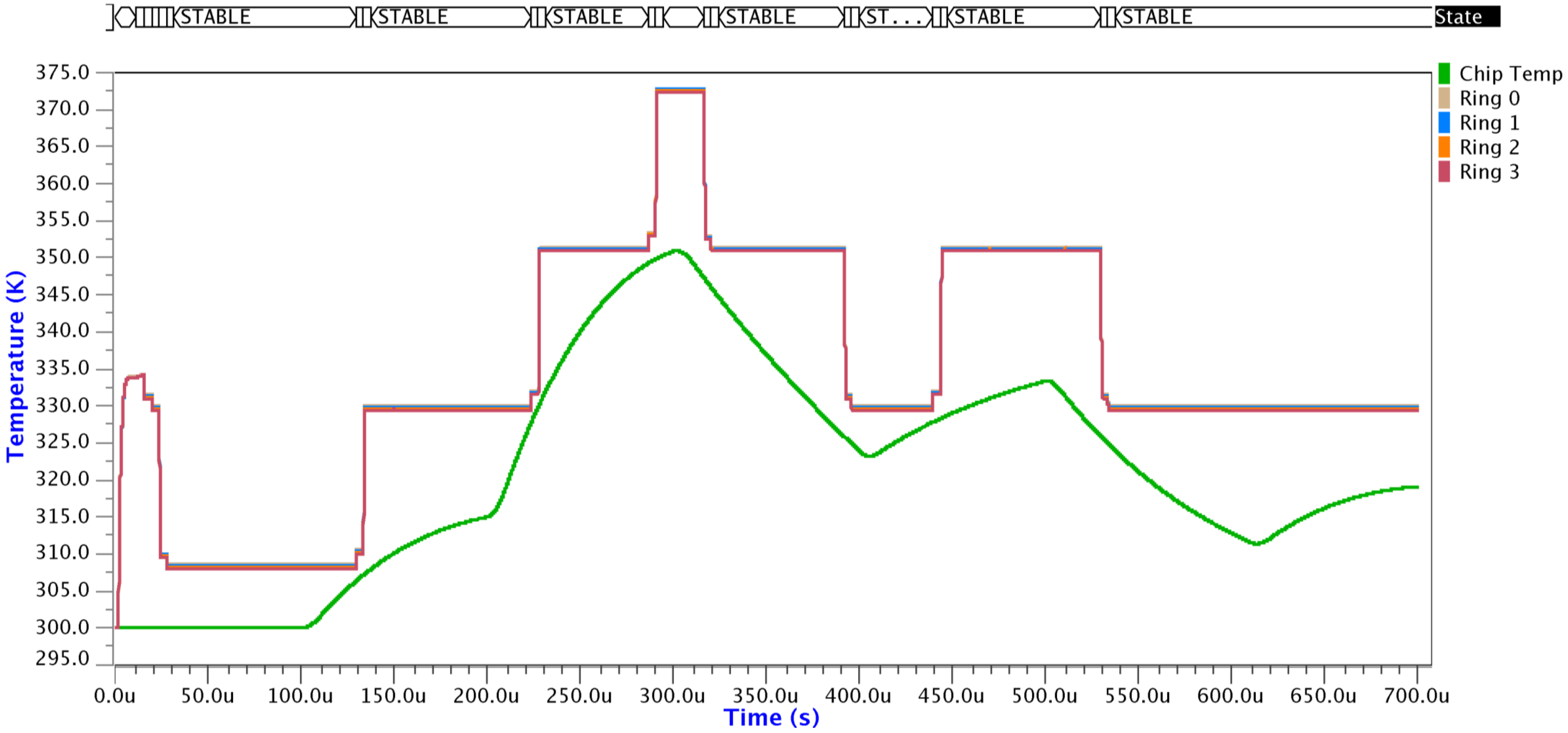
- Increasing/decreasing the reference allows leaving metastable state

Transition from one peak to another done in two steps

- Ring is never driven in open-loop






STABLE
STABLE
STABLE
STABLE
ST...
STABLE
STABLE
State
Chip Temp
Ring 0
Ring 1
Ring 2
Ring 3
375.0
370.0
365.0
360.0
355.0
350.0
345.0
340.0
335.0
330.0
325.0
320.0
315.0
310.0
305.0
300.0
295.0
Temperature (K)
0.0u
50.0u
100.0u
150.0u
200.0u
250.0u
300.0u
350.0u
400.0u
450.0u
500.0u
550.0u
600.0u
650.0u
700.0u
Time (s)

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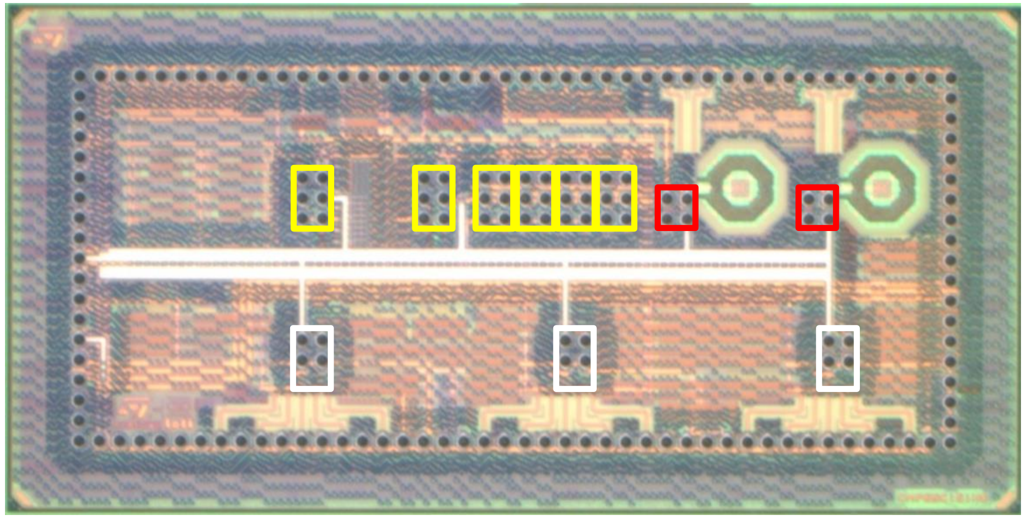
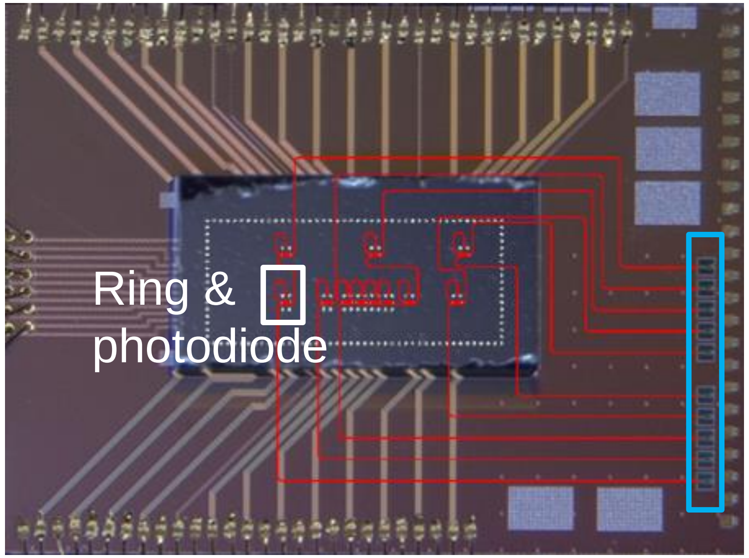
ELECTRONIC DIE, PHOTONIC DIE & ASSEMBLY



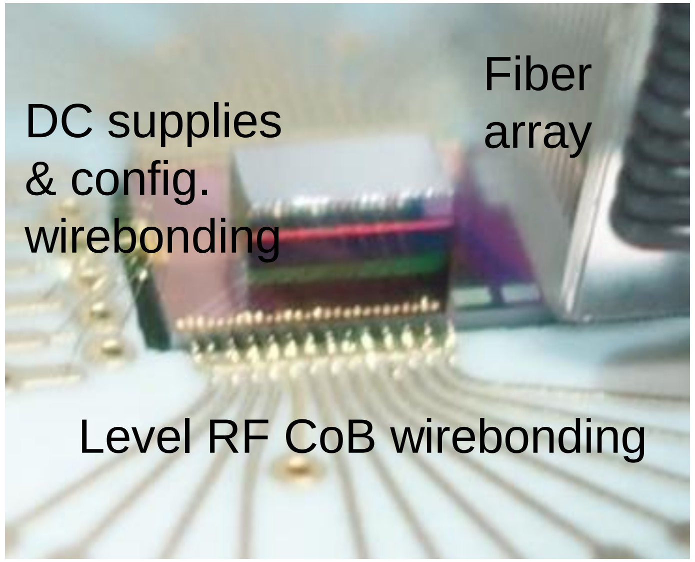
TIA w. tuning
& 50Ω output buffers

Tx w. tuning

TIA+Rx w. tuning



Grating
coupler
array



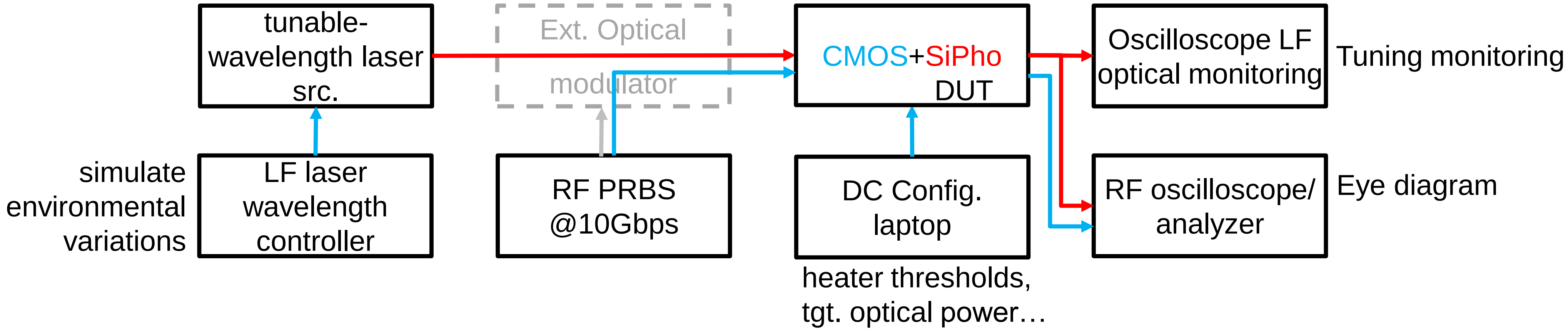
Functional area

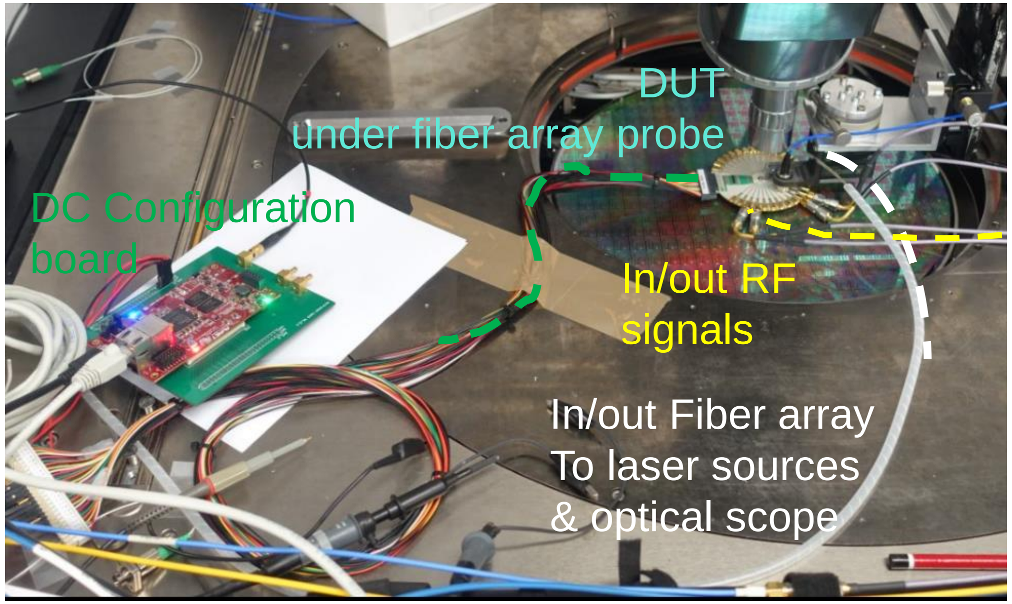
- Heater control
- 40×40µm²/λ
- 40×40µm²/WDM
- Tx Driver
- 40×40µm²
- Rx Driver
- 80×40µm²

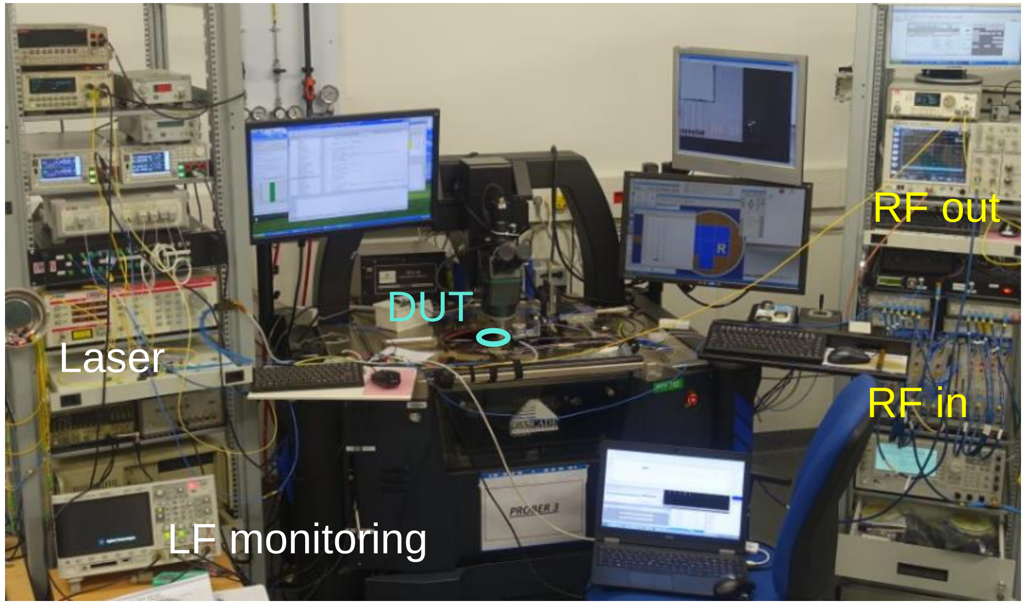
Dominated by
6 Cu-Pillar area

- Pitch 40µm
- 2 for Modulator
- 2 for Photodiode
- 2 for Heater

EXPERIMENTAL SETUP







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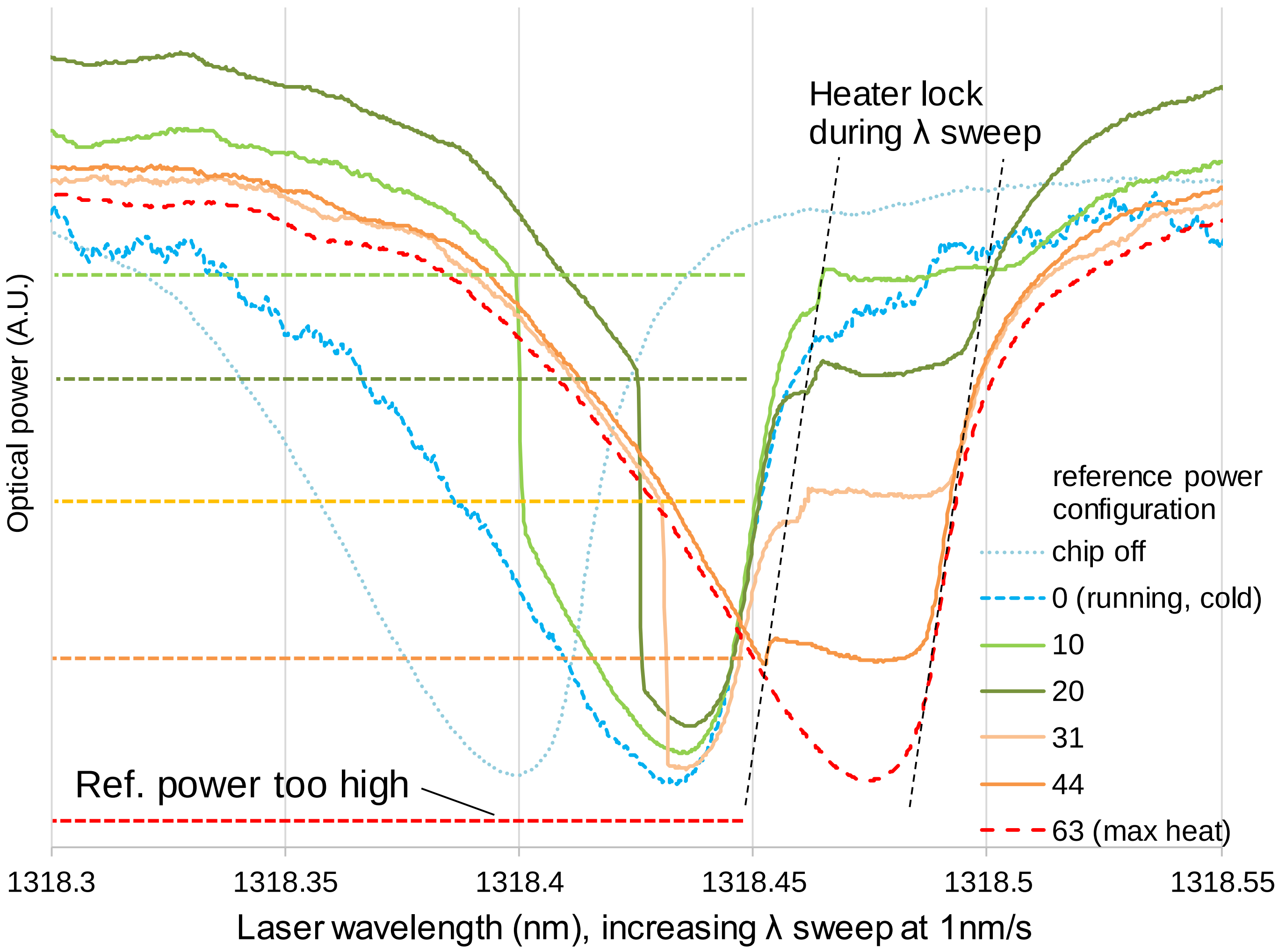
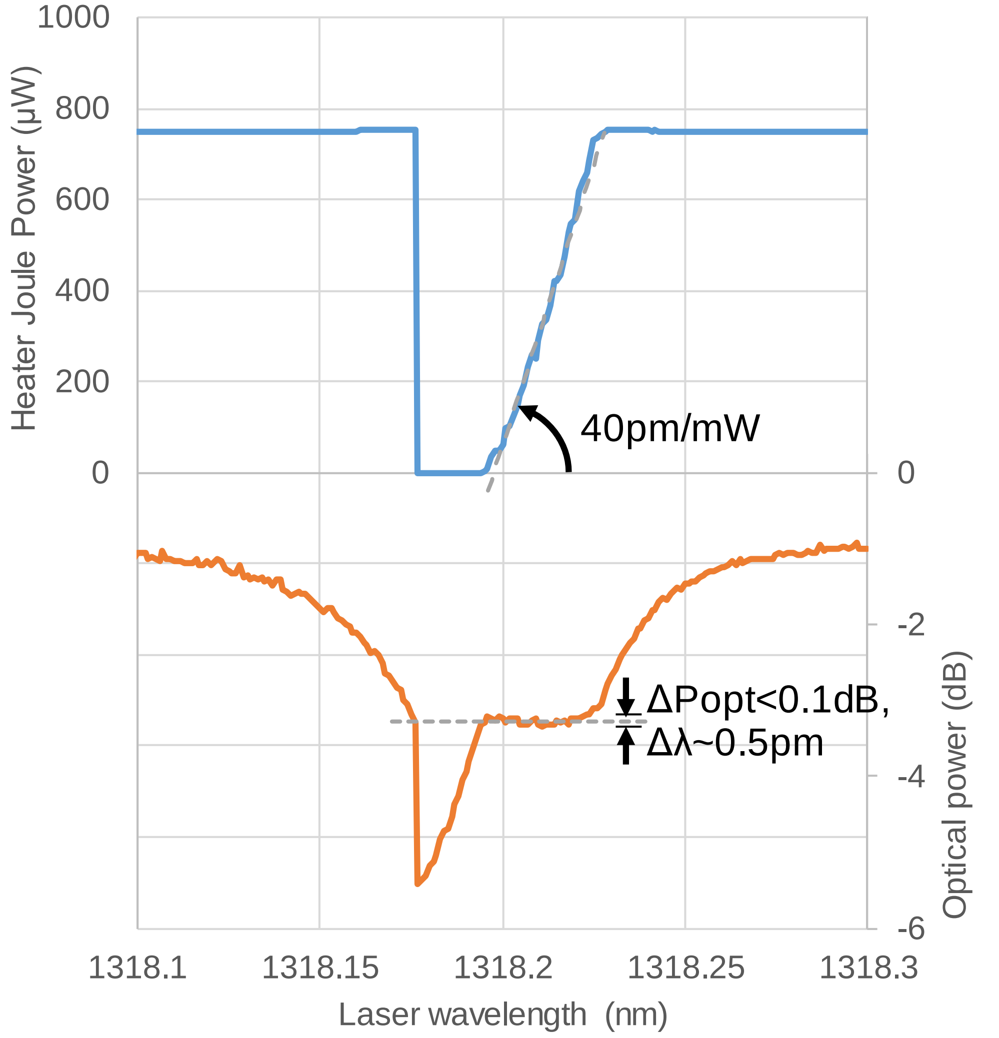
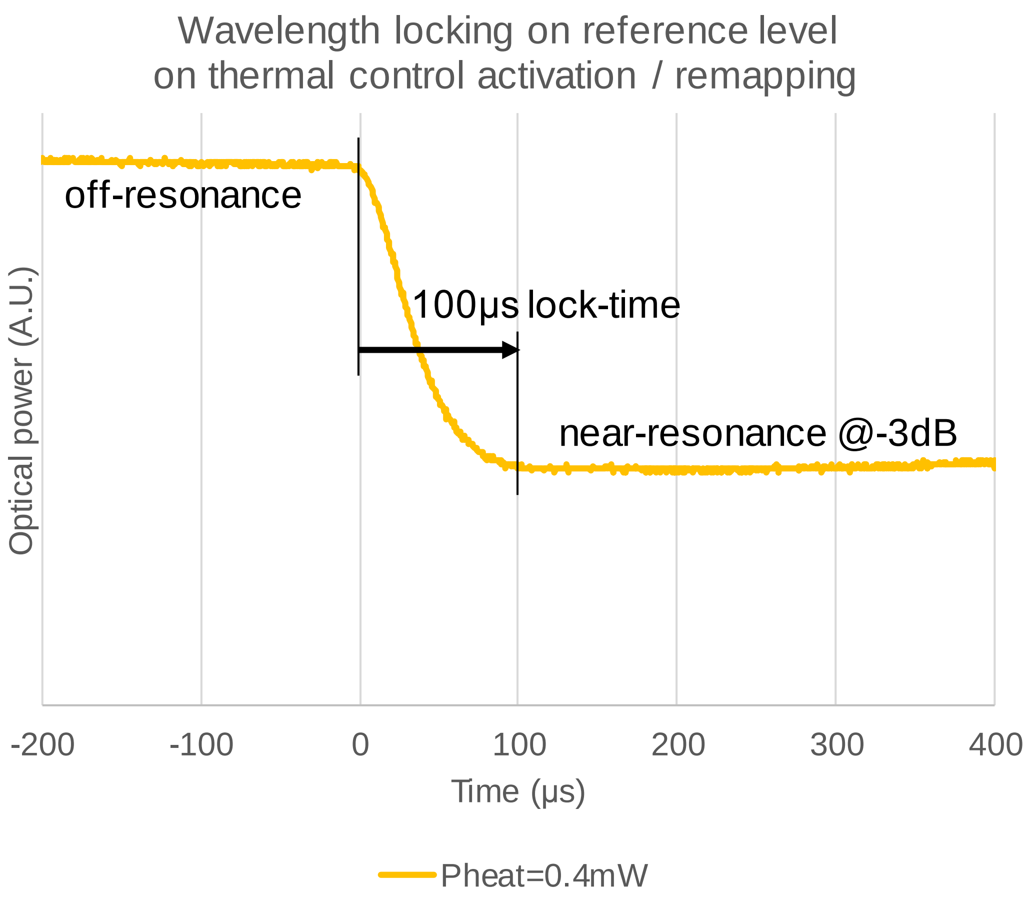
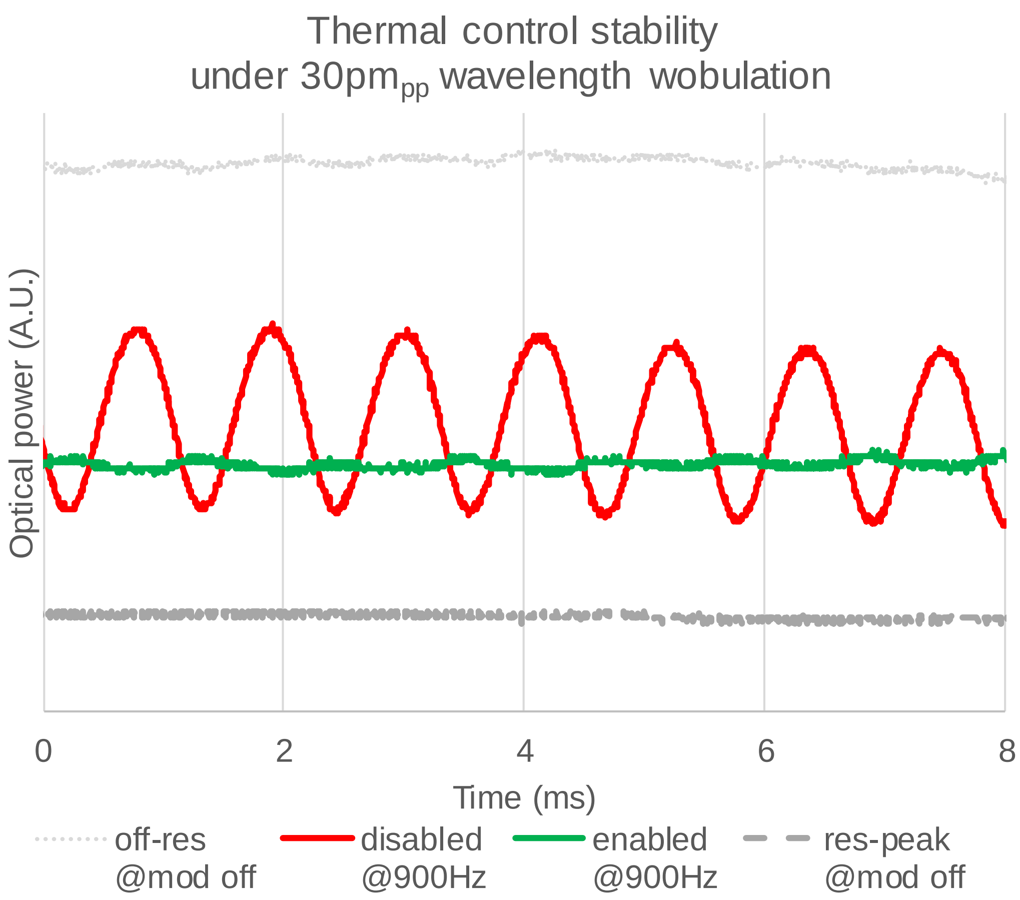
THERMAL TUNING WITH LAMBDA SWEEP



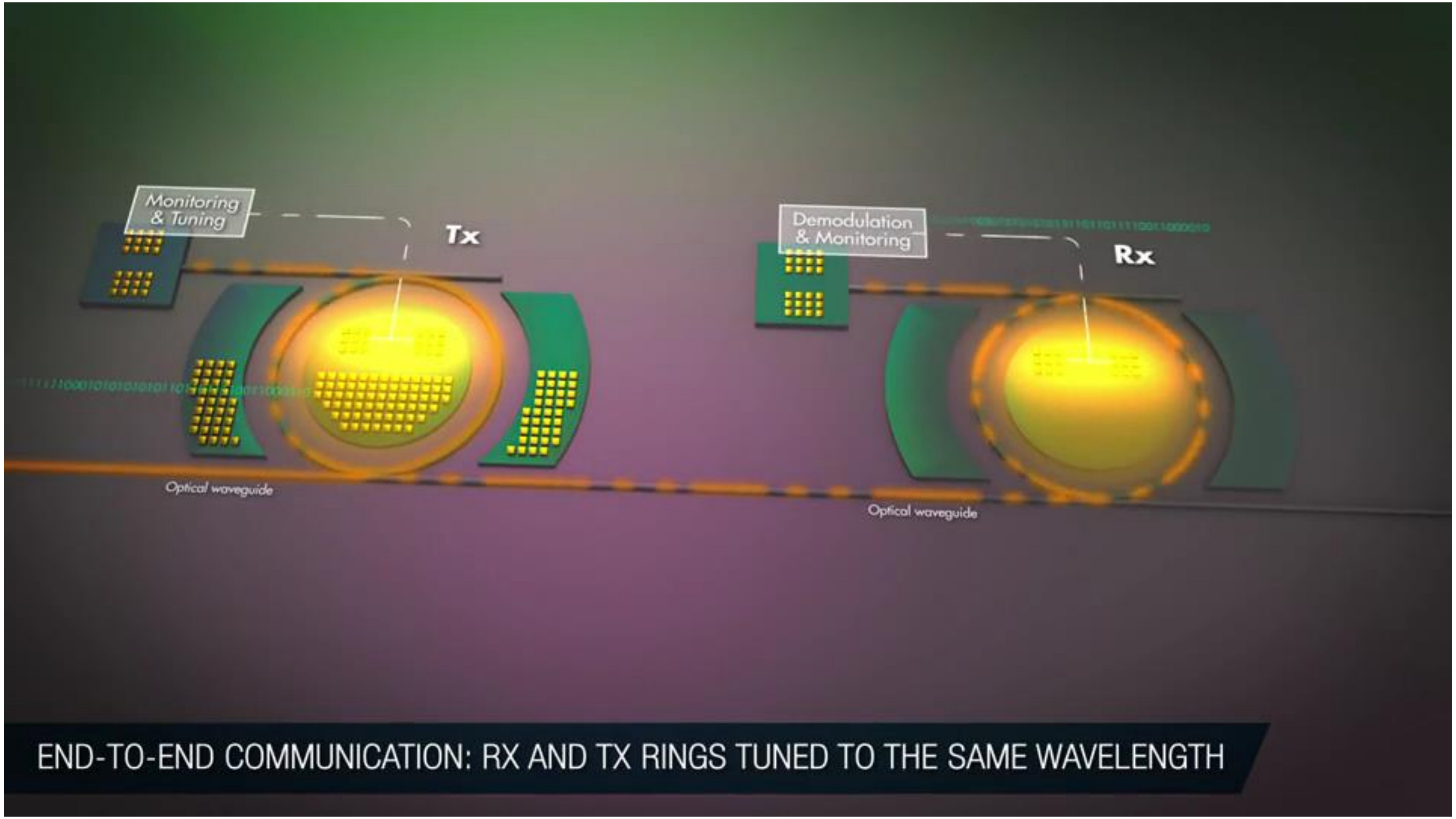


THERMAL LOCKING AND STABILITY





ROBUST ELECTRO-OPTICAL LINK OPERATION UNDER PERTURBATION



BENCHMARKING

	[2] Rakowski ISSCC2015	[3,4] Li, Yu ISSCC2015	[5] Sun JSSC2016	This work
Integration scheme	3D face-to-face	2D proximity wirebonding	Monolithic	3D face-to-face
Technology	130nm SOI SiPh 40nm CMOS	130nm SOI SiPh 65nm CMOS	45nm CMOS SOI	100nm SOI SiPh 65nm CMOS
Datarate	20 Gbps	24 Gbps	10 Gbps	10 Gbps
Ring Q factor	~5500	~5000 Tx, ~18000 Rx	~11600	~30000
Wavelength	1550nm	1550nm	1180nm	1310nm
WDM channels	4	5	11	4
Thermal tuning	Open-loop	Digital closed-loop avg/peak det.	Digital closed-loop bit-statistical (Tx only)	**Analog closed-loop with digital reconfiguration**
Wavelength remapping	No / External	No / External	No / External	**Integrated <1ms remap time***
Heater efficiency	0.16nm/mW	0.16nm/mW	1.25nm/mW	0.04nm/mW
Tuning ctrl. power	N.A. – External	170µW	720µW	**150µW**
Tuning precision	N.A. – External	Not reported	5pm	**0.5pm**
Tuning lock-time	N.A. – External	700ms	6.7ms	**120µs**
Tuning bandwidth	N.A. – External	~1Hz (from transient meas.)	~1Hz (from transient meas.)	**900Hz**
Tuning area / ring	0.04mm^2 (pad area)	0.03mm^2	0.0024mm^2	**0.0016mm^2**
Tot. driver area / λ	0.14mm^2 (Tx or Rx)	0.1 / 0.06 mm^2(Tx / Rx)	0.0205mm^2 (Tx)	**0.0096mm^2 (Tx or Rx)**
Bandwidth density	142 Gbps/mm^2	300 Gbps/mm^2	391 Gbps/mm^2	**1 Tbps/mm^2**

* Remapping simulated for heater efficiency of 1.25nm/mW (not attained due to lack of selective substrate removal as in [5])

3D-stacked CMOS-on-Si-photonic 10Gbps transceiver chip for short-range optical communication

- Focus given on digitally-supervised analog wavelength stabilization and remapping using microring heaters
- Wavelength locking on a constant wavelength achieved in 120µs
- Stability of the tuning is maintained under 900Hz environmental fluctuation.
- Total CMOS footprint for control and drivers is 0.01mm^2 per microring for up to 1Tbps/mm^2 communication density.

Thank you!

With special acknowledgments to all contributors & collaborators:

Mounir Zid, José Luis Gonzalez Jimenez, Guillaume Waltener, Robert Polster, Olivier Dubray, Florent Lepin, Stéphane Bernabé, Sylvie Menezo, Gabriel Parès, Olivier Castany, Laura Boutafa, Philippe Grosse, Benoît Charbonnier, Alexandre Siligaris, Sébastien Martin, Frédéric Hameau, Jérôme Prouvée, Christian Bernard, Eric Guthmuller, Marie-Sophie Redon, Sylvain Choisnet, Pascal Vivet, Benjamin Caillat, Edouard Grellier, Maryse Fournier, Vincent Reboud, Benjamin Blampey

Eric Cassan, Charles Baudot, Sébastien Le Beux, Jiang Xu, Sébastien Rumley, Ayse Coskun & their respective groups

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