Kishore Padmaraju* and Keren Bergman

Resolving the thermal challenges for silicon microring resonator devices

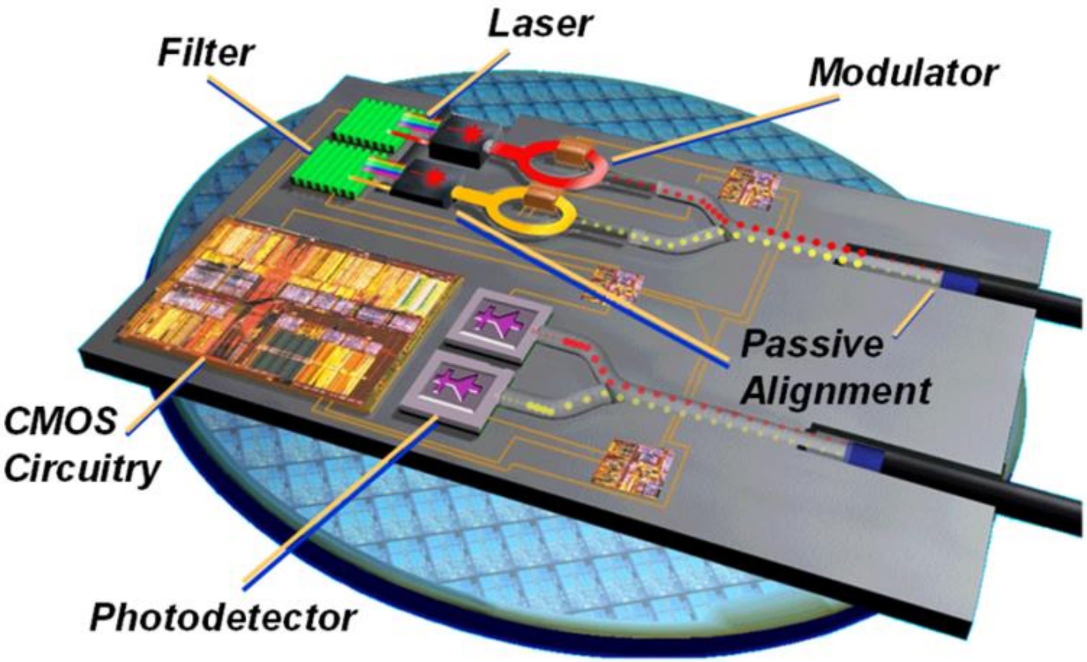
MyungJin Shin

High-Speed Circuits & Systems Lab.
Dept. of Electrical and Electronic Engineering
Yonsei University

Outline

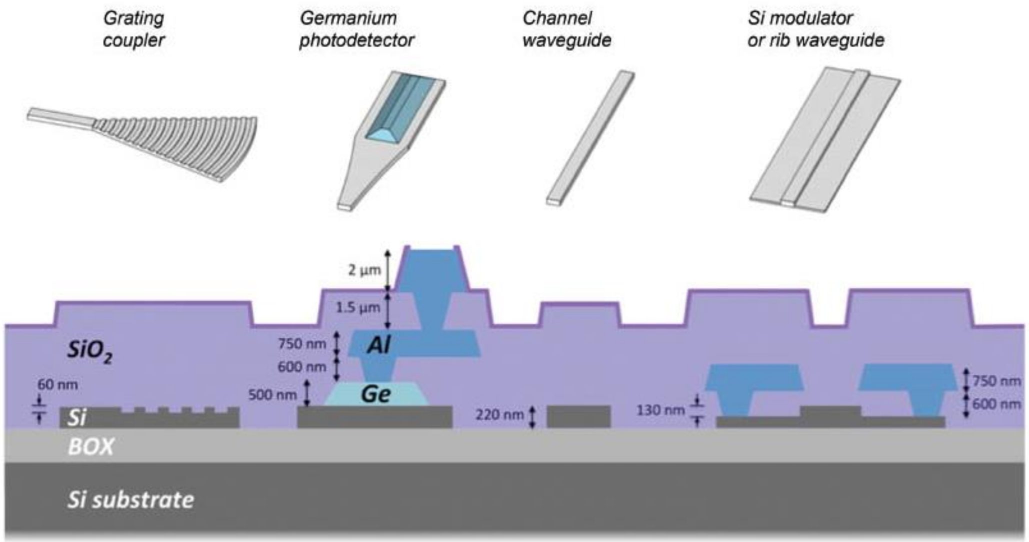
- Silicon Photonics
- Thermal effects on microring resonator based devices
- Athermal devices
  - Negative thermo-optic materials
  - Interferometric structure
- Control-based solution
  - Integrated heaters
  - Methods for control-based solutions
- Conclusion

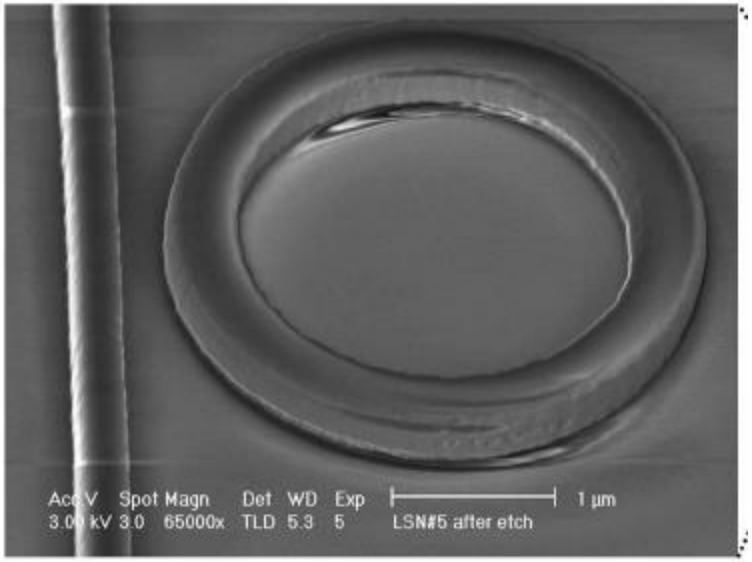
Silicon Photonics



- Growing bandwidth needs: electronic links ➔ optical links
- Low-cost high volume components which can be integrated with electronics ➔ Silicon photonics
- Waveguide, waveguide crossing, MZM, AWG, PD

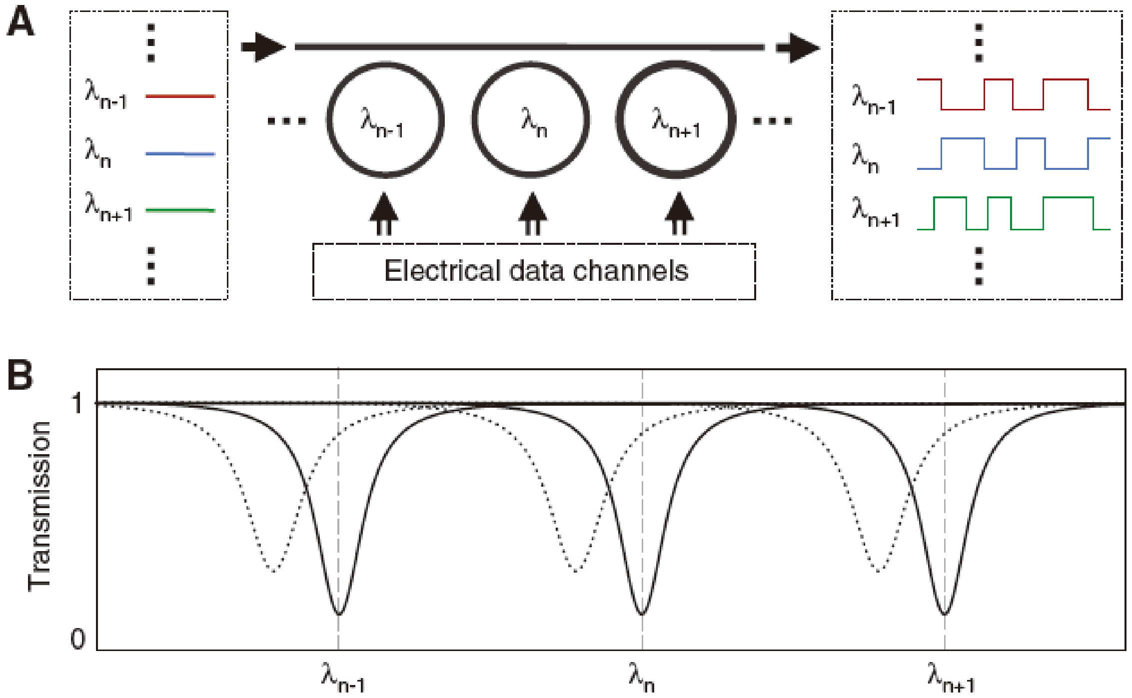
Advantages of Silicon Photonics





- High index contrast between silicon and silicon-on insulator (SOI)
  - Small footprint, high energy-efficiency
- 1.5µm radius ring resonator has been reported

Importance of Thermal Control



- Microring based devices ➔ low-cost WDM communication
- Insertion loss, cross-talk, footprint, modulation-bandwidth, linearity should be considered for optimization
- Thermal sensitivity is another important issue ➔ resonance shift

Thermal effects on micro-ring resonator

- Sensitive to temperature
  - High thermo-optic (TO) coefficient of silicon (1.86×10^{-4}/K)
  - Wavelength selectivity of microring resonators
- Resonance wavelength shift respect to temperature

$$\frac{d\lambda}{dT} = \frac{\delta n_{eff}}{\delta T}\frac{\lambda_0}{n_g}$$

- Each terms have wavelength dependence
- SiO_2 and Si substrate effect is omitted
  - TO coefficient of SiO_2: 1×10^{-5}/K
  - TO coefficient of Si substrate: 2.6×10^{-6}/K

Resolution for Temperature Sensitivity

- Solutions that reduce thermal dependence (athermal devices)
  - No additional active power
  - Difficult to fabricate (either through incorporation of non-CMOS material or additional photonics structure)
  - Laser source: fixed wavelength & stable throughout optical link

- Solutions that actively maintain local temperature (control based circuit)
  - Typical control-based systems needed (heaters, PDs etc.)
  - Additional active power consumption
  - Laser source: no constraints are needed

Athermal Devices

- Main idea: decrease temperature-dependence of the microring resonator

- Techniques
  - Using materials with negative thermo-optic coefficients in WG claddings
  - Embedment of microring in thermally balanced interferometer

Using Negative Thermo-Optic Materials

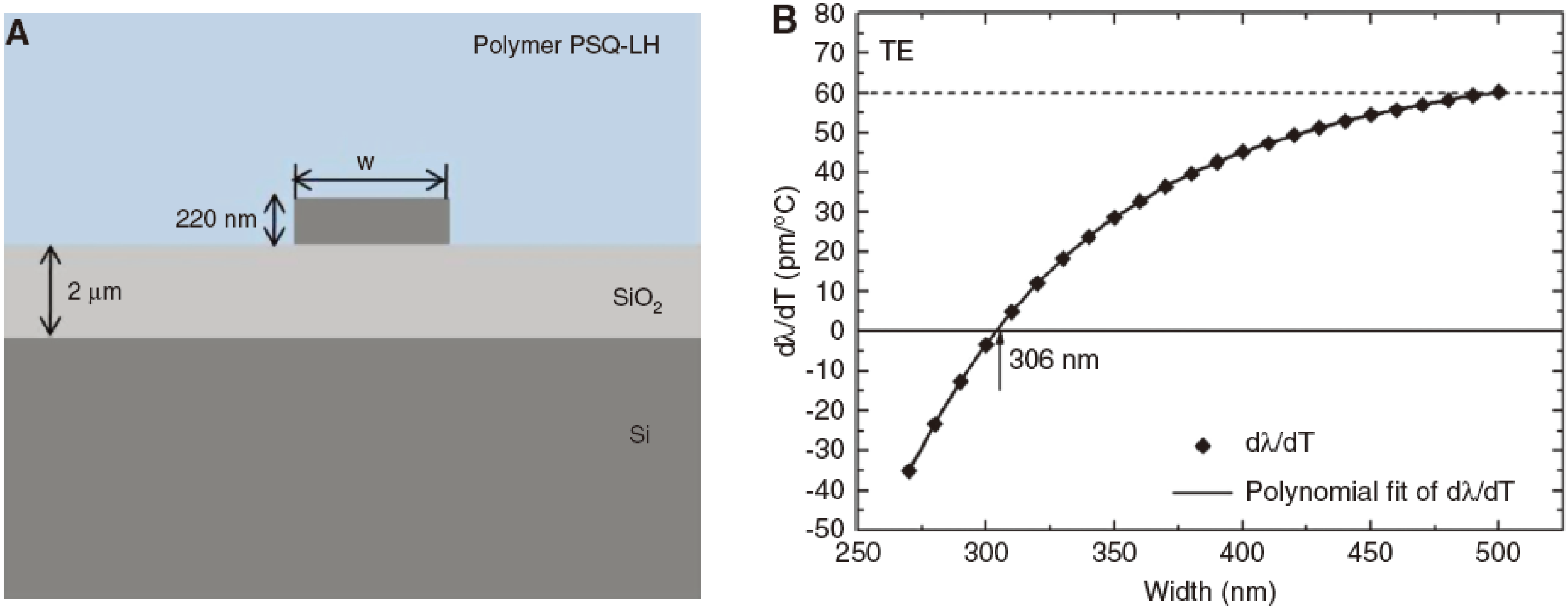
- Goal: zero thermo-optic coefficient for waveguide

$$\frac{\partial n_{eff}}{\partial T} = \Gamma_{core}\frac{\partial n_{core}}{\partial T} + \Gamma_{cladding}\frac{\partial n_{cladding}}{\partial T} + \Gamma_{substrate}\frac{\partial n_{substrate}}{\partial T}$$

Γ: modal confinement factors

- Positive thermo-optic coefficient
  - Core (silicon), substrate (silicon oxide)
- Negative thermo-optic coefficient
  - Cladding
- High Γ_{cladding} needed

Polymer-Cladding on Narrowed Waveguide

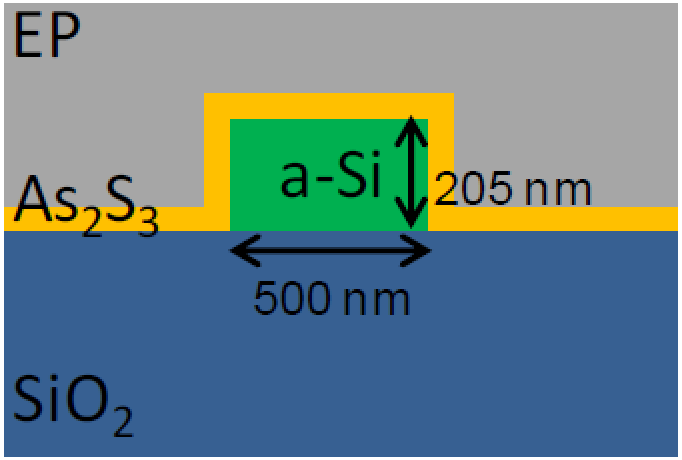


- Narrow WG make optical mode to distributed more in cladding
- Temperature dependent resonance shift (TDWS): -5 pm/K
- Recent work: 0.2pm/K for TDWS

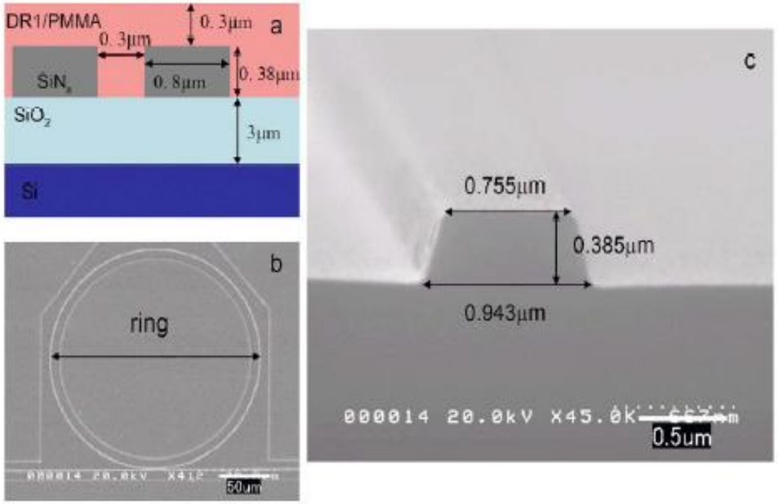
Photosensitive Material

- Strict requirement on waveguide dimensions (Polymer-cladding)

  ➔ difficult to achieve desired athermalization



As_2S_3: photosensitive layer
EP: negative thermo-optic polymer

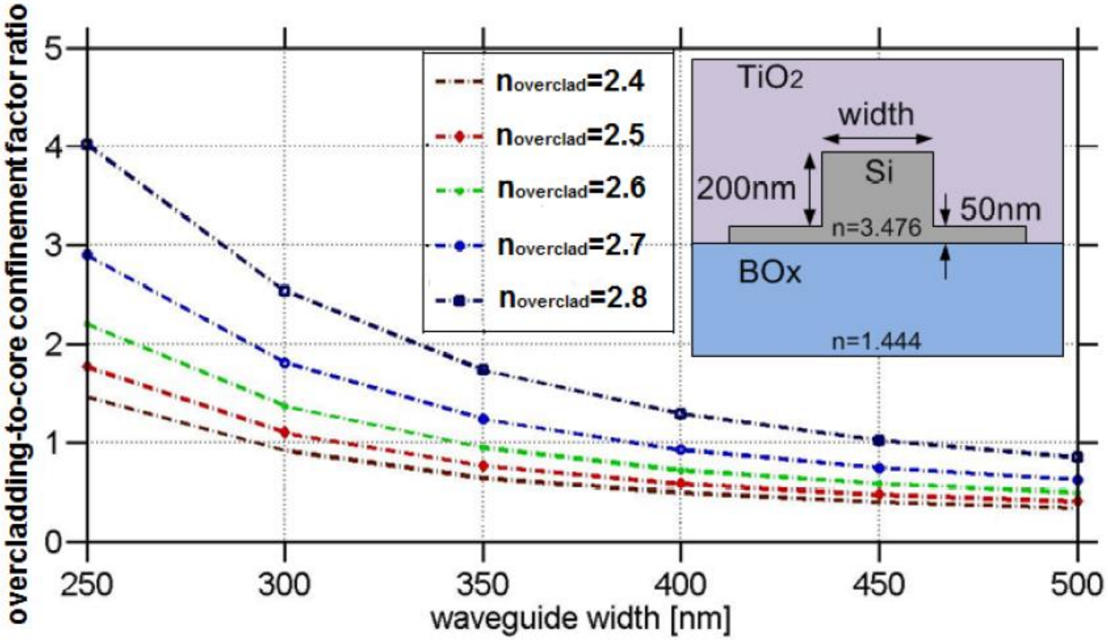


DR1/PMMA: Disperse Red 1-doped poly(methyl methacrylate)

- Trim thermo-optic coefficient after fabrication
- Vulnerability
  - High temperature(exist in CMOS-production cycles), chemical instability, UV aging and poor mechanical characteristics

CMOS-Compatible Cladding Material

- Titanium dioxide (TiO_2) for negative thermo-optic coefficient cladding
- CMOS compatible material with similar TO coefficient with Si (~1.8×10^{-4}/K)



- TDWS<2pm/K over range of 5K

Summary of Negative TO Materials

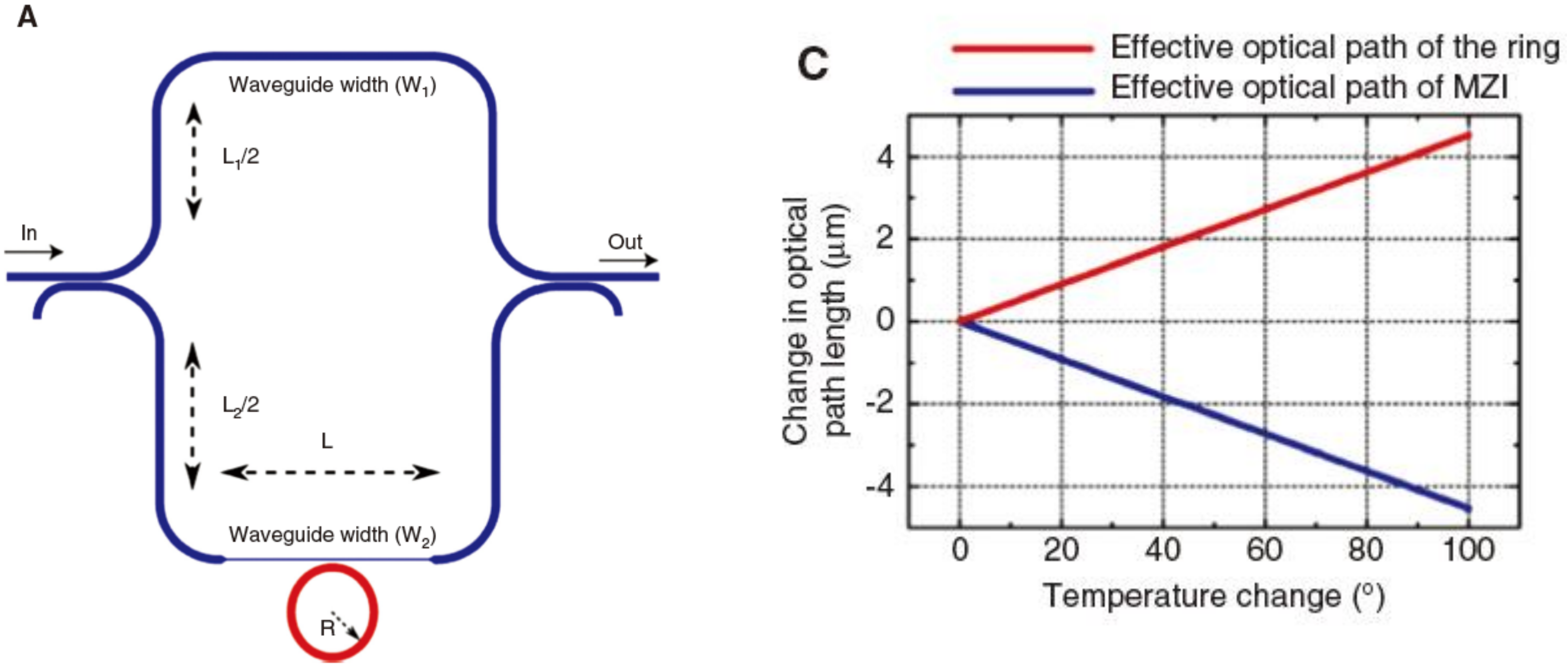
- Solutions
  - Polymer material for cladding
  - Photosensitive material to tune the TO after fabrication
  - TiO_2 for cladding material (CMOS compatible)

- Disadvantages
  - Fabrication difficulty
  - Reduction in modal confinement of the core
    - loss on straight and bent configuration

      ➔ negative impact on footprint & Q-factor

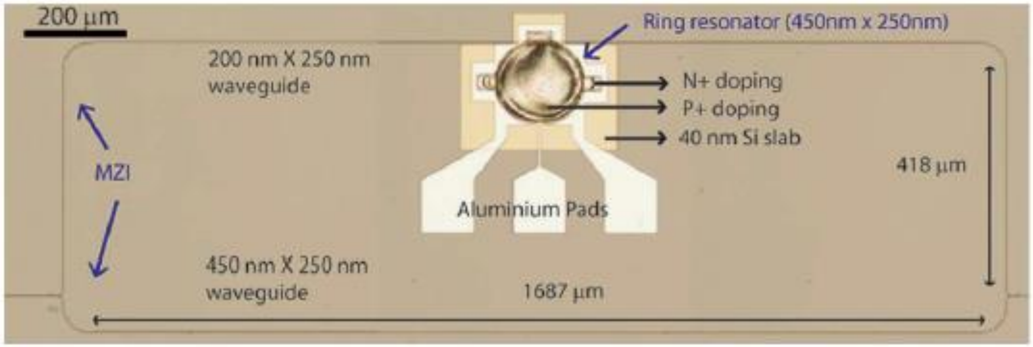
Using Interferometric Structure

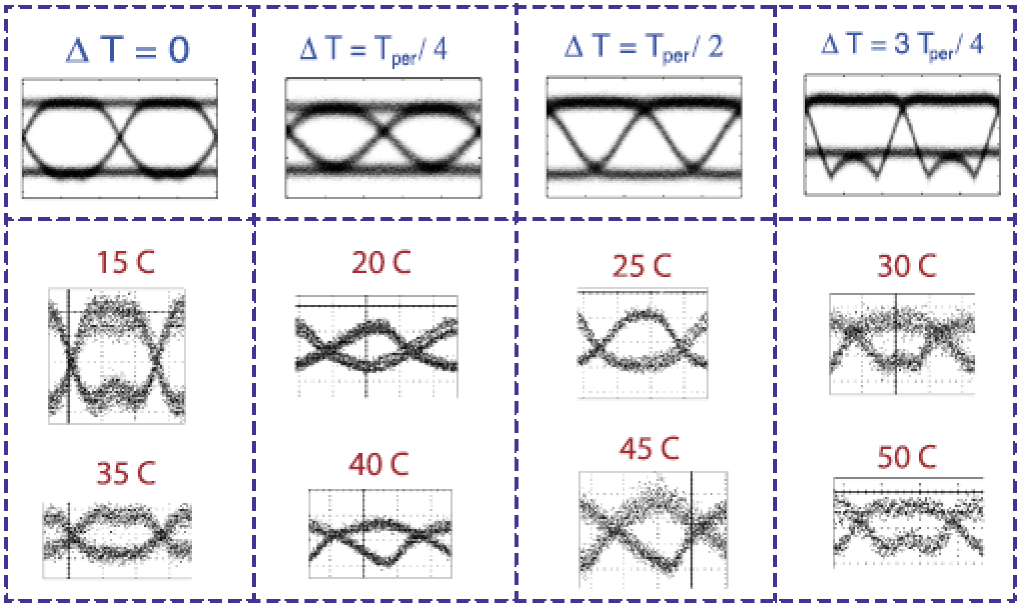
- Si MZI can be athermalized by different optical mode in each arm
  - Different width for each waveguide arm ➔ different effective TO coefficient



- Thermal sensitivity of microring can be compensated by MZI
- Optical resonance deformed across temperature range
  - Different phase shift dependence between MZI (linear), microring (nonlinear)

Athermal Electro-Optic Modulator Using MZI





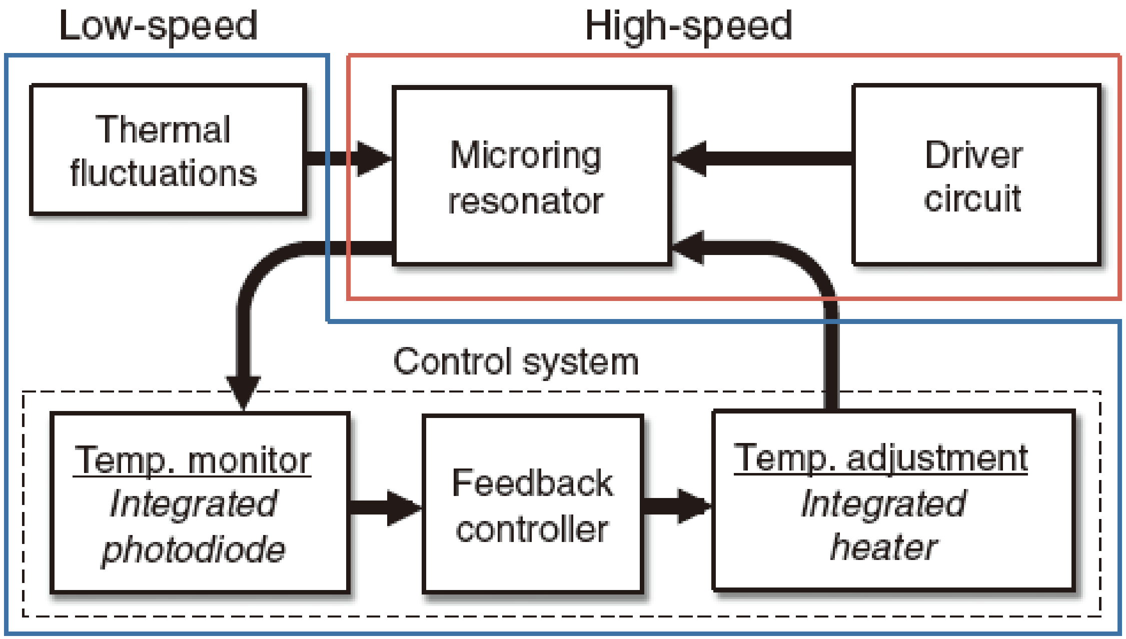
- Different waveguide width
  - Upper arm: 200nm
  - Lower arm: 450nm
- Measured over 35°C (two temperature period)
- Periodic change in eye shape for different temperature
  - Phase shift difference between MZI and microring

Summary of Athermalization with MZI

- Advantages
  - Does not require incorporation of new layers or materials in fabrication of Si Photonic structure
  - Easy to integrated using current CMOS-fabrication techniques

- Disadvantages
  - Sensitivity to fabrication tolerance
  - Increases footprint of microring structure

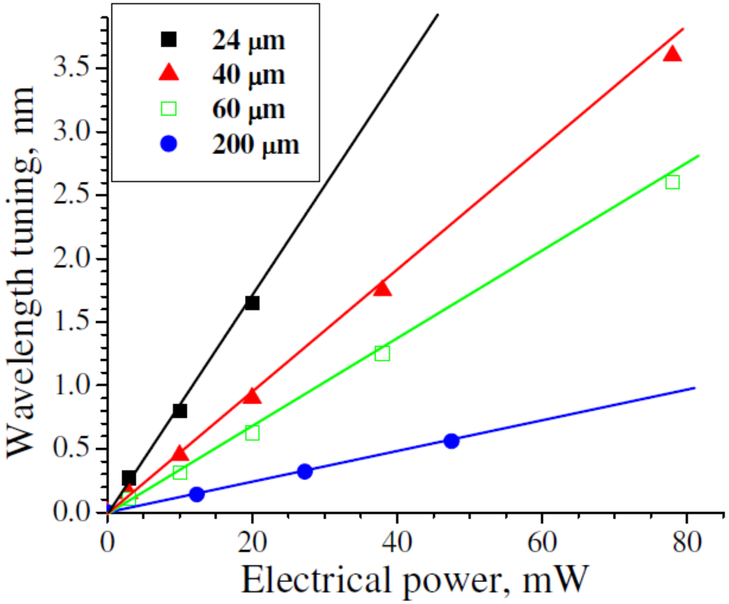
Control-Based Solutions



- Maintain local temperature by integrated heater localized to microring resonator
- Major components
  - Integrated heater: controlling local temperature
  - Control-system: driving integrated heater

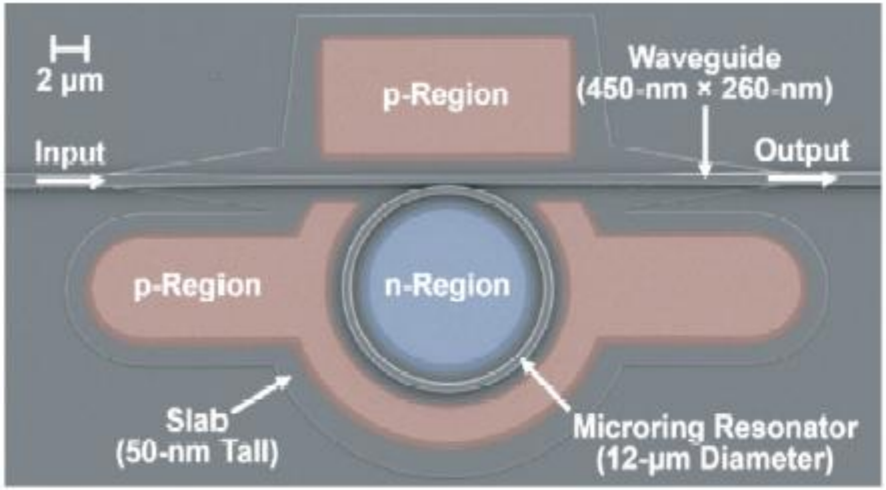
Integrated Heaters

- Integrated heaters are resistive elements
  - Nichrome, titanium or doped silicon materials
- Integrated heater metrics
  - Tuning efficiency
    - mW/nm: increases with microring size
    - mW/FSR: remain relatively constant with size (decrease in FSR)
  - Tuning speed



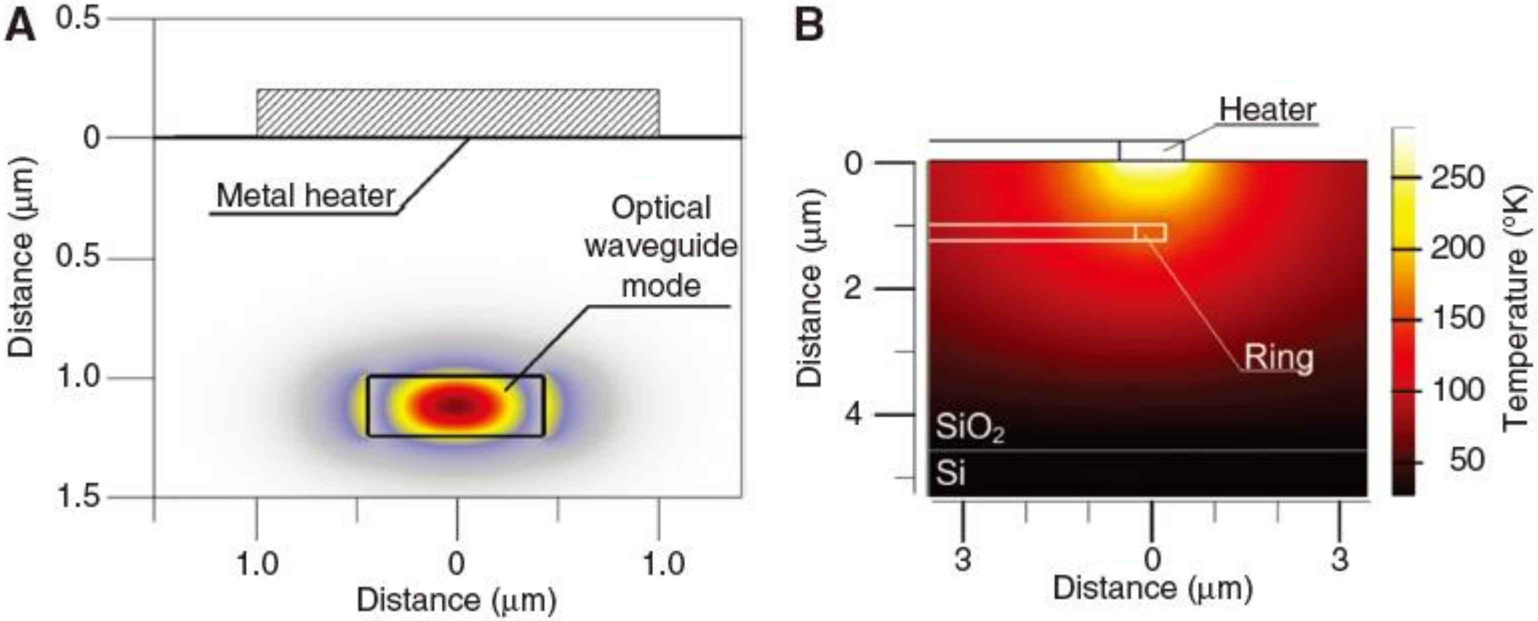
Direct Heating Microring Resonator

- Available for carrier-injection microring modulator
  - Adjust bias current of the diode junction
  - First control system for thermally stabilizing microring resonator
  - Limited temperature tuning range
  - Bad effects on optical modulation



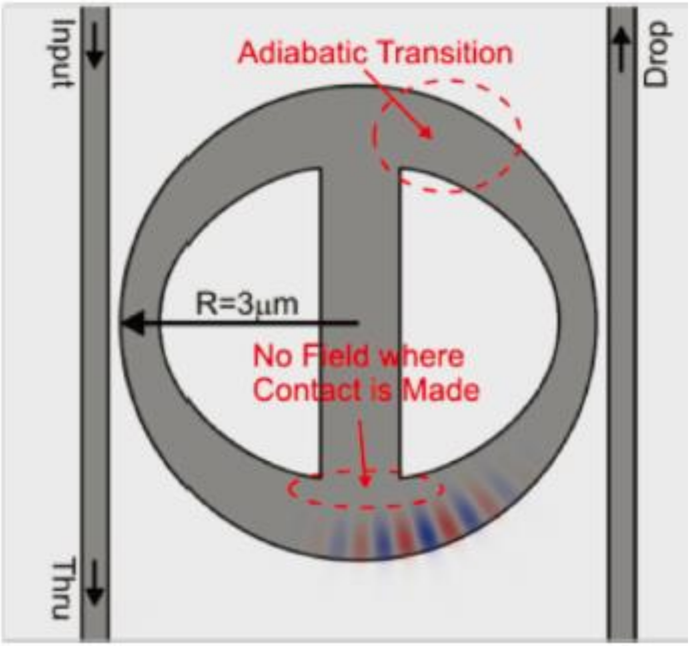
- Separation between high-speed electrical operation and low-speed thermal stabilization is needed

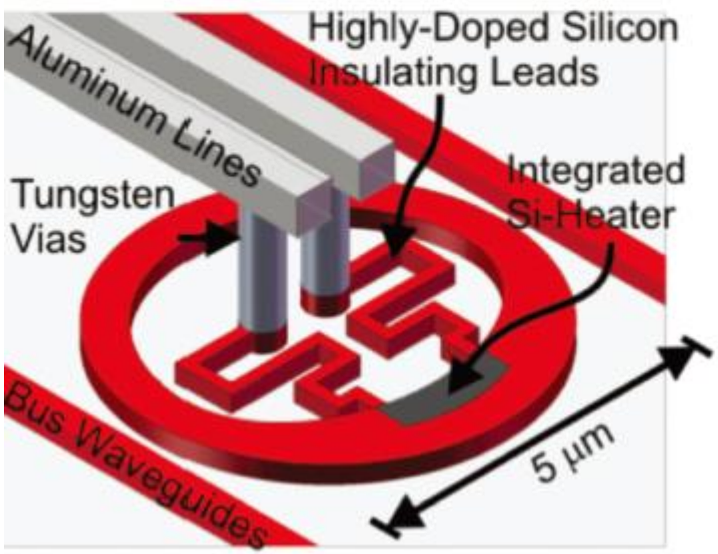
Microring Resonator with Separated Heater



- Locating integrated heater closer ➔ tuning efficiency ↑, scattering loss ↑
- Best performance: ~42mW/FSR, 14μs
- For better tuning efficiency improved thermal isolator in microring is needed

Adiabatic Microring Resonator

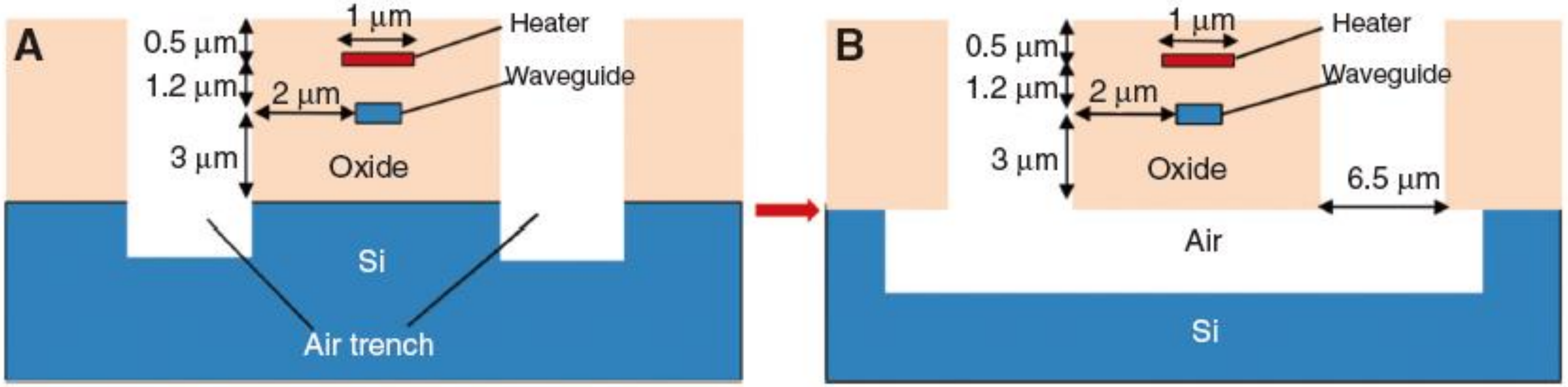




- Microring resonator with interior connected heater
- ~20mW/FSR tuning power, 1μs tuning speed
- Adiabatic microring modulator can be fabricated
  - Error-free 10Gb/s modulation, 60K temperature range, comparable tuning efficiency

Thermal Isolation Method

- Problem
  - Heat dissipated into the surrounding oxide and substrate

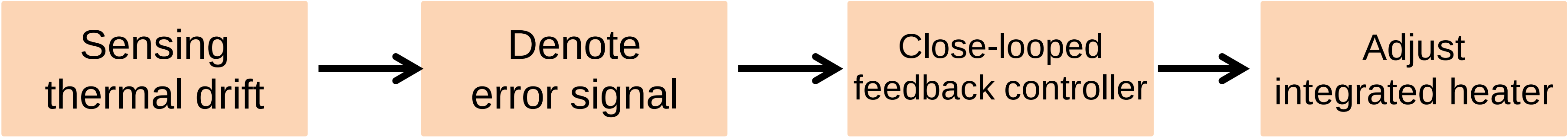


- Air trench increase thermal isolation
- Figure A: 21mW/FSR tuning power, <10μs for tuning time
- Figure B: 2.4mW/FSR, 4.9mW/FSR (topside silicon undercut-etching)

  3.9mW/FSR (backside substrate etching)
- High thermal time constant (~170μs)
- Sensitive to optical bistability effects

Control-Based Circuit System

- Mechanism



Sensing thermal drift

Denote error signal

Close-looped feedback controller

Adjust integrated heater

- Performance standard
  - Low-cost, energy efficiency
  - No additional photonic structures
  - Compatible with WDM
  - Implementable for passive or active microring modulators
- Method
  - Using signal optical power
  - Using Bit-error-rate (BER)
  - Using dithering signal

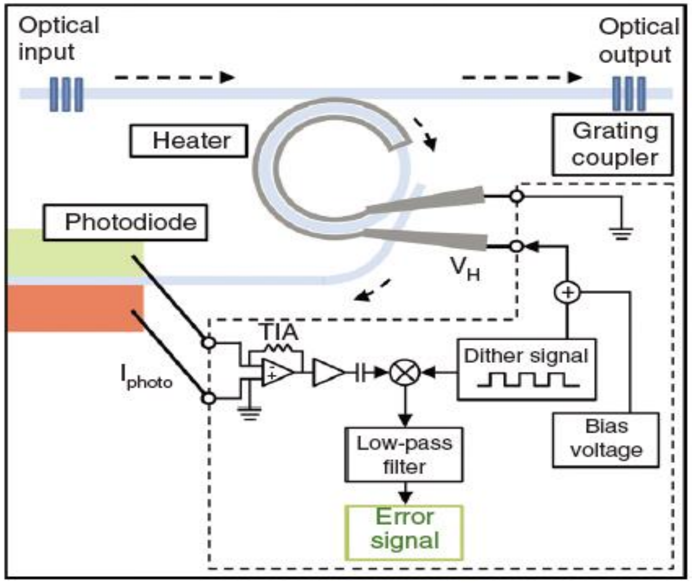
Thermal Variation Monitoring Method

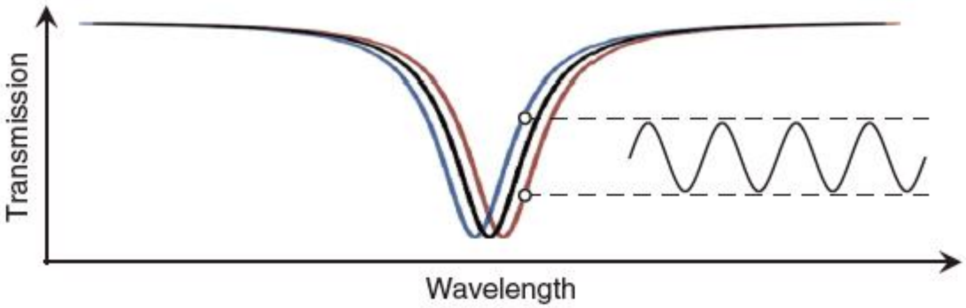
- Utilizing signal optical power
  - Sensing laser wavelength by monitoring mean modulated power
  - By using drop port ➔ eliminates power tap, yields WDM compatibility
  - Susceptible to fluctuations in laser power
  - Not applicable to passive resonator

- Directly Monitoring BER
  - Wavelength locking and thermal stabilization over 32K
  - Keep high quality of generated data by monitoring
  - Need complex circuit and high speed receivers ➔ high power consumption
  - Only applicable for modulators not switches or filters

Thermal Variation Monitoring Method

- Dithering Signal





$$\cos(f_D t)\otimes\cos(f_D t+\phi)=\frac{1}{2}[\cos(2f_D t+\phi)+\cos(\phi)]$$

f_D: dithering signal frequency
Φ: relative phase (0 or π) of modulated signal

  - Mixing driving dithering signal and modulated optical signal
  - In-, or out-of-phase depends on which side of the resonance the laser offset
  - Reduction of extinction ratio by dithering is negligible
  - Advantages
    - Simple circuit, immune to laser power fluctuation, compatible with WDM
    - Applicable to microring modulators

Conclusion

- Athermal device solutions
  - Using negative TO coefficient for WG cladding and integration with MZI
  - Zero-power consumption
  - Difficult to fabricate and incorporate with non-CMOS materials
  - In full system analysis, power to stabilize laser source is needed

- Control-based solutions
  - Integrated heater and control circuit is needed
  - Wavelength-lock & thermally stabilized both passive and active is possible
  - Additional active power consumption

Kishore Padmaraju* and Keren Bergman

Resolving the thermal challenges for silicon microring resonator devices

slayier55@gmail.com

High-Speed Circuits & Systems Lab.
Dept. of Electrical and Electronic Engineering
Yonsei University