# About Omics Group

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# A Novel CMOS-compatible Hybrid Material and Device Platform for Reconfigurable Integrated Nanophotonics

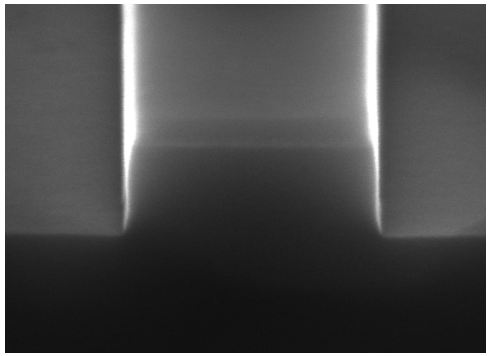
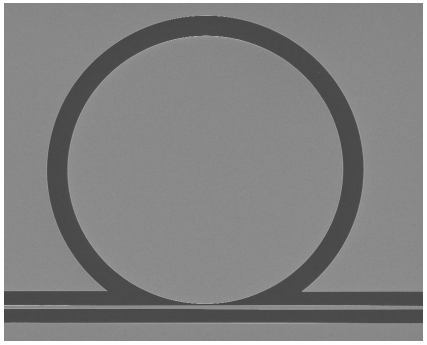
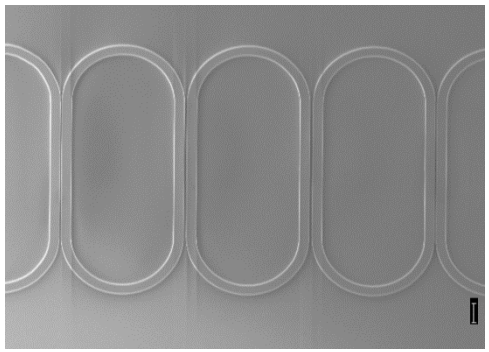
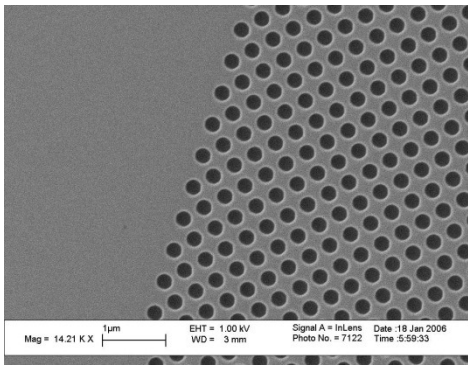
Majid Sodagar, Amir H. Hosseinnia, Hesam Maoradinejad, Qing Li, Amir H. Atabaki, Ali A. Eftekhar, and Ali Adibi

School of Electrical and Computer Engineering

Georgia Institute of Technology

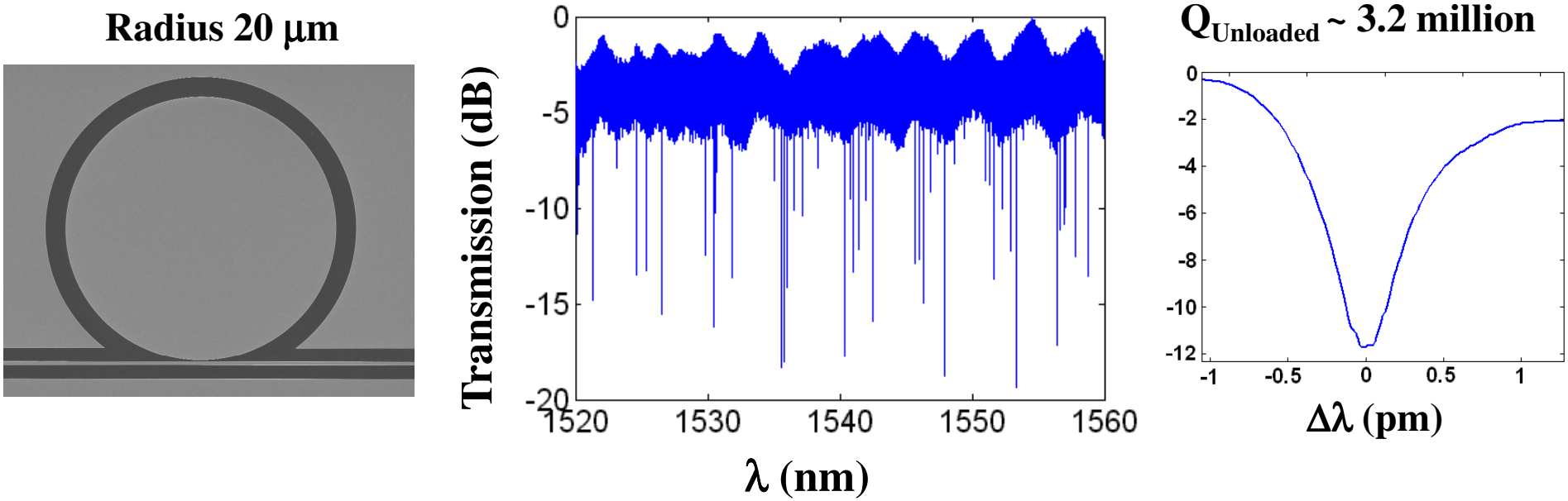
# Recent Advances in Si Photonics

- High speed modulators
- Source and detector integration
- Ultra low loss waveguides
- Ultra high Q resonators
- High performance functional devices (e.g., couplers, high order filters, spectrometers)
- Photonic crystal device technology


**Current performance promises high quality reconfigurable photonics structures**

# High-Q Microdisk Resonators on Chip

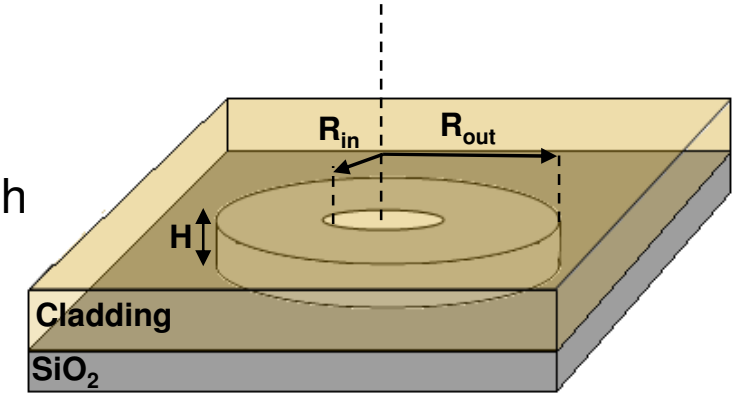



- Highest Qs to date for disks on substrate (visible and IR)
- Problems:
  - Higher order modes
  - Small free spectral range (FSR)
  - Critical coupling achieved at very small gaps

# Miniaturized Microdisk Resonators

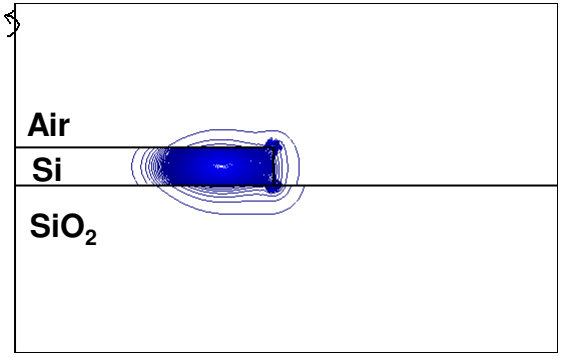
## Objectives:

- ❑ Ultra-compact, high Q, large FSR microdisk
- ❑ Single mode operation over a large bandwidth
- ❑ Ultrafast thermal tuning using the zero field region in Si to place the heaters
- ❑ Replacement of microring resonators



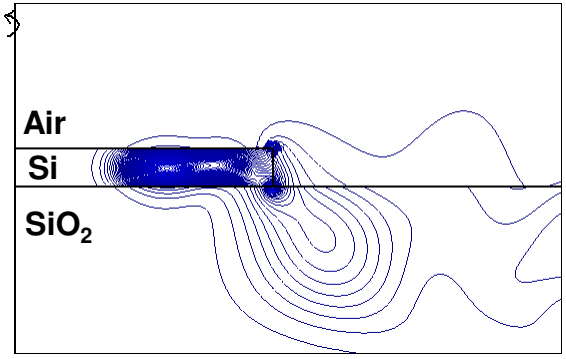

**Example**

**Electric energy: 1st order mode**



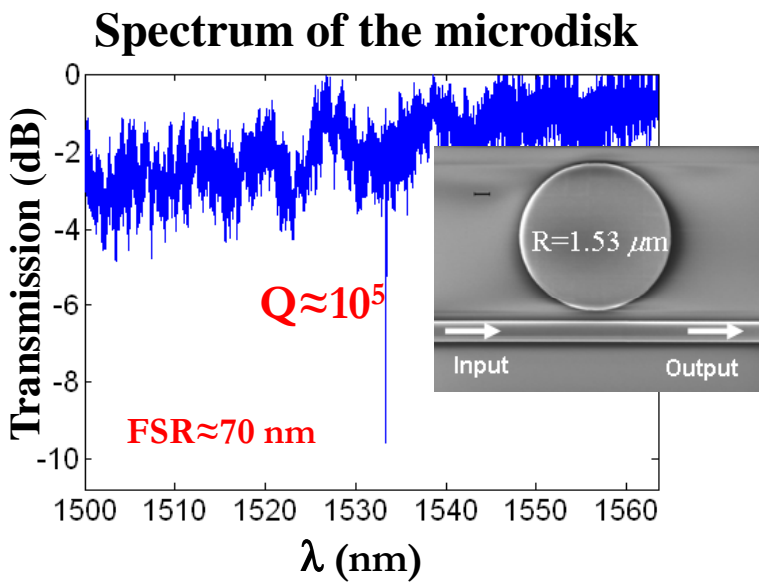

**Disk radius = 1.4 $\mu$m**
**Disk thickness = 200 nm**

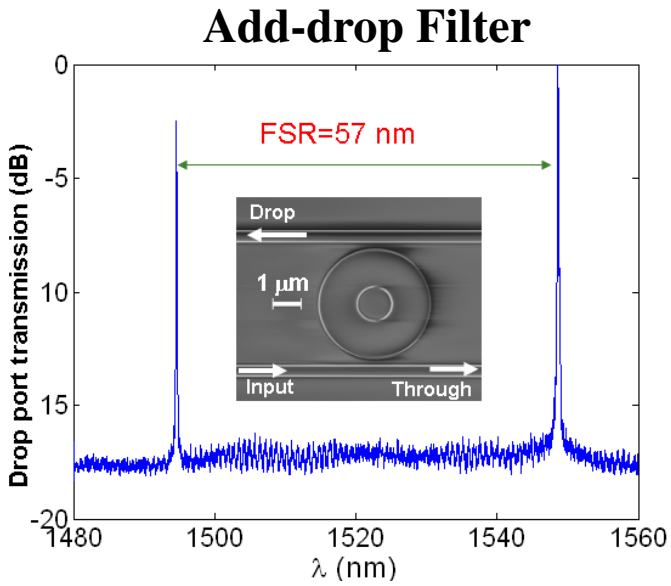
**Electric energy: 2nd order mode**



# Miniaturized Microdisk Resonator in SOI

- Ultra-small and high Q microdisk
- Single mode operation over a large bandwidth



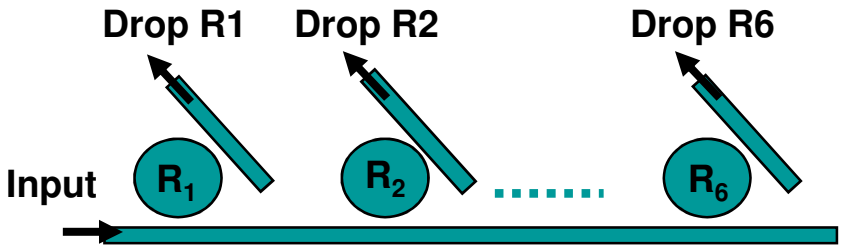



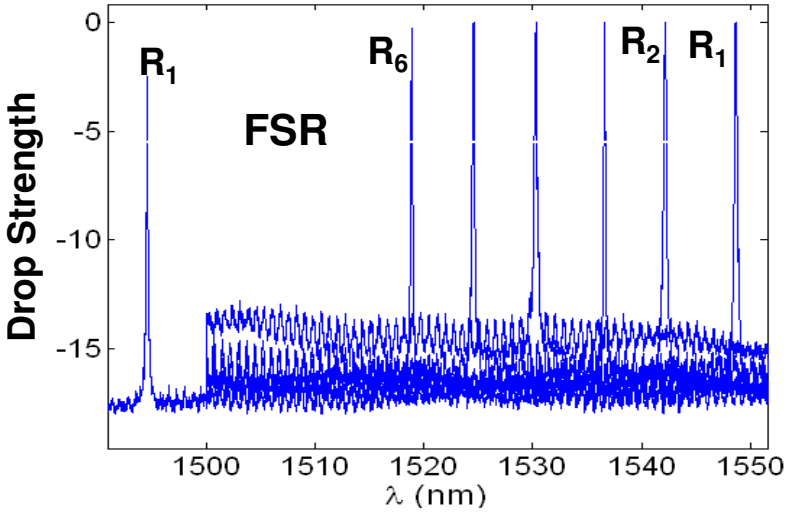

- Q~100,000 and mode volume $0.15(\lambda_0)^3$ was observed
- A microdisk with a radius of 2 μm showed a Q~150,000

Depending on the application, Qs in the range $10^5$-$10^6$ is achievable

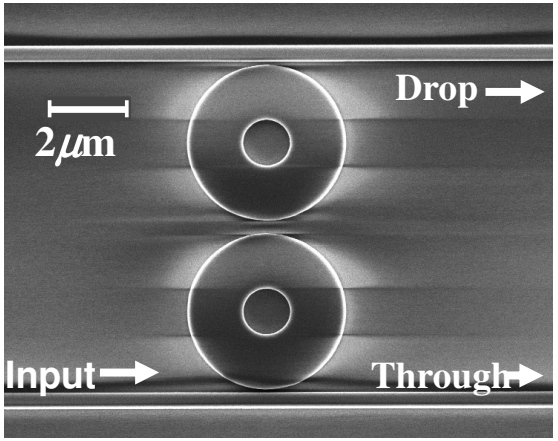
# Engineering the Spectral Response of Microdisk Resonators Over a Large Bandwidth

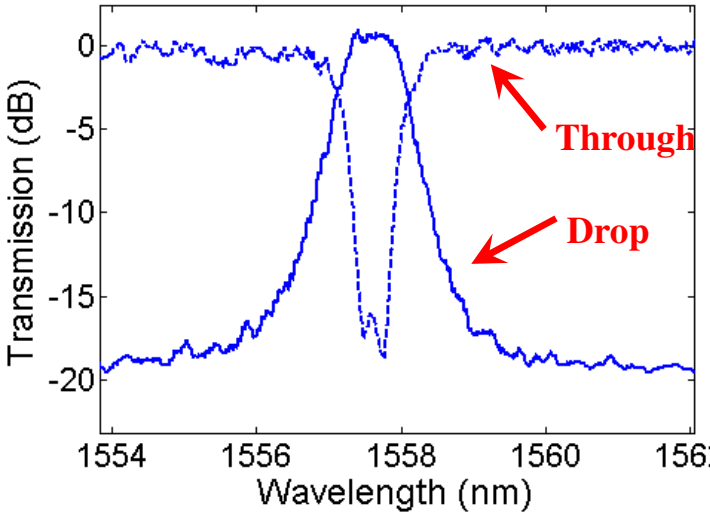
- Experimental response of an array Si resonators with radii around 2μm.



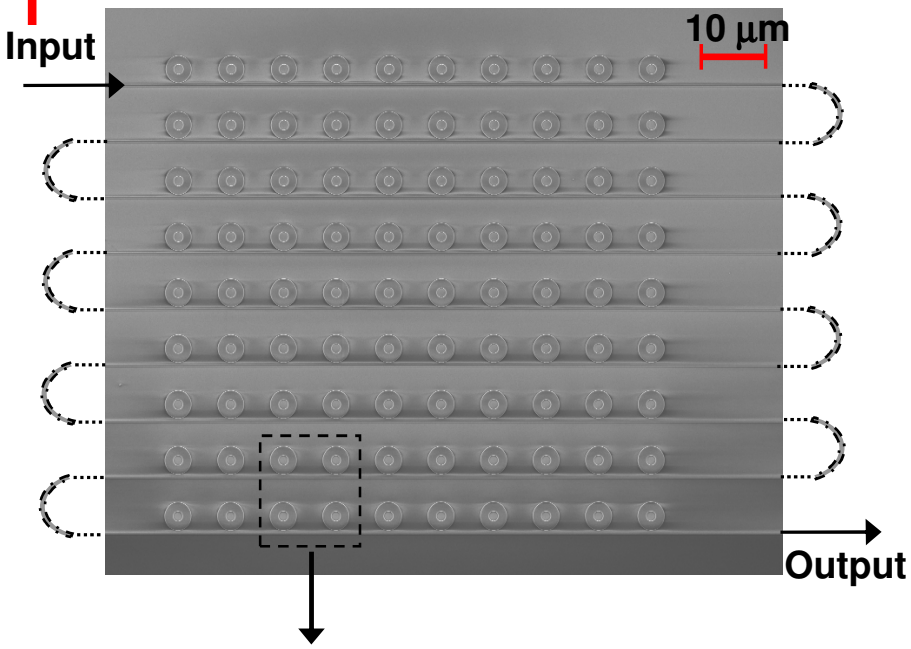



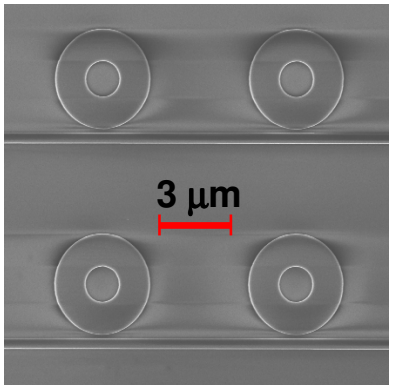

- Experimental response of CROW using disks with radii around 2μm.

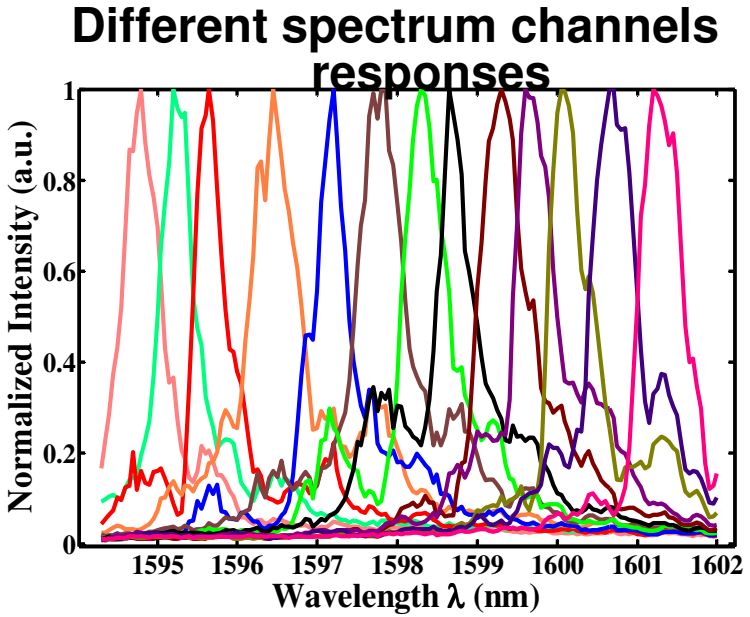


# High-Resolution Compact On-chip Spectrometer



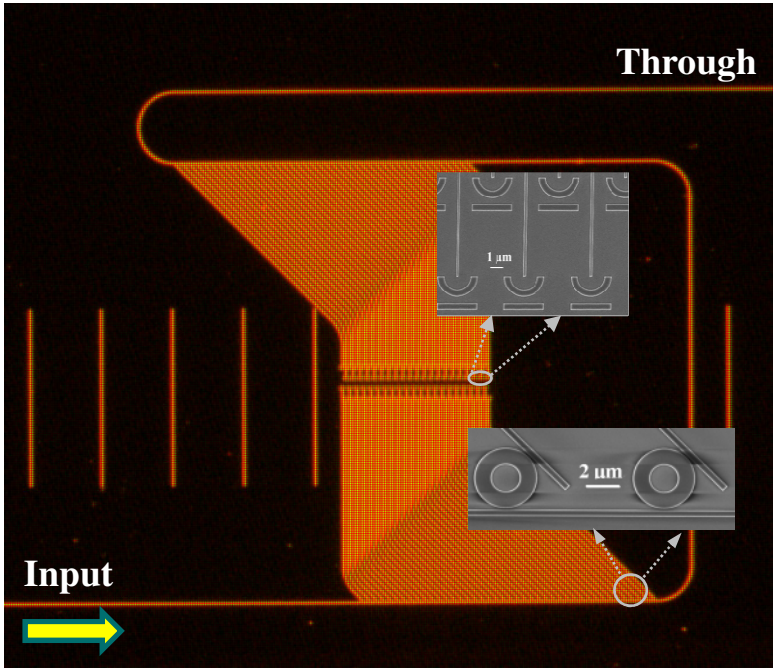



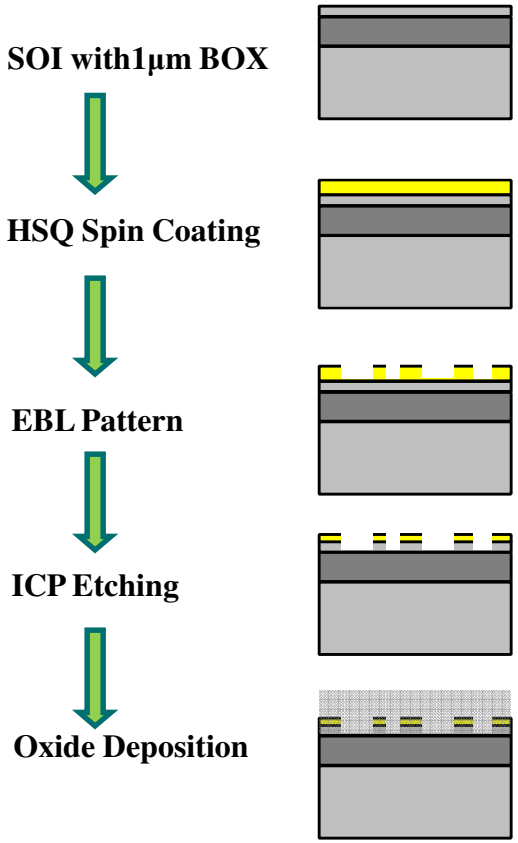




- 90-channel spectrum in less than 60 × 60 μm$^2$Area
- Down to 0.1 nm resolution:
- Up to 60nm bandwidth
- Less than 0.5 dB insertion loss

# Design and Fabrication

## An on-chip spectrometer using microdonut resonators

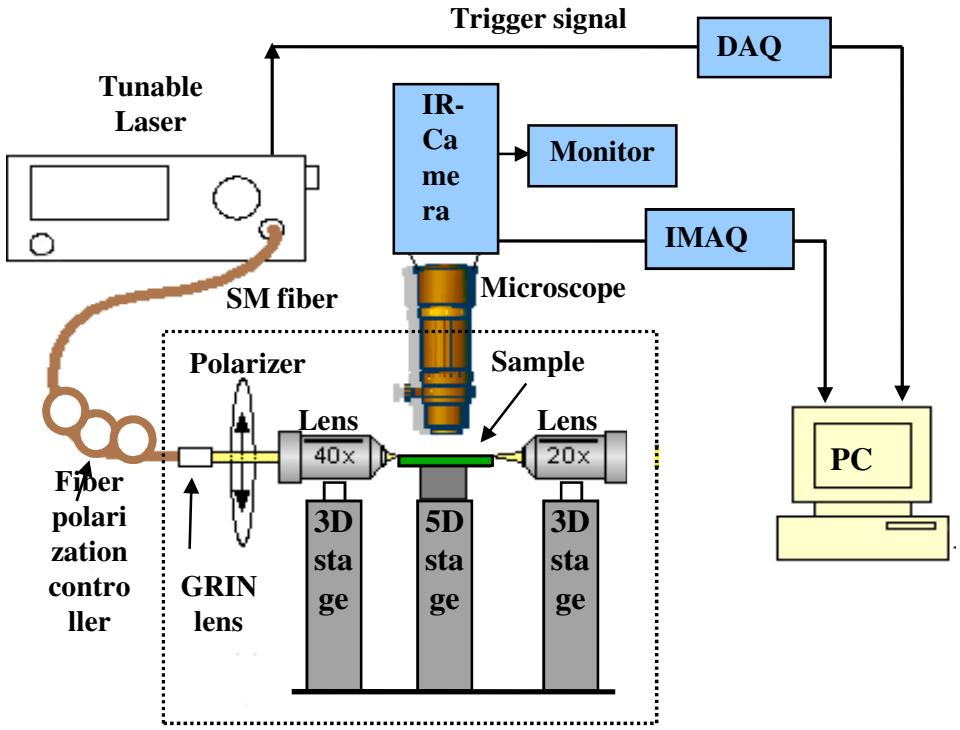



- Large scale array of 84 microdonuts
- Outer radius – 1.950 to 2.033 µm, step – 1nm
- 84 Scatterers for top-view imaging

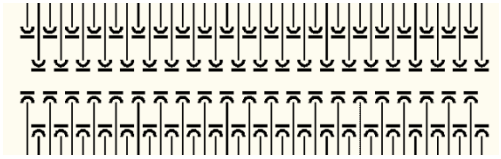
# Characterization

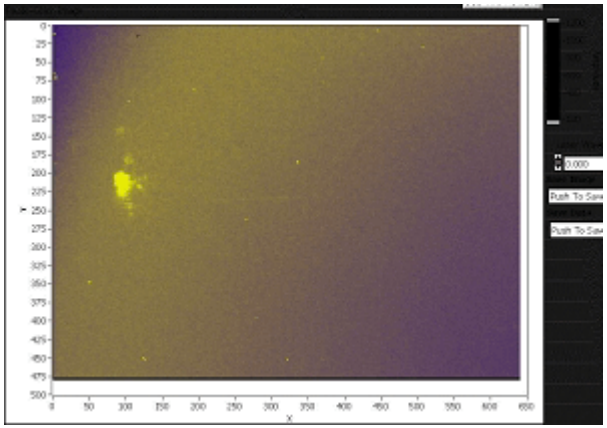
## Top View Imaging




Experimental Setup

### Scatterer Array





Top View image evolution as the wavelength scans from 1550.0 nm to 1601.30 nm

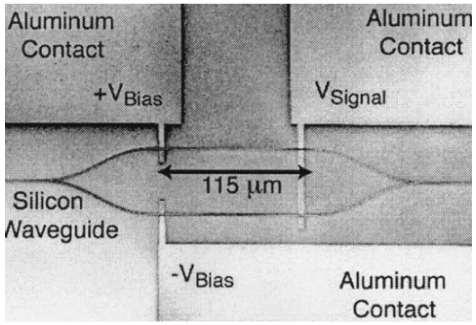
# Photonic Reconfiguration in Silicon

## Desired Features

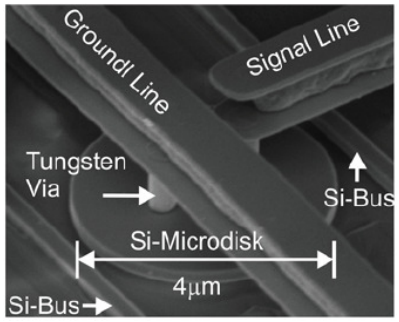
- CMOS compatible
- Low power
- Wide tuning range
- Fast
- Low loss

## Methods

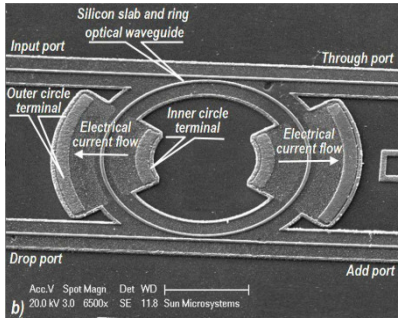
- Free-carrier plasma dispersion
- Thermo-optic effect
- Electro-optic effect in hybrid polymer-based devices
- Opto-mechanical tuning



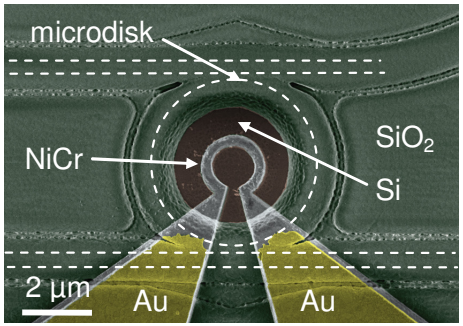

Lyszczarz *et at* 2007




Watts *et al* 2009




Cunninghum *et al,* 2010



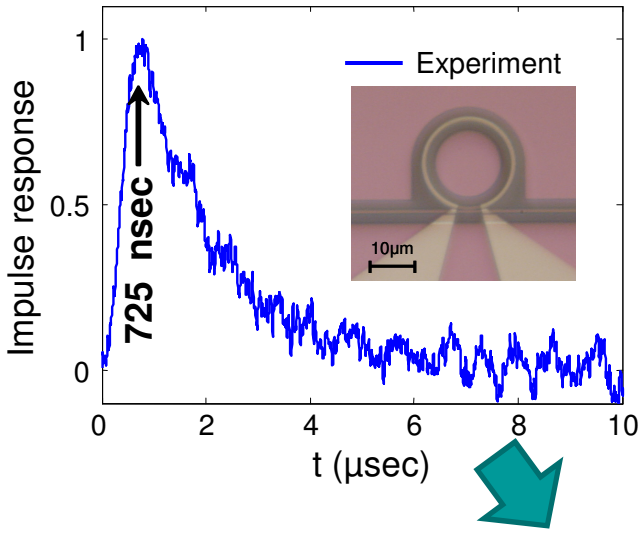

Atabaki, *et al* 2011

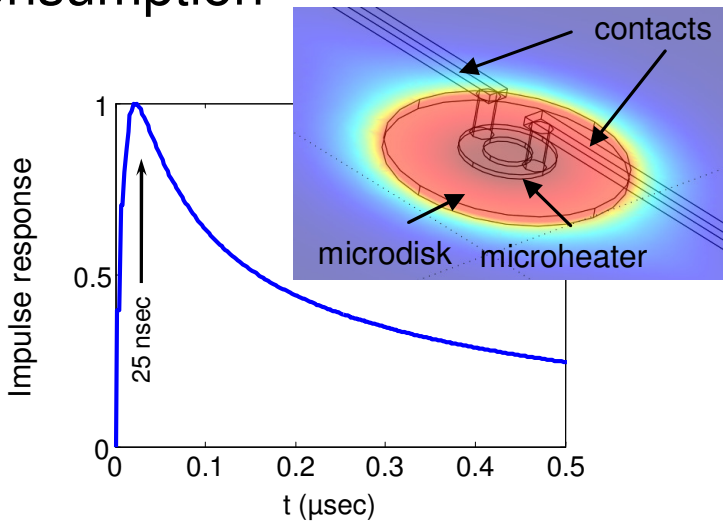
**Thermo-optic effect suitable for wideband tuning**

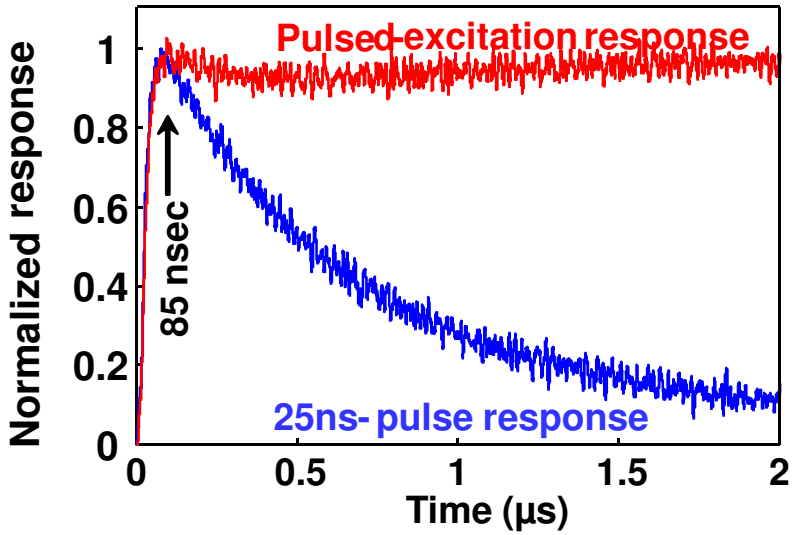
**Reconfiguration speed is a bottleneck**

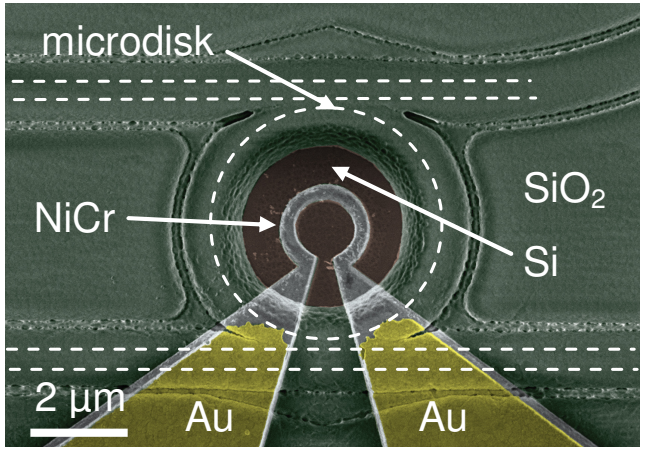
# Ultra-fast and Low-Power Thermal Tuning

- Directly heating Si reduced heat propagation delay
- Small microdisk for low power consumption



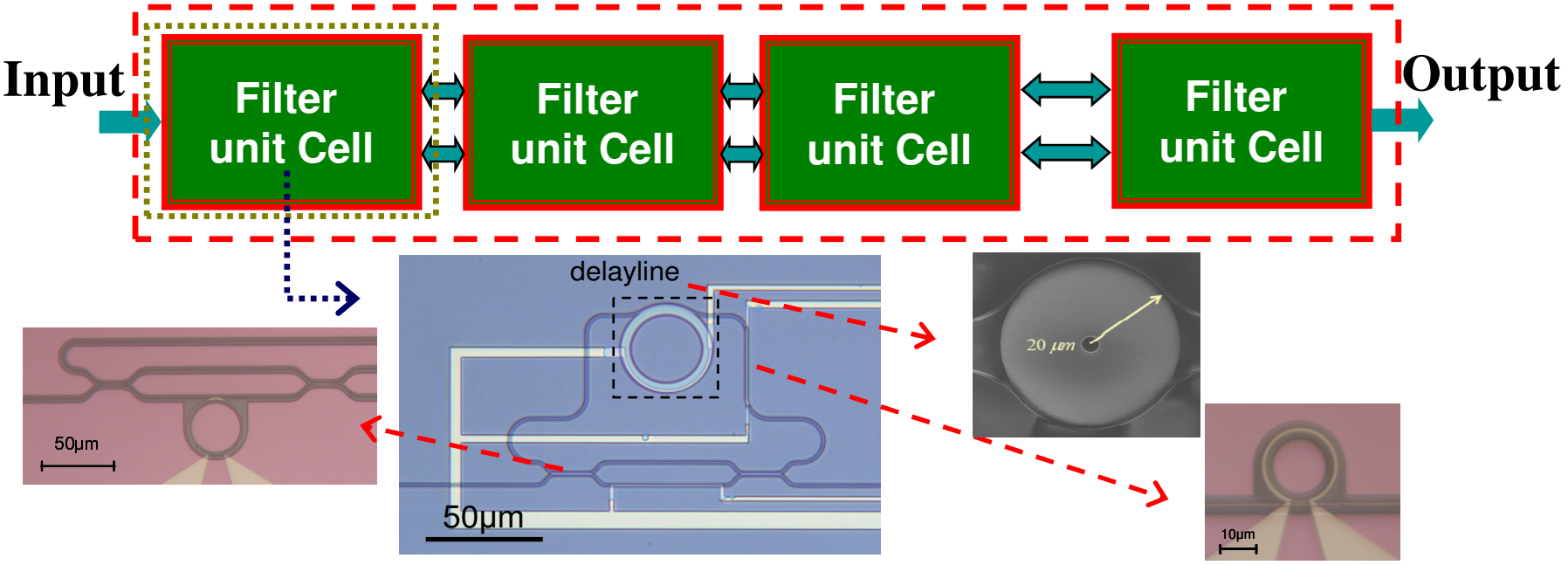



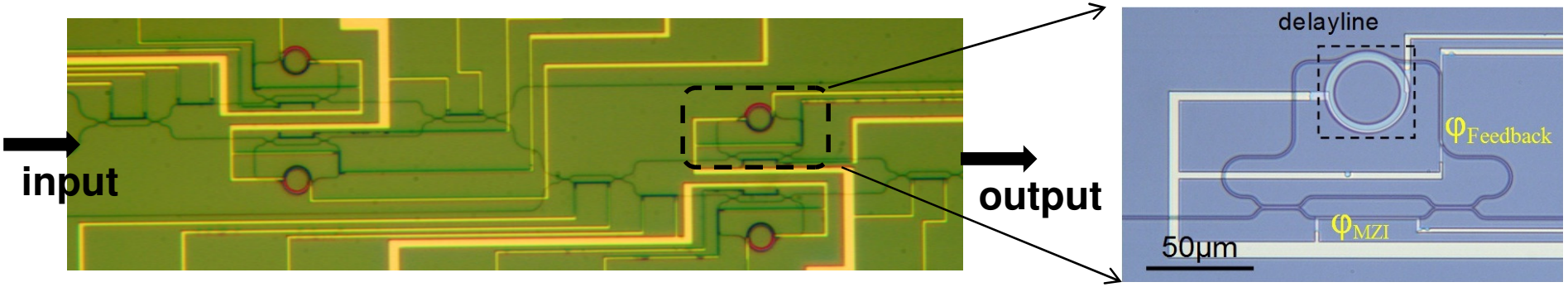
# Example: A Reconfigurable High-order Filter

- Higher order filter design based on cascading unit cell elements

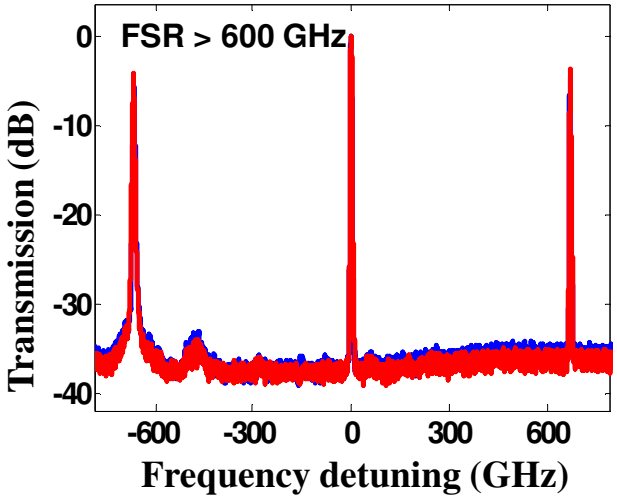



- Unit cells require only three basic functionalities
  - Delay lines (fixed and tunable)
  - Phase shifters
  - Couplers

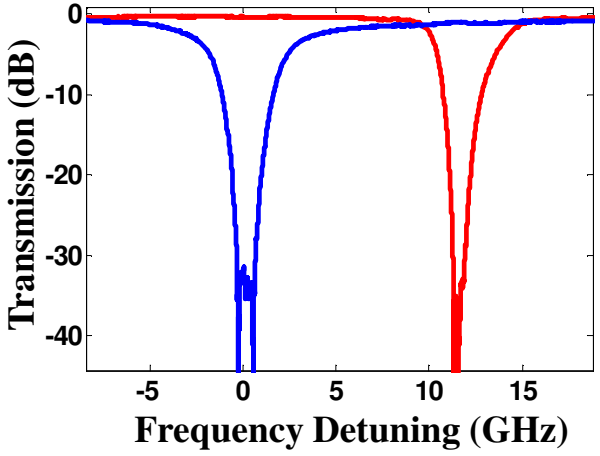
# Cascaded Coherent Processing/Filter Units



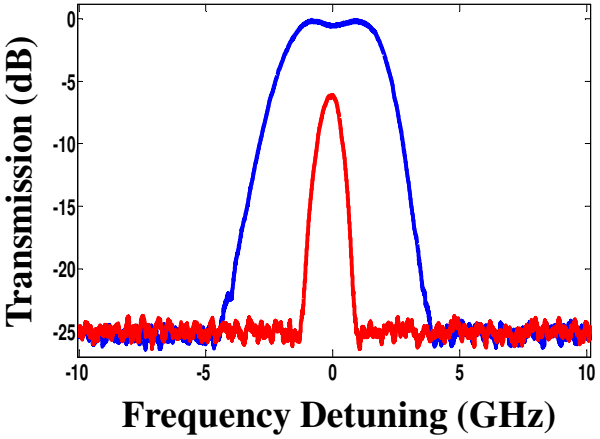

P. Alipour *et al,* group IV photonics 2010




Notch response



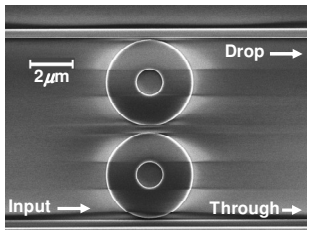

Filter Reconfigurability
900 MHz – 4 GHz

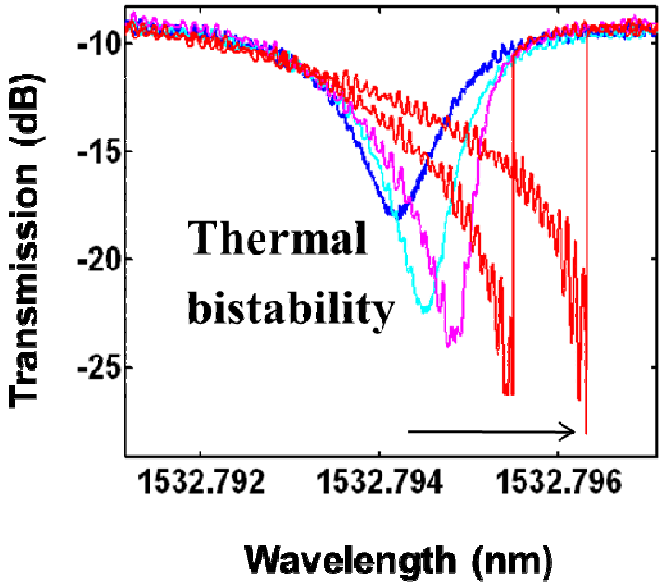


# Need for a New Material Platform

- Optical resonators in Si platform: key to compactness and low power reconfiguration/modulation
- Strong nonlinearity in Si: bottleneck for practical applications at power levels > a few 100 μW
  - Two photon absorption (TPA)
  - Free carrier absorption (FCA)
  - Optical instability

Compact add-drop filter

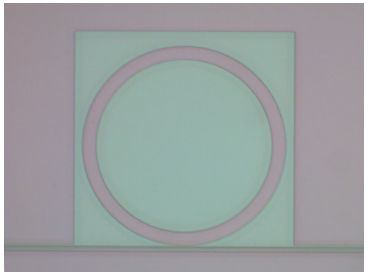



- SiN has 20x less effective nonlinearity without any FCA
  - Ultrahigh-Q resonators can be implemented in SiN

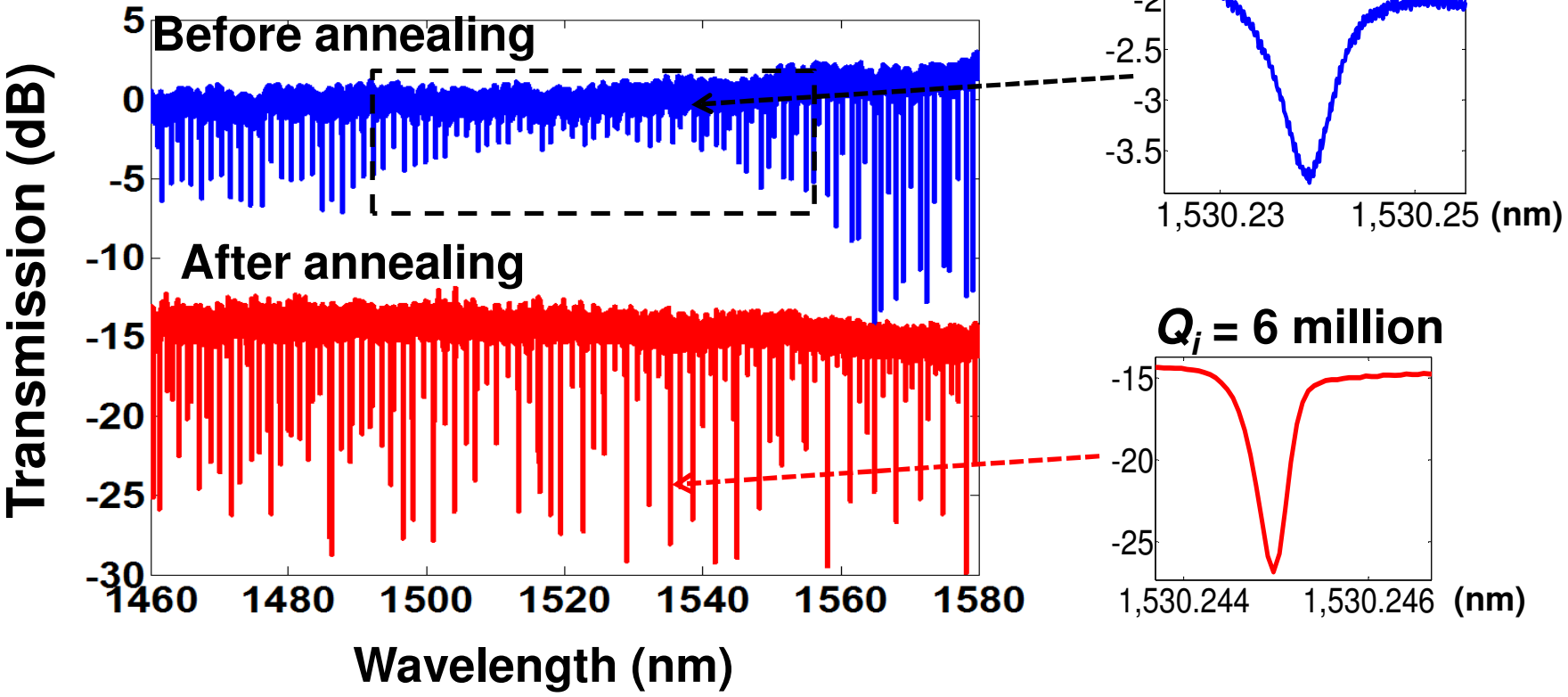
→ 1-2 orders of magnitude higher power handling in a hybrid Si/SiN platform

# The effect of Annealing on the Q of SiN Resonators



R=60 μm

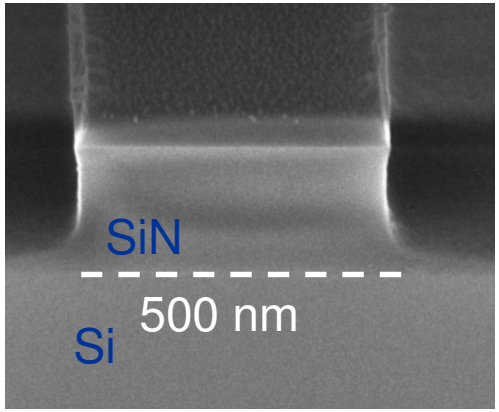
Thickness = 400 nm

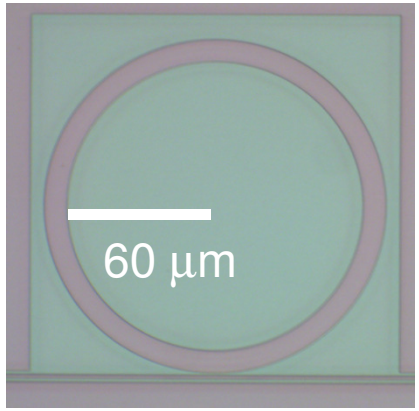


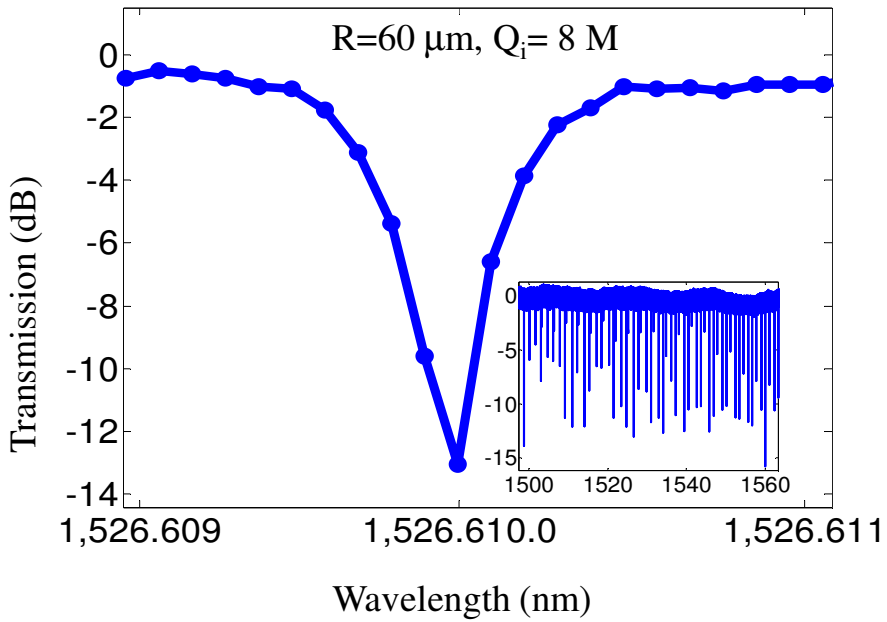

**Before annealing, SiN has strong material absorption from 1490-1560 nm due to the OH bonds.**

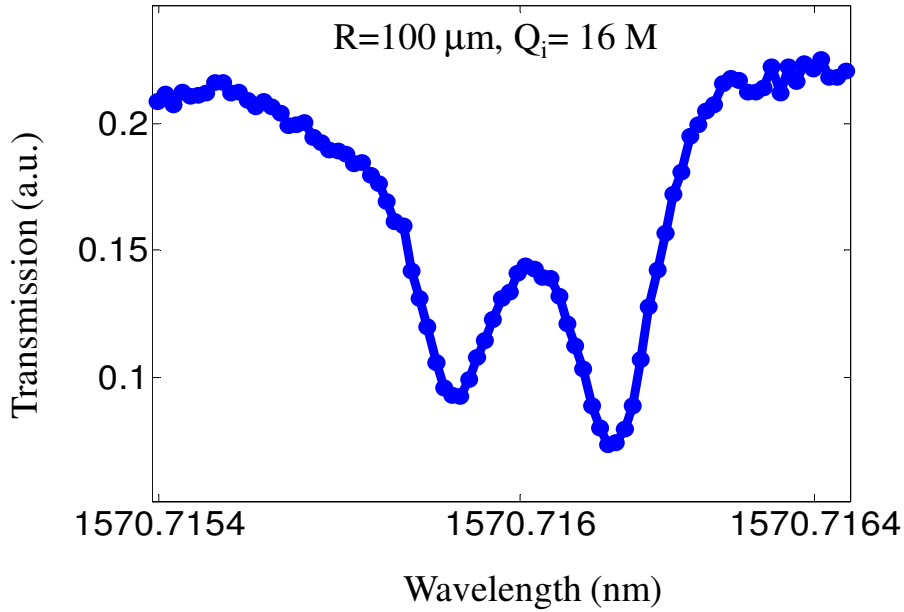
# Scaling of Q with the Resonator Size

- 400 nm SiN grown in LPCVD
- Fabricated by: EBL and CF4/CHF3 plasma etching



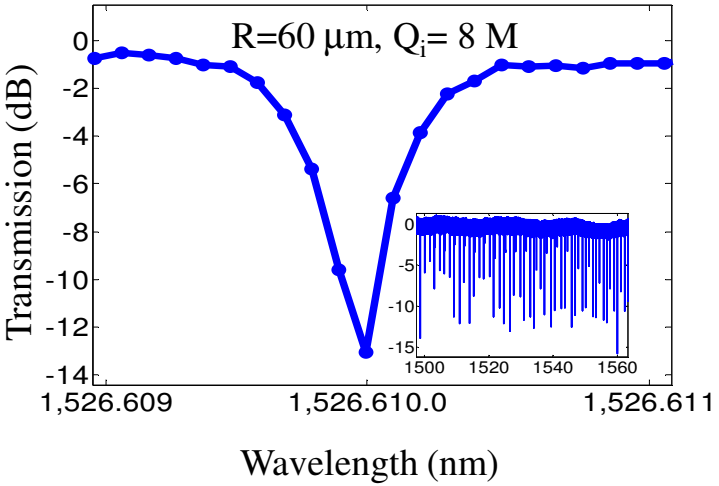



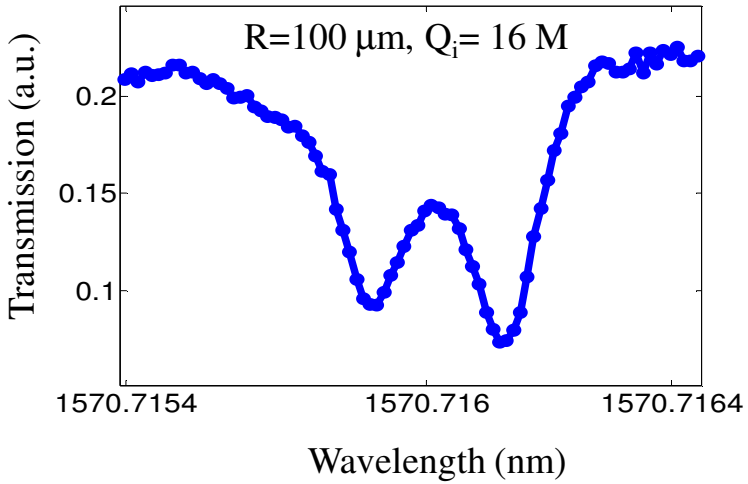



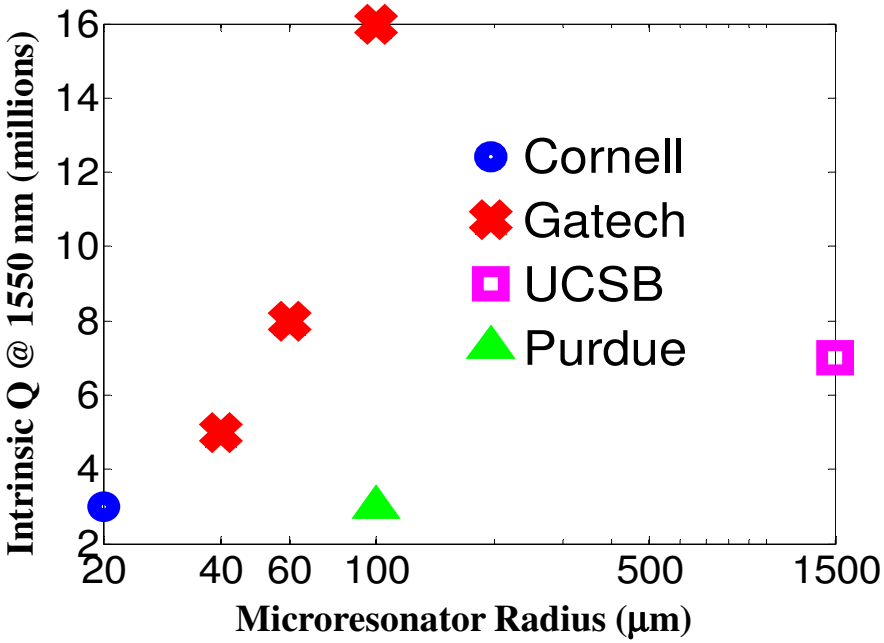



# Compact and High Q SiN Microresonators

- Q and Q/V matter in different applications

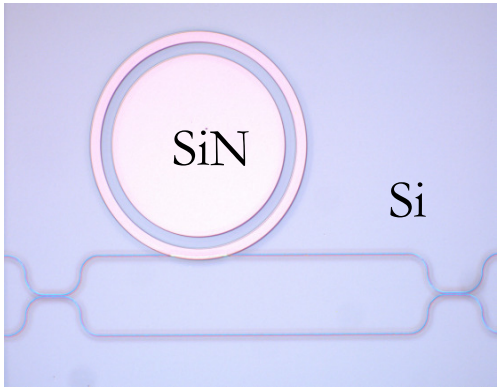


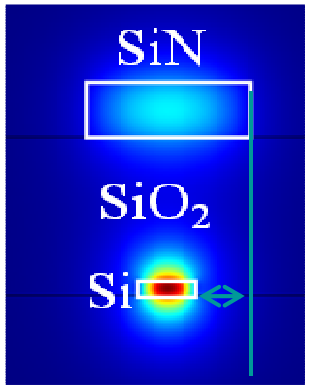



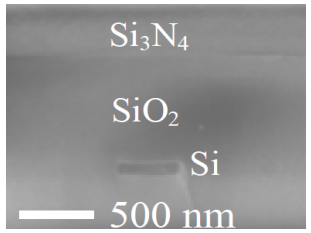

Achieved highest Q to-date for SiN microresonators

# 3D Integration of Si and SiN Materials

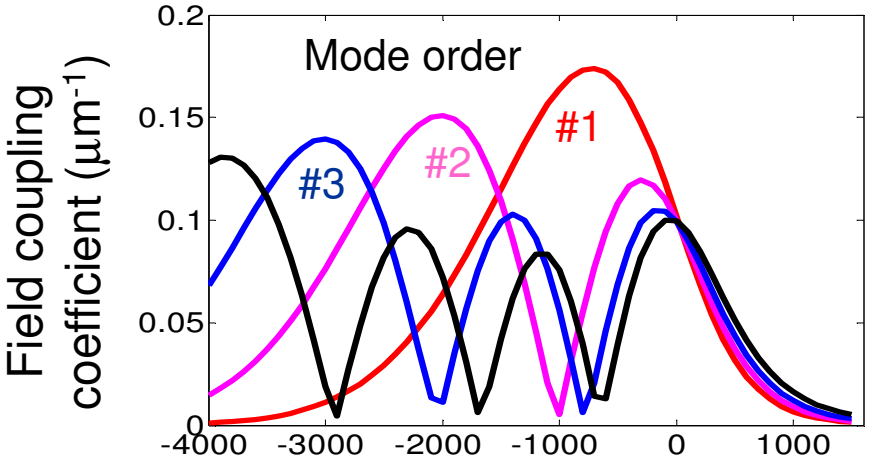


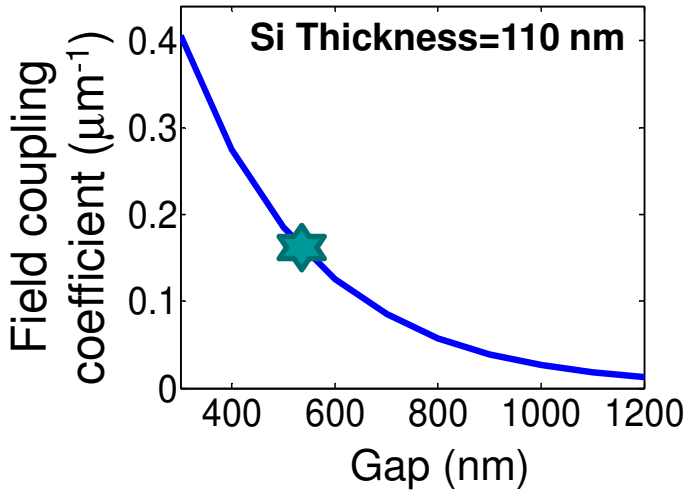




Evanescent coupling




Lateral shift

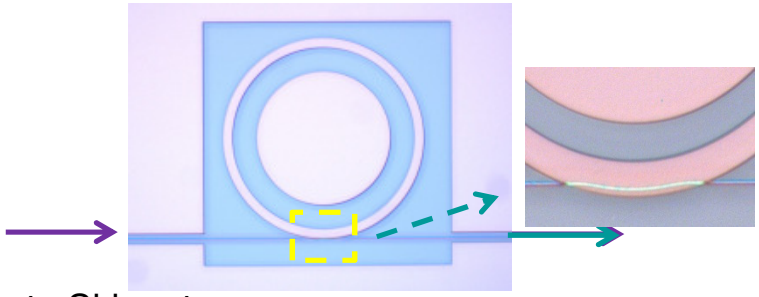


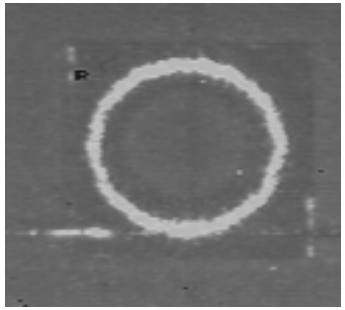

- Thin SOI for phase matching between SiN and Si modes
- Strong coupling between SiN and Si layers are achievable

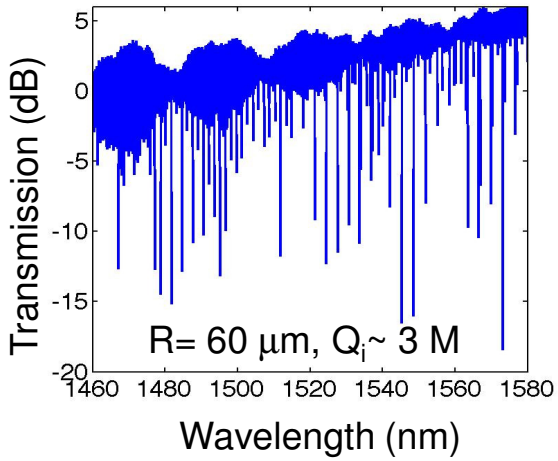
# Reconfigurable Photonic Devices in Si/SiN Material

- Critical coupling

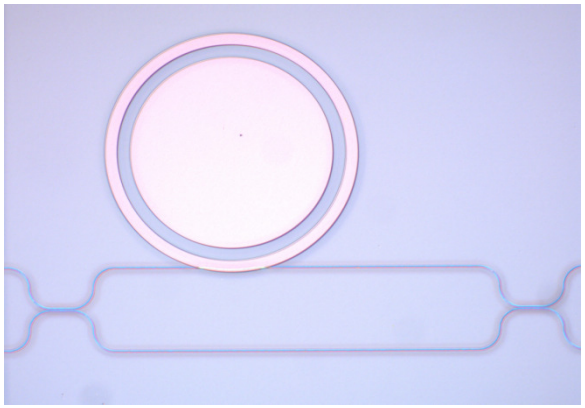


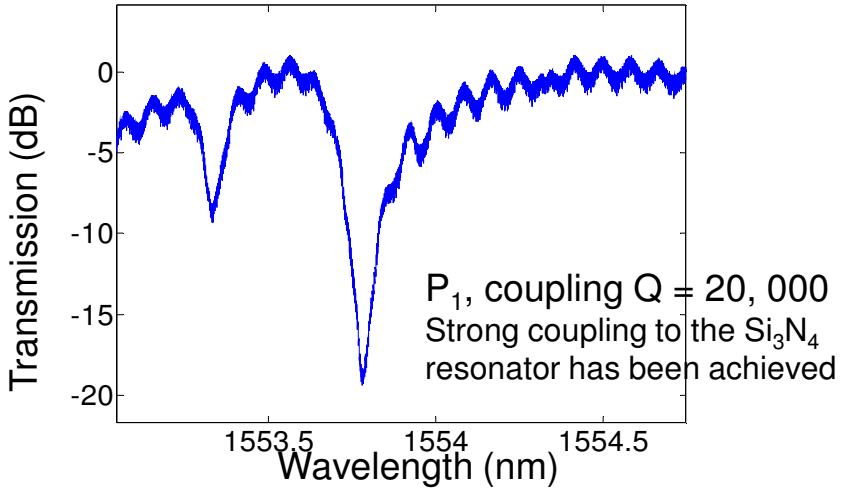

Top infrared image






- First-order filter: over-coupled microresonator

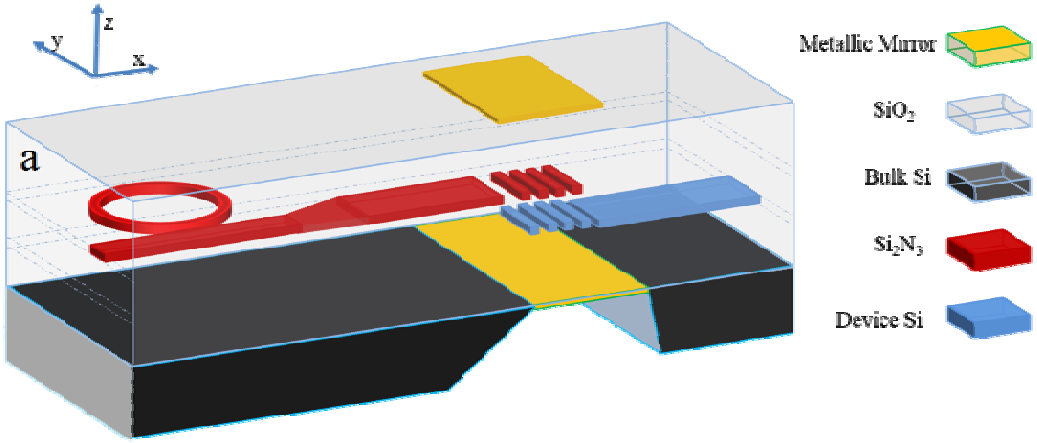


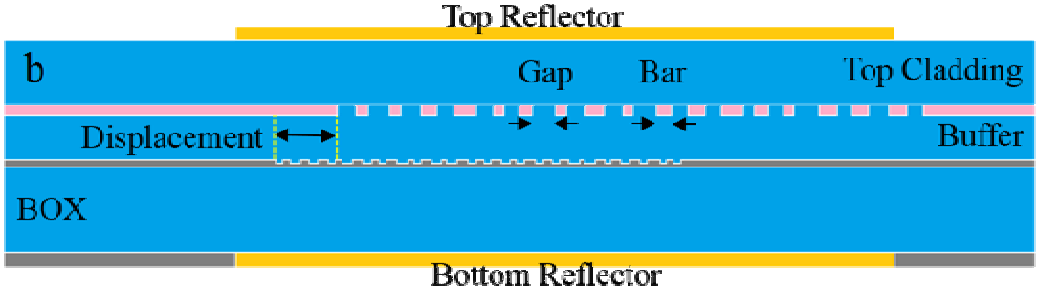

The Si/SiN integration of tunable Si devices with low-loss SiN delay lines

# Si/SiN Interlayer Grating Coupler

3D Schematic

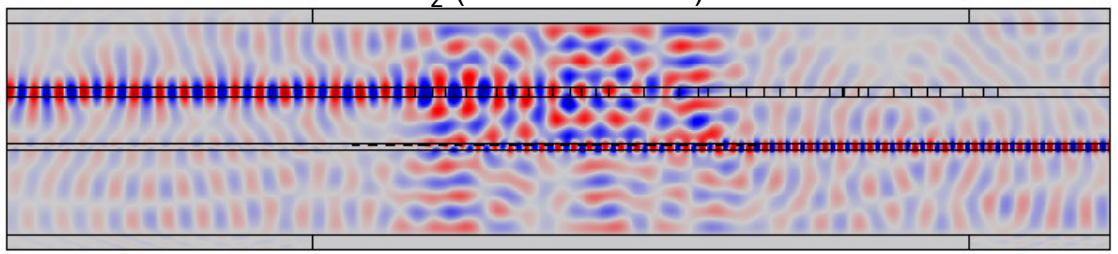



Geometrical Optimization
Via Genetics Algorithm

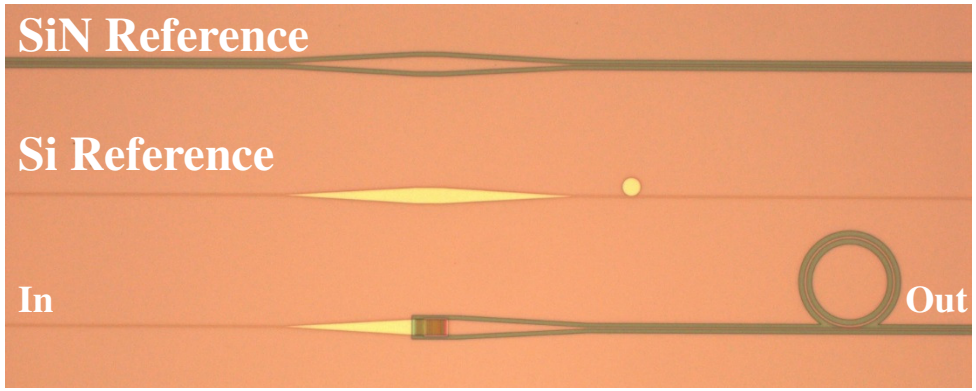


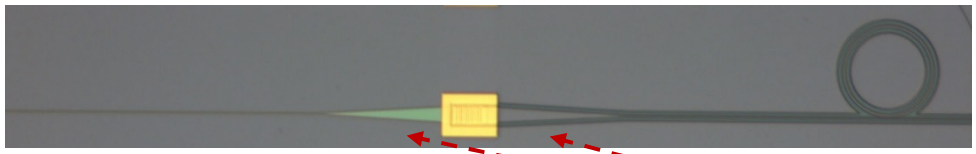

Calculated
Insertion Loss = 0.5 dB

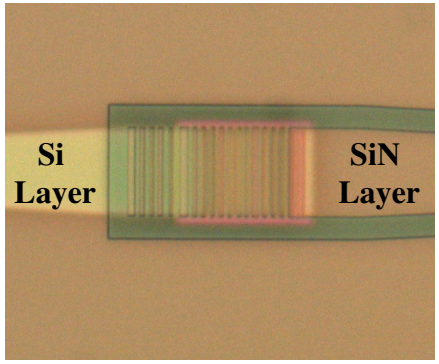
$E_z$ (Double-Mirror)

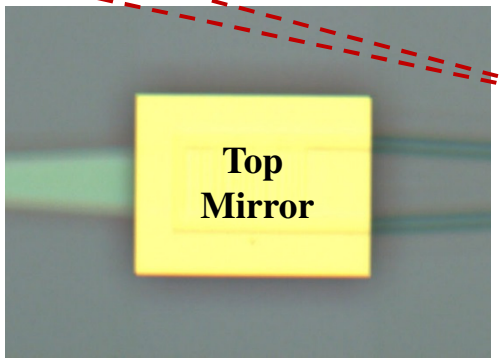


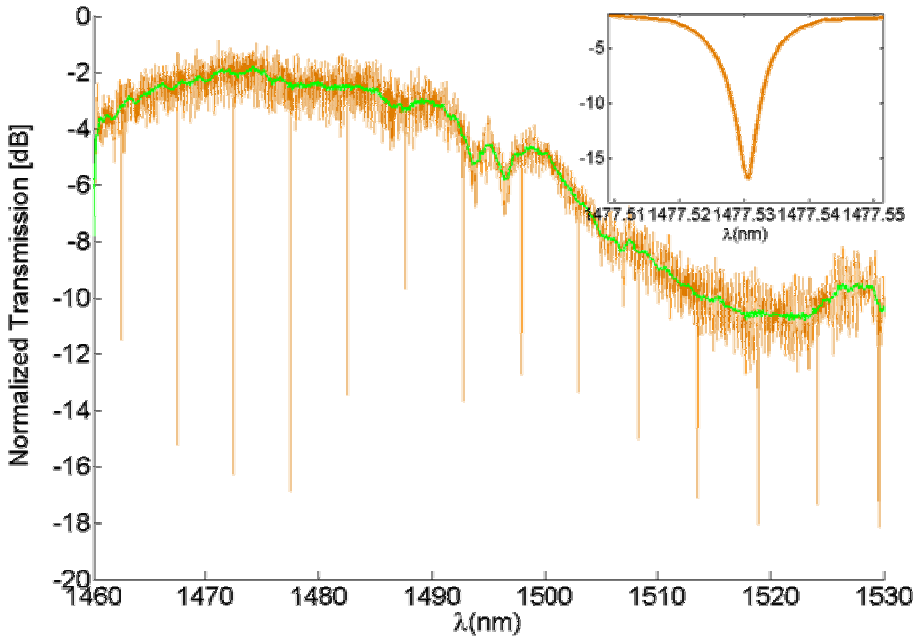
# Results for Single (Top) Reflector





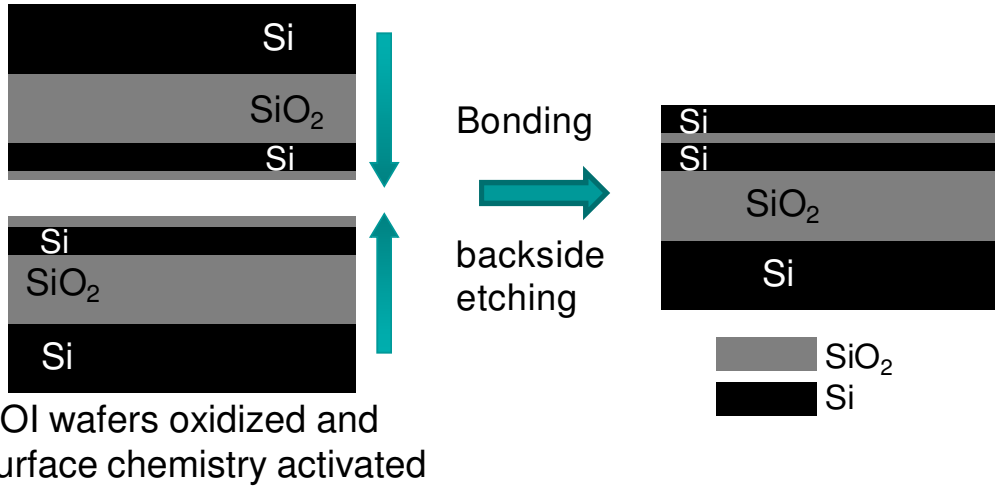




**Tapers**

**Measured Insertion Loss ~ 2dB**
**Measured Bandwidth > 40nm**

# Double-SOI Material Platform

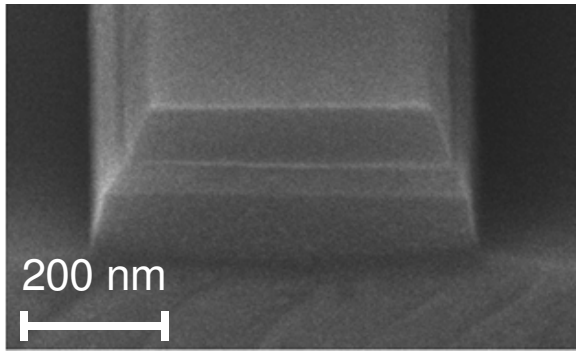
- Fabrication



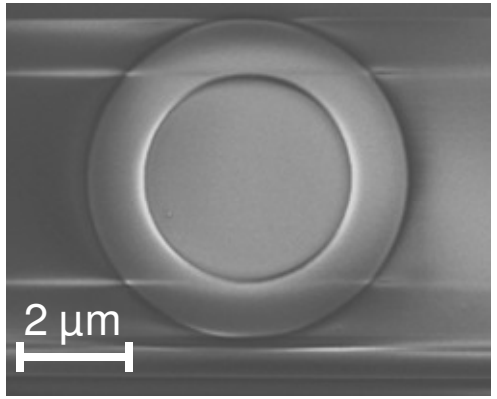

SOI wafers oxidized and
surface chemistry activated

- SEM

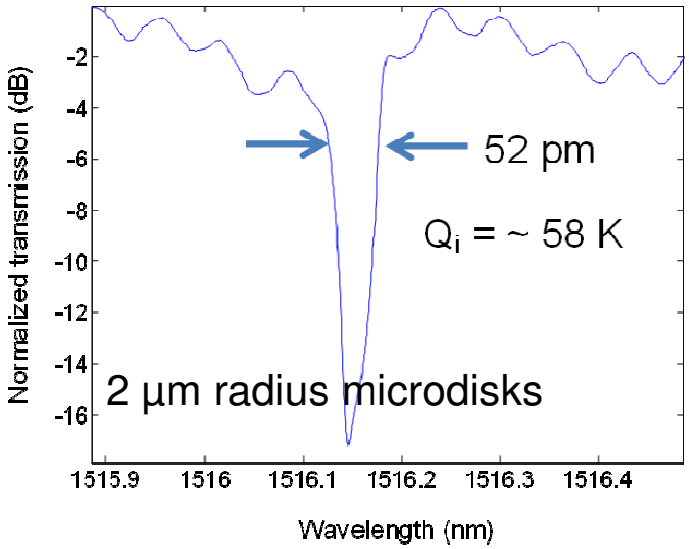
Cross-section of double-SOI waveguide

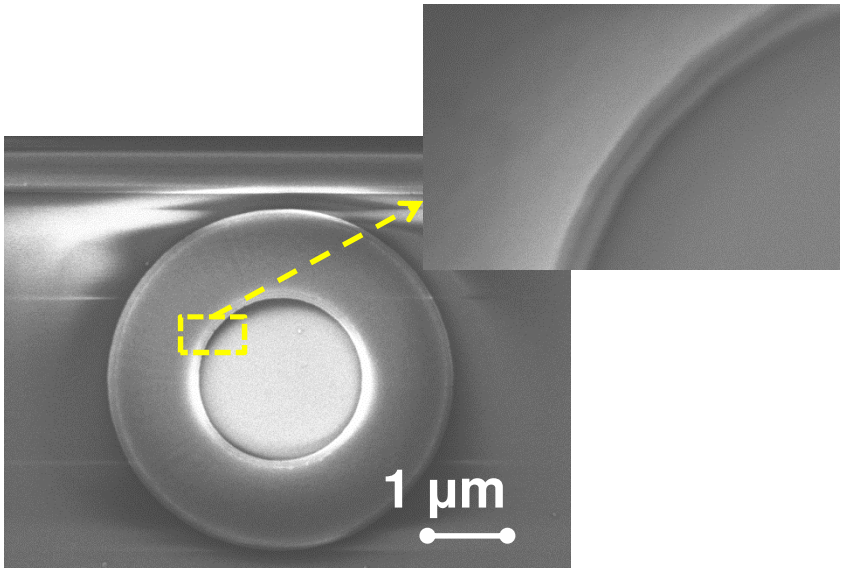


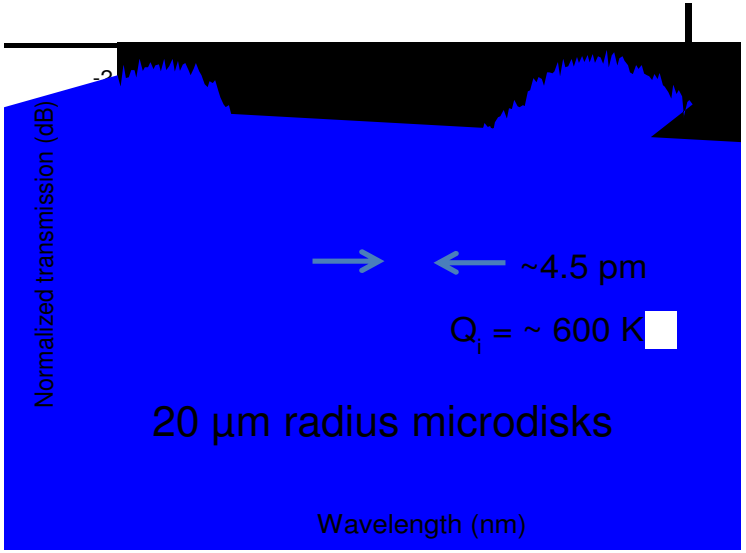

Top view of a double-SOI waveguide-resonator

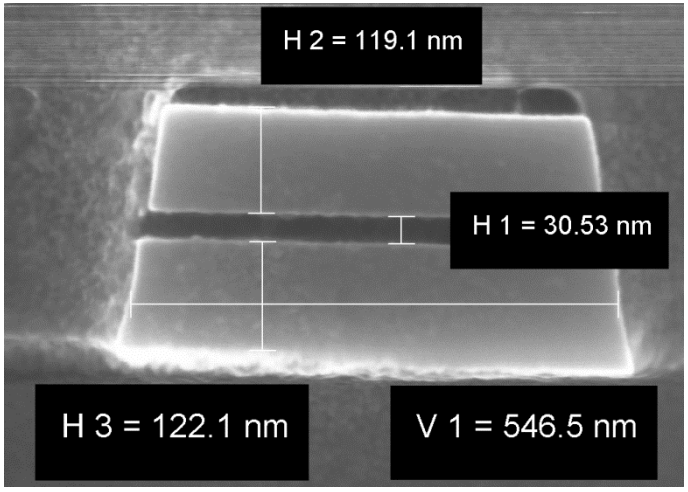


# Double-Layer SOI Through Wafer Bonding



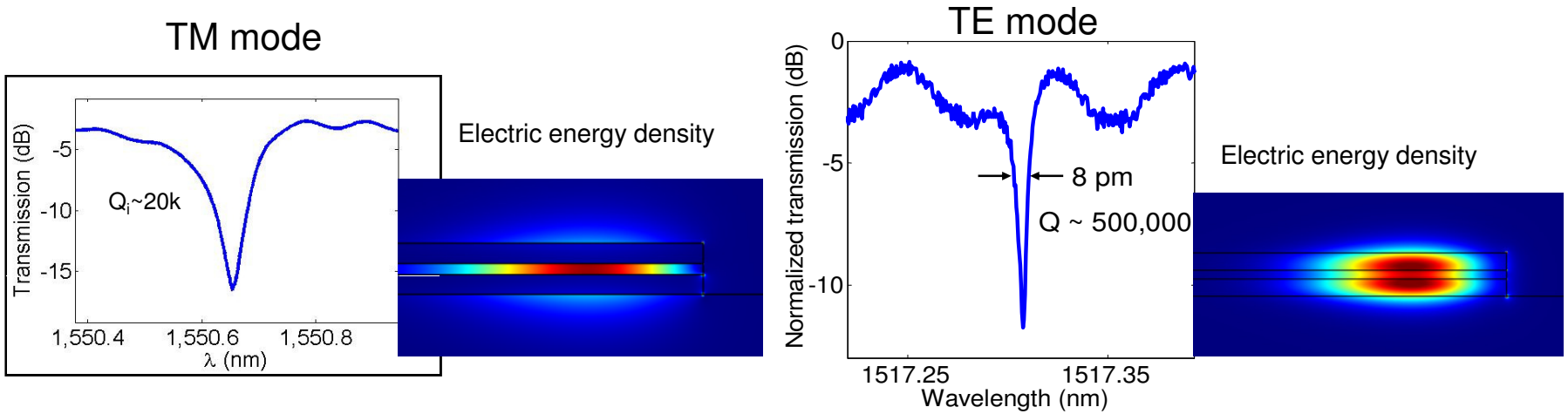



# High Q and High-Filed Enhancement Using Slot Structure in Double-Layer SOI Structure

- 20 μm radius microdisks

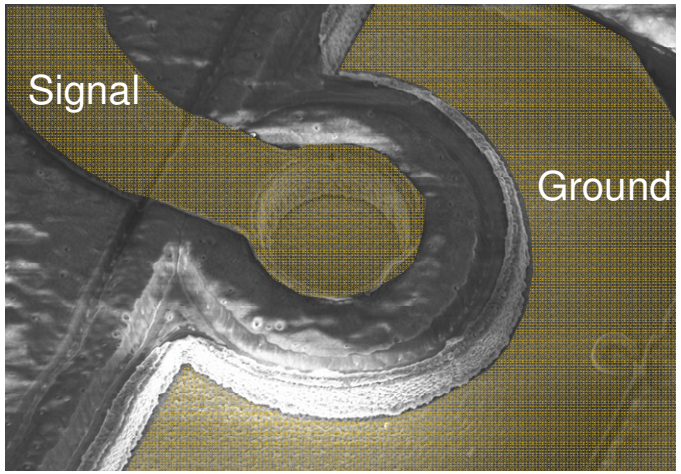


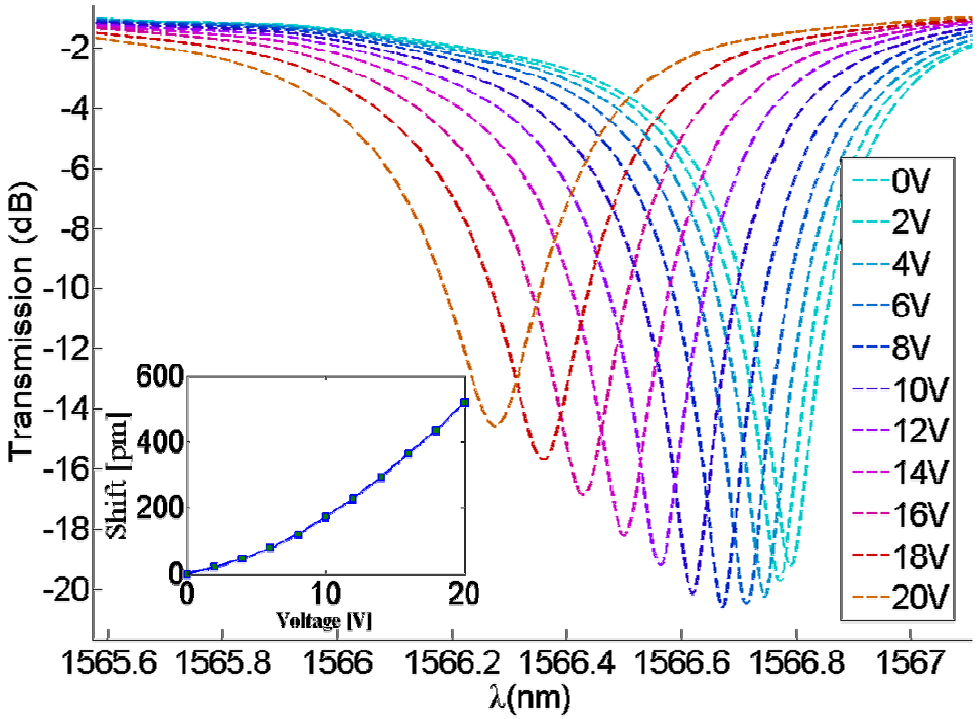

Comparison with the similar state-of-the-art double-layer resonators

| | Radius | $Q_i$ (TE) | $Q_i$ (TM) | Fab. Method |
|---|---|---|---|---|
| **This Work** | **20 μm** | **500 K** | **20-50 K** | **Bonding** |
| **This Work** | **5 μm** | **250 K** | **-** | **Bonding** |
| M. Lipson, Opt. Exp. **17** (2005). | 100 μm | - | 83 K | Deposition |
| H. Atwater, Appl. Phys. Lett. **94** (2009). | 200 μm | 42 K | 13 K | Bonding |
| L. Pavesi, Opt. Exp. **17**, (2009). | 20 μm | - | 15 K | Deposition |
| H. Tang, Opt. Exp. **18**, (2010). | 100 μm | ~125-175K | - | Deposition |
| L. Kimerling, Opt. Exp. **15**, (2007). | 10 μm | - | 15 K | Deposition |

# Application: Accumulation Modulator

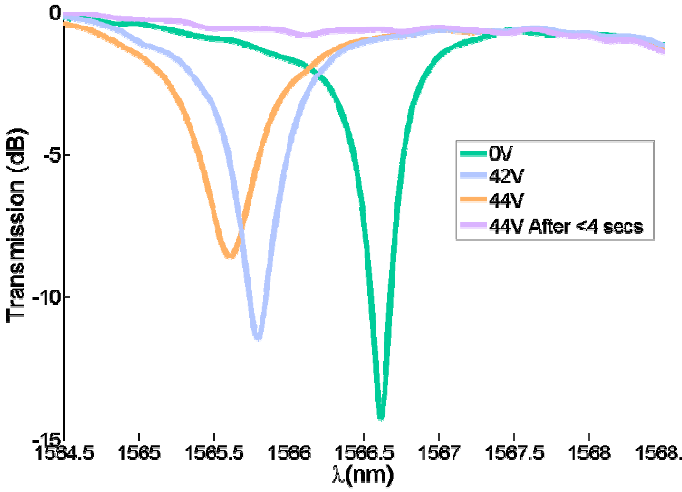
- Capacitive charge accumulation in double-layer Si by an applied voltage results in resonance shift
- High Qs (e.g., 20K) small disks on 50nm pedestal



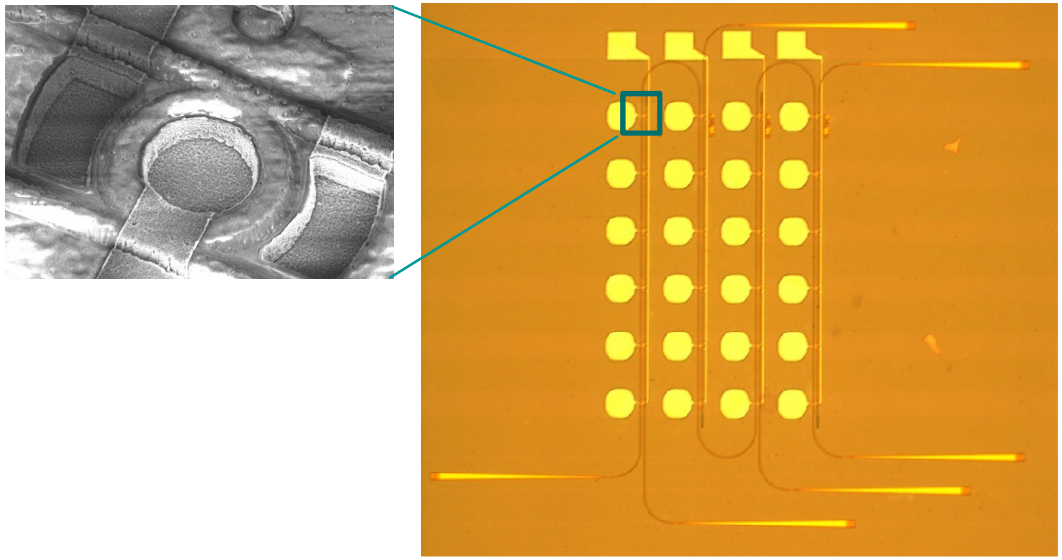



# Application: Field-configurable Devices

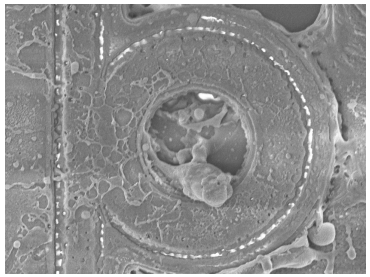
- Applications of 44V proved to be enough to cause breakdown and resonance elimination.
- Optical spectrometer has been fabricated and being tested.



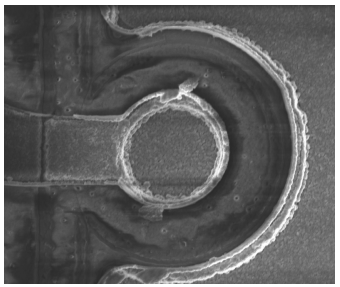

**Optical Spectrometer**

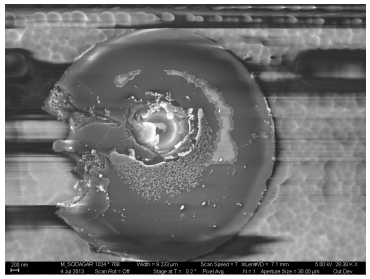


**After breakdown**



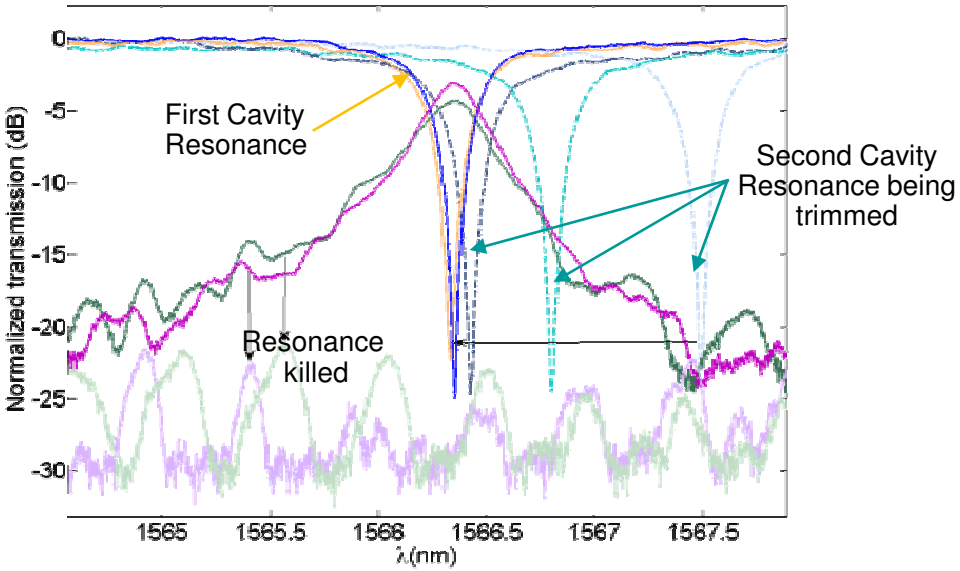
**Before breakdown**



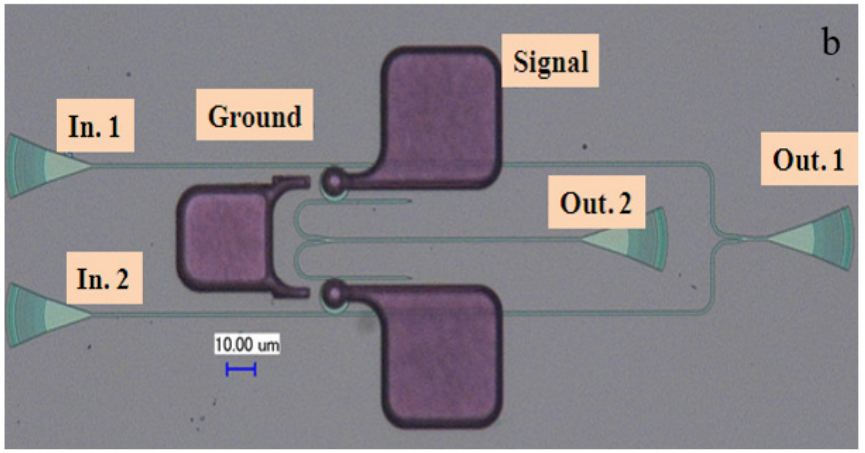


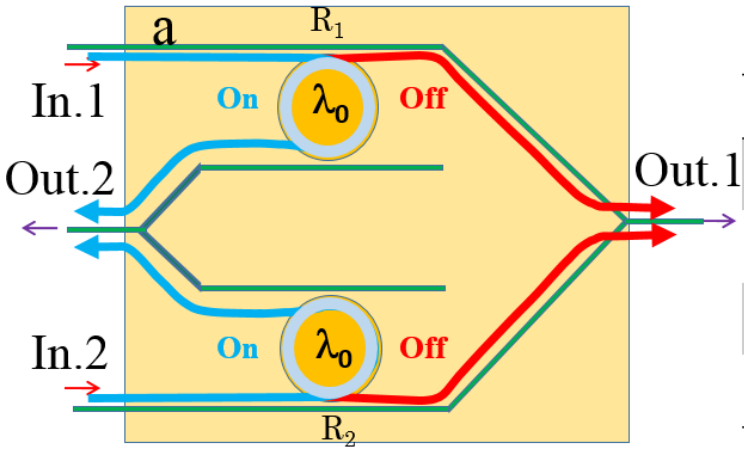
**Damaged Resonator**

# Optical Field Programmable 2X2 Switch




Optical Micrograph



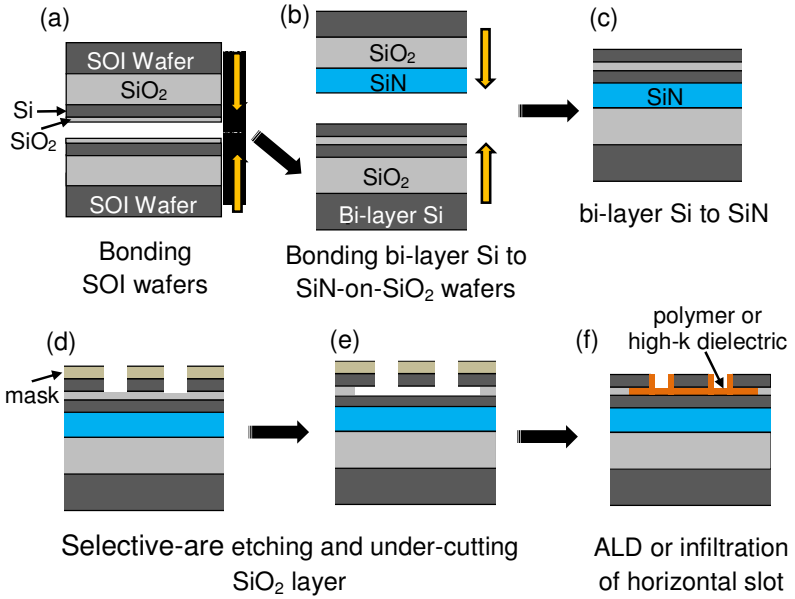



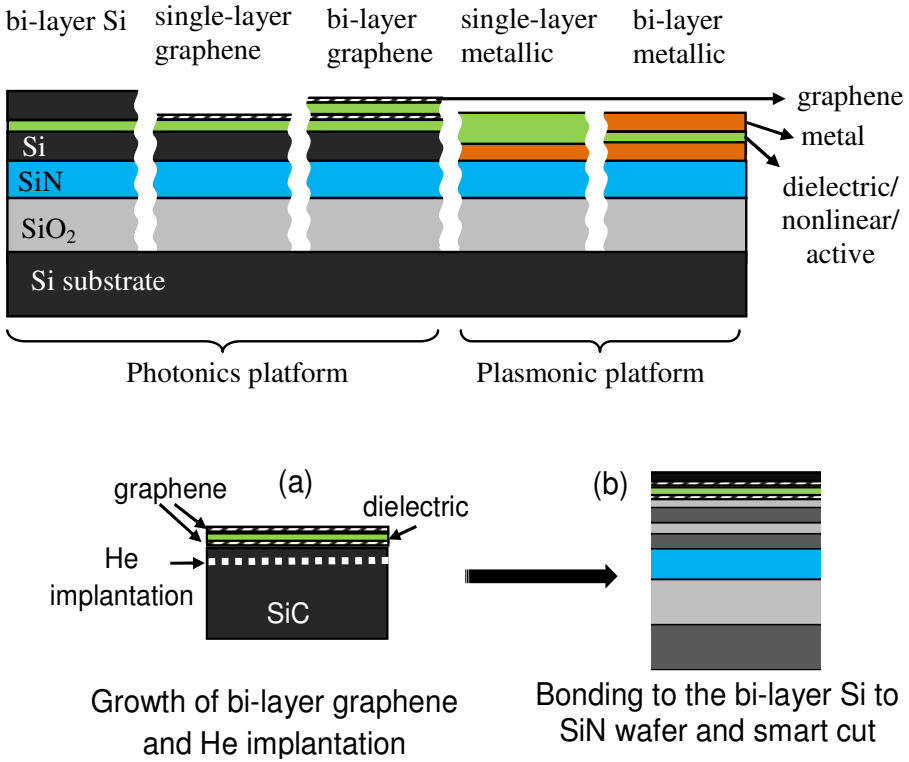

b Operation Table

| Input | $R_1/R_2$ | Output |
|---|---|---|
| In.1 | Off/X | Out.1 |
| In.2 | X/Off | Out.1 |
| In.1 | On/X | Out.2 |
| In.2 | X/On | Out.2 |

# Hybrid Material Platform: Extension

- New hybrid material platforms for hybrid photonic/plasmonic structures
  - Si/SiN as the backbone
  - Thin horizontal slots for polymer incorporation (high field-enhancement)
  - Graphene (ultrafast carrier dynamics) and metal layers (nanostructures)



# Conclusions

- Using high-Q resonators in Si photonics enables the formation of ultra-compact reconfigurable integrated structures.

- The low-power handling and loss issues in Si can be addressed by using a hybrid Si/SiN material platform that results in highest Qs reported to date.

- A multi-layer Si-based structure with a thin horizontal slot allows for the addition of new optical functionalities in a very compact and efficient structure.

# Acknowledgement


- Our colleagues in photonic research group at Georgia Tech
- Funding support from DARPA and AFOSR

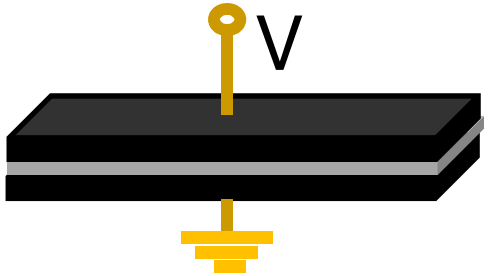


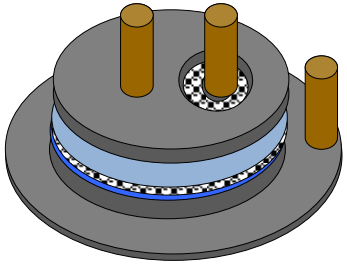


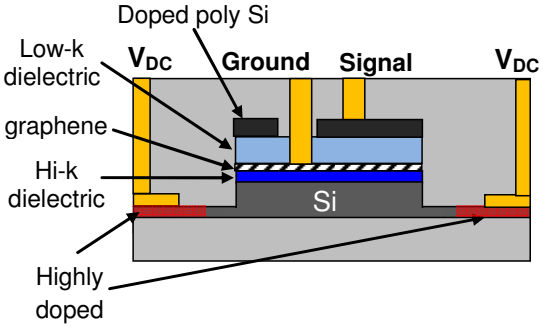


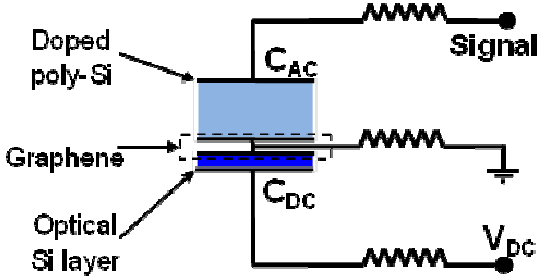
# Graphene-based Optoelectronics

- Very large carrier mobility results in ultra-fast carrier dynamics for ultra-fast devices (e.g., modulators) with very low operating voltages (fraction of 1V) and low power consumption
- Use of multi-layer graphene along with active materials for light generation and detection
- Strong nonlinearity in graphene
- Graphene-based plasmonic devices at mid-IR



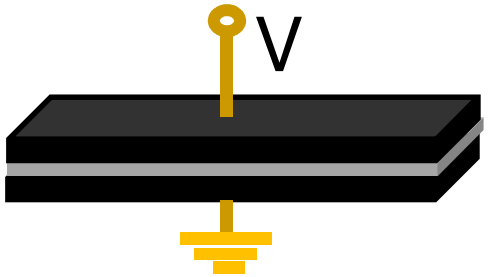



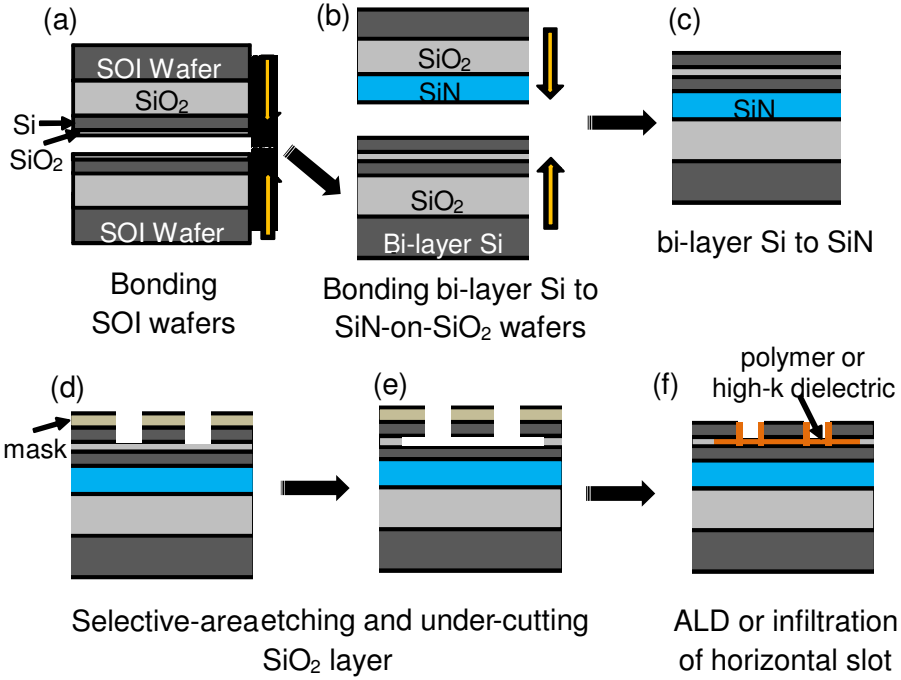


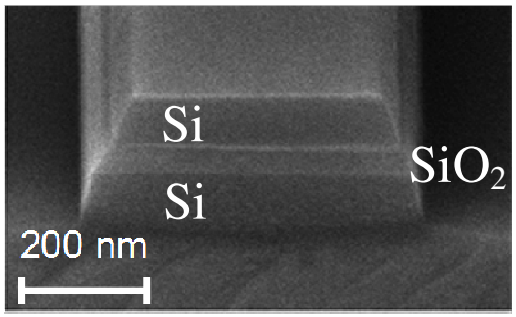



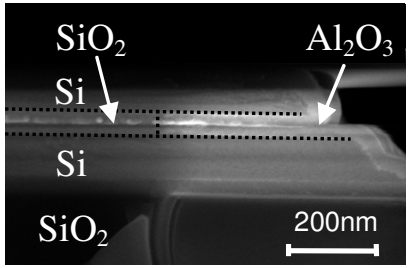
# Hybrid Polymer-infiltrated Integrated Optoelectronics

- Horizontal slots for low-voltage operation
- EO and nonlinear polymer to enable a large range of active devices
- Amplification and light generation by doping with Er



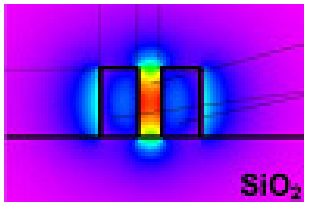



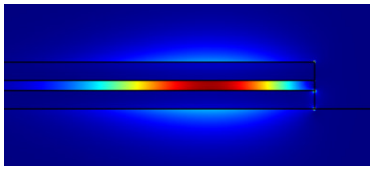



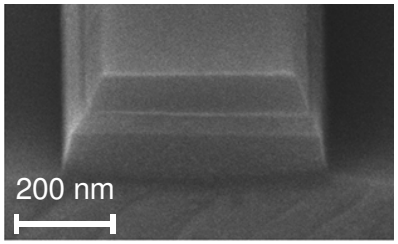
# Hybrid Si-Polymer Modulators

- Electrooptic polymers provide THz modulation bandwidth
- Hybrid Si-polymer modulator are demonstrated using vertical slots
  - Slots provide high field enhancement
  - Shortcoming is high scattering loss because of etched sidewalls → No tangible resonator-based is demonstration yet



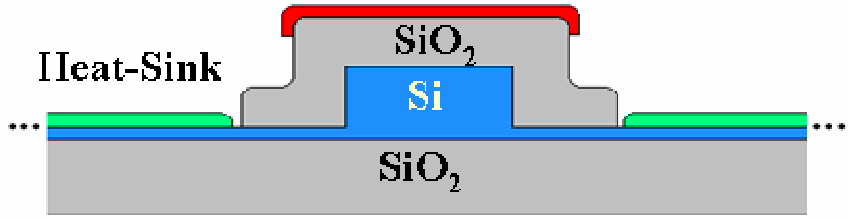
- High quality horizontal slots through wafer-bonding
  - Very low loss because of atomically smooth sidewalls
  - High-Q resonators already demonstrated
    Q ~ $2.4 \times 10^5$ for TM mode

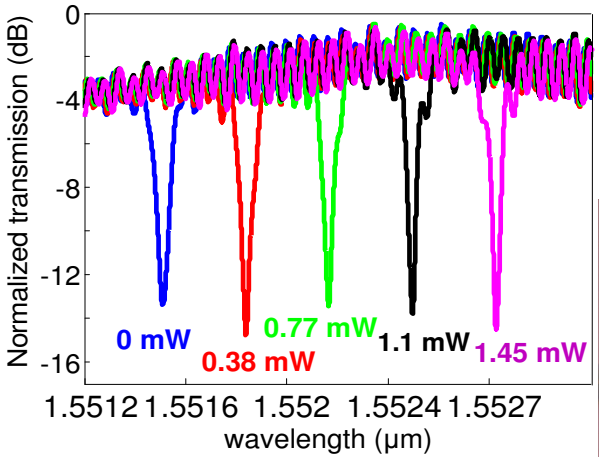


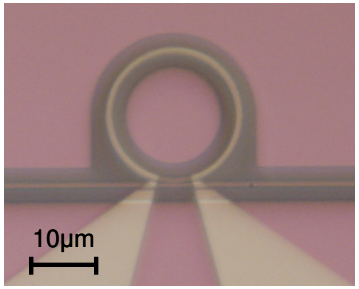

Great possibility for demonstrating modulators

# Thermal Tuning of Optical Devices

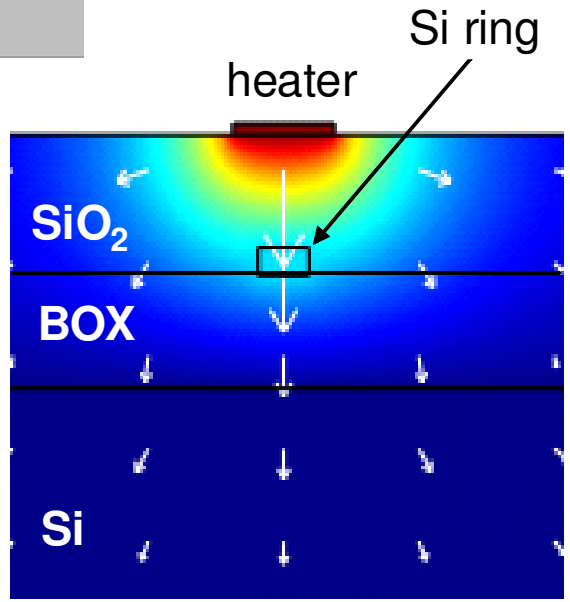
- Low-power tuning (strong thermo-optic effect in Si)
- Extremely low-loss



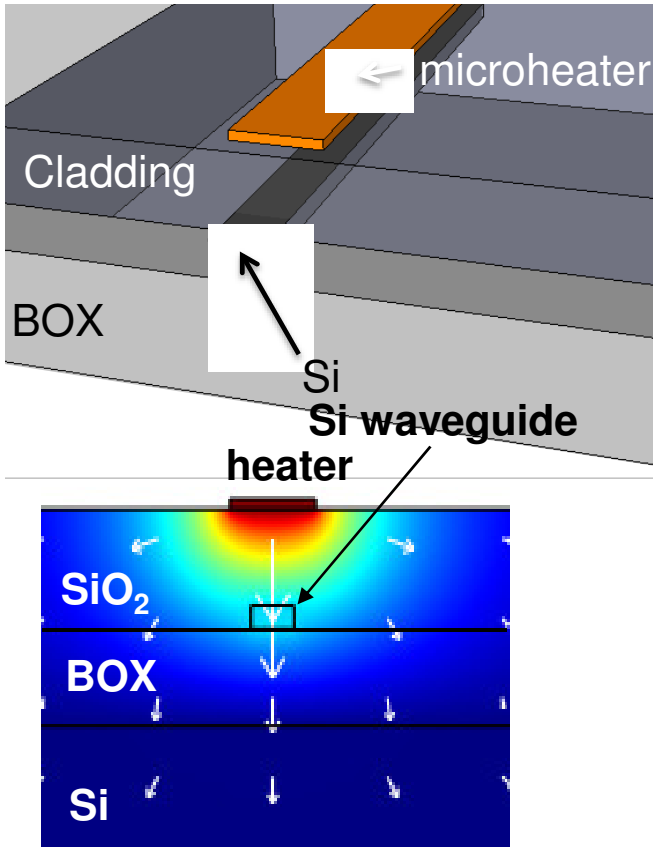

**Δλ/ΔP = 0.247 nm / 1mW / *ring (d=20*μm)**



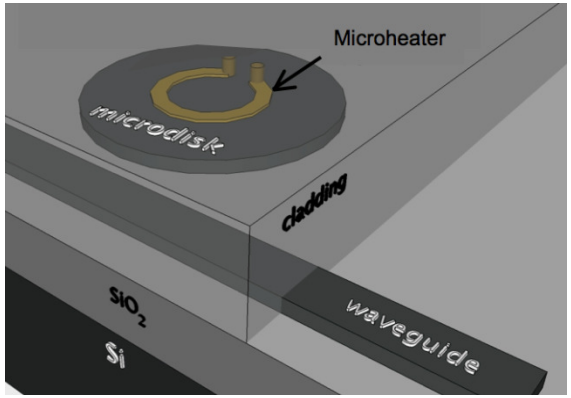

**Temperature distribution at the cross-section of microheater**

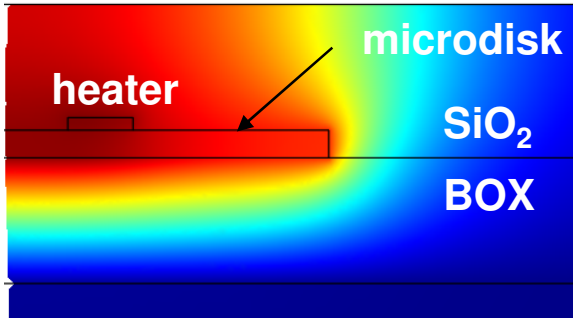
# Architectures for Thermal Tuning

- Thin-film micro-heaters over cladding layer
  - Device optimization
  - Pulsed excitation



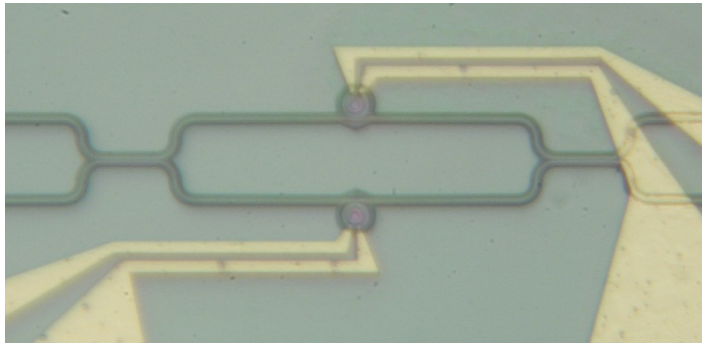

- Thin-film micro-heaters on Si microdisk
  - Possibility to improve reconfiguration speed

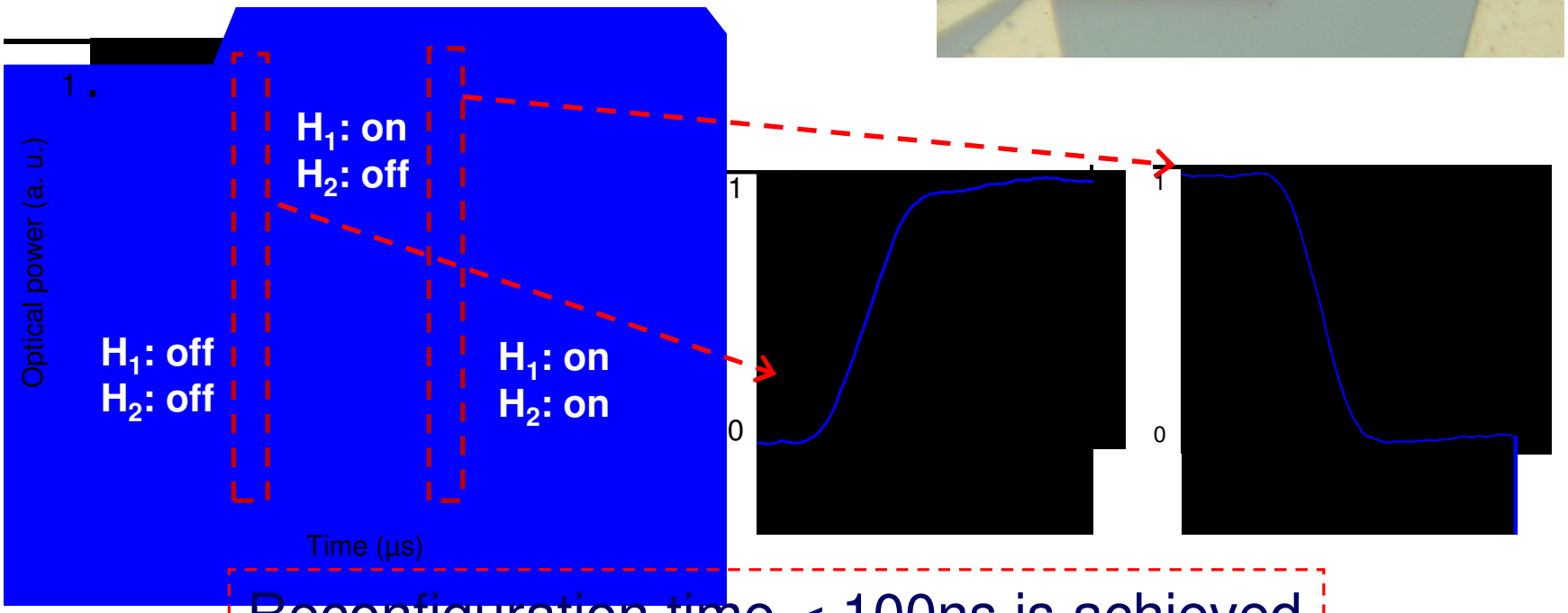


# Differential Microheater Structure

- Fast reconfiguration with differential architecture
  - Low power consumption allows for large dynamic range electronic driver for the phase shifter



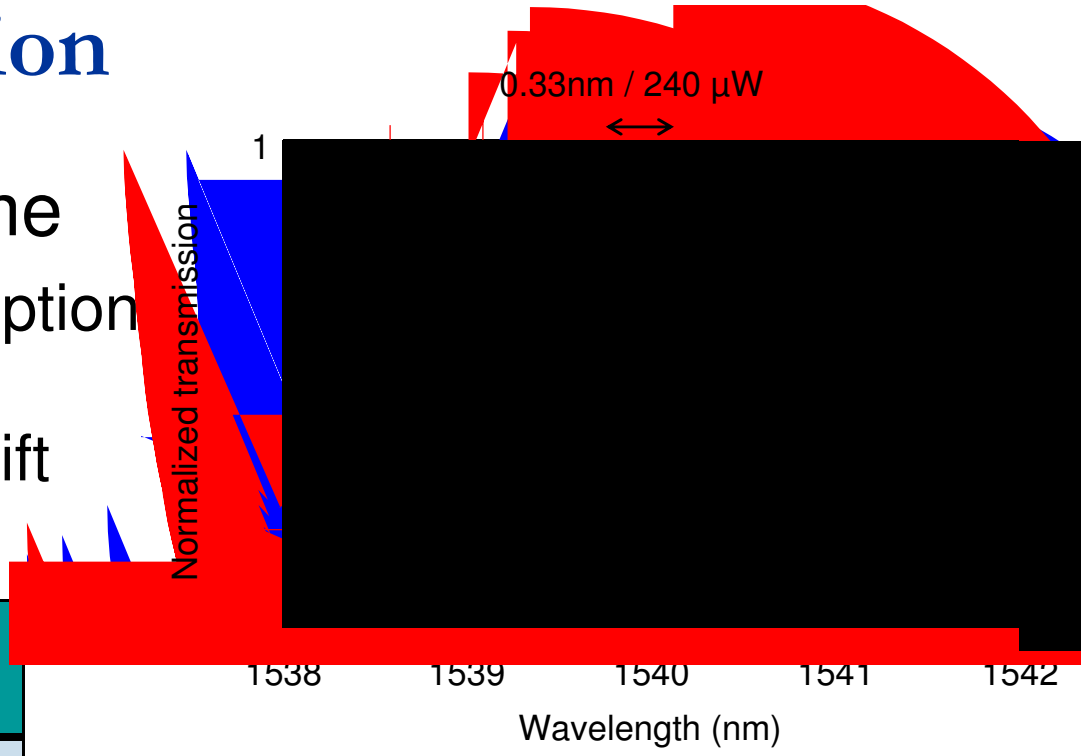



Reconfiguration time < 100ns is achieved

# Power Consumption

- Small heating volume

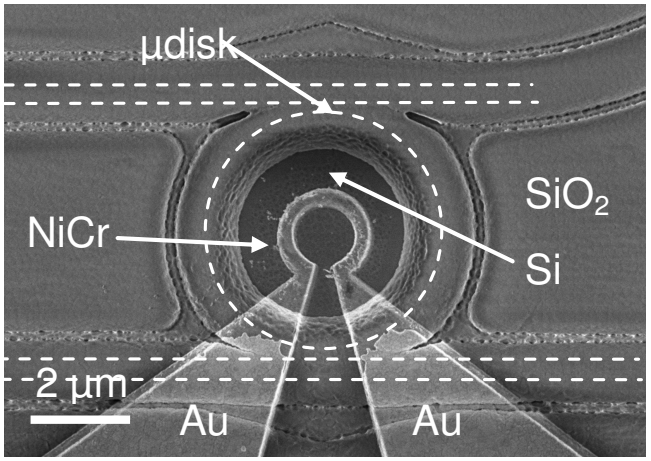
  ⟹ low-power consumption




Resonance frequency shift per mW power on µdisk

| d = 4 µm | d = 5 µm |
|---|---|
| **265 GHz** | **177 GHz** |

- Low-loss phase-shifters with less than 0.36mW per π phase-shift (0.5 nm bandwidth)



# Erbium-doped Lasers for Interconnect

- No practical source exists for optical interconnects
  - Ge laser are not mature
  - Comb sources require high power pump
  - Hybrid III-V are not currently scalable at low cost

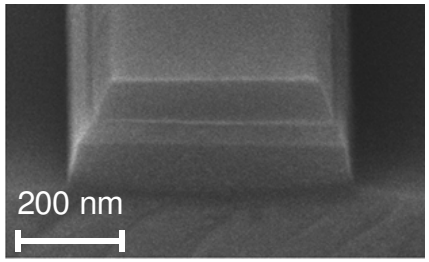
- Er-doped oxides provide electroluminescence in 1.5 μm
  - Excellent candidate for electrically pumped lasers

- Bottleneck of is the low gain (absorption x-section) of $Er^{3+}$
  - Low losses are required for lasing

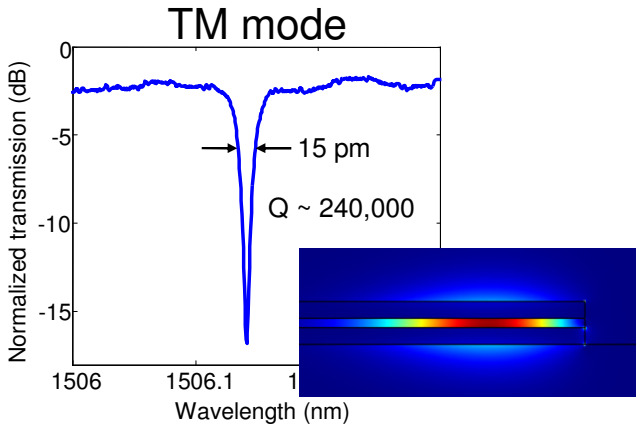
Simple calculations show $Q > 2\text{-}3 \times 10^5$ is required for lasing

# Erbium-doped Lasers for Interconnect

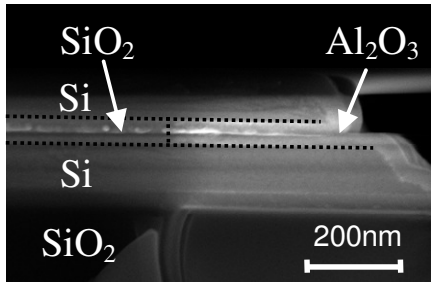
- High quality bi-layer Si is demonstrated using wafer-bonding
  - Q ~ $2.4 \times 10^5$ for TM mode already achieved
  - Thin oxide interface enables electrical pump with $V_{DC}$~10 V (easily achieved using a voltage multiplier circuit in CMOS)




- Possibilities for implementation
  - $Er^{3+}$ doping of oxide before bonding
  - Sol-gel: slot filling after bonding




Slot filling tested on bi-layer Si



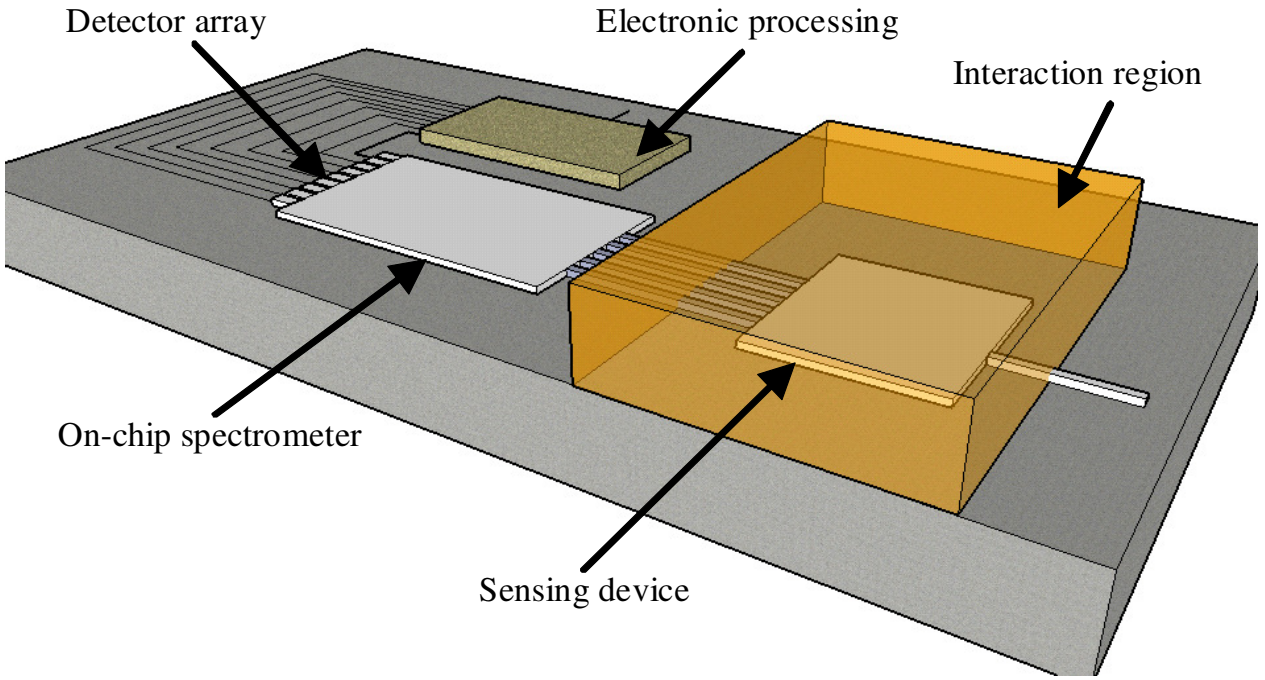

Electrically pumped Er-doped oxide lasers are not far from reach

# Outline

- Introduction and Motivation
- Resonance-based Reconfigurable Structures in Si
- Resonance-based Structures in Hybrid Materials
- Resonance-based Integrated Photonic Sensors
- Conclusions

# Multimodal Multiplex Sensing

- Multimodal: Integration of different sensing modalities, e.g. Refractive index, fluorescence, surfaced enhance Raman
- Multiplexed: Enabling multiple parallel sensing elements responding to different input analyte (through different surface coating)
- Compact: Resonance-based sensing elements, on-chip spectroscopy



# Resonance-based Integrated Photonic Sensors

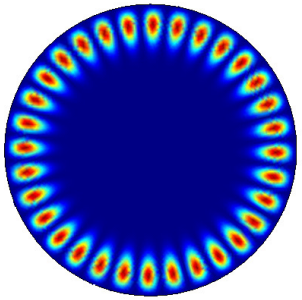
- High Q resonators coated with appropriate materials

**Main properties**

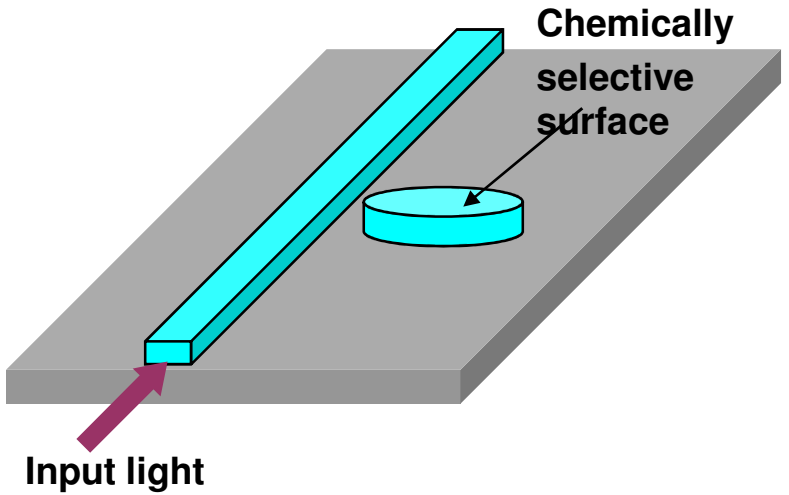
1. Long photon life time
2. Field enhancement

**Main parameters**

1. High Q factor
2. Low mode volume



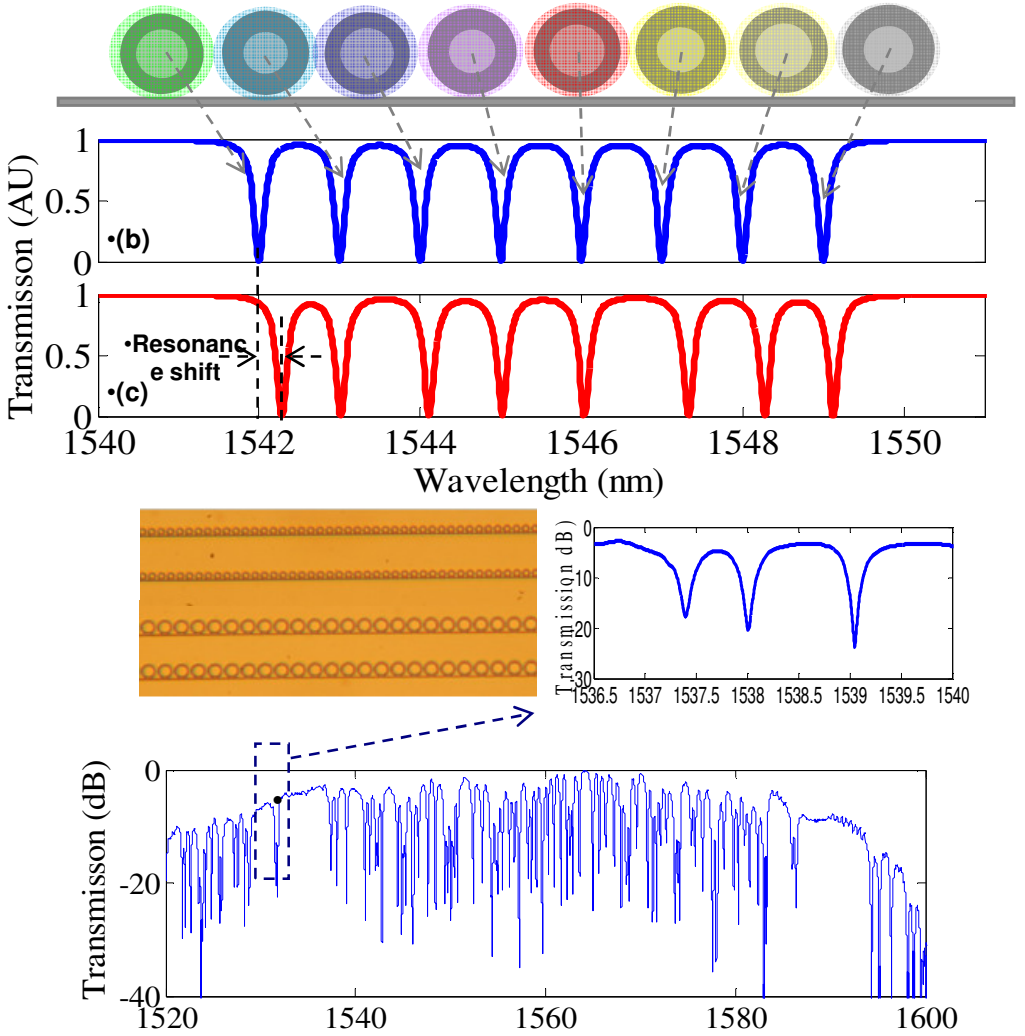
- Advantages
  - Compactness
  - High sensitivity (field enhancement)
  - Minimal amount of specimen requirement
  - Multiplexing capability



# Multiplexed Refractive Index Sensing

- Multiplexed analyte sensing: each device is coated with a separate surface coating
- On-chip reference resonator: differential shift measurement

  → compensate for laser wavelength and thermal variations




**A large number of resonators integrated on-chip for applications such as multiplexed gas sensing**

# Multiplexed Gas Sensing Using Polymer-coated Sensing Elements

- **High sensitivity:**

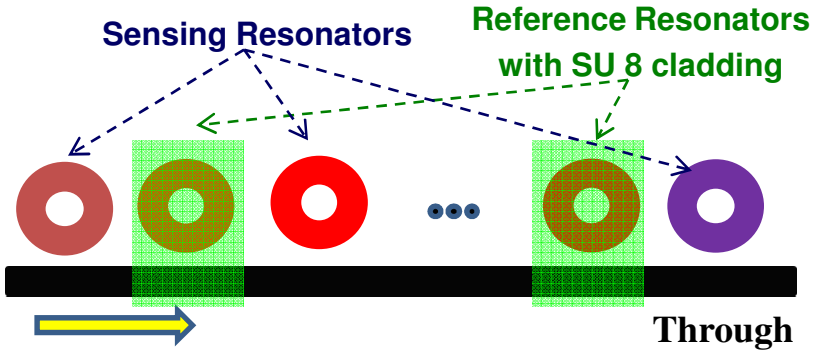
→ Optimized resonator structure

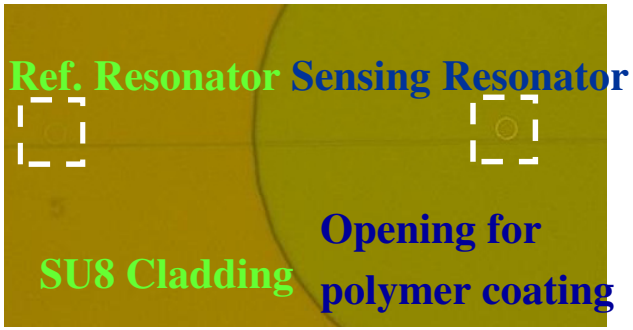
→ On-chip referencing for temperature compensation

- **High specificity:**

→Use a large array of resonators coated with different polymers using inkjet printing

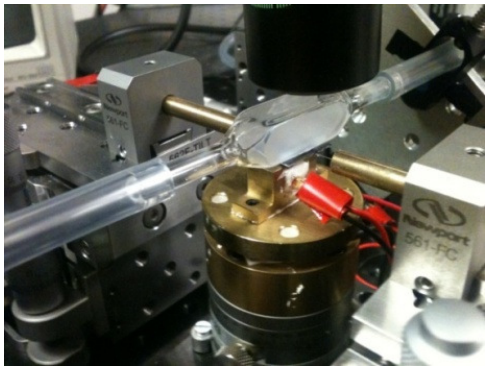
→ Estimate the concentration of each gas based on finding the response Matrix and solve for inverse problem



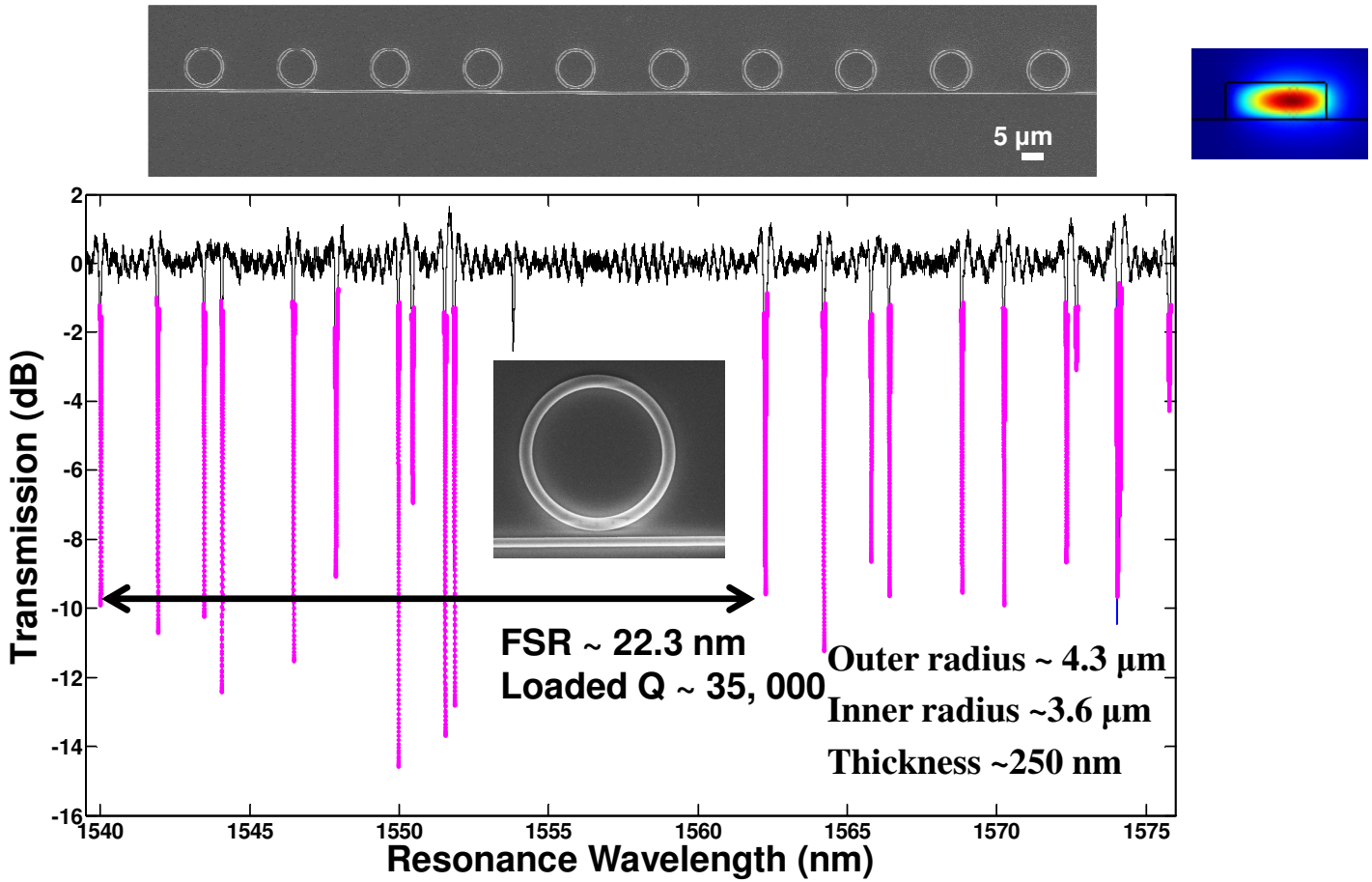




**Response Matrix ($R_{MN}$)**

| | Polymer 1 | Polymer 2 | ... | Polymer N |
|---|---|---|---|---|
| Analyte 1 | $r_{11}$ | | | |
| Analyte 2 | | | | |
| Analyte 3 | | | | |
| Analyte 4 | | | | |
| : | | | | |
| Analyte M | | | | $r_{MN}$ |



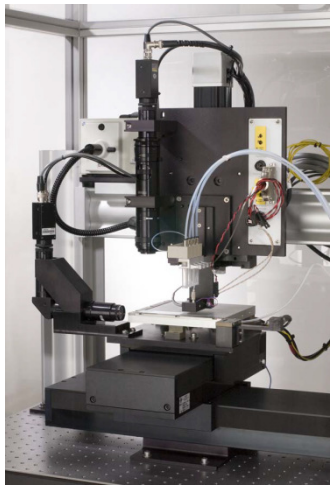
# Multiplexed Gas Sensing using Compact Resonators



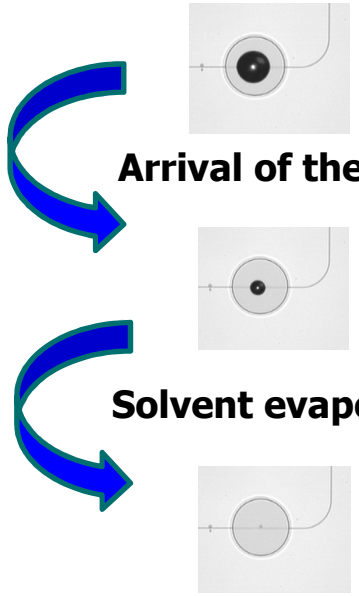

**Transmission of an array of 10 microring resonators under TM polarization**

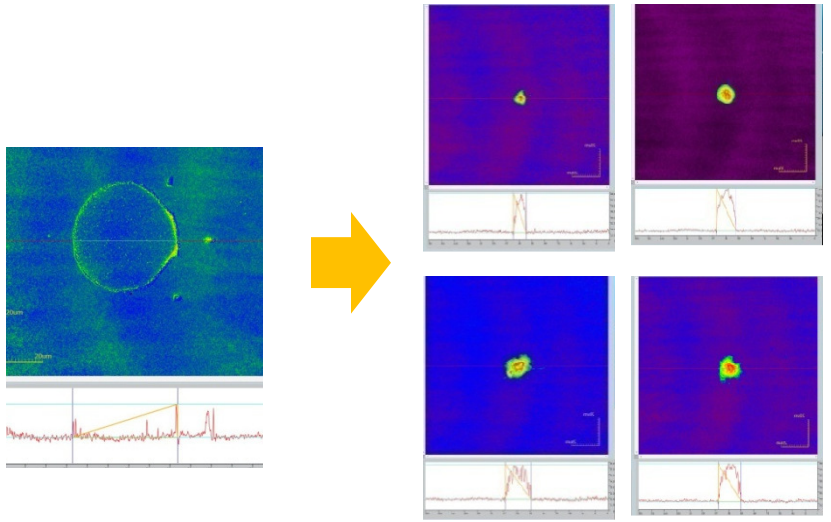
- **High Quality factor (35,000@1550nm) → High detection resolution;**
- **Compact resonator (radius ~ 4.3 μm) → Large free spectral range (FSR)**
- **TM polarization → High sensitivity**

# Selective Coating of Sensing Resonators with Different Polymers



**Jetlab II Inkjet printer**

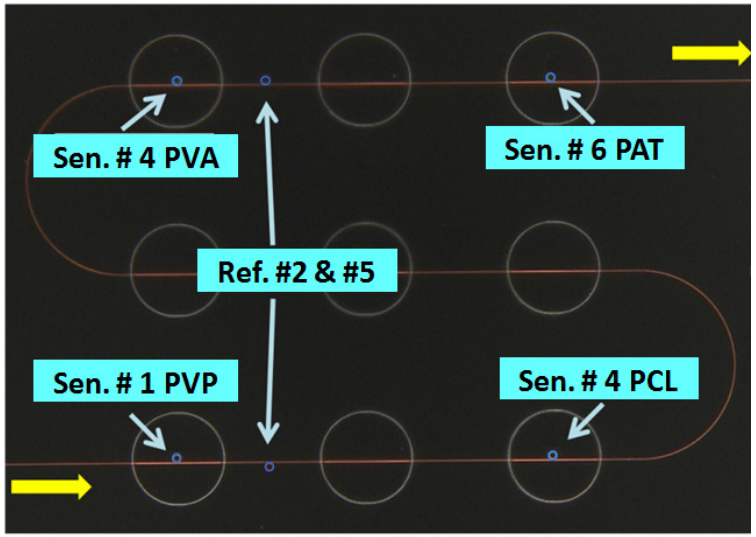


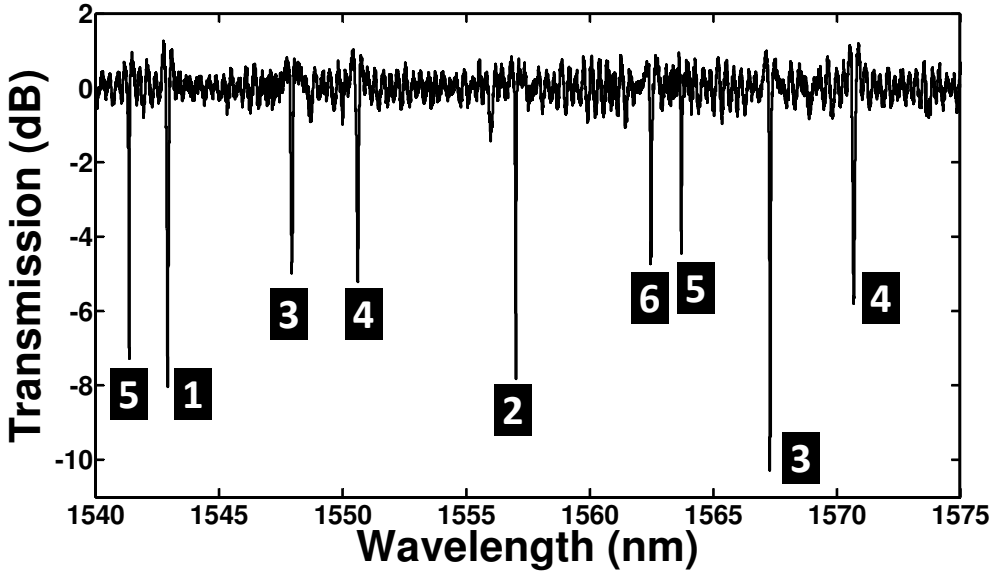



- (left) Coffee stain effect during the solvent evaporation prevents the sensing elements from being reliably covered by polymers;
- (right) Silanization of the surface helps to minimize the adverse effect, leading to better coverage and control of the polymer profile.

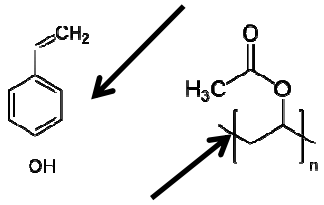
- Well-controlled polymer drop coating can be repeatedly achieved after optimization

# Resonator Array After Polymer Coating




**PVP** Poly(4-vinyl phenol)

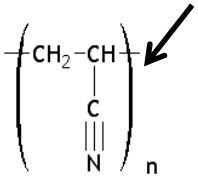


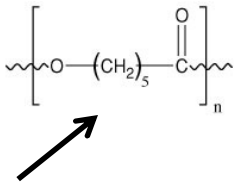




**PVA** Poly(Vinyl acetate)

**PAT** Poly(acrylontrile)

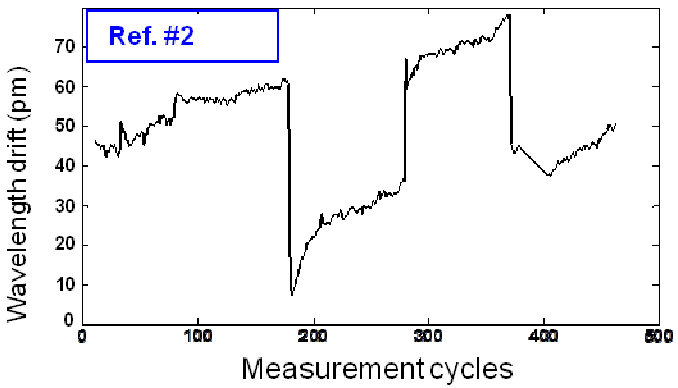


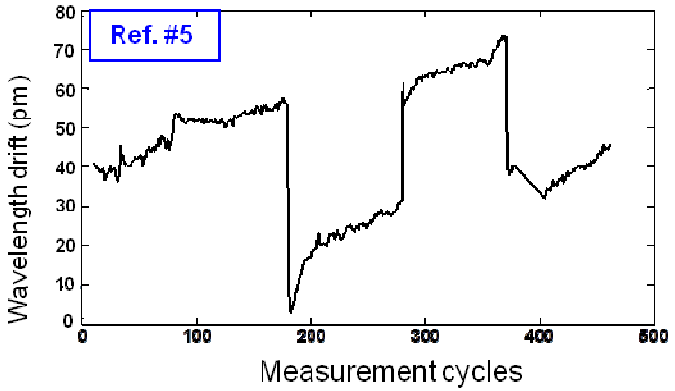



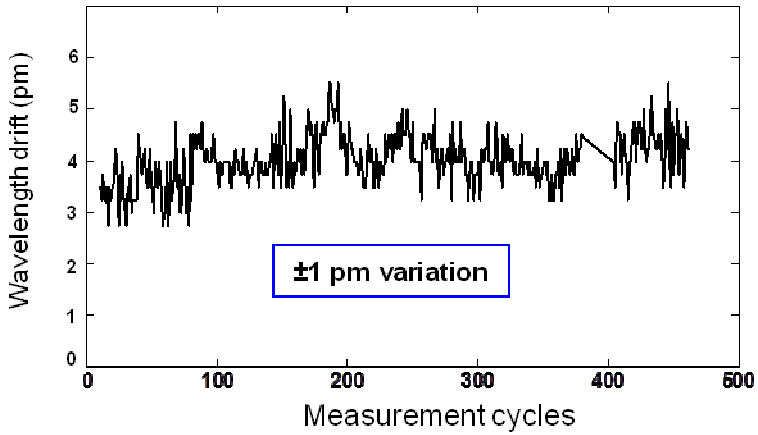

**PCL** Poly (caprolactone)

- Four different polymers are selected to coat the resonators individually.
- The resonances of the sensing elements are first identified in the calibration.
- Resonators #2 and #5 are designed to compensate the adverse environmental effects.

# Sensor Calibration using On-chip Reference Resonators



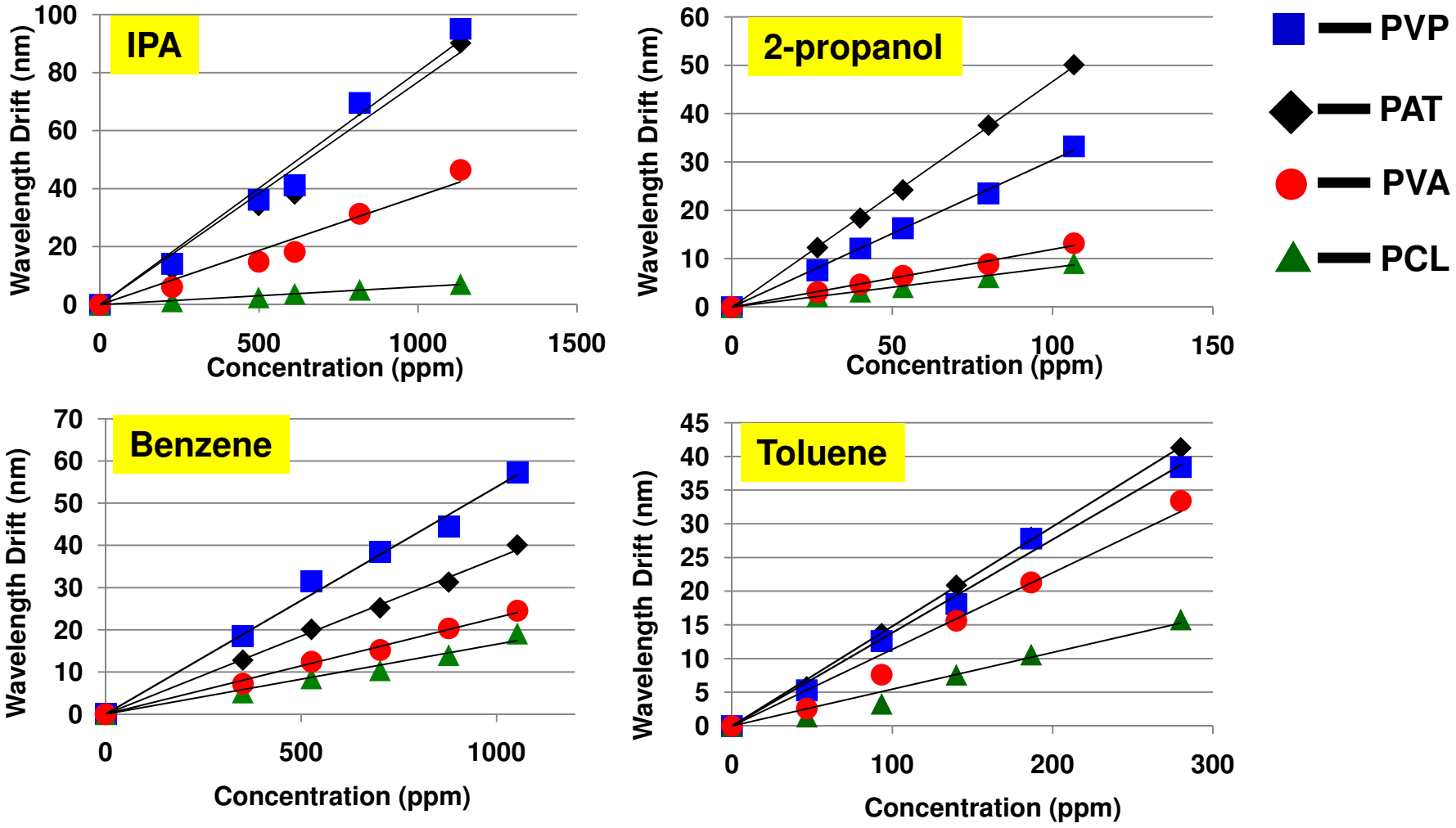




On-chip reference enables to significantly reduces the variation from more than 70 pm to less than 1 pm

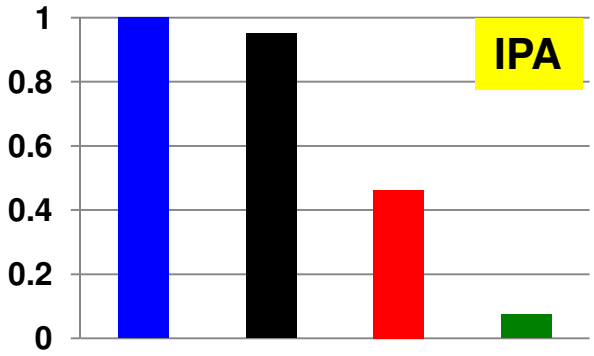
- Differential measurement compensates for laser wavelength and thermal variations.

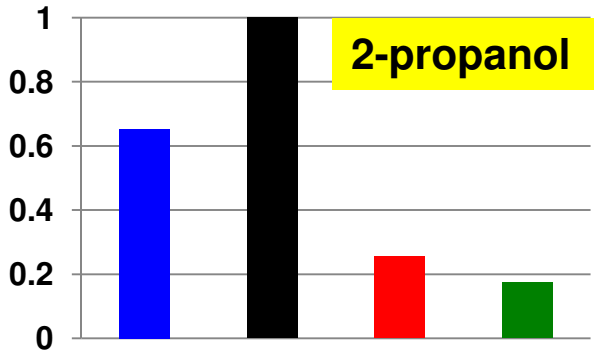
# Gas Sensing Response of Resonator Array

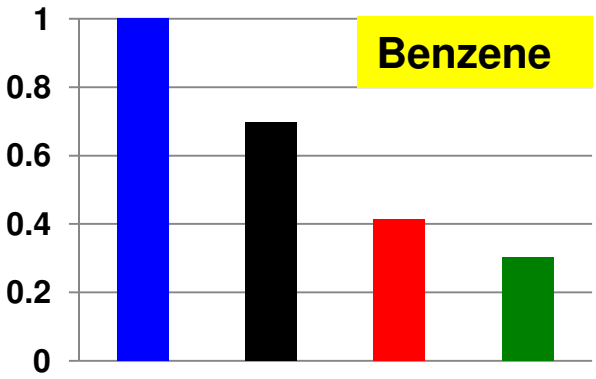


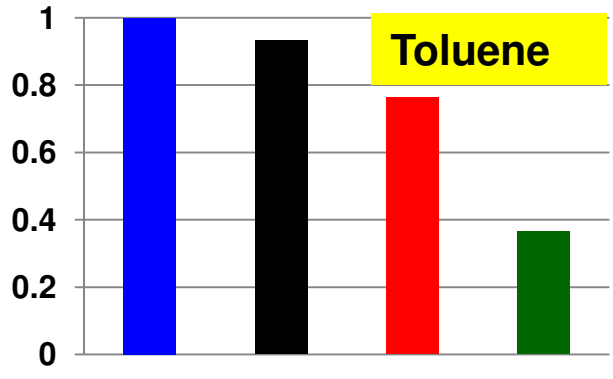

- Good linearity of response is obtained over the concentration range of interest.

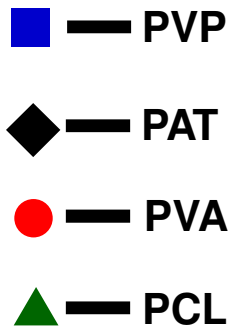
# Diversity and Limit of Detection



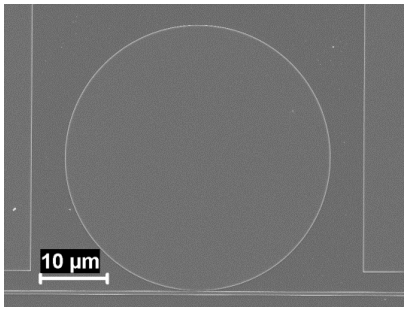



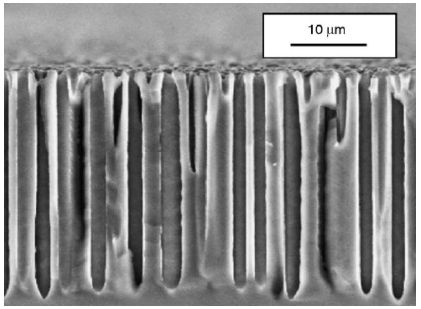

- Good diversity of responses obtained.
- Detection of sub-ppm gas analyte is feasible with sub-pm resolution in wavelength interrogation.

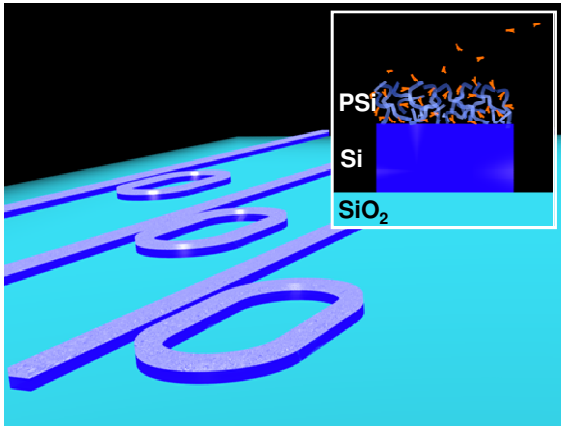
| Detection limit | IPA (ppm) | 2-Propanol (ppm) | Benzene (ppm) | Toluene (ppm) |
|---|---|---|---|---|
| PVP | **12.5** | 3.3 | **18.9** | **6.8** |
| PAT | 13.1 | **2.1** | 27.0 | 7.2 |
| PVA | 27.0 | 8.4 | 45.5 | 8.8 |
| PCL | 166.7 | 12.3 | 62.5 | 18.5 |

Spectral resolution is assumed to be 1 pm.

# Optical Resonators with Porous Si (pSi) Cladding for high sensitivity detection




**SOI optical resonators**

- ✓CMOS compatible
- ✓High integration density
- ✓Low power consumption
- ✓High spectral resolution

**Porous silicon**

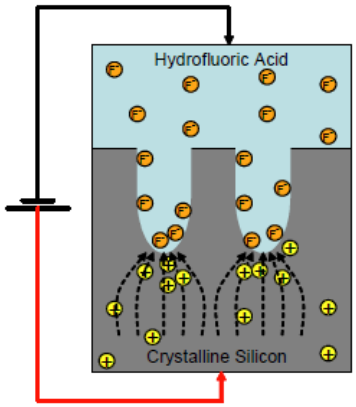
- ✓Large surface to volume ratio
- ✓Mature surface modification
- ✓Increase binding sites for analytes

**Limit of detection = Resolution/Sensitivity**

Combine the best of the two platforms

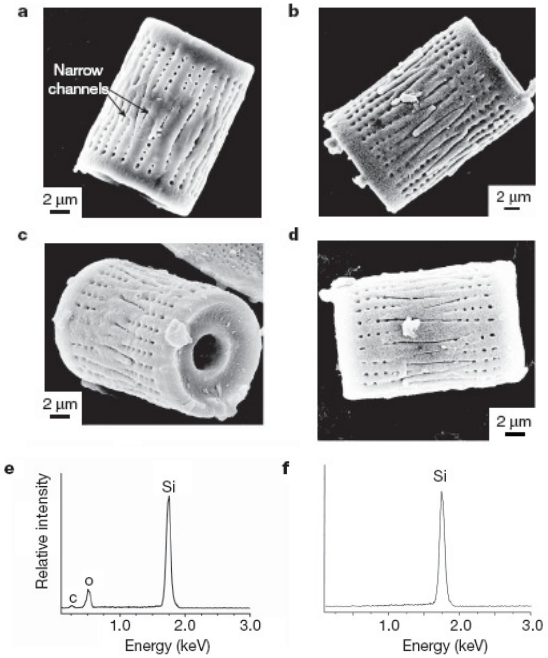
Z. Xia, S. Davis, *et al*, Magnesiothermically-Formed Porous Silicon Thin Films on Silicon-on-Insulator Optical Microresonators for High-Sensitivity Detection, ***Advanced Optical Materials***, In production, 2014

# Magnesiothermic reaction: Oxide to pSi Conversion




## Anodization VS Magnesiothermic reaction

- Conventional anodized pSi is difficult for precise 3D patterning and incompatible with SOI platform
- Optical resonators with multilayer anodized pSi exhibits modest Q-factors (less than 5,000)
- Trade-off between Q-factor and accessibility of multilayer pSi resonator based sensors




**Conversion demonstrated with $SiO_2$ diatom frustules**

a. Silicon dioxide
b. After conversion
c. After HCl
d. After HF
e. EDX - SiO2
f. EDX – Si

Z. Bao, et al, Chemical reduction of three dimensional silica micro assemblies into microrporous silicon replicas, ***Nature***, 446, 172 175, 2007.

**$SiO_2$ converted to Porous Silicon**

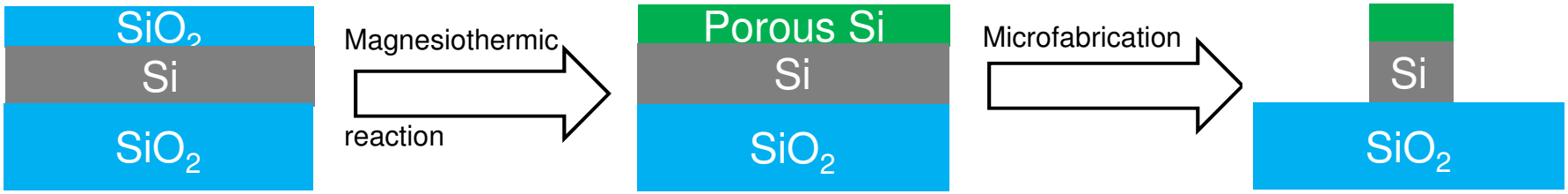
$$2\,Mg(g) + SiO_2(s) \rightarrow 2MgO(s) + Si(s)$$

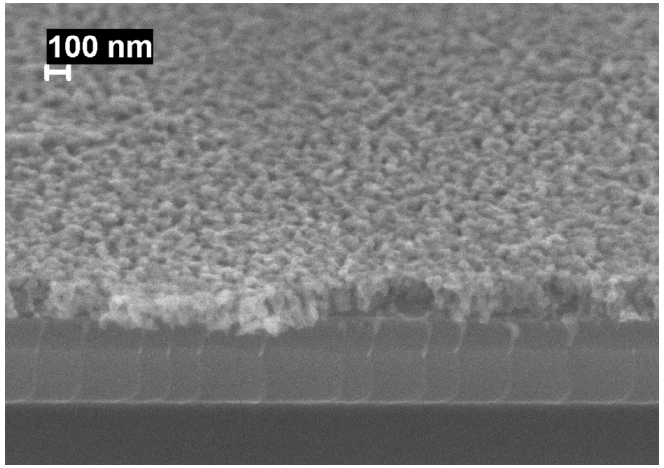
- Shape preserving process that only converts silicon dioxide into pSi

Only one step of conversion is needed to make pSi on an SOI platform

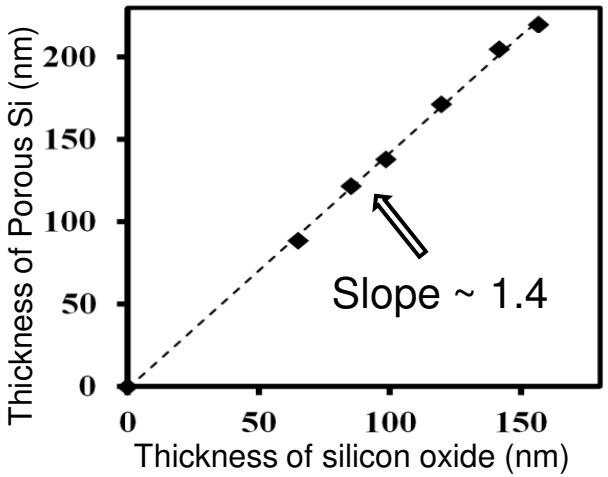
# Fabricating Thin pSi Layers on SOI Platform

**React-then-pattern**



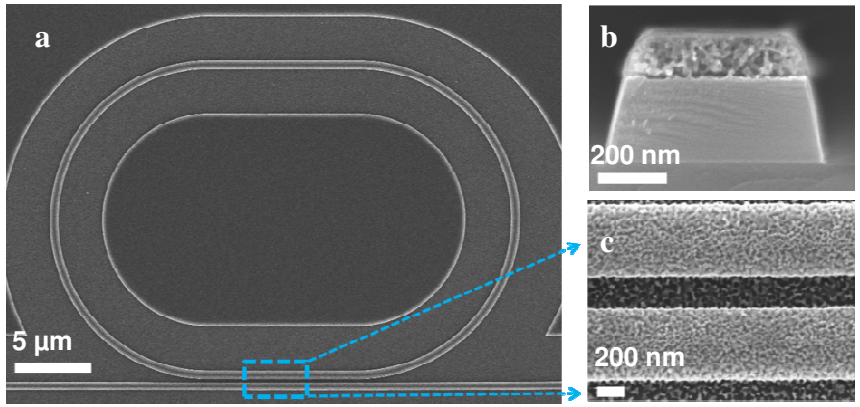

Thin pSi film on SOI substrate



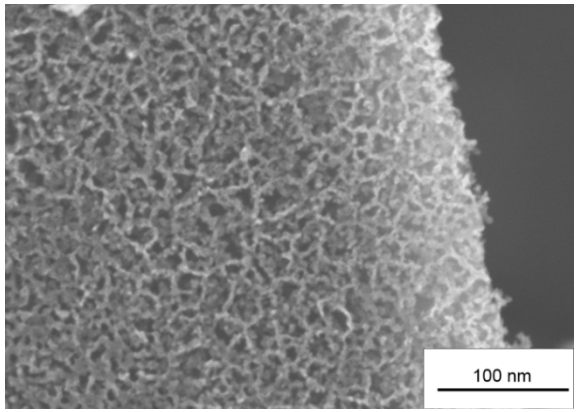

Thickness of magnesiothermically-formed pSi film versus the initial silica film thickness

Controlled fabrication of SOI optical waveguide with pSi films

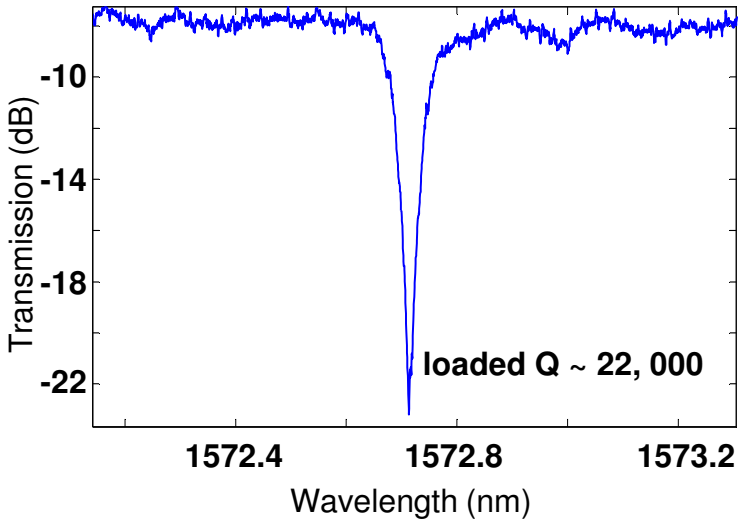
# High Q-factor pSi Cladded Resonator

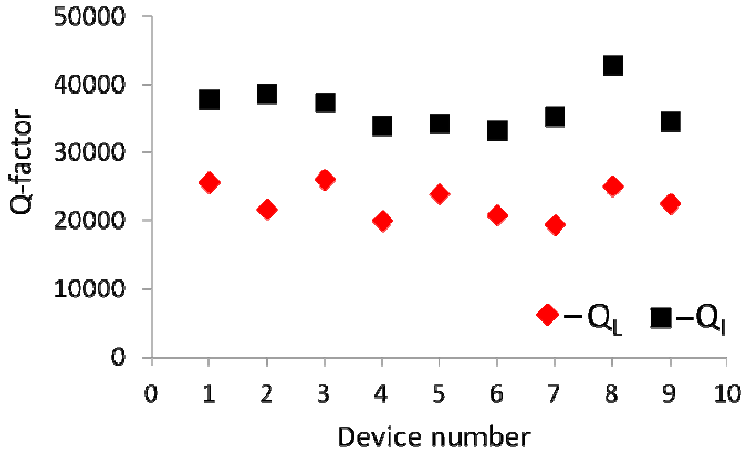



pSi cladded 10 µm radius racetrack resonator




Top-down SEM of pSi film, with an average pore size of ~ 25 nm

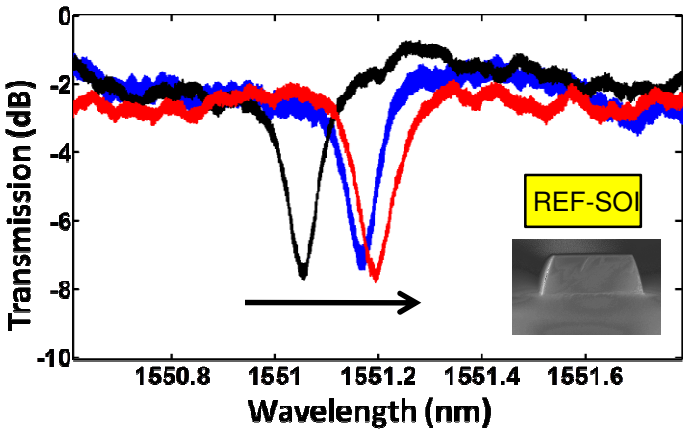


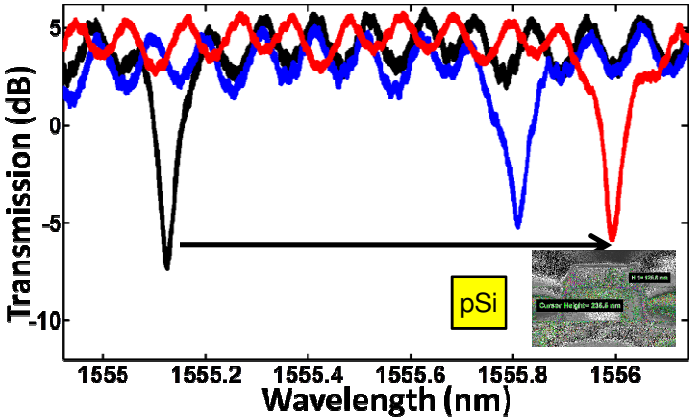




Loaded Q-factor of ~ 22,000 is consistently obtained with pSi cladded resonators

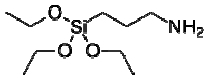
# Enhanced Resonance Shift Sensitivity of pSi-Clad Sensor for Biosensing

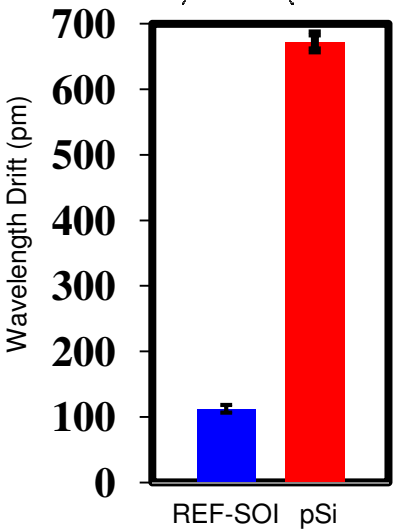
Response of reference and pSi cladded sensors with monolayer APTES (0.9 nm) and NHS-Biotin



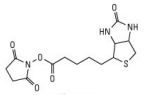



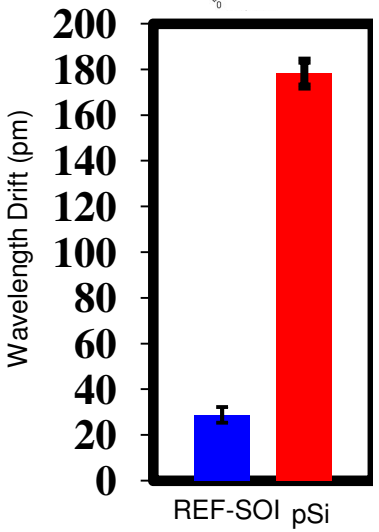

**APTES**




**NHS-Biotin**






REF-SOI: No porous silicon cladding
pSi: With porous silicon cladding

- Sensitivity enhancement of ~ 6 was observed in both cases;
- Areal mass sensitivity is ~ 0.8 pm/(pg/mm$^2$);
- With 1 pm spectral resolution, the estimated areal mass density LOD is ~ 1 pg/mm$^2$, an order of magnitude better than other anodization-based pSi sensors.

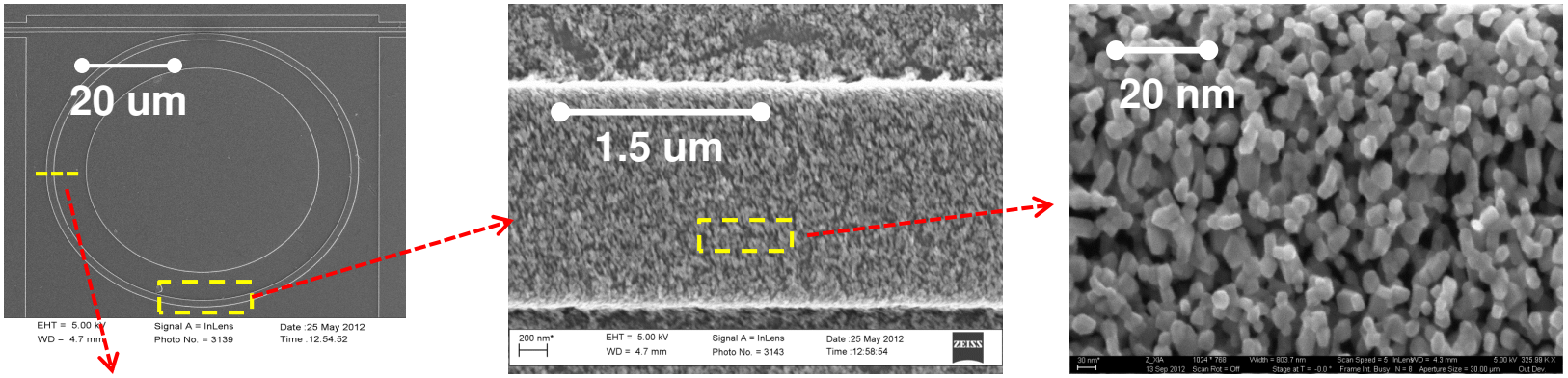

Z. Xia, S. Davis, *et al*, Magnesiothermically-Formed Porous Silicon Thin Films on Silicon-on-Insulator Optical Microresonators for High-Sensitivity Detection, ***Advanced Optical Materials***, In production, 2014

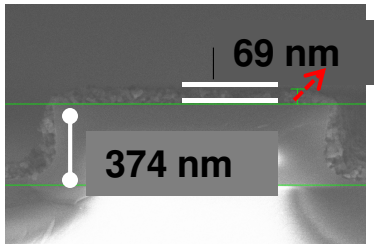
# Porous $TiO_2$ on Silicon Nitride

- Motivation – large surface area, good thermal stability, and available from visible to IR wavelength range;
- Fabrication – Pattern and React

  Step 1: SiN device is patterned

  Step 2: TiO2 coating by Protamine-Polymer Spheres (26 nm) Method

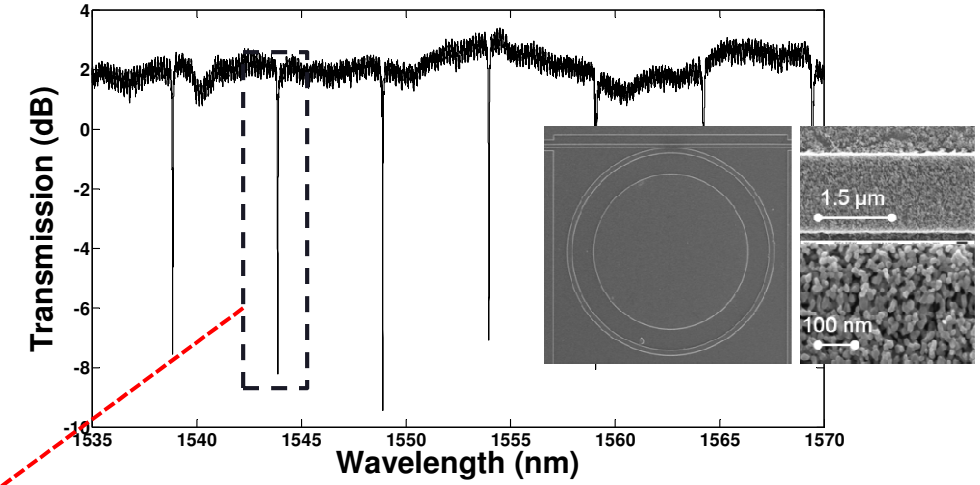


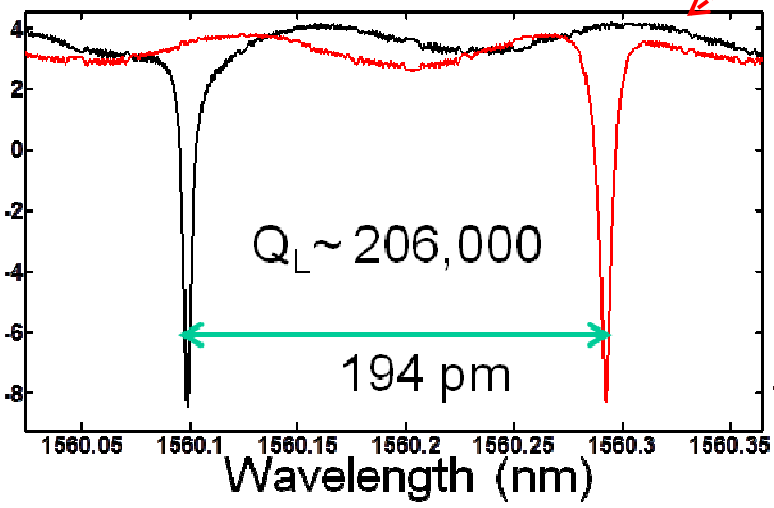



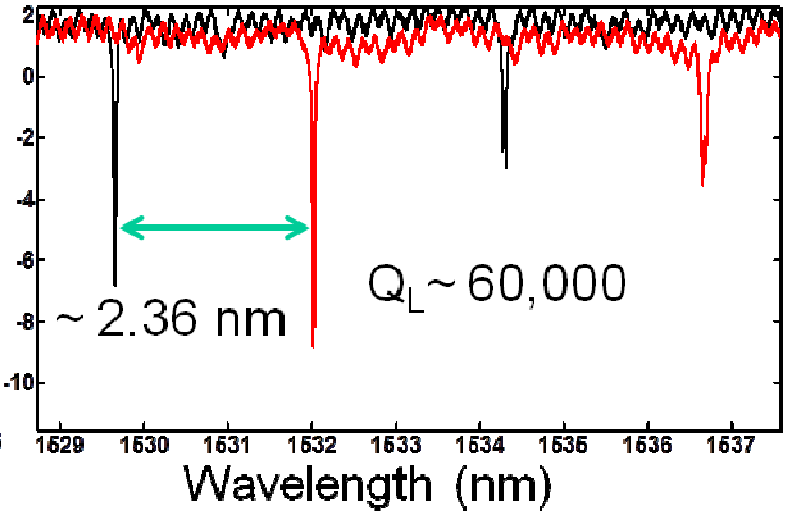

**P-$TiO_2$ on SiN waveguide, $TiO_2$ is pretty dense and uniform**

# Porous $TiO_2$ on Silicon Nitride Biosensors

- Demonstration of improved sensitivity by coating the sensor surface with APTES
- Large resonance shift sensitivity is observed



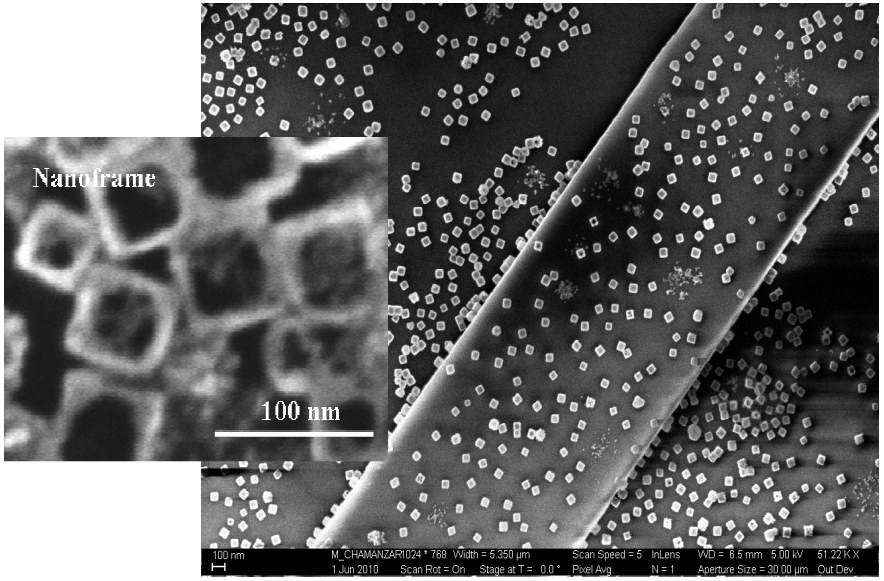




**Sensitivity enhancement factor of ~ 12 is observed experimentally.**

# Hybrid Plasmonic-Photonic Structures for On-Chip Sensing Using LSPR and SERS

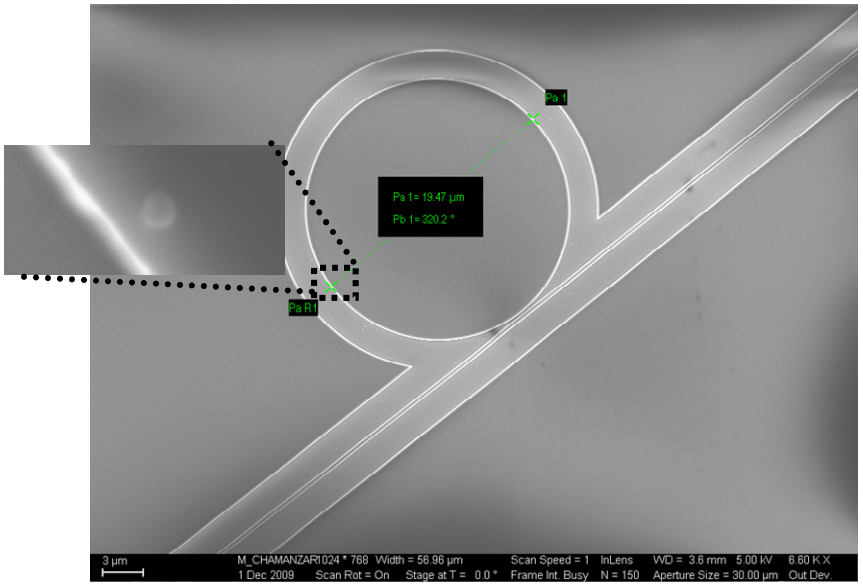
- Hybrid photonic-plasmonic resonators: Nanoparticles on SiN
- Combining the best of photonics and plasmonics
- Novel hollow-core nanoparticles such as AuNC/AuNF with the largest field enhancements.
- Implementations:

Chemically synthesized nanoparticles




× Random locations and orientations !

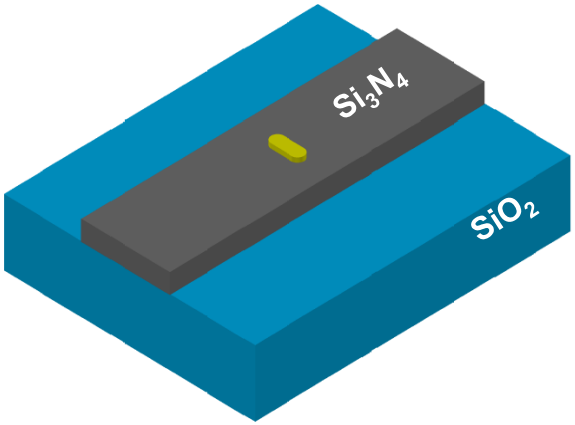
Lithographically patterned nanoparticles

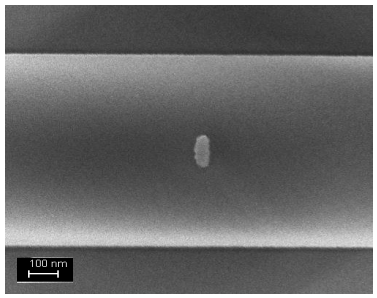


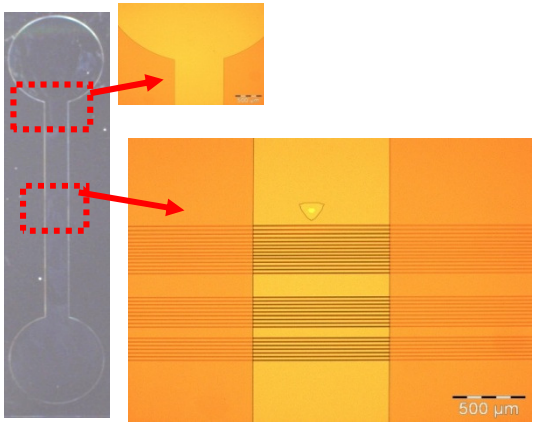

× Not suitable for hollow-core nanoparticles !

# Hybrid Waveguides for LSPR Sensing

- SiN ridge waveguide coupled to a plasmonic nanoresonator



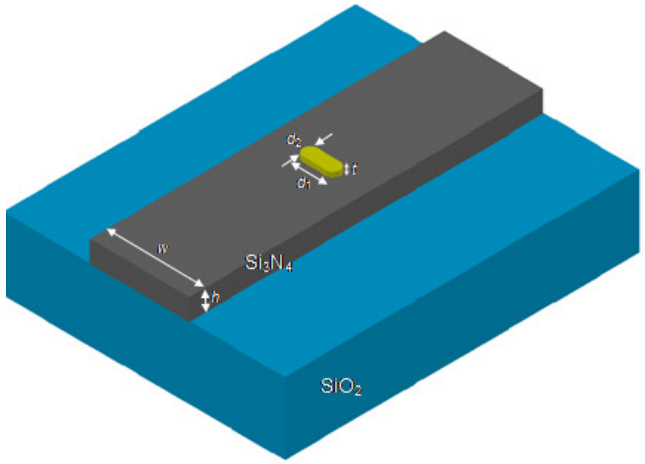



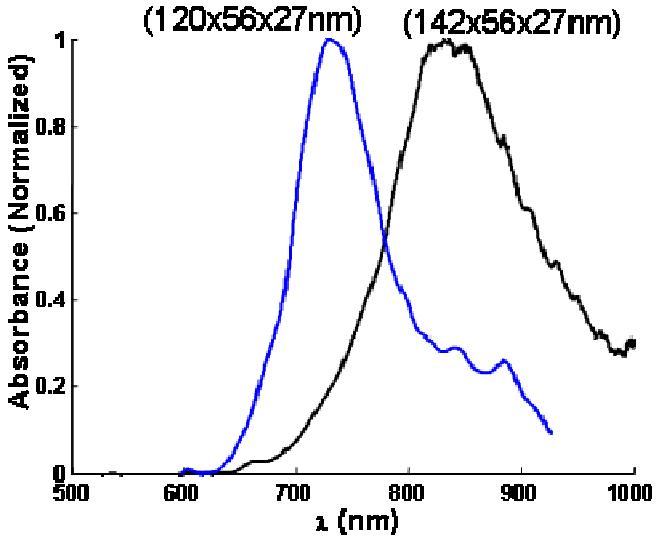




- Very efficient
- Fast
- Robust
- Ultra-compact
- Large SNR
- Very large sensitivity

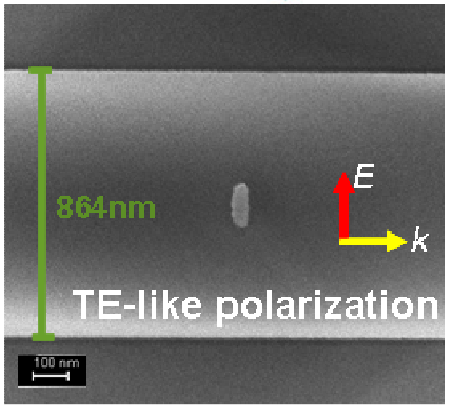
•Multiplexed sensing (parallel array of nanoparticles)
•Dense integration
•Point-of-care diagnostics
•Single nanoparticle studies

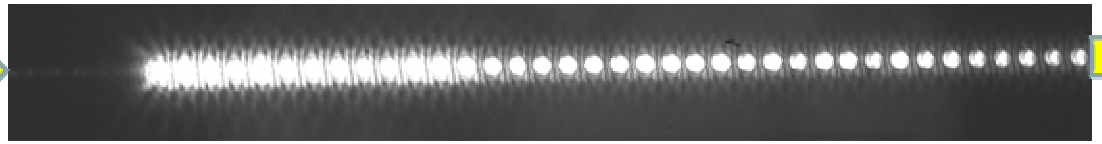
# Integrated Plasmonic-Photonic LSPR Sensing



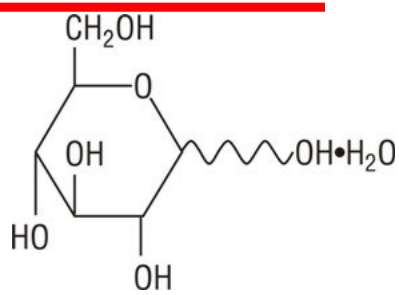

$$Absorbance = -10\log\left(\frac{Trans(Sample) - BKGND}{Trans(ref) - BKGND}\right)$$

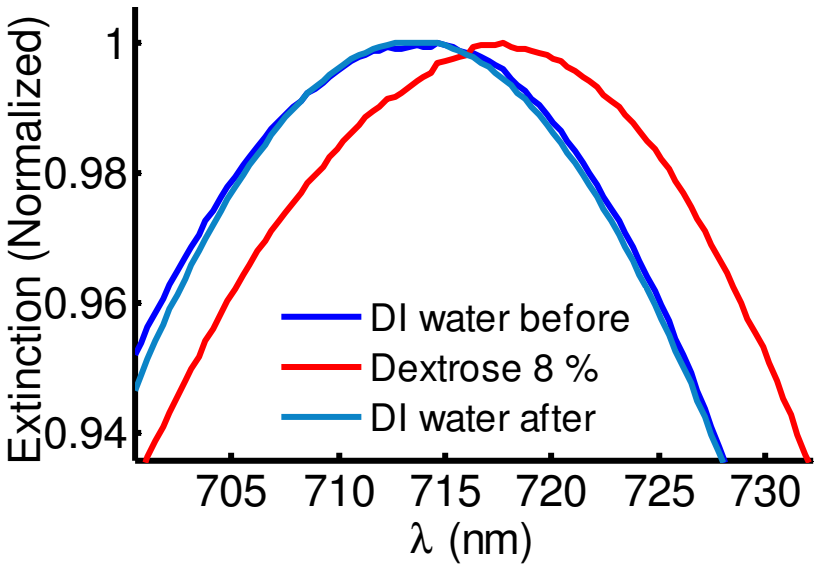


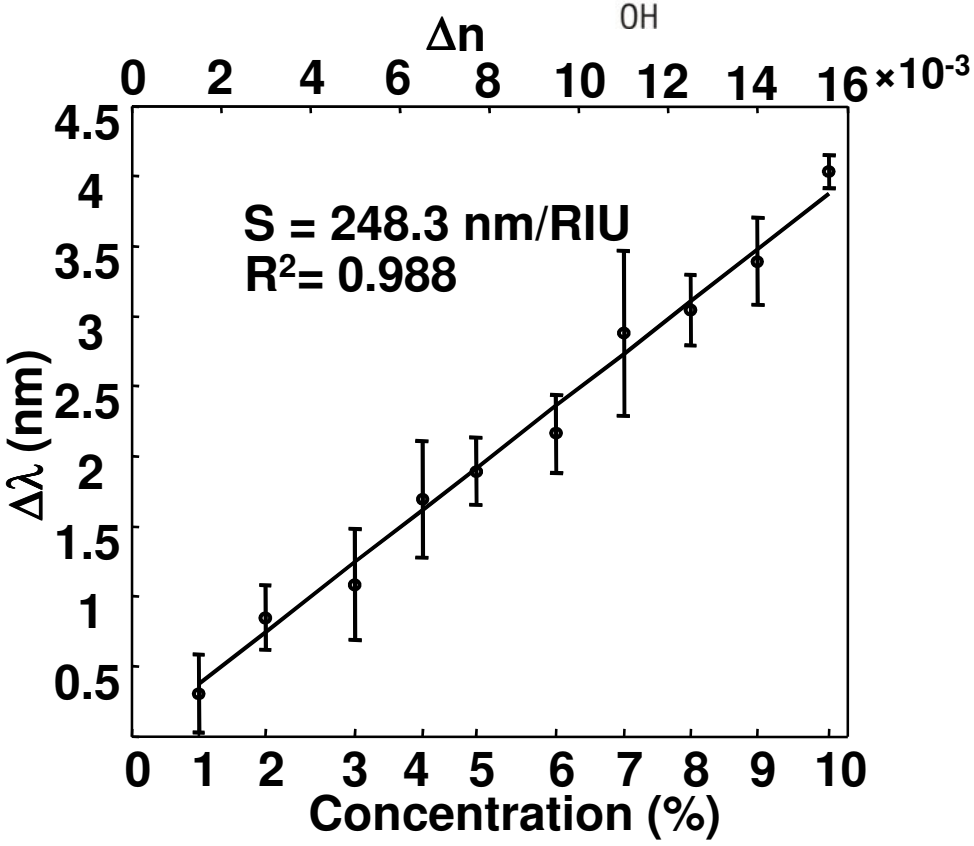
- Excitation: (500nm-1700nm), -54dBm/nm
- Only 1 sec integration time
- Spectrometer Ocean Optics USB 2000+ @ room temperature

# Dextrose Sensing Results



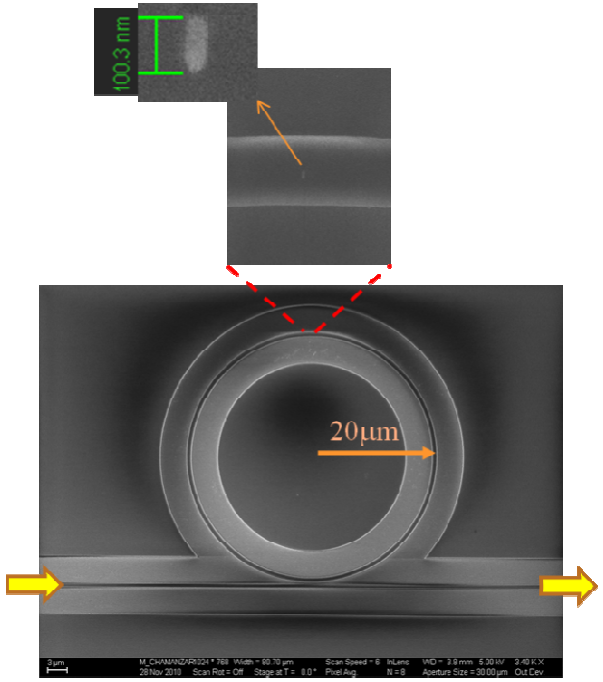

**~3 nm Shift**

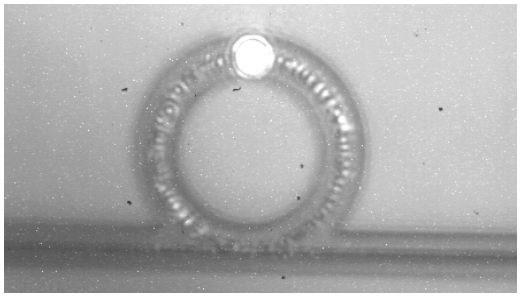



- Large sensitivity ~250 nm/RIU
- Reversible
- Coupling Efficiency (w/ water): ~8.1% to individual gold nanorods
- SNR~24 dB
- DL ~ 0.75% concentration, limited by the spectrometer resolution

# Hybrid Plasmonic-Photonic Resonators

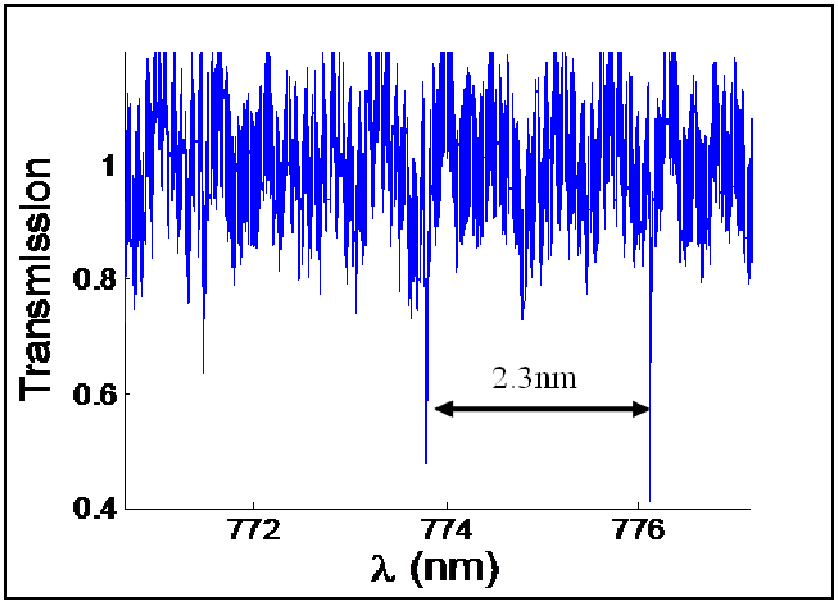
- Large field enhancement on a chip



**Excitation $\lambda_0$=773.77 nm**

Microring-nanorod (100.3x56x30nm) resonator

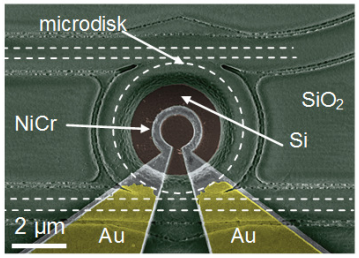



- ~ 10% coupling efficiency to a single nanoresonator !

- Large coupling efficiency
- Large field enhancement
- Possibility of on-chip SERS at very low input powers

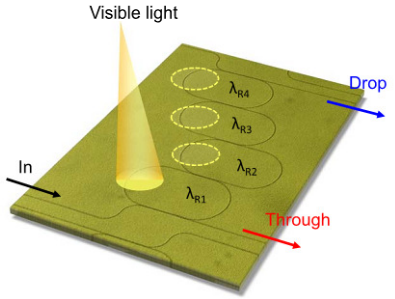
# Compensation of Random Variations in Si Photonic Devices using Post Fabrication Trimming

- **Problem:** High sensitivity of optical devices to dimensional variations: Better than 1nm dimensional accuracy is needed
- Limited by: Lithography and fabrication variations, and Wafer-scale Si thickness variation

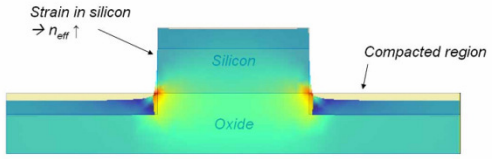



**Atabaki *et al,* CTuE7, CLEO 2010**

- **Solutions**
- Active tuning: Applying heat using microheaters
  - Challenges: Number of required controls, power consumption
- Permanent post-fabrication trimming (PFT)
  - Previous demonstrations
    - Modifying stress and strain of core/cladding
    - Irradiating photo-sensitive cladding
  - Need for high accuracy and high throughput practical PFT



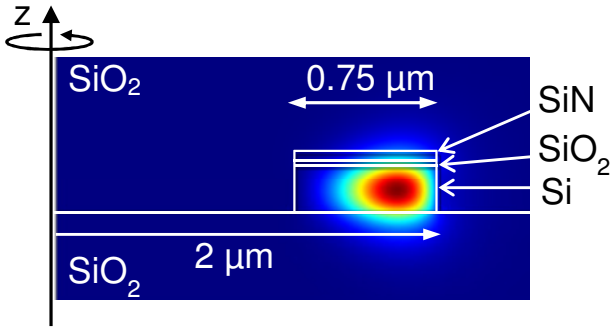

**A. Canciamilla *et al,* Opt. Lett. 32 2011.**

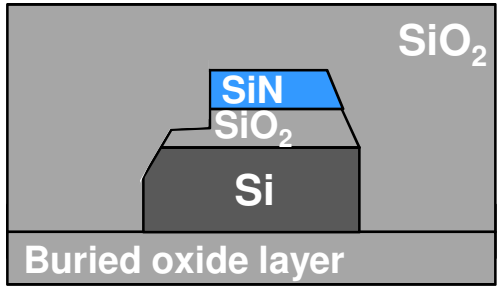



**J. Schrauwen *et al,* Opt. Express. 16 2008.**

# Post-Fabrication Trimming through Multi-layer Structures

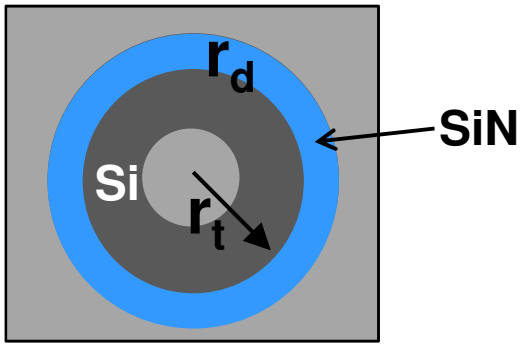
- Use a thin trimming layer: Less sensitivity to lithography variations
- Etching SiN in less sensitive area



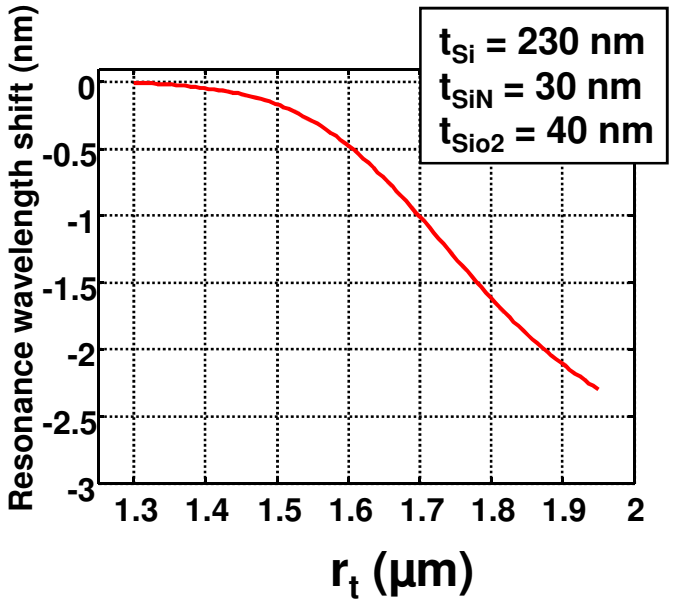




**Cross-section of the device**

- Simulation of resonance wavelength shift

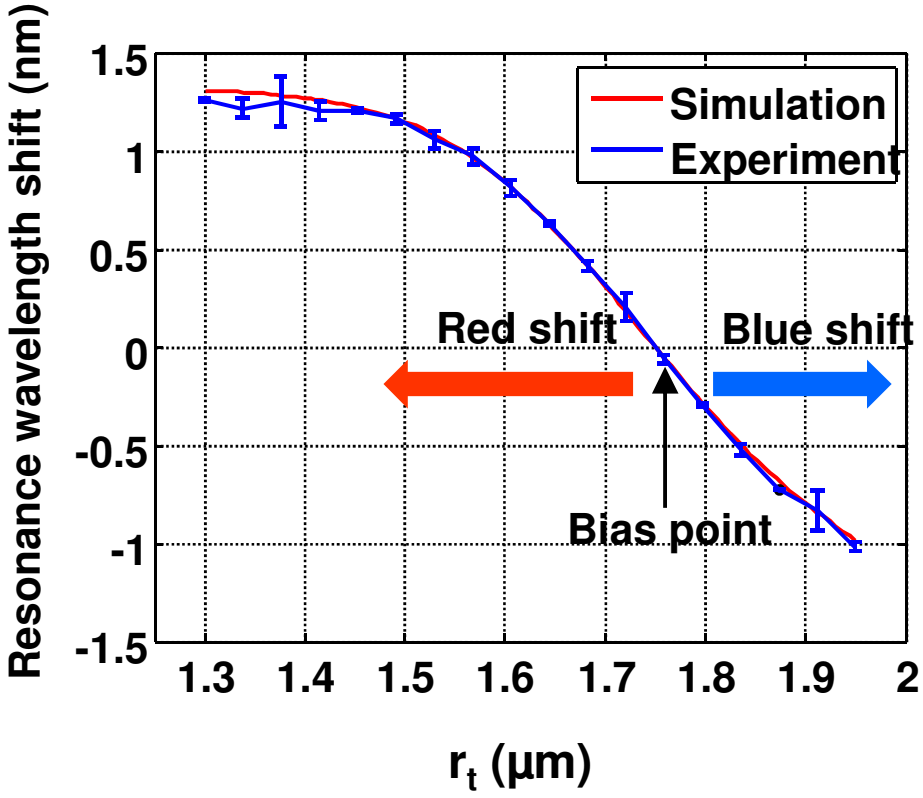


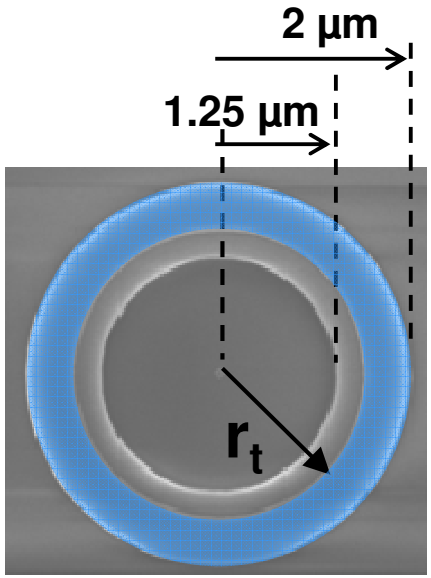

**Microring**



# Calibration of PFT

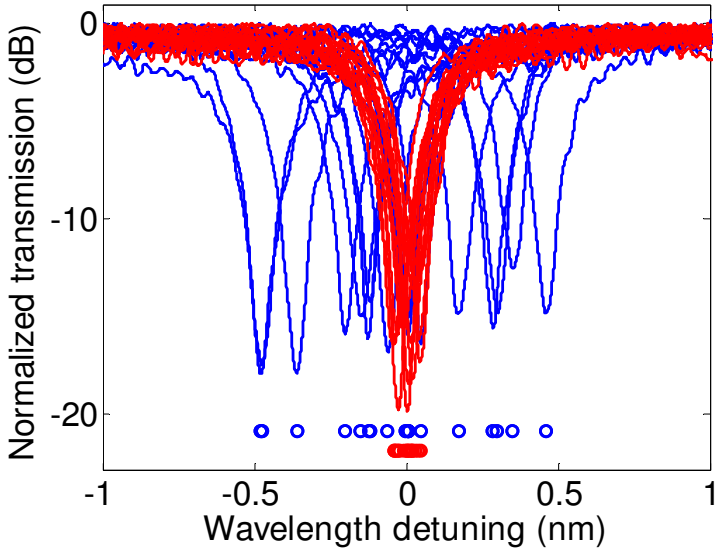
- Measuring actual data of wavelength shift vs. trimming parameter ($r_t$)



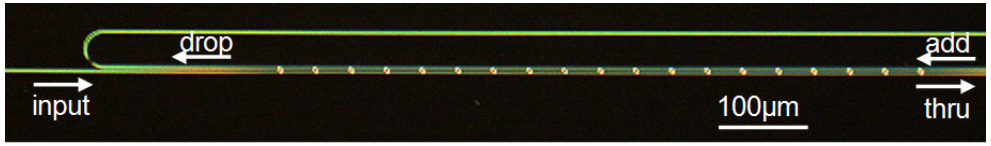
# Post-Fabrication Trimming

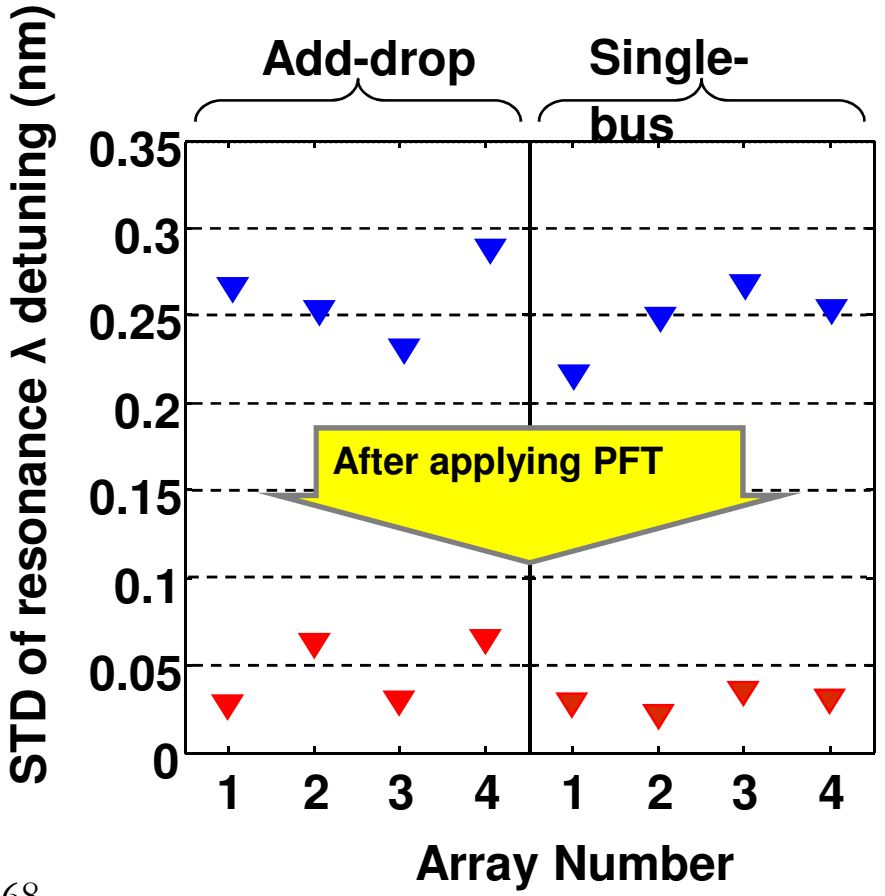
- 8 sets of 19-element microring arrays




**Device parameters**

$t_{Si}$ = 230 nm
$t_{SiN}$ = 30 nm
$t_{Sio2}$ = 40 nm
$r_d$ = 2 µm
Δr = 4 nm
$w_{WG}$ = 400 nm
$w_d$ = 750 nm

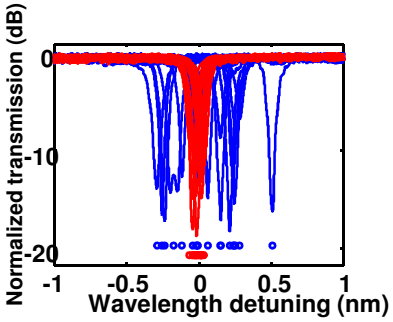


# Effect of PFT in High-Order Filters

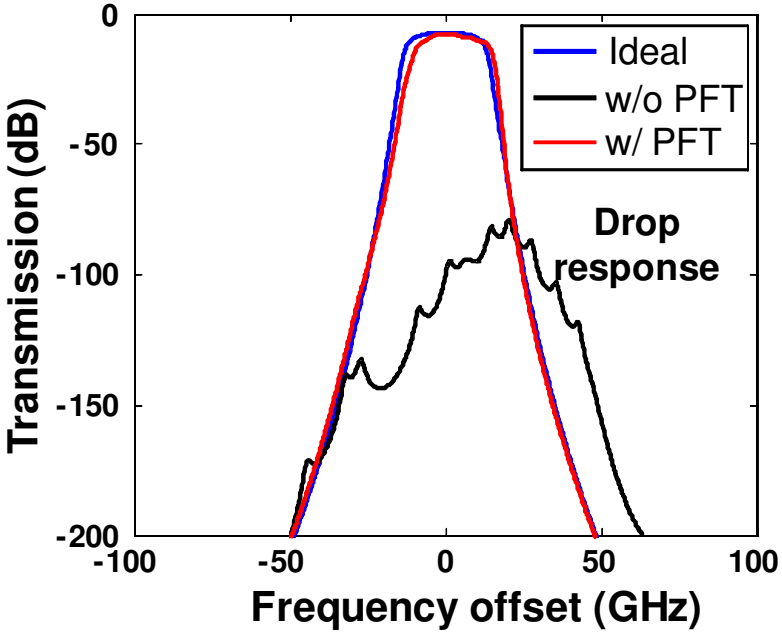
- A flat-top coupled-resonator 18$^{th}$-order filter
  - 3dB bandwidth: 25 GHz
  - $Q_i$ = 100,000

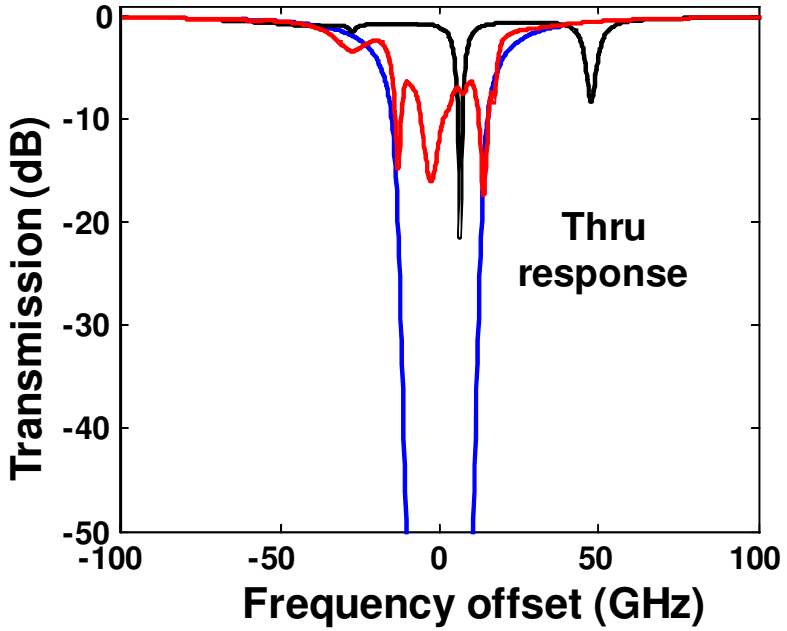
  (Simulation based on experimental PFT accuracy data)



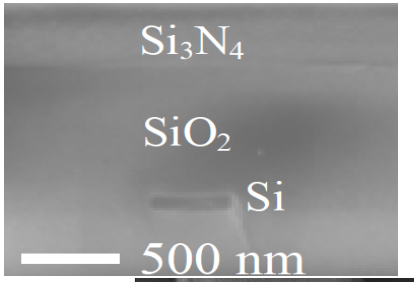


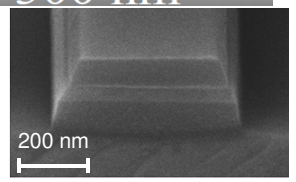




# Improving the Reconfigurable Photonic Material and Device Platform



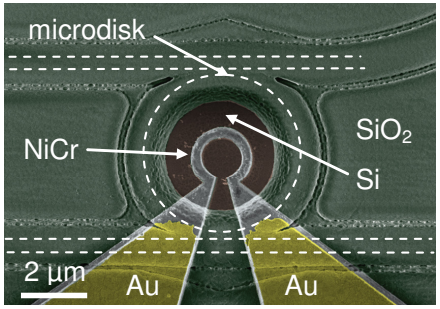



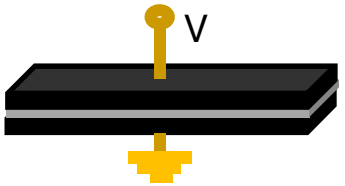

## Material platform

- SOI: Loss, nonlinearity, and Limited functionality
- Alternative: Multi-layer SOI, Hybrid Si/SiN, 3D integration

## Reconfigurable device

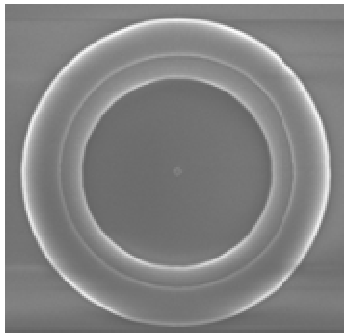
- Modulators: Need for lower power and faster modulators



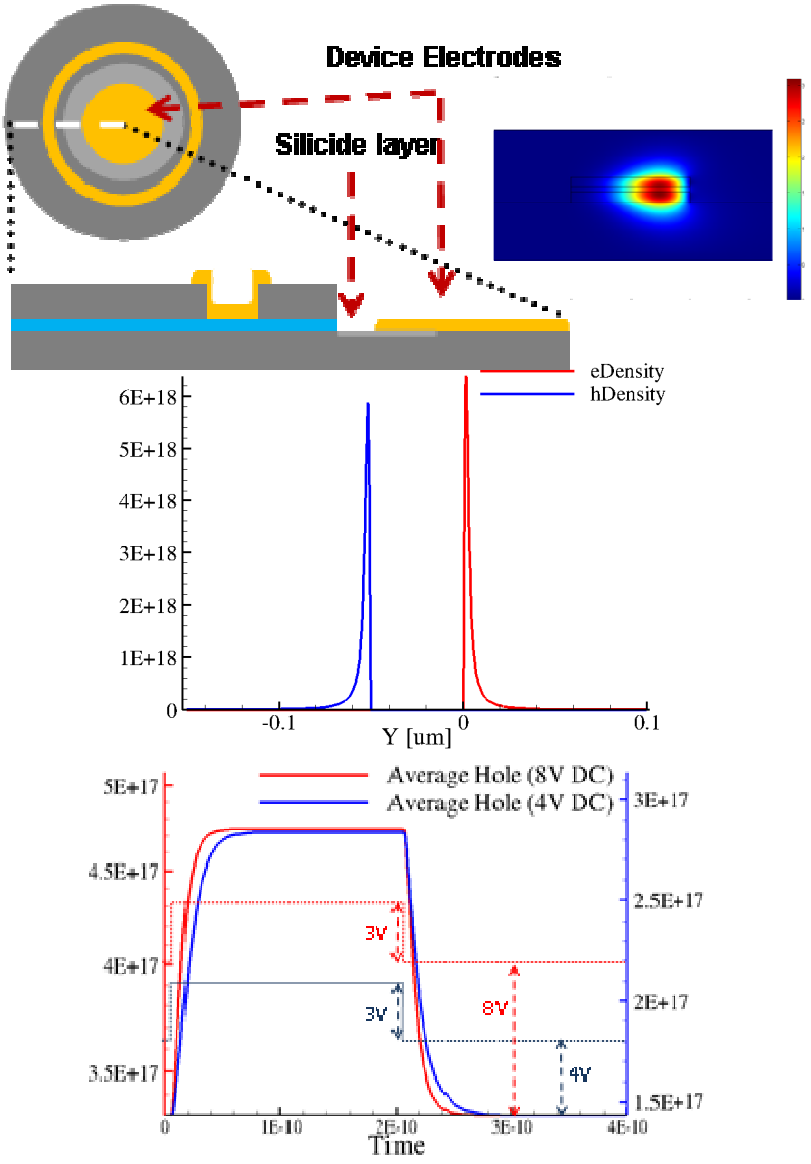

## System

- Random variation of the device
  - Mechanical tuning
  - Free-carrier reconfiguration based on carrier accumulation



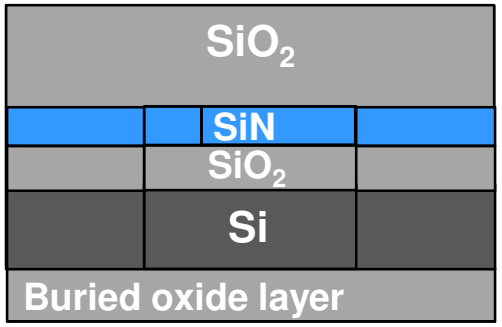
# Accumulation Based Modulator Devices

- Modulation base on majority carrier accumulation
  - Capacitive structure: low power
  - Majority carrier: High speed
  - Carrier accumulation: large tuning
- Multilayer SOI platform: double layer SOI with a thin isolator layer
  - High efficiency: high resonance shift: (>2nm/V)
  - High quality crystalline Si
  - High optical mode overlap with accumulated carriers



# Fabrication and Characterization

- PECVD of $SiO_2$ and SiN thin films
- E-beam lithography and dry-etching of device layer
- Coating Index-matched polymer
- Characterization of the device
- Removing cladding polymer
- Dry-etching SiN layer
- PECVD of $SiO_2$ cladding




**SEM of a 4 µm diameter microring**

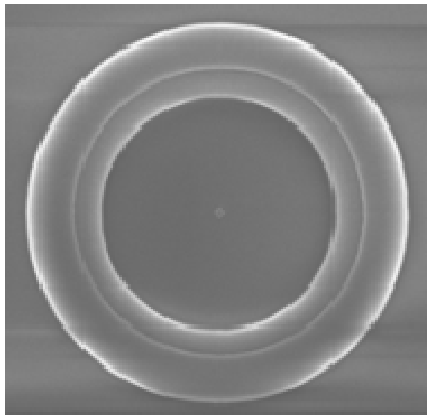
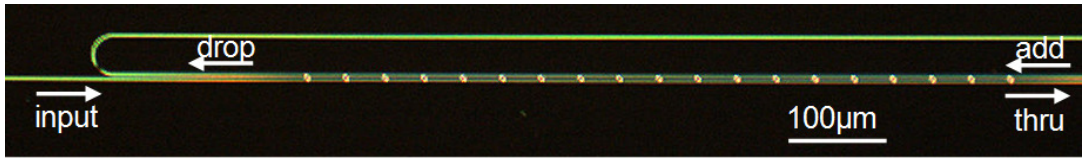


**Image of a 19-element microring add-drop array**



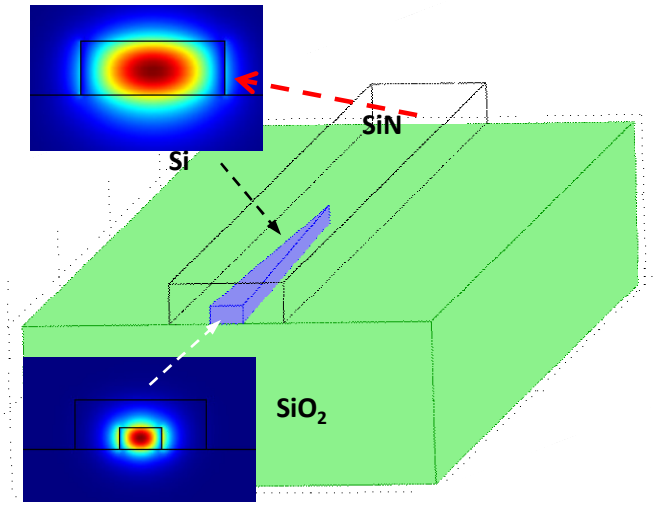
# Hybrid Si/SiN Platforms for Low-loss and Low Nonlinearity Reconfigurable Photonic Devices

- Silicon
  - Low-loss and high confinement
  - Various tuning mechanisms
  - High nonlinearity (TPA and $\chi^{(3)}$)
  - High temperature sensitivity

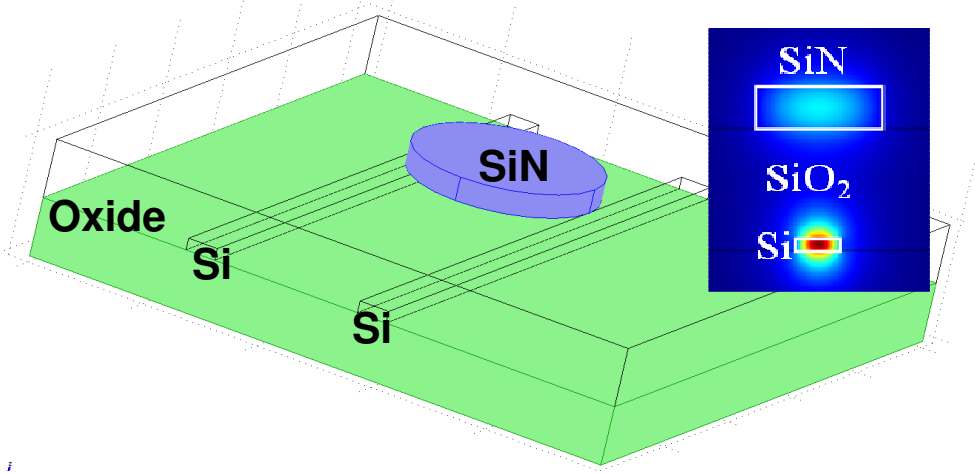
  Good for short-distance and tunable devices

- SiN
  - Very low loss
  - High power handling capability
  - Low temperature sensitivity
  - Large mode volume

  Good for passive devices such as high Q resonators and long waveguides for delay lines



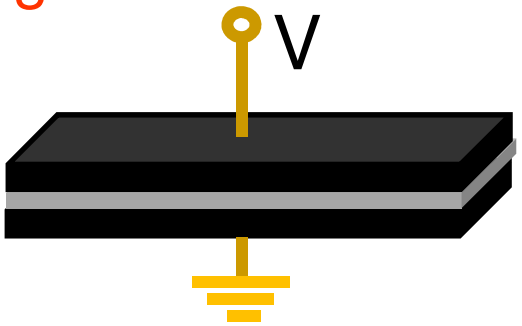

nanotaper assisted interface

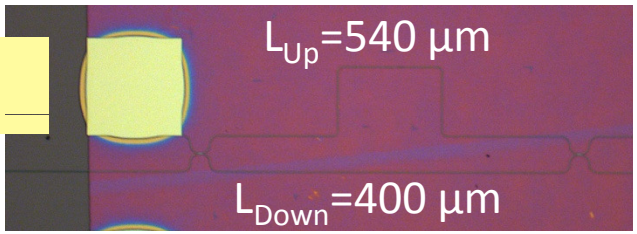


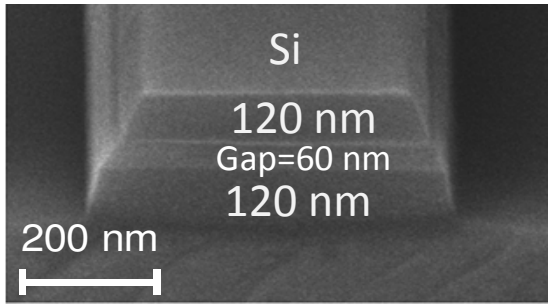

resonator based interface

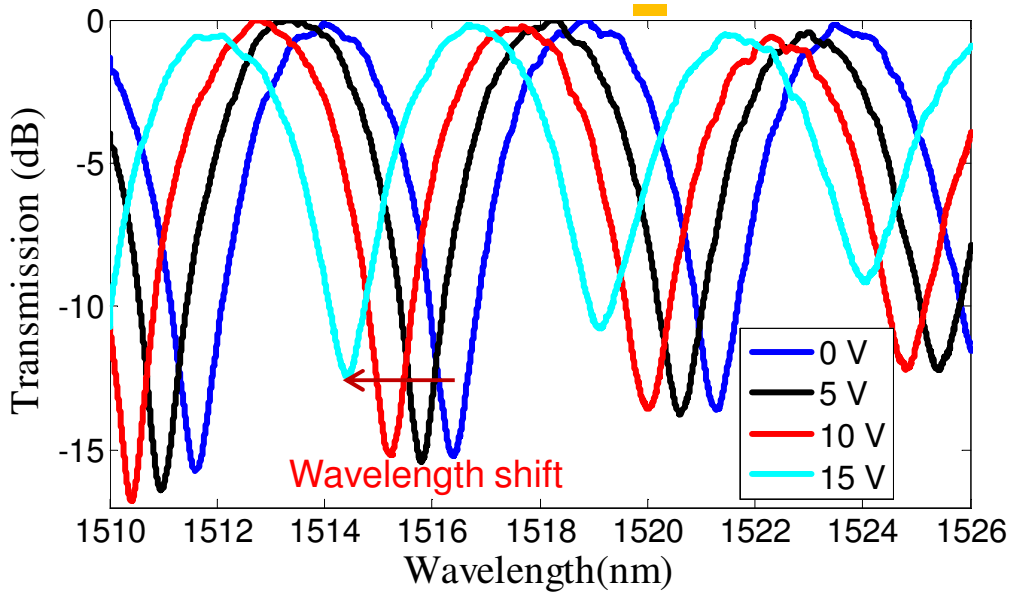
# Experimental Demonstration of Reconfigurable Devices through Carrier Accumulation

- Wideband, low-power and fast reconfigurable structures
- Reconfigurable MZ-based structure
  - No background doping
  - 60nm $SiO_2$ isolation layer



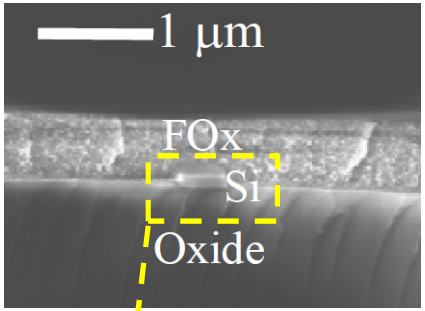



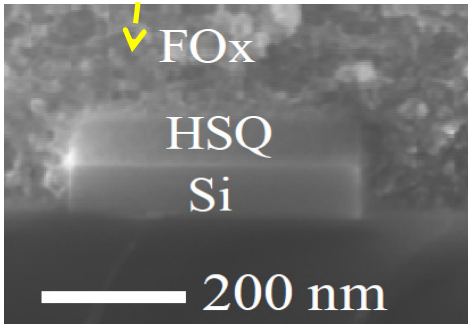



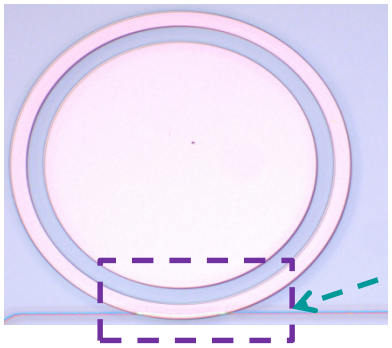

The tuning voltage can be considerably reduced by reducing the gap size

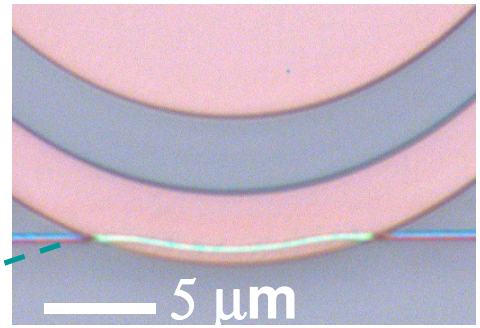
# Fabrication of Hybrid Si/SiN Structure

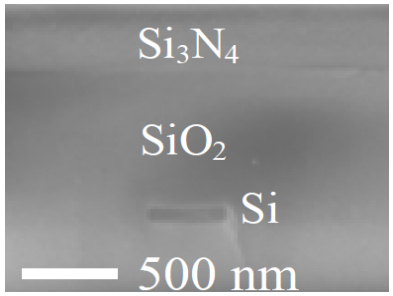
- The Si structure is fabricated on SOI wafer
- Flowable oxide (Fox) for coupling control and planarization
- LPCVD SiN deposition
- Patterning SiN layer






Fox allows a flat top surface for SiN deposition
Good alignment between SiN and Si layers can be achieved



# EBL Exposure Time

- Exposure time of the trimming pattern of a single 4 µm diameter resonator
  - Dosage: 300 µC/cm$^2$
  - E-beam gun current: 2 nA

  } → **7.6 ms / resonator**

- Excluding e-beam calibration and alignment time
  - 1000 resonators per die → 7.6 s
  - 5x5 mm$^2$ dies → ~ 5000 dies / 8 inch wafer

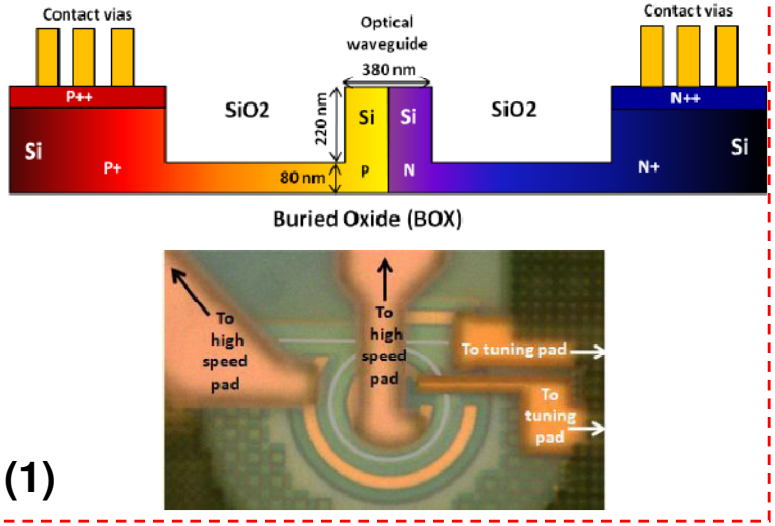
    → ~ 10.5 hours exposure time

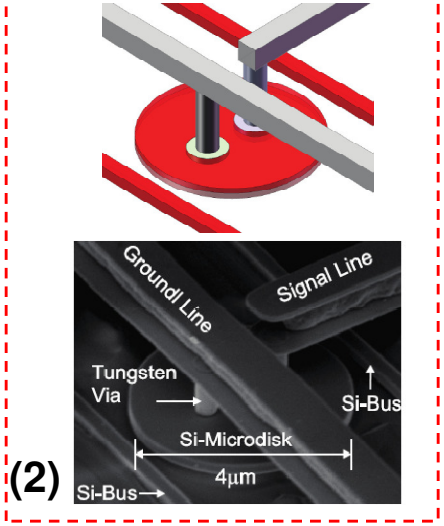
**PFT can be practical for low to medium volume device manufacturing**

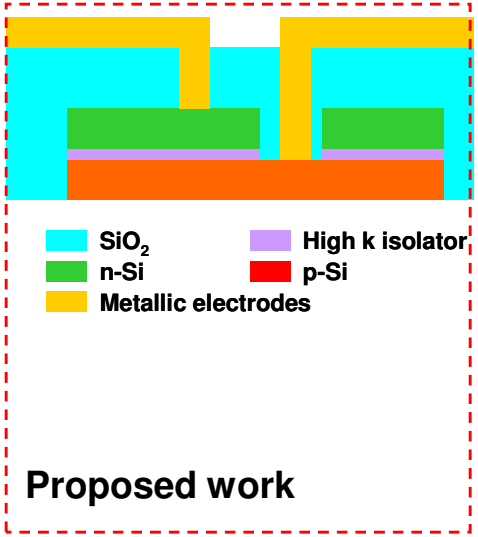


# Comparison with the State-of-the-Art

| Modulator device | Frequency shift | Modulation speed | Modulation depth | Insertion loss | Power consumption |
|---|---|---|---|---|---|
| (1) Vertical PN junction | <15GHz@5V | 25 GHz | 5 dB/1V | Very high | 7fJ/bit |
| (2) Vertical PN junction | 20 GHz@3.5 V | 12.5 GHz | <5 dB/1V | 1.5 dB | 3fJ/bit |
| Proposed work | > 200 GHz/V | > 40 GHz | > 15dB/V | <1 dB | Sub fJ/bit |



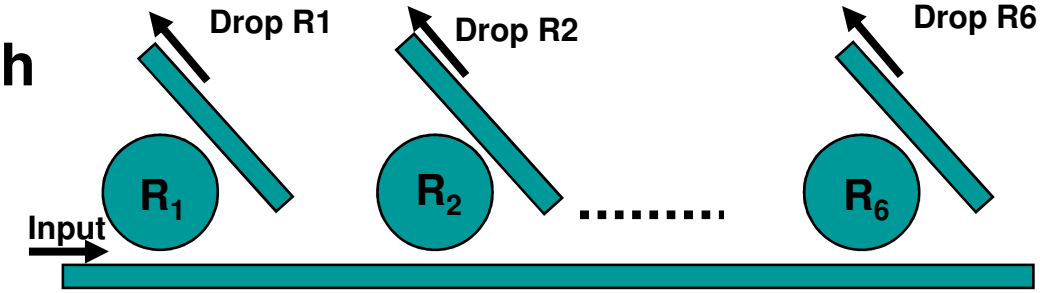

1- G. Li, et. Al., "25Gb/s 1V-driving CMOS ring modulator with integrated thermal tuning," Opt. Express **19**, 20435-20443 (2011)
2- M. R. Watts, et. Al., "Vertical junction silicon microdisk modulators and switches," Opt. Express **19**, 21989-22003 (2011)

# Conclusions

- Reconfigurable cellular photonic arrays enabled by dynamic and fast tuning of optical elements offer new opportunities for several integrated photonic applications and potentially can provide a general purpose platform for coherent optical processing.
- Sub-100-nanosecond reconfiguration time is achieved in a novel microheater architecture directly placed on a microdisk. Sub-10 ns can be obtained.
- Relatively low power consumption (e.g., frequency shift as large as 265GHz per mW power consumption ) provide the potential for large-scale optical signal processing applications.
- Technology transition toward a reliable large scale manufacturing of photonic systems should be developed .

# Microdisk Resonator Arrays with In-plane Coupling

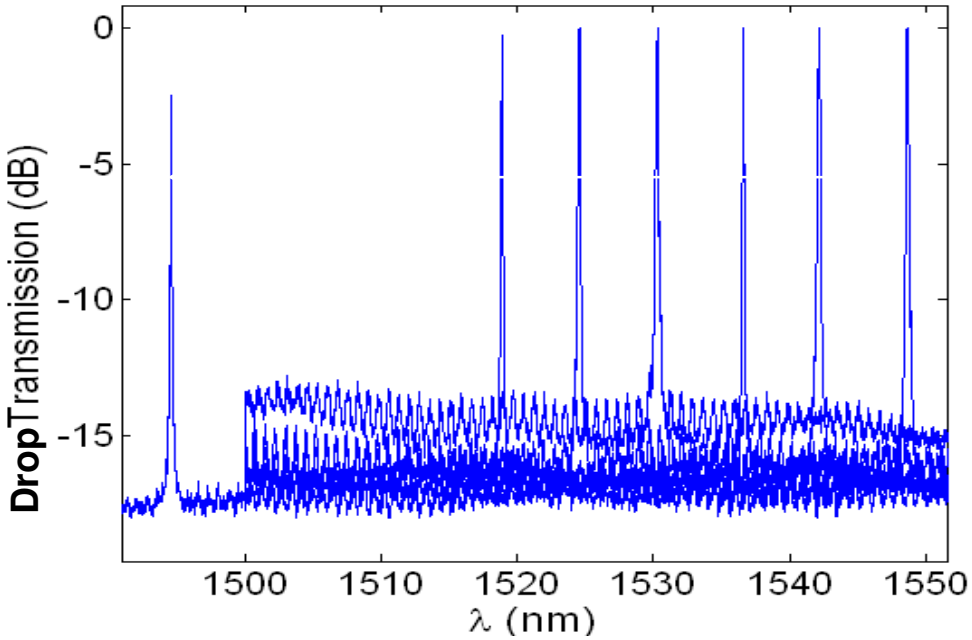
- An array Si resonators with radii around 2μm was fabricated.




- For practical purposes, the structure was covered by oxide.

- By fine-tuning of the resonators size and coupling to waveguides, the spectral response of the array structure can be engineered.

**Experimental results**



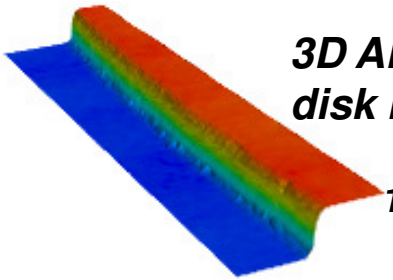
# System Specifications

- Wide variety functionalities can be implemented
- Possibility of high level software programming of RCPAs
- Fine channel frequency and bandwidth tuning
- Thermal Tuning with 60°C temperature control
  → Up to 1.0 THz tuning bandwidth at 1.55 μm
- Low loss operation (0.1 to 0.2 dB/cm)
- Low power consumption (<0.1 nJ/element/switching)
- Small steady state power consumption (< 1mw/element )
- Fast element reconfiguration speed ( < 10ns)

# Technology Transition: Manufacturability

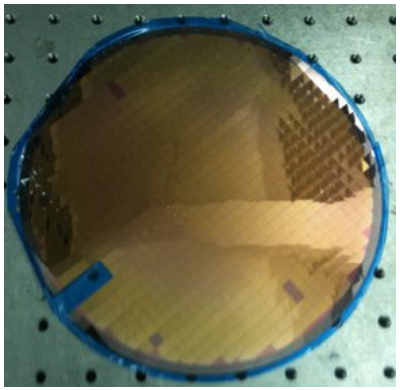
Currently

- Litho: E-beam, ICP etch :
  - rms roughness < 1 nm
  - Correlation length < 25 nm



***3D AFM of disk resonator edge***

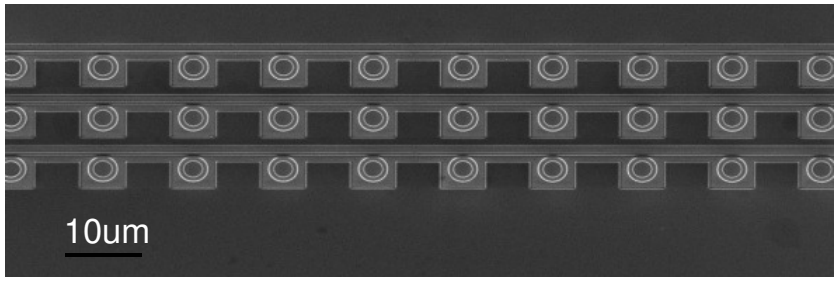
***193nm DUV processed Si PIC***

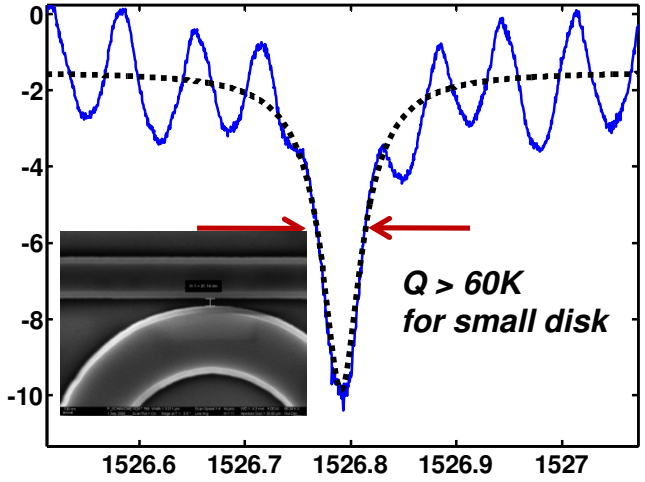


**Transition to**

- CMOS (193nm DUV; 0.13 or 0.18 mm node) :
  - IMEC: < 1% (1σ) for 450nm waveguides
  - Die: 6 mm x 6 mm (> 800 die on 8-inch wafer)
  - Each die fits upto 48 of 4th order filters

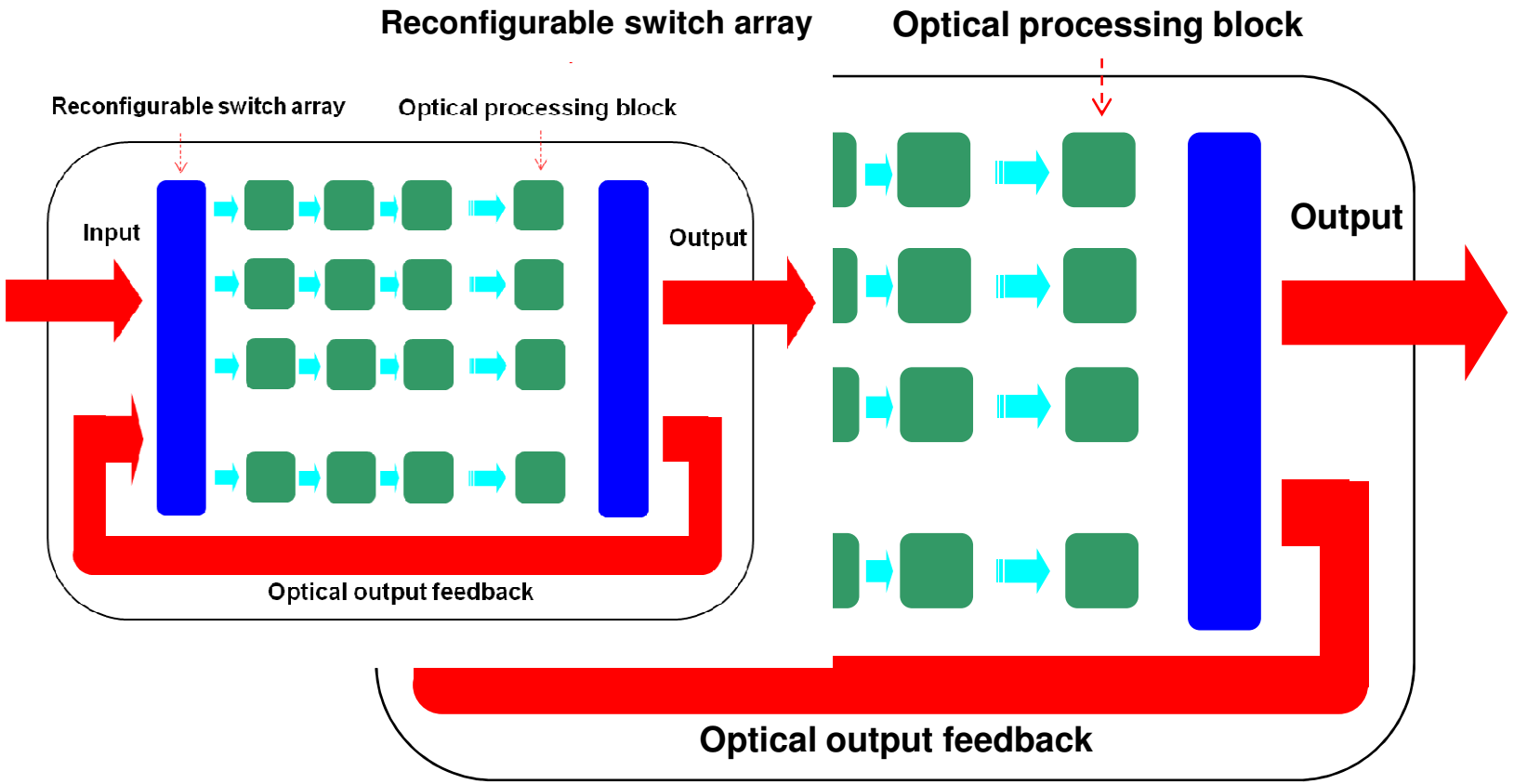
- Nanoimprint Lithography
  - Quality factors similar to EBL for small microdik resonators



# RCPA Architecture

- Reconfiguration based on programmable routing and programmable optical processing block



# Introduction

- Optical signal processing required
  - Processing  wide-band optical signal
  - Processing high-speed data in microwave systems

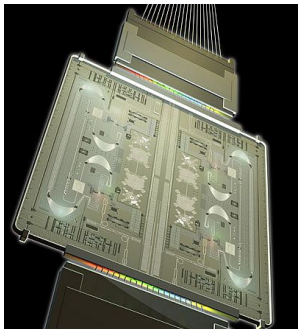
**Current  technology**

| | Cost | Size | Versatility | E/O, O/E | Bit rate |
|---|---|---|---|---|---|
| Electrical | Low | Compact | Very Hi | Yes | ~ 10G |
| Optical | Hi | Bulky | Low | No | >1T |

**Integration**



**Pentium 4**

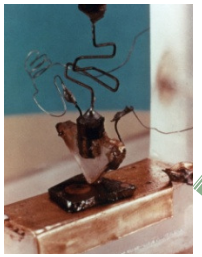


**www.infinera.com**

**Compact, inexpensive, and scalable optical systems**

# Introduction

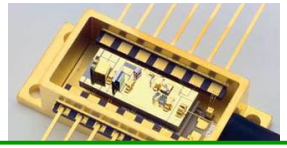
## Integration



First transistor

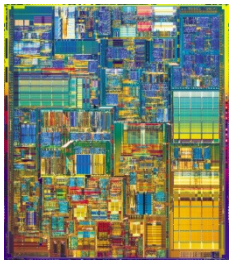


photodiode

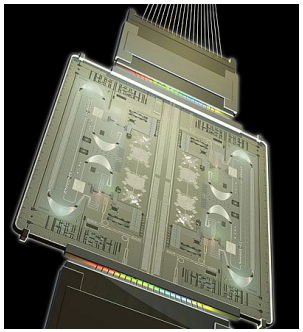


**Silicon:**
**Material for large-scale photonics?**

First IC



Pentium 4



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**Compact, inexpensive, and scalable optical SP**

# Photonic Reconfiguration in Silicon

**Desired Features**

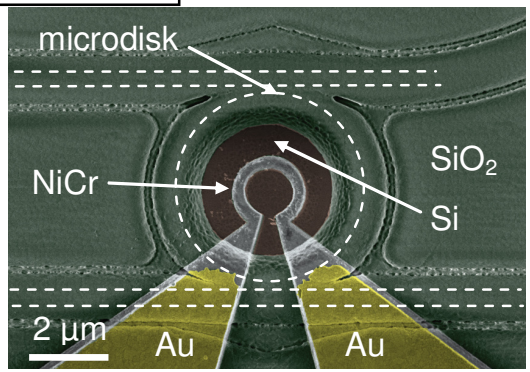
- CMOS compatible
- Low power
- Wide tuning range
- Fast
- Low loss

**Methods**

- Free-carrier plasma dispersion
- Thermo-optic effect
- Electro-optic effect in hybrid polymer-based devices

**Thermo-optic effect suitable for large-scale reconfiguration**

**Reconfiguration speed is a bottleneck**



# Acknowledgements


- AFOSR, Dr. Pomrenke,

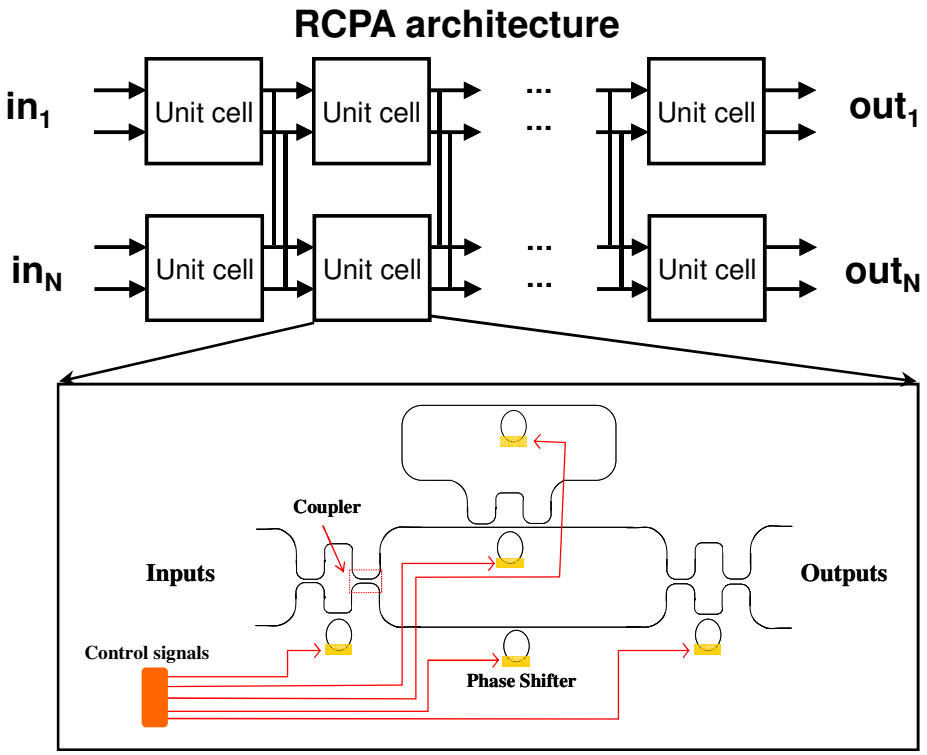
- Partial Funding from DARPA

- Colleagues in Adibi's group in Georgia Tech

# RCPA: Scalable Optical Signal Processing Platform

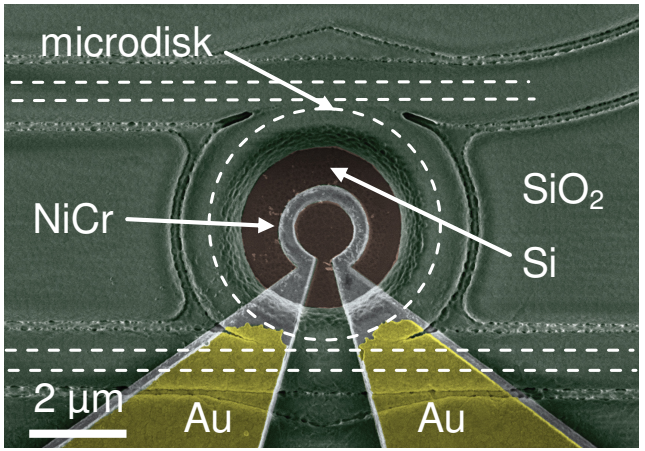
- Reconfigurable photonic unit-cell design
- Resonator-based phase-shifters
  - More compact
  - Less power consumption

→ **More integration**



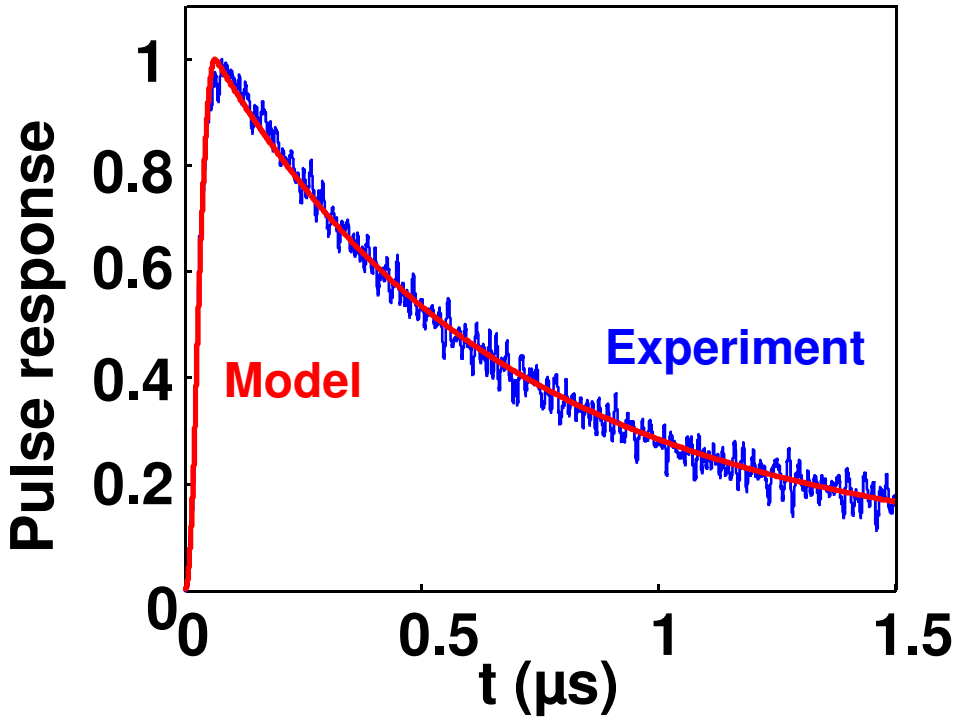

**Example of a unit-cell**

# Outline



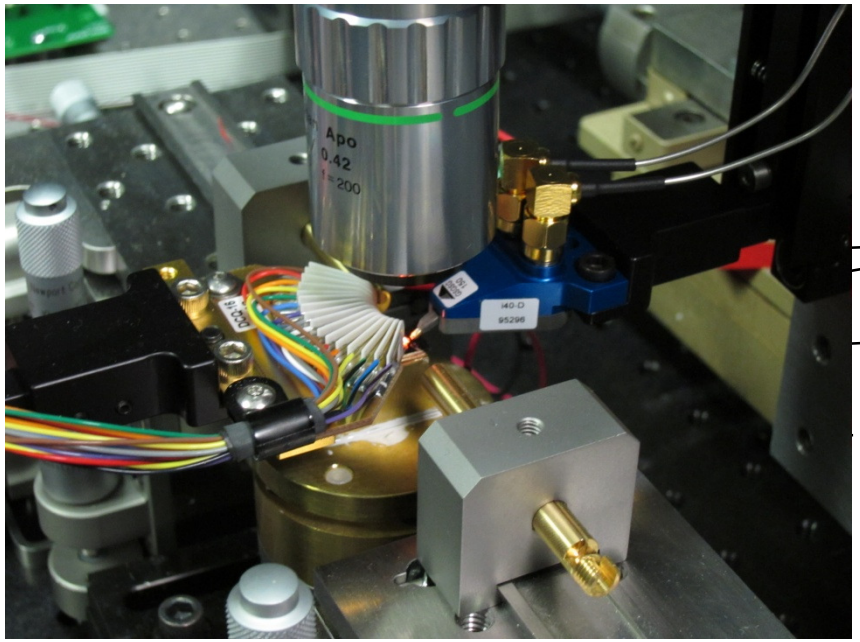

- Introduction and Motivation
  - Reconfigurable optical processor
  - Silicon Photonics
- Reconfigurable Silicon Photonics
  - Design and Implementation of thermally tuned photonic devices
- Discussion and Conclusion

# System-level Model



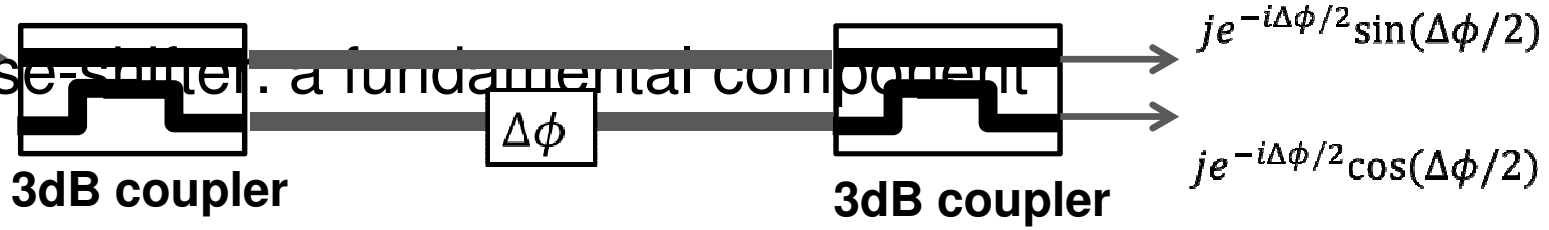
# Characterization of Microheaters

- DC signal using static DAQ-card and multi-contact probes (32 signals)
- Differential RF signaling ( $f$ = 40GHz)
- In-house thermally-stabilized sample-holder (0.01ºC accuracy)
- Ultrafast dual-channel arbitrary-waveform-generator for microheater signaling (2GSps)



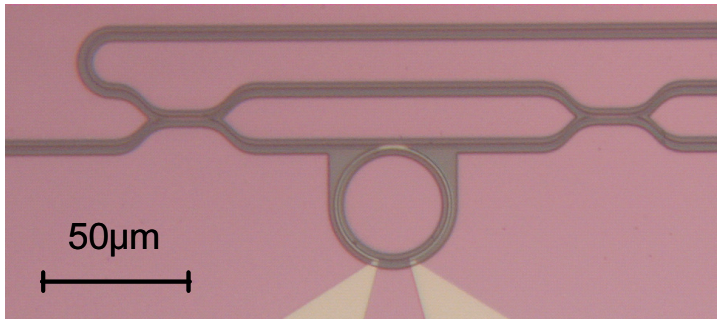
# Resonator-based Reconfiguration

- Phase-shifter: a fundamental component




- Waveguide based
- Resonator based
  - Field Enhancement

➡ **Less power consumption**

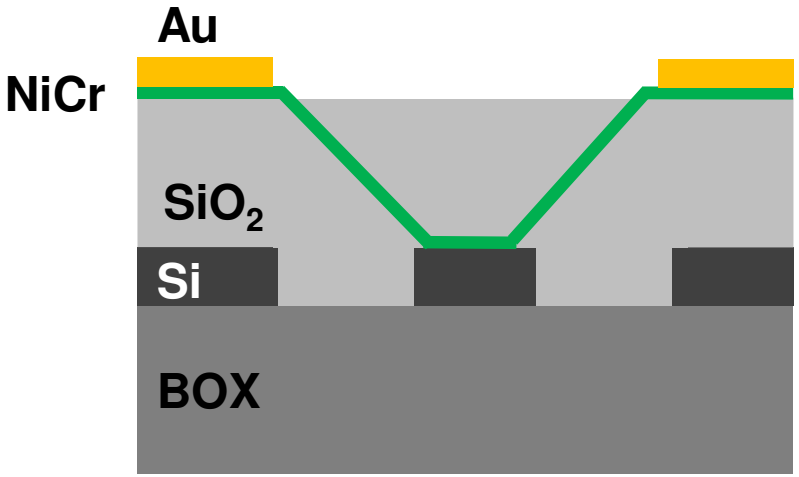



**Tunable coupler**

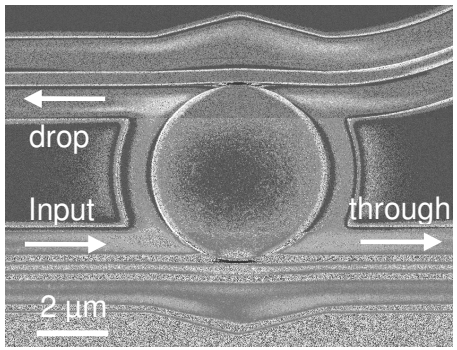
➡ **Resonator-based phase-shifter**

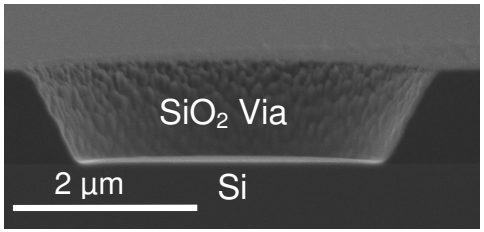
# Fabrication of Microheaters

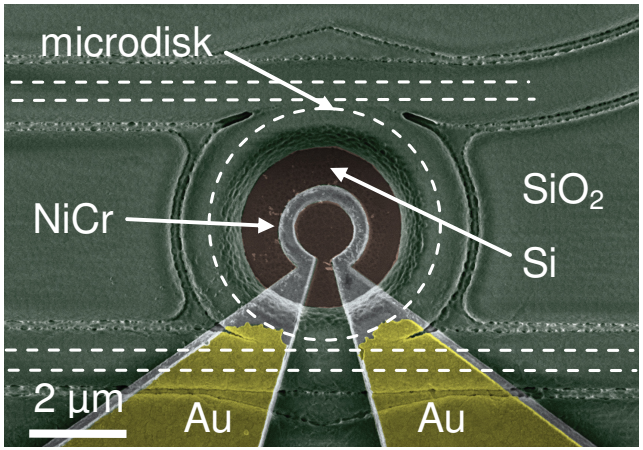
- E-beam lithography and Si etching
- PECVD $SiO_2$
- Dry and wet etching via
- Liftoff of heaters and pads



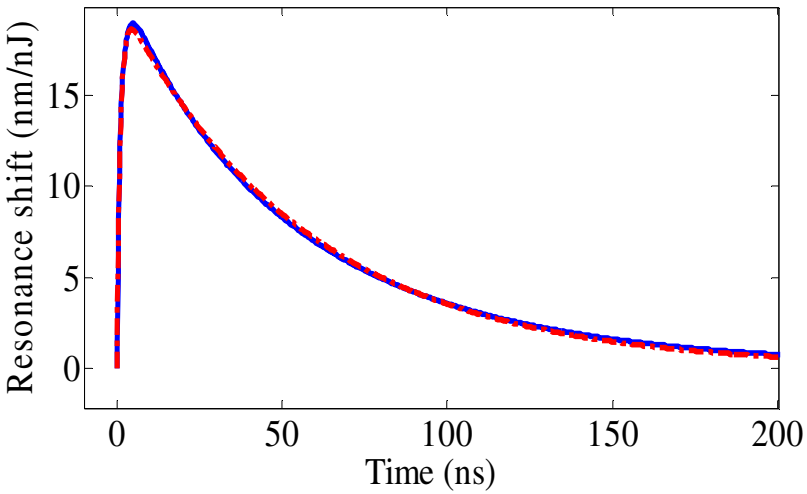

Silicon-on-insulator wafer



# Fast Tuning using Feed-Forward Control



# Top-Level Technical Summary

- Scope: Ultra-compact, low power, fast tunable filters with large dynamic range using resonance based Si integrated photonic structures

- Big Picture Schedule with Major Tasks:
  - Development of optimal filter architectures with maximum tolerance to fabrication imperfections
  - Development of necessary Si photonic infrastructure devices to enable the performance milestones
  - Demonstration of unit cells with reconfigurability
  - Demonstration of high order filters
  - Full system demonstration:

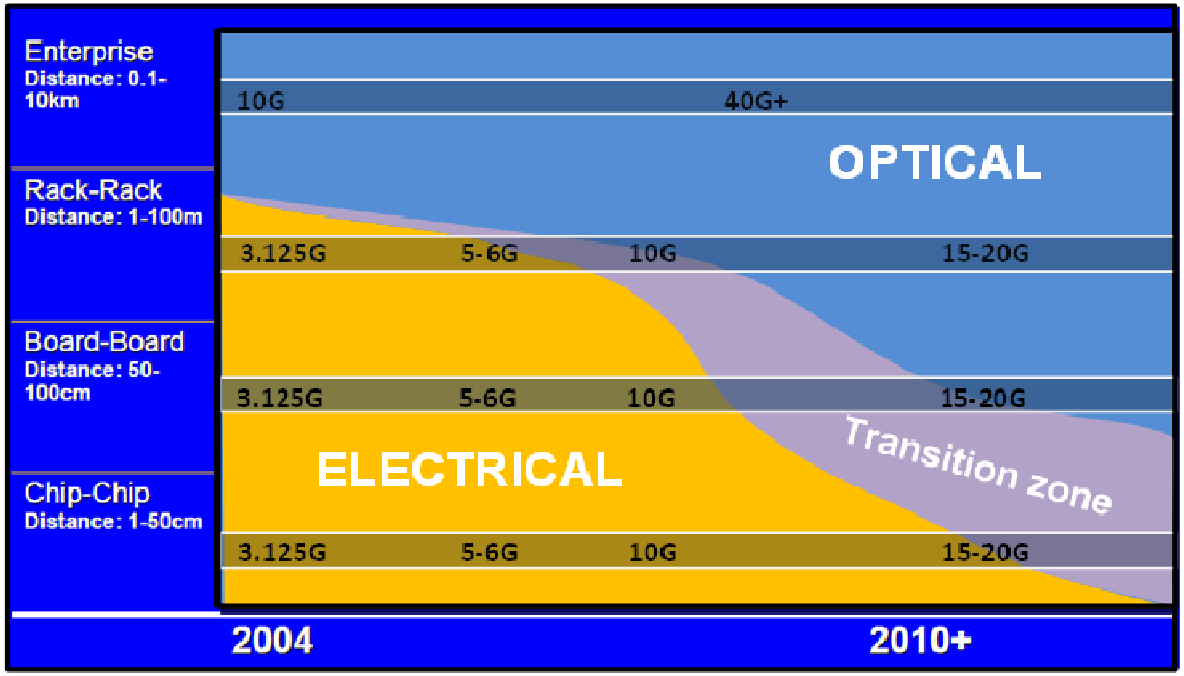
- Principal Issues and Risks:
  - Achieving all performance milestones in one device
  - Combining the ultra-compact size with high speed and low power loss

# Introduction

- Limited bandwidth and high propagation loss of electrical signals at high bandwidth (~10 GHz)

  ⇒ Optical communications/networks (> 1 THz)

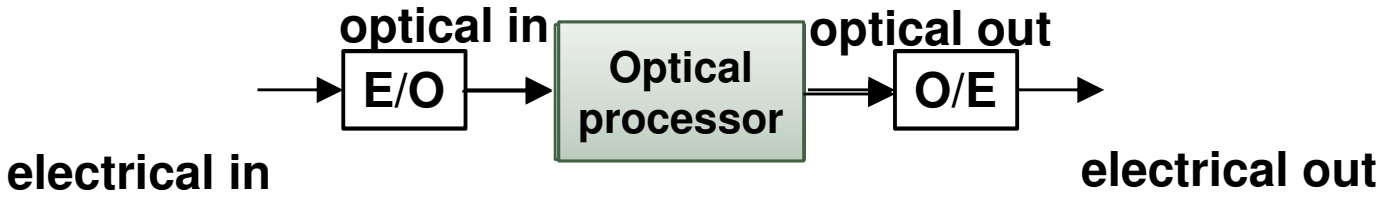
**Transition from electrical to optical communication**




**www.intel.com**

# Introduction

- All-optical signal processing required
  - Processing optical network data
  - Processing high-speed data in microwave systems




**Current technology**

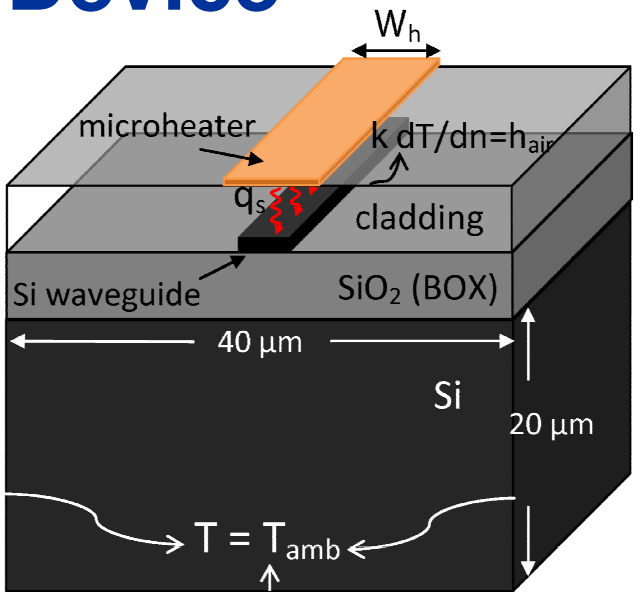
| | Cost | Size | Versatility | E/O, O/E | Bit rate |
|---|---|---|---|---|---|
| Electrical | Low | Compact | Very Hi | Yes | ~ 10G |
| Optical | Hi | Bulky | Low | No | >1T |

**Compact, inexpensive, and scalable optical SP**

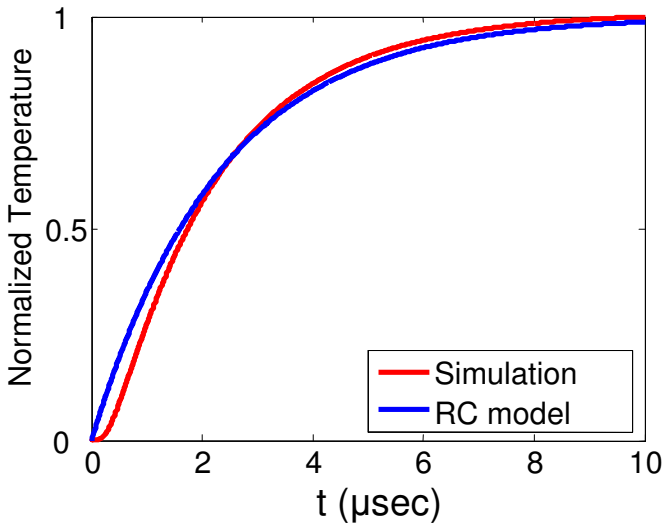
# Heat Transport in Photonic Device

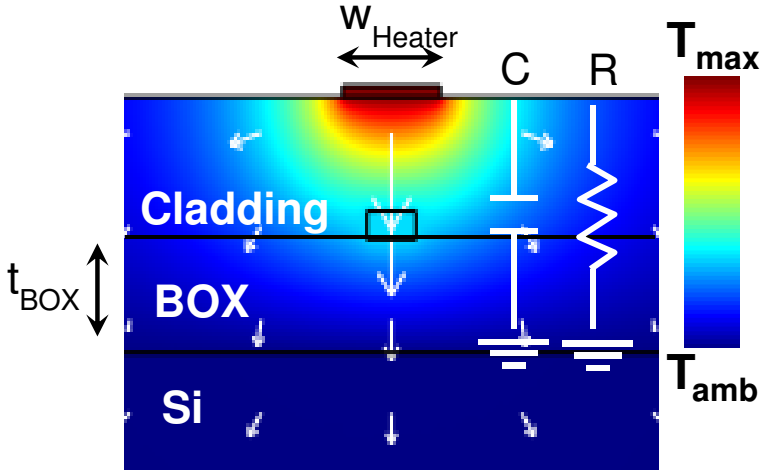
- **Heat conduction modeled by FEM**

$$\nabla \cdot (-k\nabla T) + \rho c \frac{\partial T}{\partial t} = q_s$$



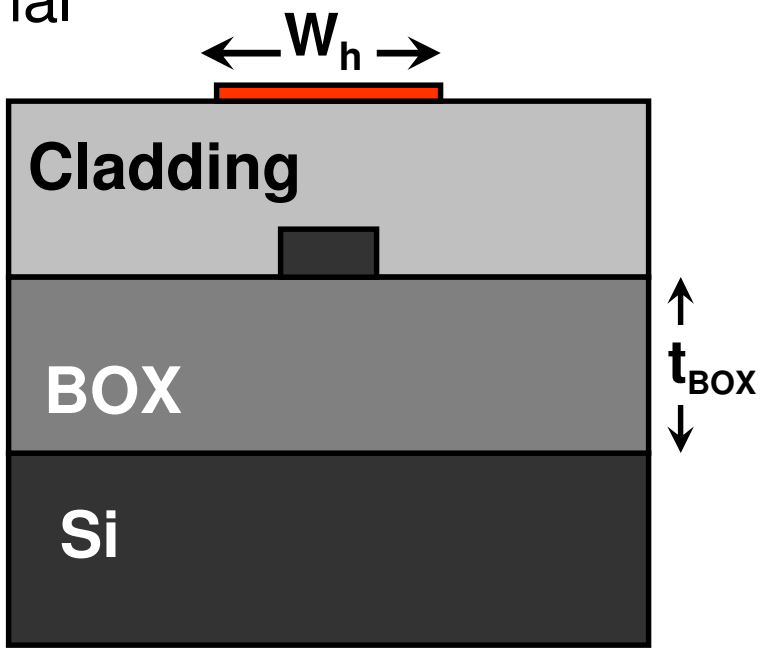

- **Simplified RC model**
  - **$R = R_{clad} + R_{BOX}$ $(R = k^{-1} t / w)$**
  - **$C = C_{clad} \,||\, C_{BOX}$ $(C = c\, t\, w)$**



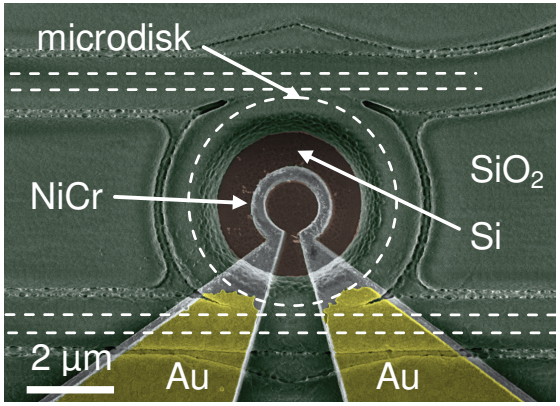
# Device Parameters

- Heater width ( $W_h$ )
- BOX thickness ( $t_{BOX}$ )
- Cladding material
  - $SiO_2$
  - SiN



# Ultra-Low-Power Fast Thermal Reconfiguration

- Ultra-compact microdisk-based reconfiguration
  - Low loss: Q>100,000
  - Ultimate miniaturization: d<5 μm
  - Low power consumption
  - Fast reconfiguration time < 100 ns



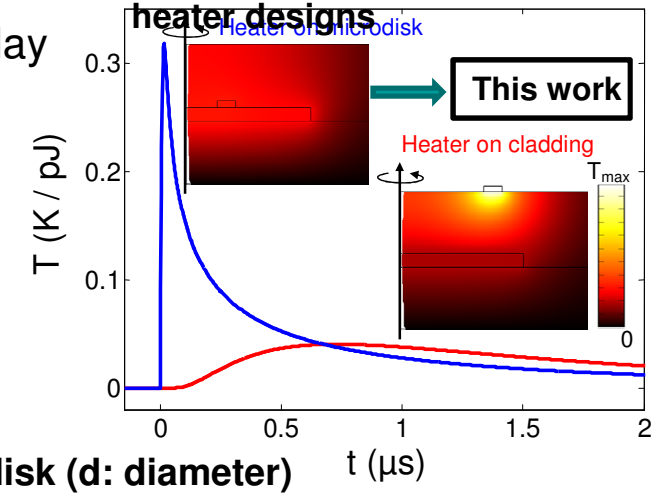

- Principles of operation
  - Microdisk instead of conventional microring resonators
    - More compact while lower loss operation (Soltani *et al,* Opt. Express 2010)
    - Possibility of direct heating of the Si layer
  - Direct integration of microheater on Si layer
    - Order of magnitude reduction in heat-propagation delay compared to conventional architecture

      ⟶ Sub-100-ns reconfiguration with no heater extrinsic loss
    - Less power consumption

# Microheater Integration on Microdisk

- Improvement over conventional design
  - One order-of-magnitude smaller heat-propagation delay due to high Si thermal diffusivity (~ 80ns)
  - ⟹ One order-of-magnitude faster reconfiguration using pulsed-excitation (~ 80ns)
  - 50% less heater temperature rise for specific resonance shift ⟹ Much less device failure
  - Less power consumption

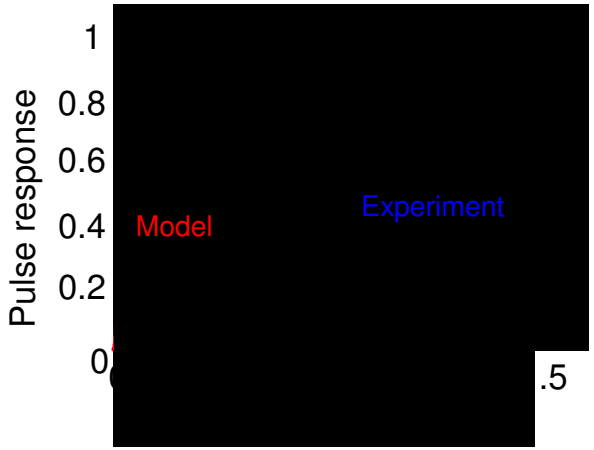
**Numerical modeling of device temperature rise for a 1-pJ power dissipation in two heater designs**



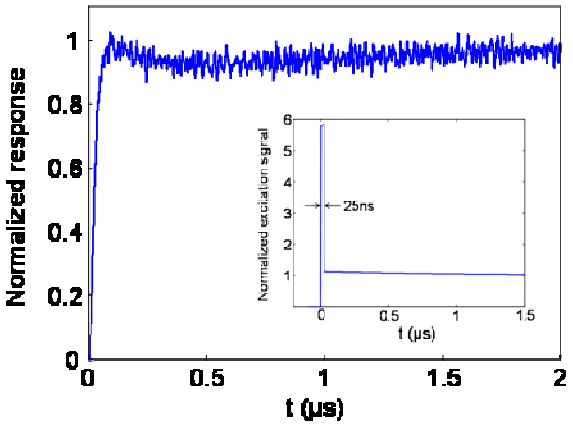

**Resonance frequency shift per mW power on μdisk (d: diameter)**

| d = 4 μm | d = 5 μm |
|---|---|
| 265 GHz | 177 GHz |

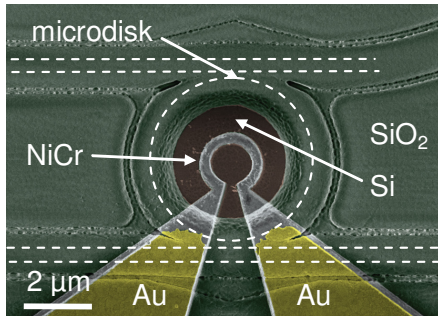
**Response to a 25 ns pulse**




**Response to pulsed reconfig. signal**

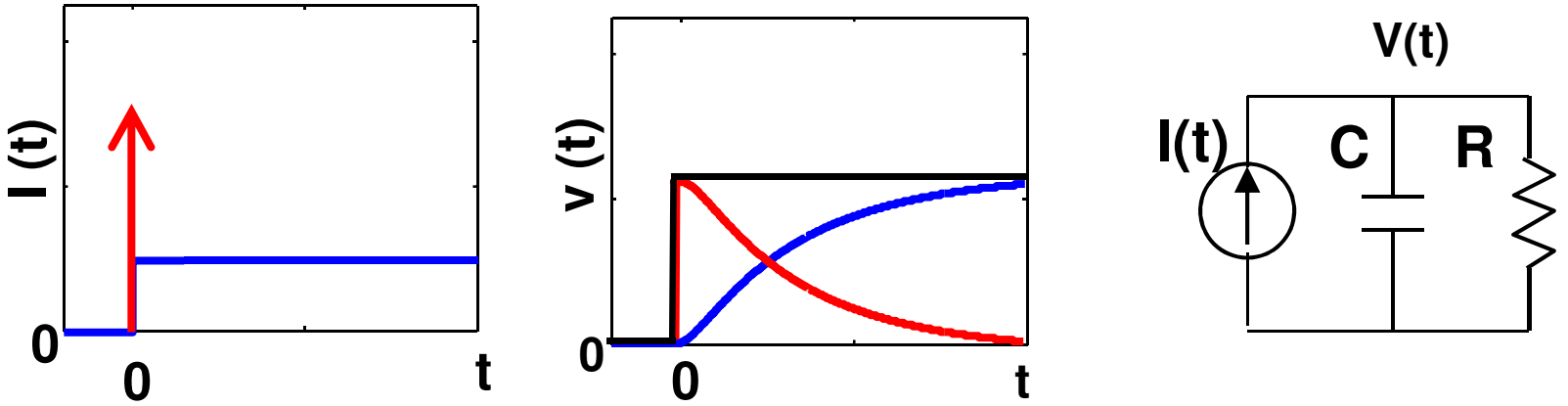



**SEM of the fabricated reconfigurable add-drop**



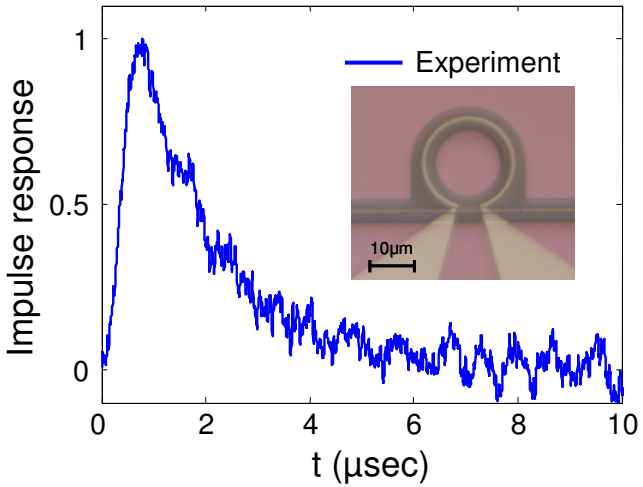
# Pulsed-Excitation

- Initial impulse to over-drive first-order systems




**Instantaneous response possible using an initial impulse**

- Impulse response of heaters
  - Not a simple first-order system



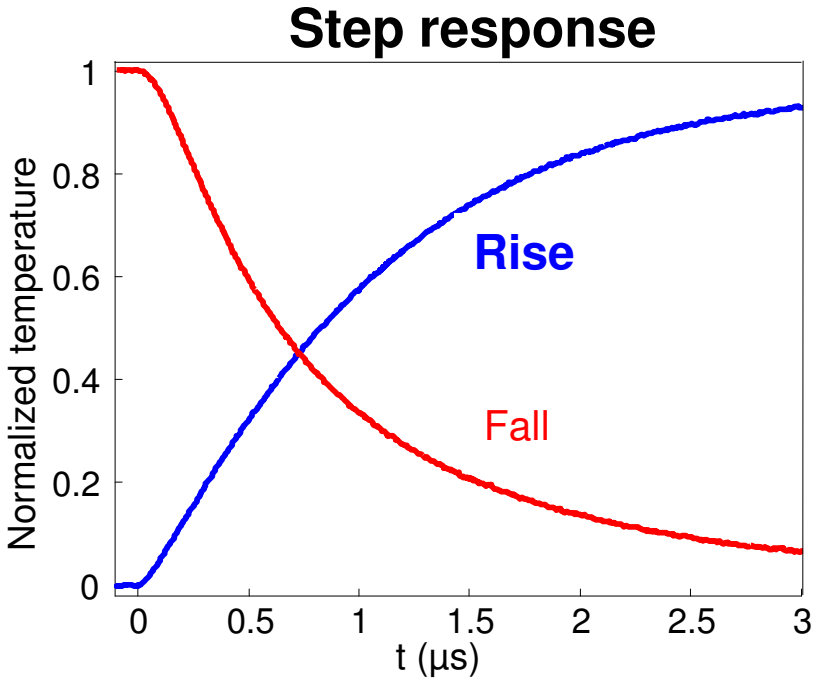

**Exact modeling of heater response is required**

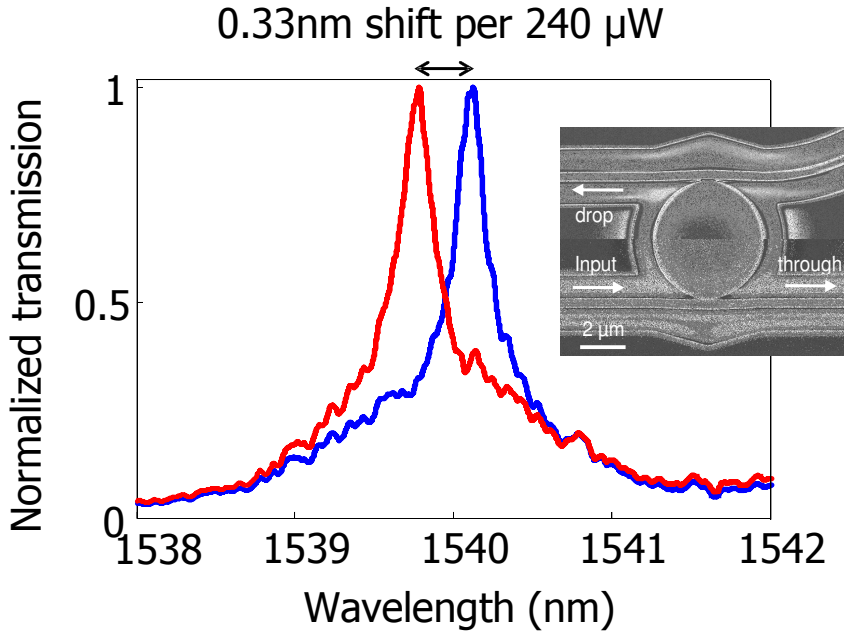
# Experimental Results

- **Resonance frequency shift per mW power on µdisk:**

| d = 4 µm | d = 5 µm |
|---|---|
| 265 GHz | 177 GHz |

- **Modulating resonator using a small signal**



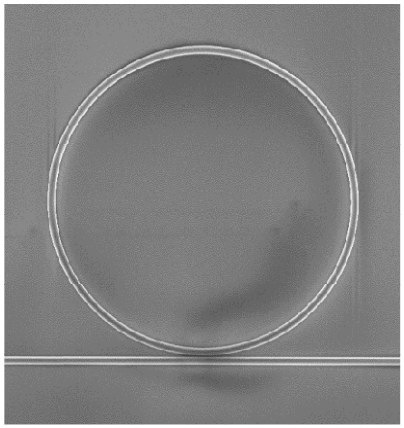



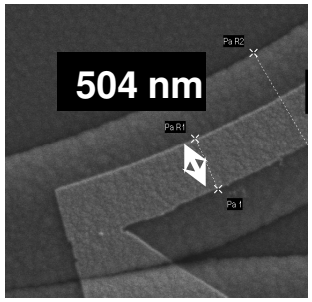

**~ 2.4 µs rise/fall time**

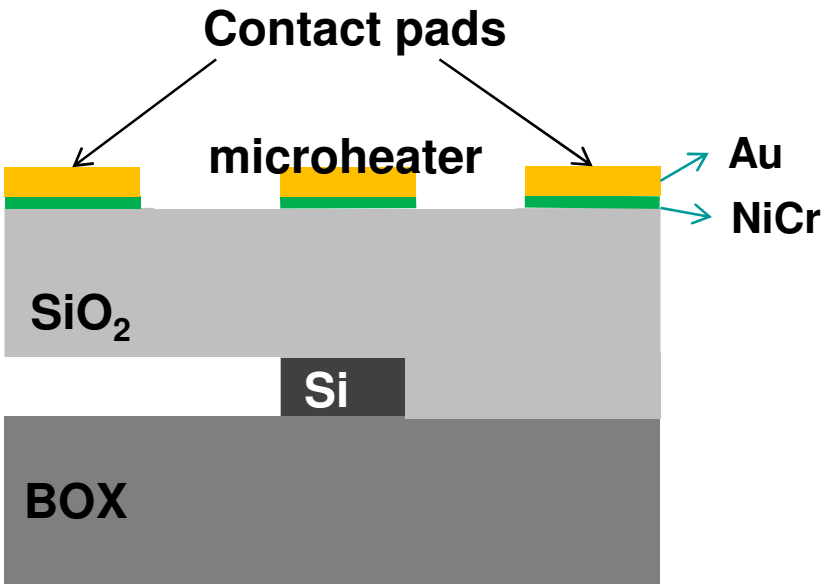


# Fabrication of Microheaters

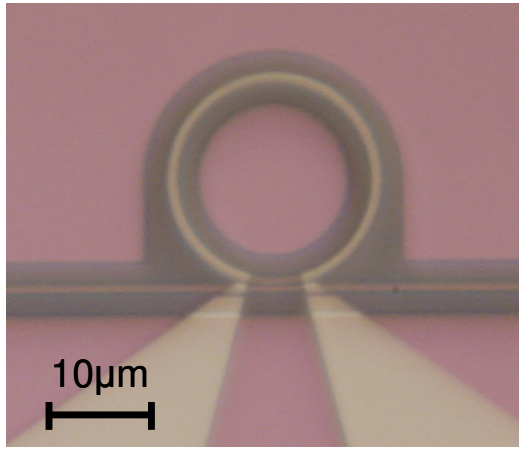
- E-beam lithography and Si etching
- PECVD $SiO_2$ as cladding
- Liftoff of NiCr/Au heaters and pads
- Wet etching of Au over the device





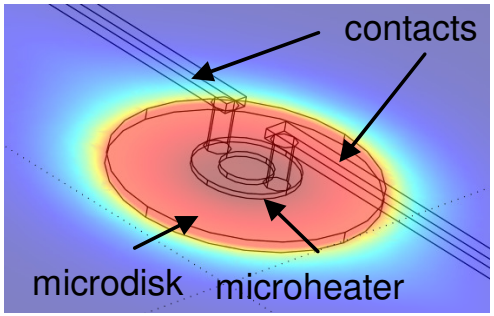



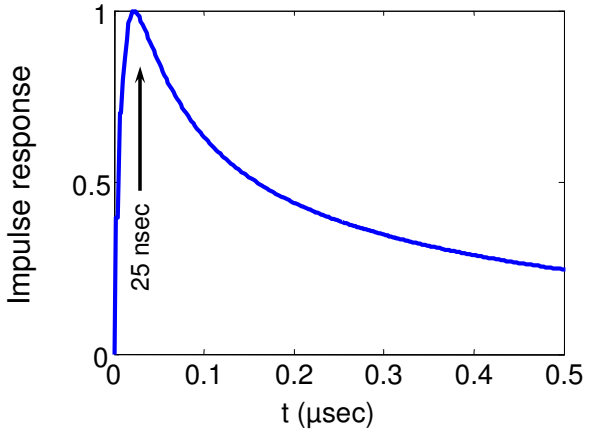

Silicon-on-insulator wafer

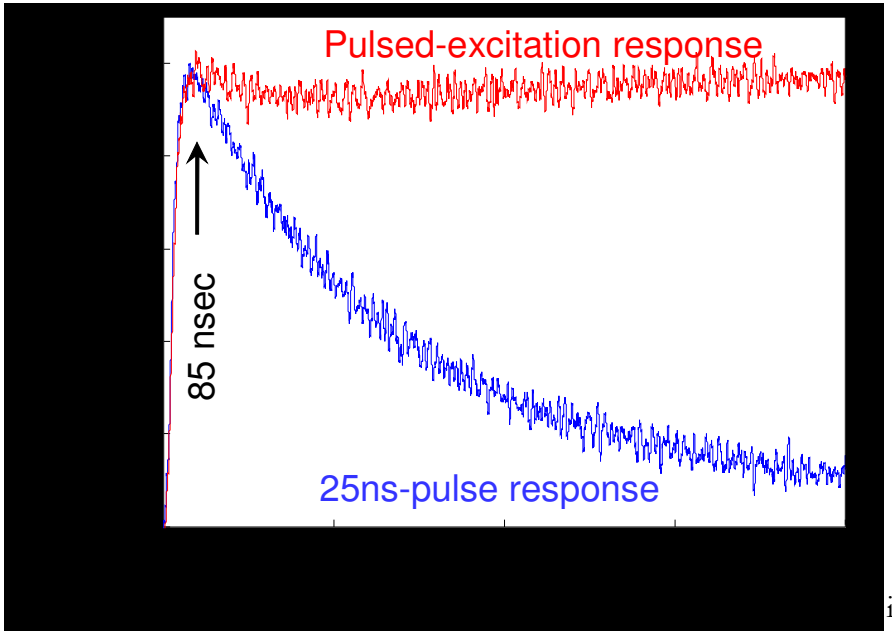


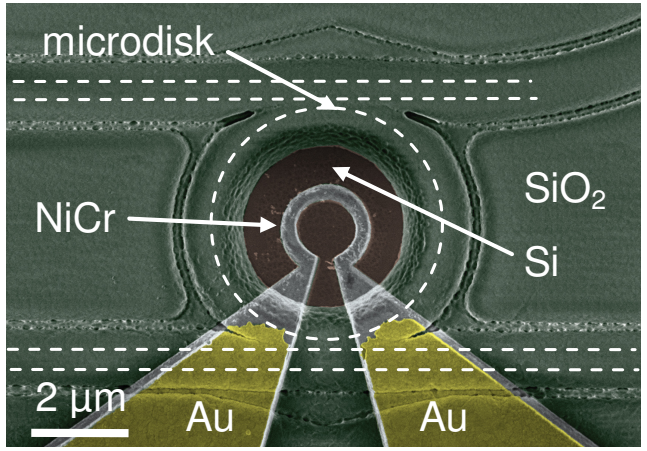
# Microheater on Microdisk

- Directly heating Si reduced heat propagation delay
- Small microdisk for low power consumption



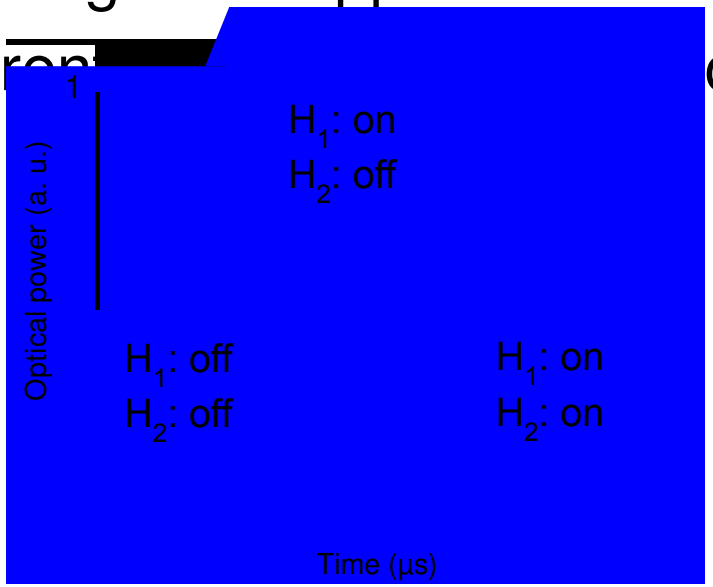



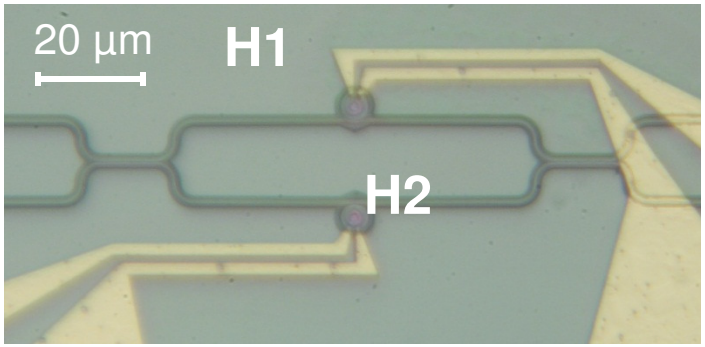

information

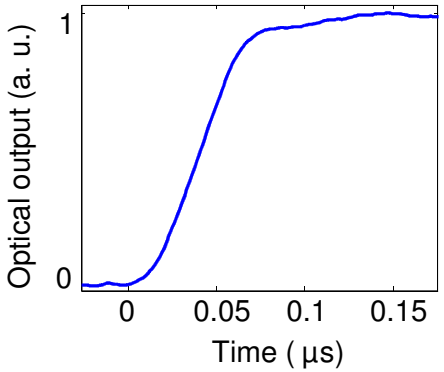
# Differential Architecture

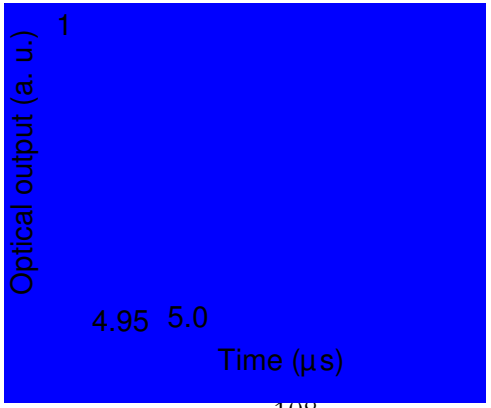
- Reconfigure in opposite directions in required
- Differ[illegible]cture




**Differential coupler**




**75ns reconfiguration of differential architecture**

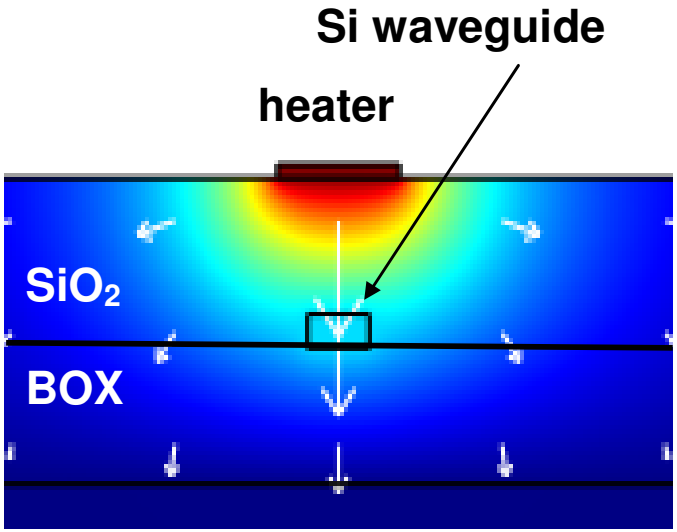
# Architectures for Thermal Tuning

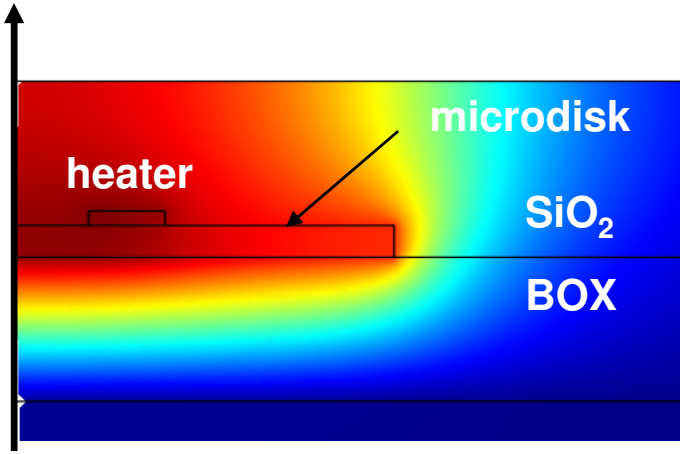
Thin-film micro-heaters over cladding layer

- Device optimization
- Pulsed excitation

**Thin-film micro-heaters on Si microdisk**

- **Possibility to improve reconfiguration speed**

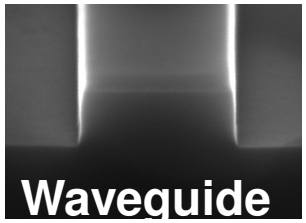


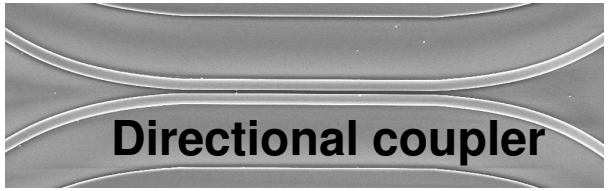



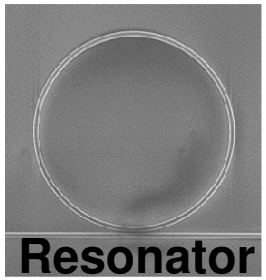

**Modeling heat conduction equation by finite-element-method**

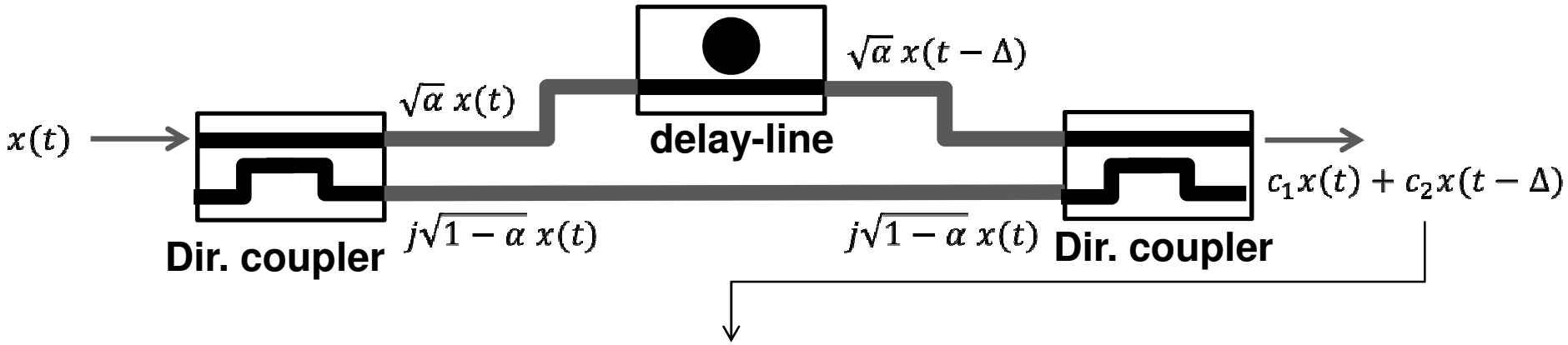
# Optical Signal Processing

- Linear optical components



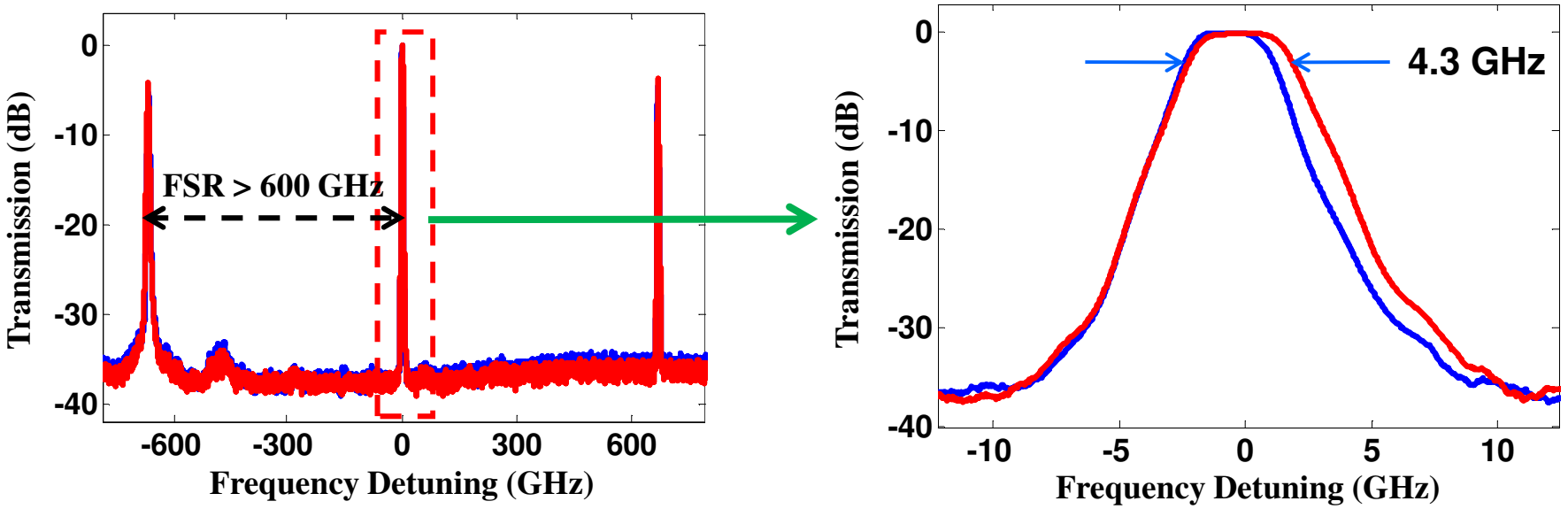




$$y[n] = c_1x[n] + c_2x[n-1]$$ **First-order FIR filter**

**Reconfiguration is essential**

# Measurement Results

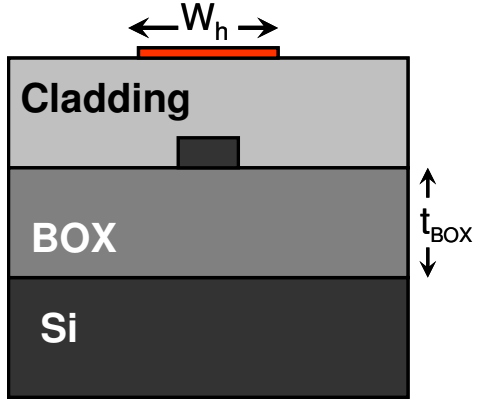
**4-pole, 4-zero 2-stage cascaded filter configured as a band-pass filter**



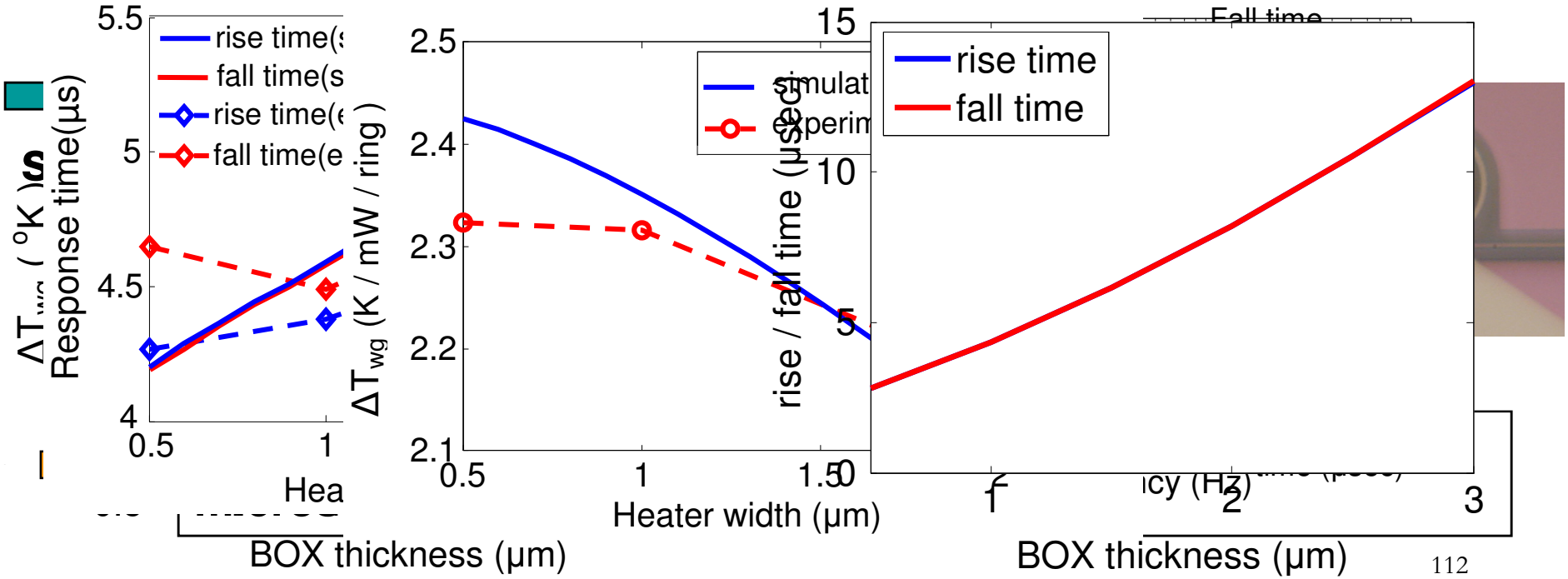

**Optical out-of-band rejection > 38 dB**

# Device Optimization

| | speed | power consumption |
|---|---|---|
| $t_{BOX}$ ↓ | ↑ | ↑ |
| $w_h$ ↓ | ↑ | ↓ |
| SiN cladding | ↑ | ↑ |



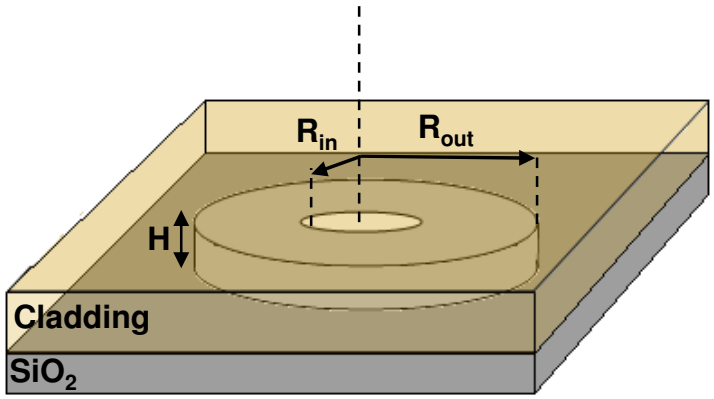

**P = 1mW / (20 μm diameter ring)** **1mW over 20μm diameter ring**



# Miniaturized Microdisk Resonator

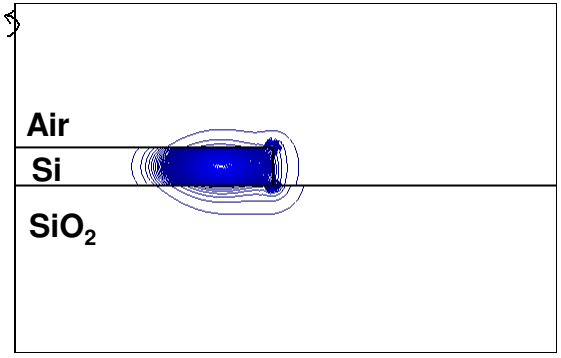
**Objective:**

- ❑ **Ultra small and high Q microdisk**
- ❑ **Single mode operation over a large bandwidth**
- ❑ **Higher order modes are pushed to cut off regime (strongly radiative)**



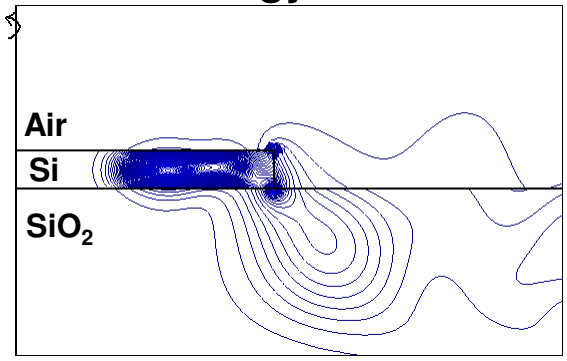

**Example**

**Electric energy: 1st order mode**

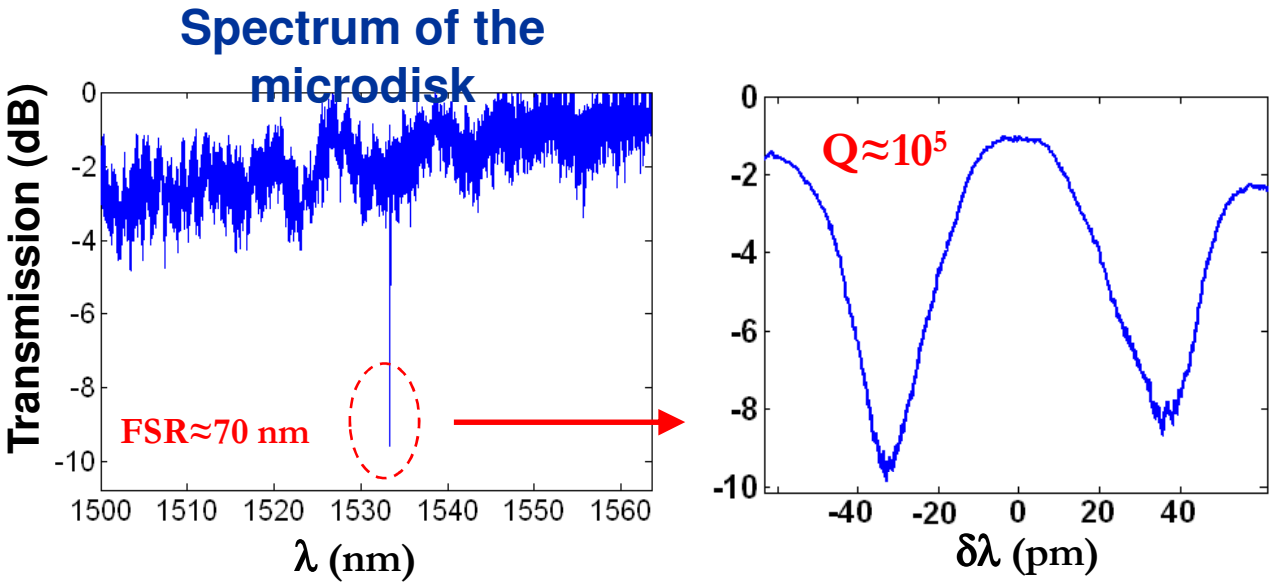


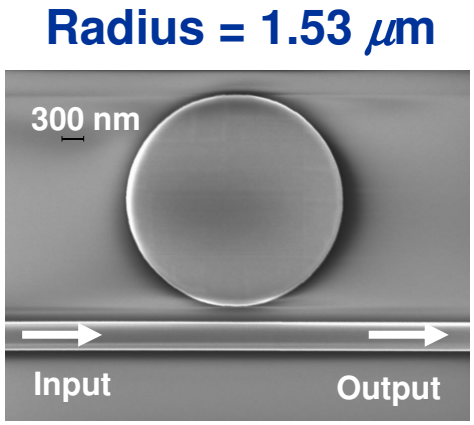

Disk radius = 1.4 $\mu$m
Disk thickness = 200 nm

**Electric energy: 2nd order mode**



# Demonstration of High Q and Low Mode Volume



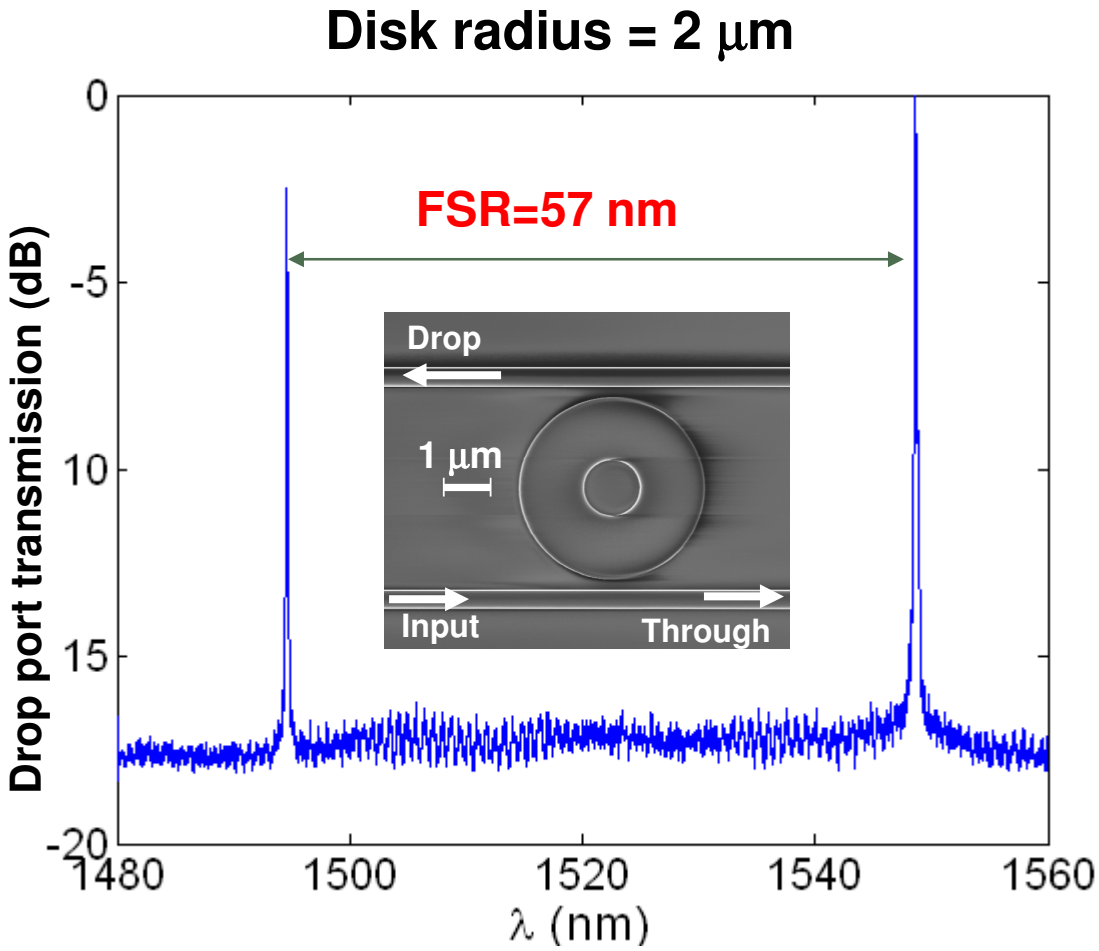




- Q~100,000 and mode volume $0.15(\lambda_0)^3$ was observed.
- Resonance splitting due to the sidewall roughness was observed
- Q can be more increased by improving the fabrication.

**A microdisk with a radius of 2 μm showed a Q~150,000**

# Add-drop Filter with Miniaturized Resonators

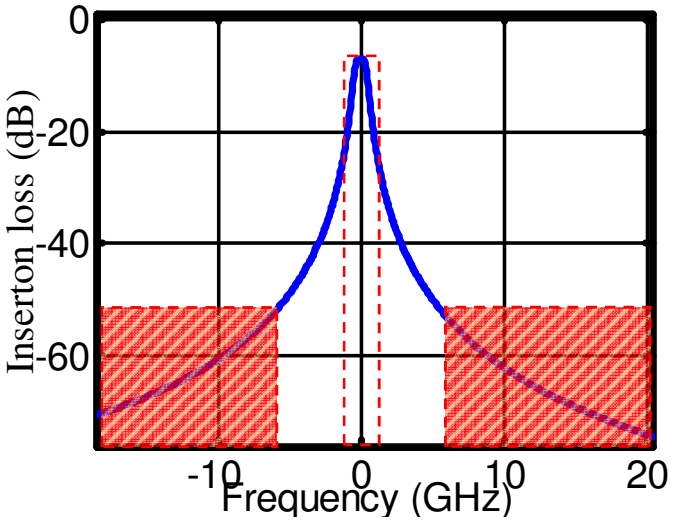
- Single mode coupling to waveguide over a wide FSR.
- Higher order modes are radiative.
- For practical purposes, the structure was covered by oxide.
- A linewidth of 50 pm and Q of 150,000 was obtained.

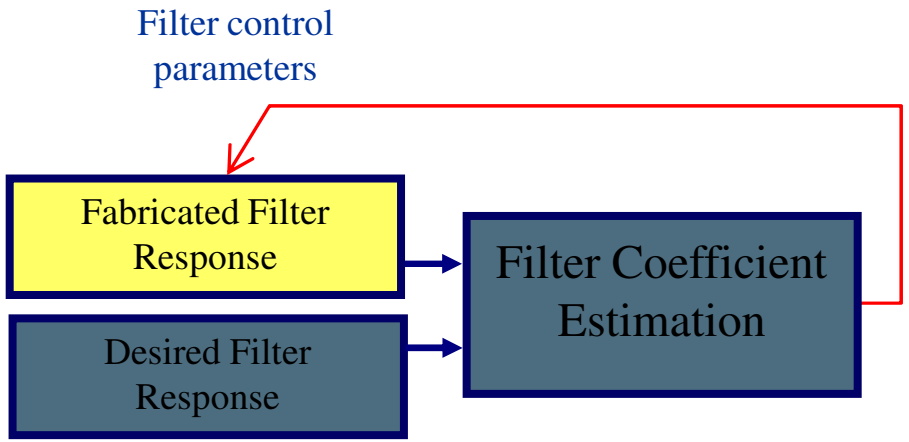



**Large bandwidth operation with high Qs and small mode volumes**

# Filter Optimization Algorithm

- Pole and zero Factorization
  → Cascading low order filters
  → Unstable for large filter orders
- Filter response recovery: The filter parameters are optimized to achieve the desired filter response
  → Constrained optimization based on weighted filter error cost function
  → Actual unit cell transfer function is used in the filter design
  → Allows for device calibration

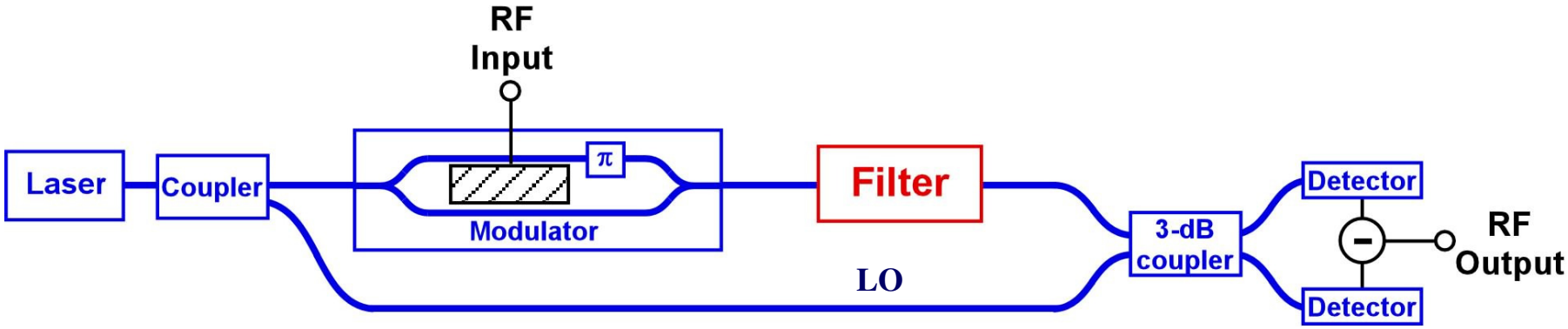


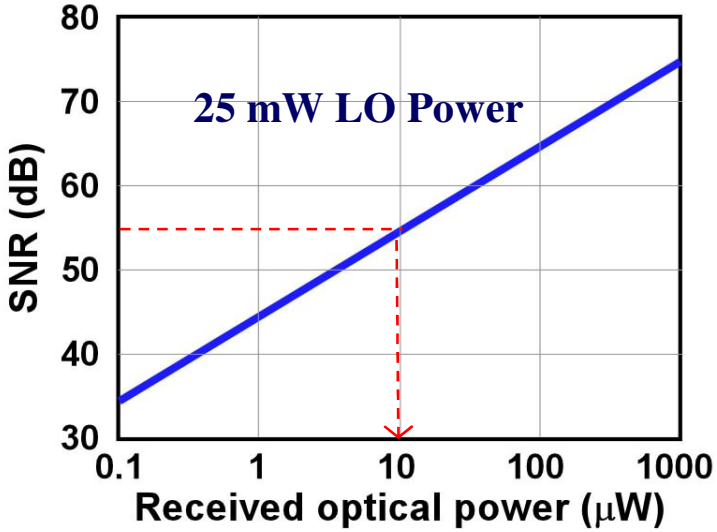




Georgia Tech proprietary information

# RF Photonic Applications of Si-PhASER Filter: Filter Requirements

- Single-Side-Band Modulation with carrier suppression

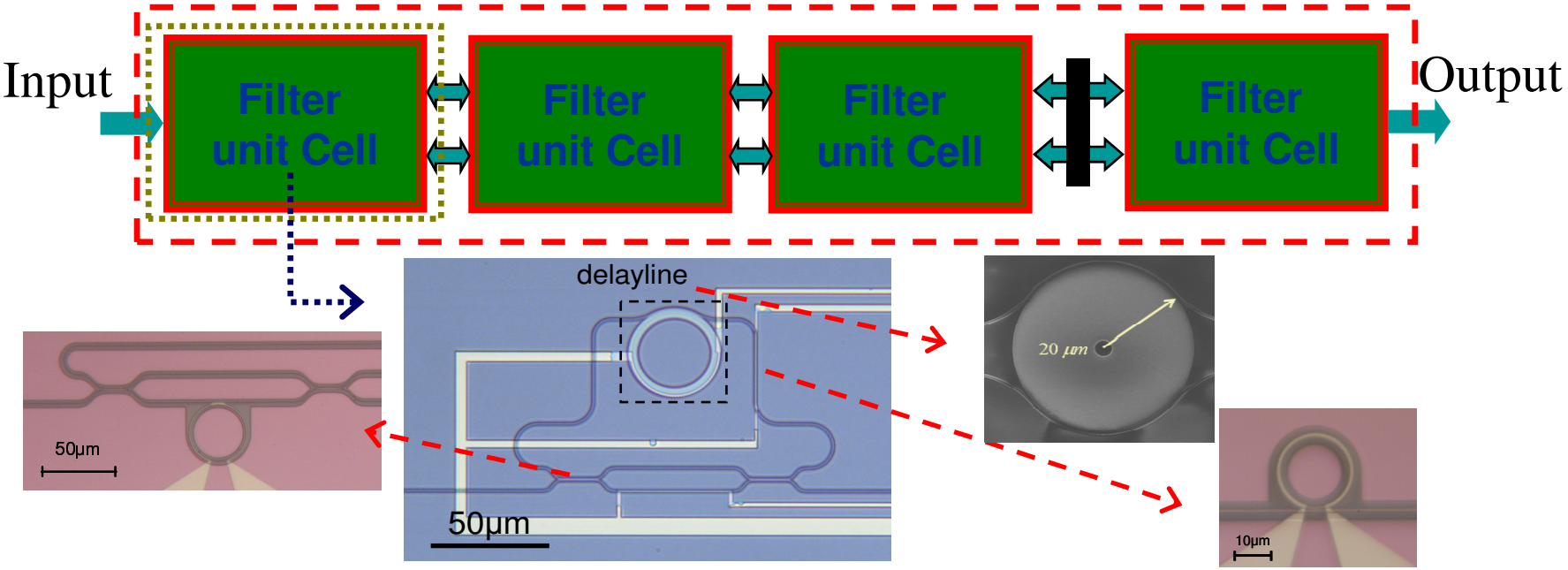



- 55dB SFDR @ 50MHz bandwidth
  → ~13 μW power requirement at the detector (40 μW for 60 dB SDFR)
- Input power: Limited by nonlinearity (< 2mW)
  → < ~20 dB total acceptable insertion loss (~14 dB for 60 dB SFDR)
  (< 2.5 dB waveguide to fiber coupling loss )

# Systematic High-Order Filter Design

- Higher order filter design based on cascading unit cell elements




- Unit cells require only three basic functionalities
  - Delay lines (fixed and tunable)
  - Phase shifters
  - Couplers

Georgia Tech proprietary information

# Acknowledgement


- This work was supported by the Air Force Office of Scientific Research











# Broadband On-Chip Coherent Optical Processing

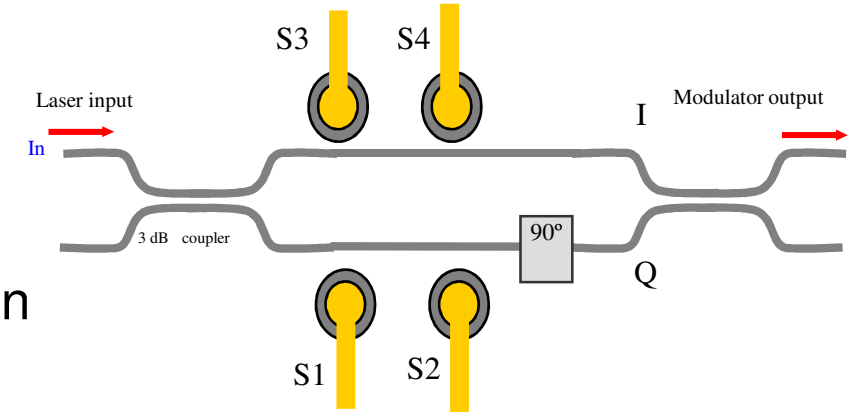
- Wideband coherent optical processing
  - Wideband optical signal (>THz bandwidth)
  - High spectral resolution (< GHz)

- Applications
  - Wideband communication modulators: Fiber optic networ, optical on-chip interconnection
  - Optical imaging and ranging (high resolution Lidar)
  - High speed optical front-end (High speed ADC)

- Requirements
  - Wideband coherent optical sources
  - Large scale integration of low power optical elements
  - Reconfigurable photonic circuits
  - Precise fabrication of photonic devices

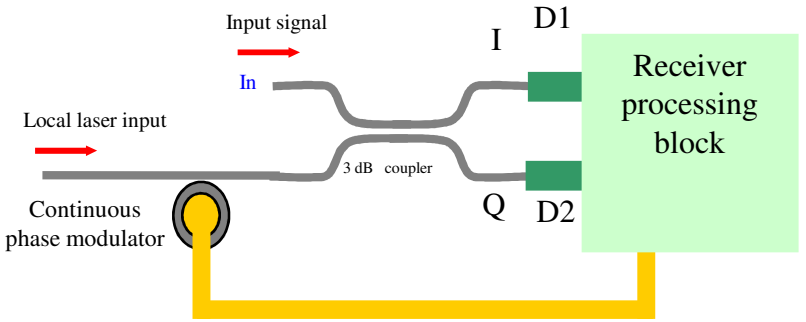
# Higher Spectral Efficiency Coherent Modulation

- Coherent modulation
  - Transmitter: Multiplexing multiple input stream
  - Receiver: Coherent detection with an on-chip PLL




**Integrated 16 QAM modulator**

- Advantages
  - Higher spectral efficiency
  - Lower switching power
  - Possibility of Reconfigurable modulation schemes

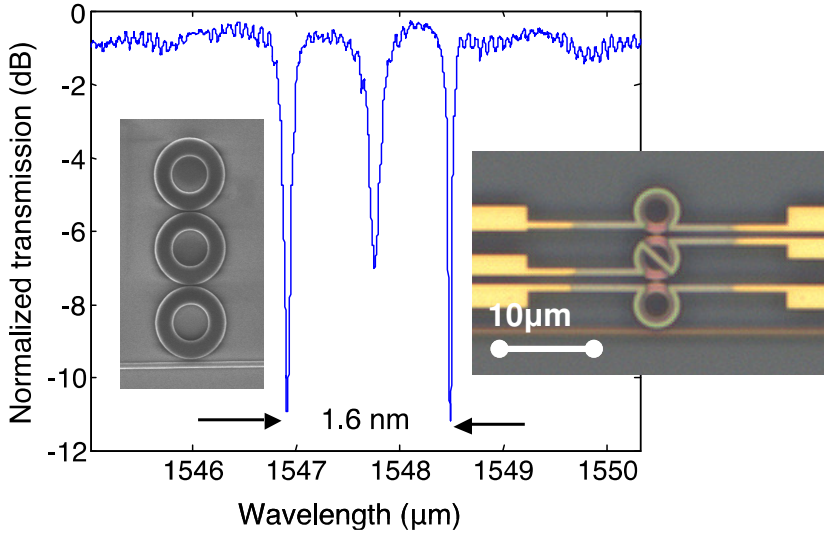



**Integrated coherent receiver**

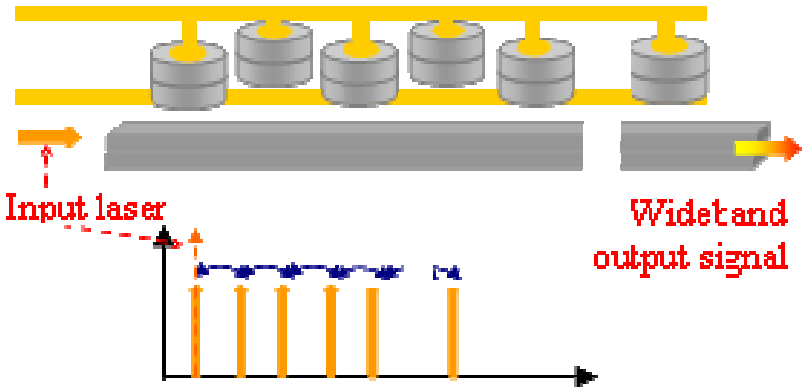
Coherent modulations enable higher

# On-chip Wideband Comb Generation

- Comb generation based on cascaded coupling through slight modulation
  - Array of coupled resonators with equally spaced resonance wavelengths
  - Coherent tone generation bu coupling of two resonator modes with carrier modulation
- Compact and high Q micro-resonators
  - Low power
  - High conversion efficiency



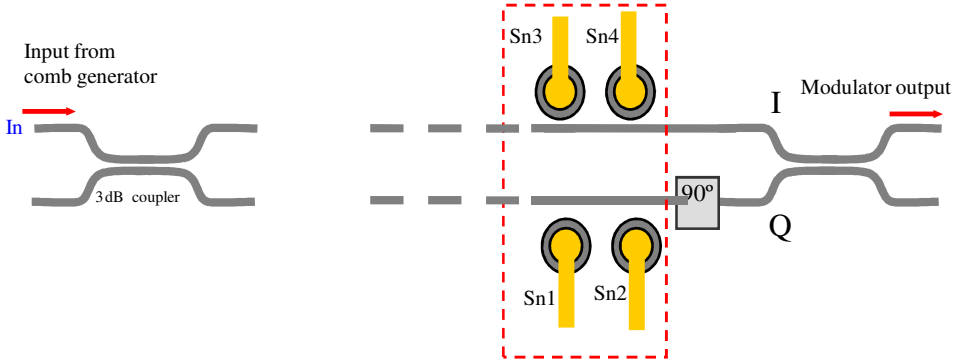

**Coupled resonators spectrum**




**On-chip comb Generation based on cascaded frequency tone generation**

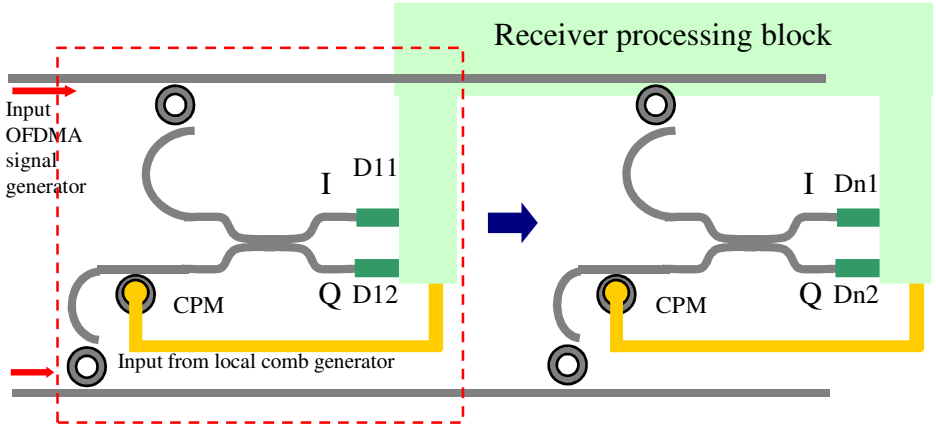
# Wideband Optical OFDM Modulation

- Optical OFMD modulation
  - High data rate modulation with single input laser
  - Enables more efficient local laser phase locking




**Integrated multi-tone optical OFDM modulator**

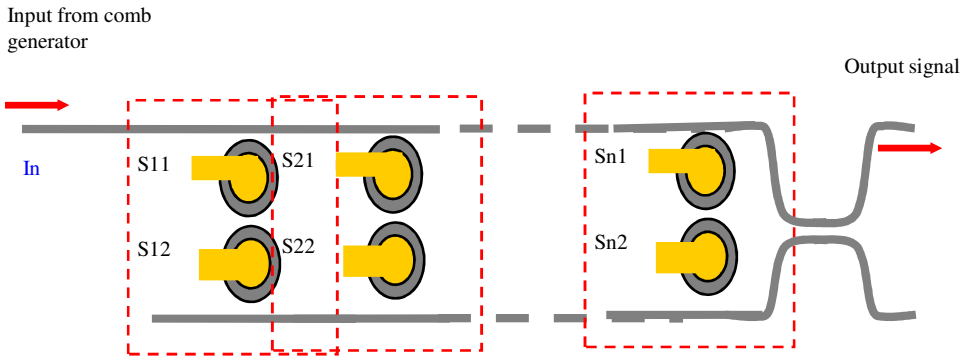
- On-chip Implementation
  - A comb generator as the input source
  - An array of higher spectral efficiency modulators



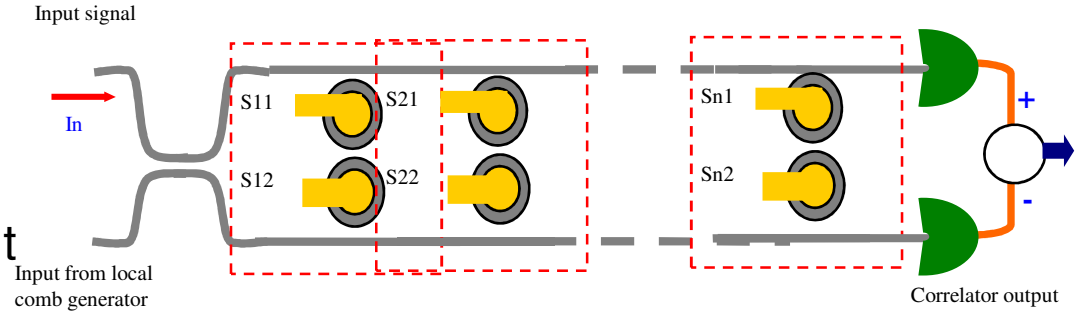

**Integrated optical OFDM Receiver**

# Wideband Spectral Optical Pulse Shaping and Optical Correlator for Lidar Applications

- Wideband and high temporal resolution pulse compression and correlation
  - Spectral and temporal multiplexing
  - Bandwidth: Comb input
  - Pulse period: modulating sequences
- Pulse shaper
  - A comb generator as the input source, array of modulator
- Correlator
  - Integration over time and spectrum



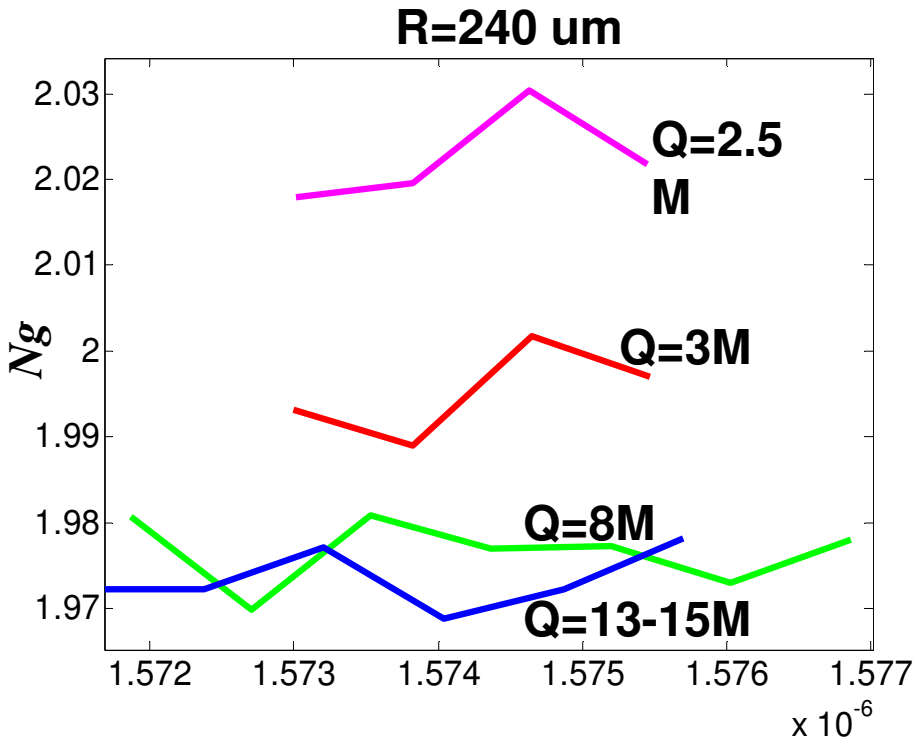

**Integrated spectral domain optical pulse shaper**

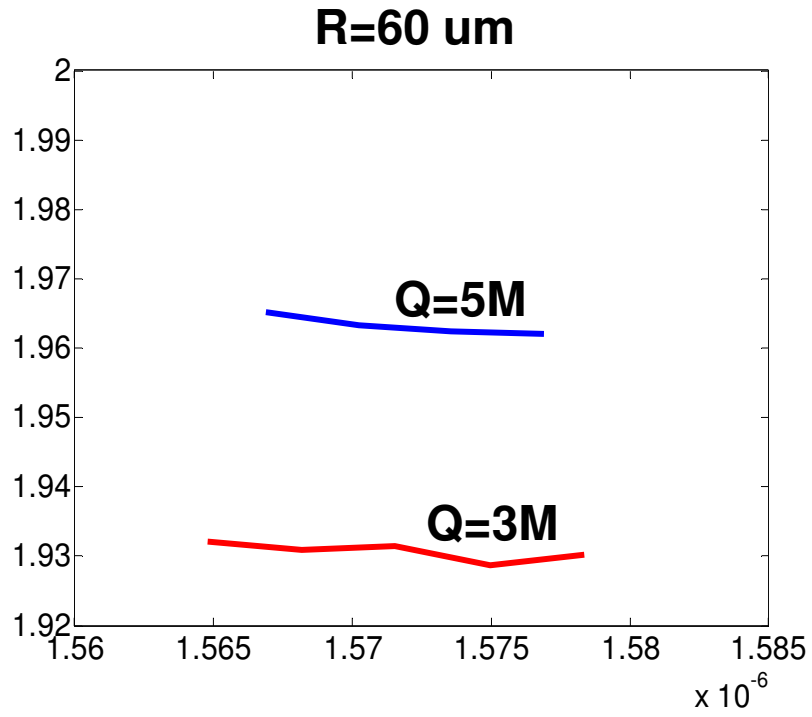



**Integrated time/spectral domain optical correlator**

Wideband optical correlator enables high resolution continuous Lidar

# Added on July 18 2012



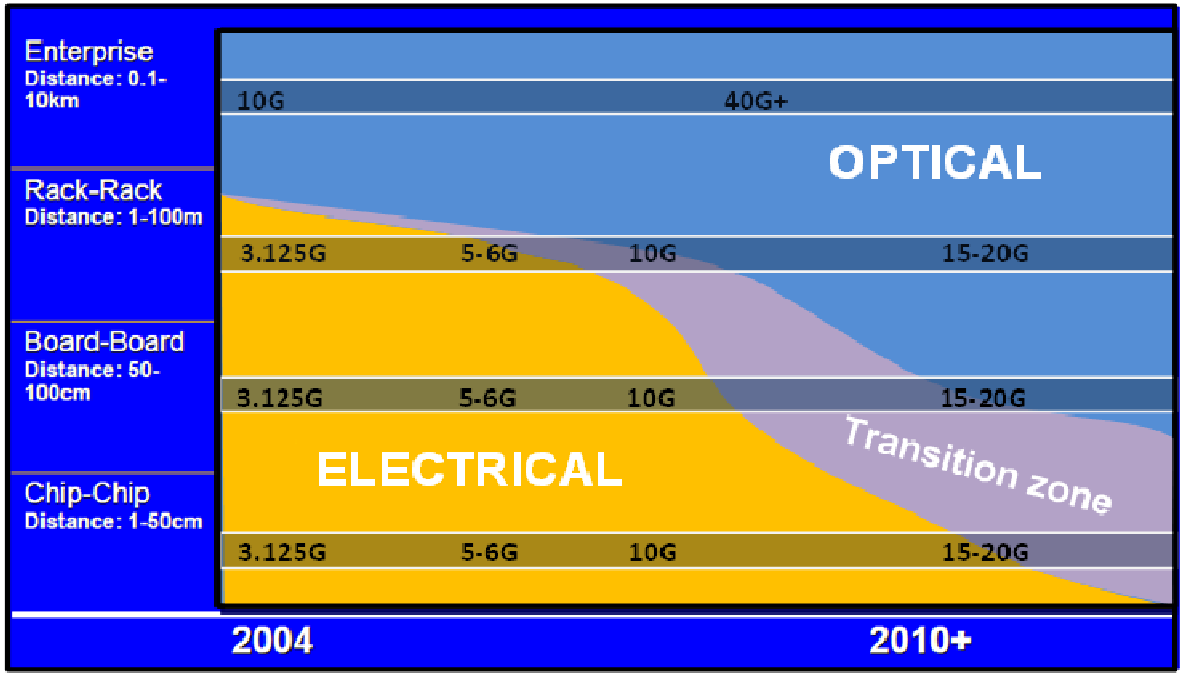



# Introduction

- Limited bandwidth and high propagation loss of electrical signals at high bandwidth (~10 GHz)

  ⇒ Optical communications/networks (> 1 THz)

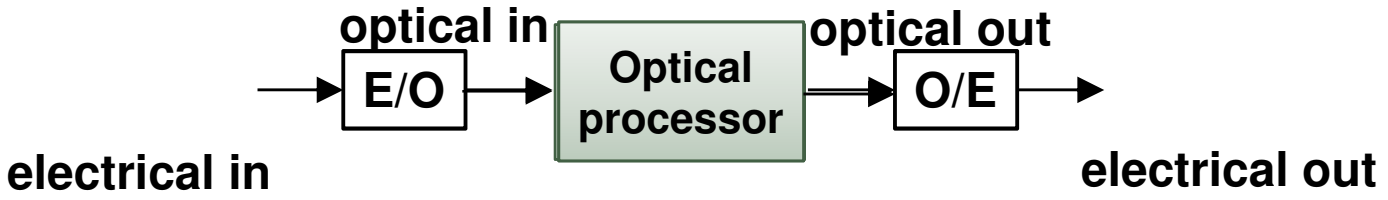
**Transition from electrical to optical communication**




**www.intel.com**

# Introduction

- All-optical signal processing required
  - Processing optical network data
  - Processing high-speed data in microwave systems




**Current technology**

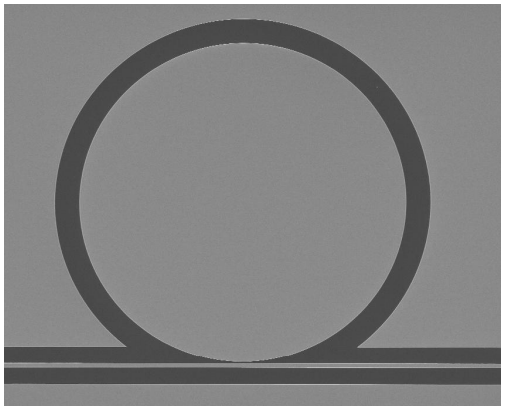
| | Cost | Size | Versatility | E/O, O/E | Bit rate |
|---|---|---|---|---|---|
| Electrical | Low | Compact | Very Hi | Yes | ~ 10G |
| Optical | Hi | Bulky | Low | No | >1T |

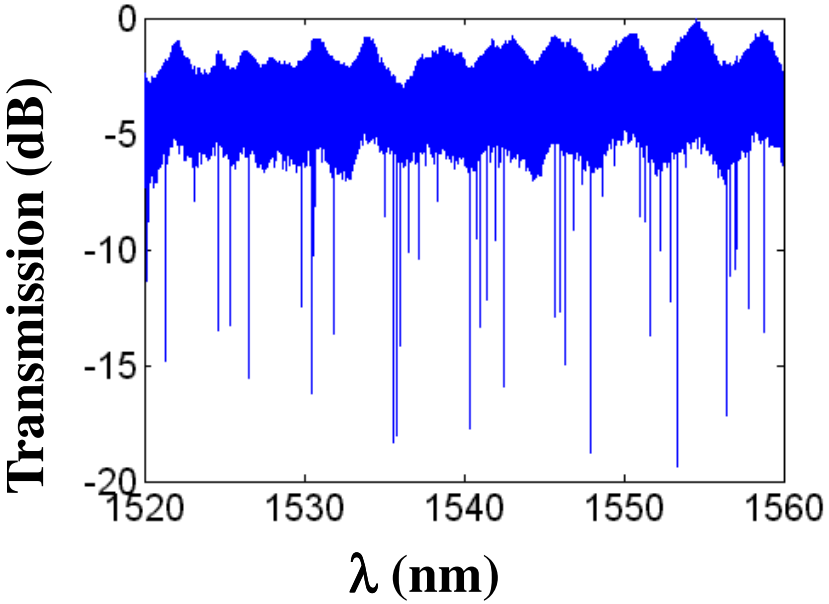
**Compact, inexpensive, and scalable optical SP**



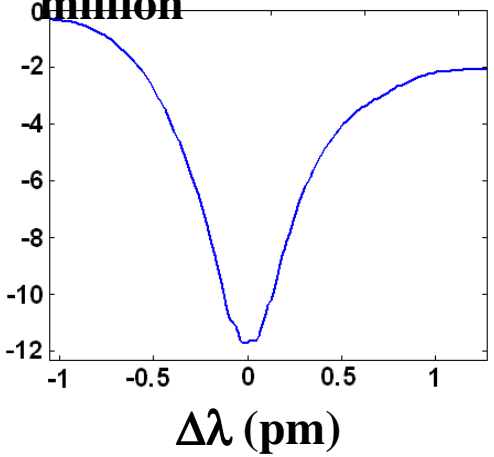
# Experimental Results on Ultra-high Q Microdisk

Radius 20 μm





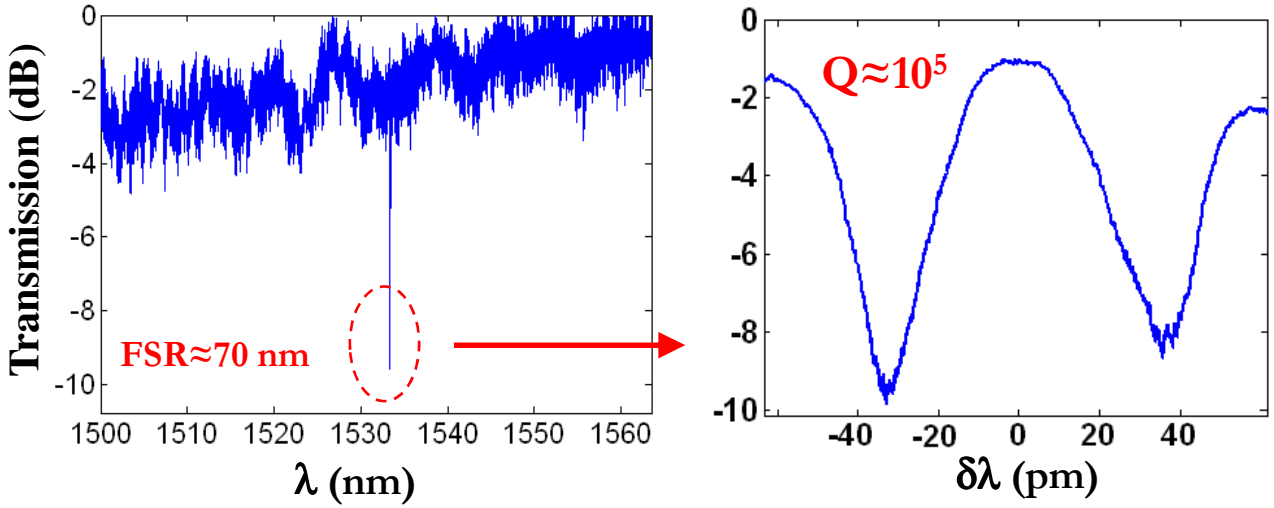

$Q_{Unloaded}$ ~ 3.2 million



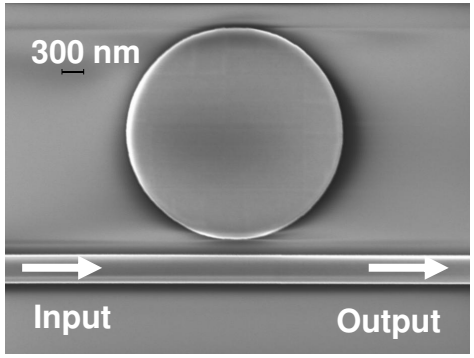

- Highest Qs to date for disks on substrate (visible and IR)
- Problems:
  - Higher order modes
  - Small free spectral range (FSR)
  - Critical coupling achieved at very small gaps

# Demonstration of High Q and Low Mode Volume

## Spectrum of the microdisk




Radius = 1.53 $\mu$m

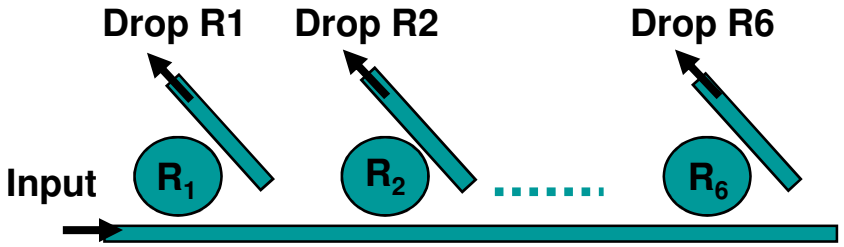


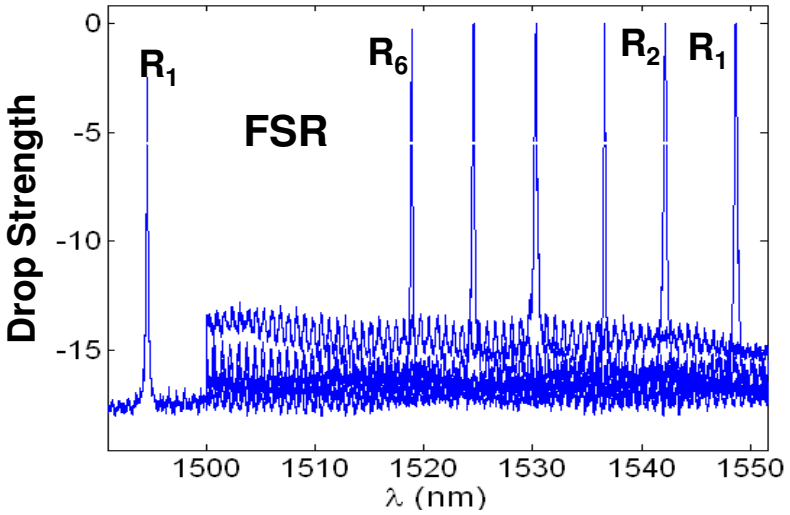

- Q~100,000 and mode volume $0.15(\lambda_0)^3$ was observed.
- Resonance splitting due to the sidewall roughness was observed.
- Q can be more increased by improving the fabrication.

**A microdisk with a radius of 2 μm showed a Q~150,000.**

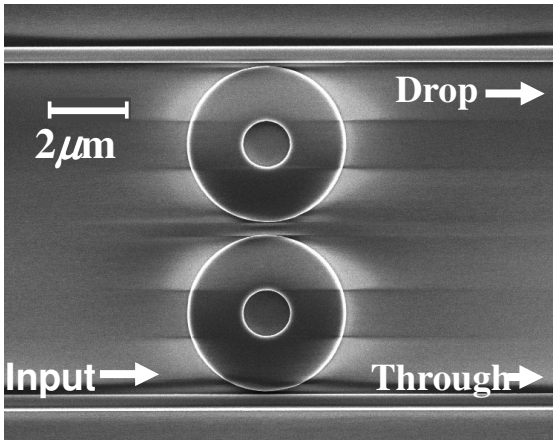
# Engineering the Spectral Response of Microdisk Resonators Over a Large Bandwidth

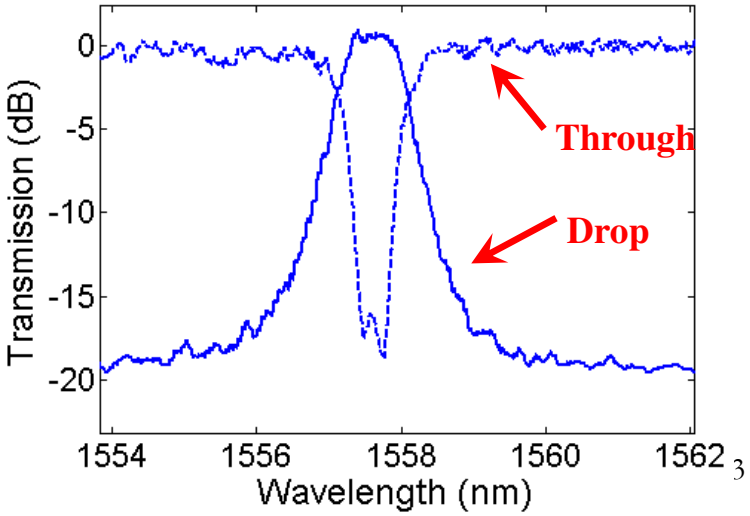
- Experimental response of an array Si resonators with radii around 2μm.



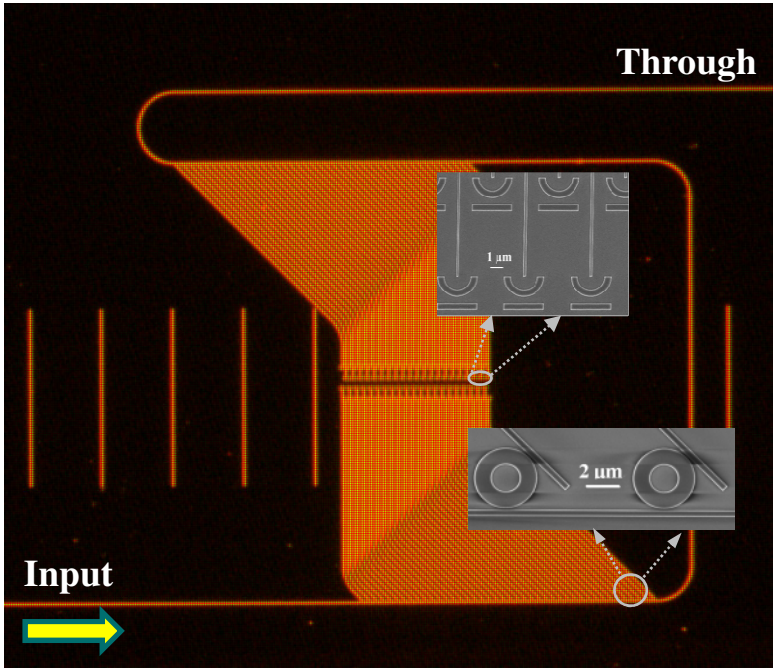

- Experimental response of CROW using disks with radii around 2μm.

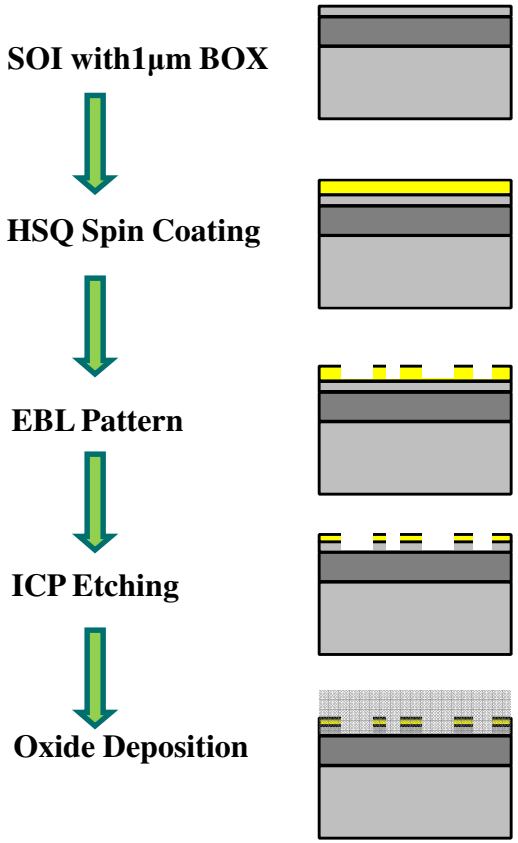


# Design and Fabrication

## An on-chip spectrometer using microdonut resonators

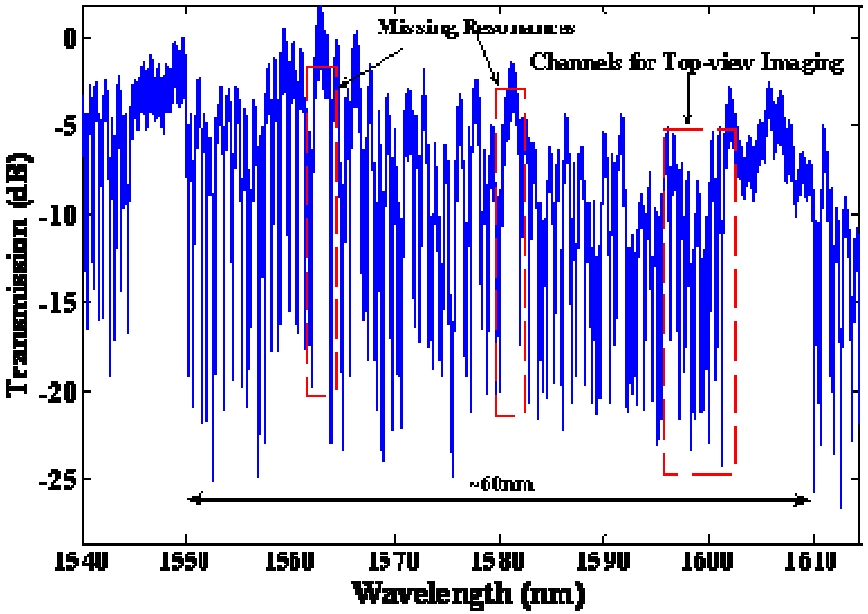


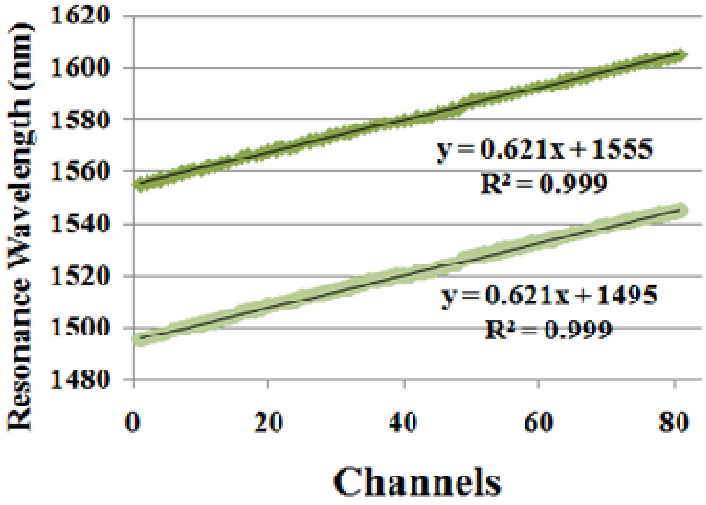

- Large scale array of 84 microdonuts
- Outer radius – 1.950 to 2.033 µm, step – 1nm
- 84 Scatterers for top-view imaging

# Characterization

## Through Port Spectrum



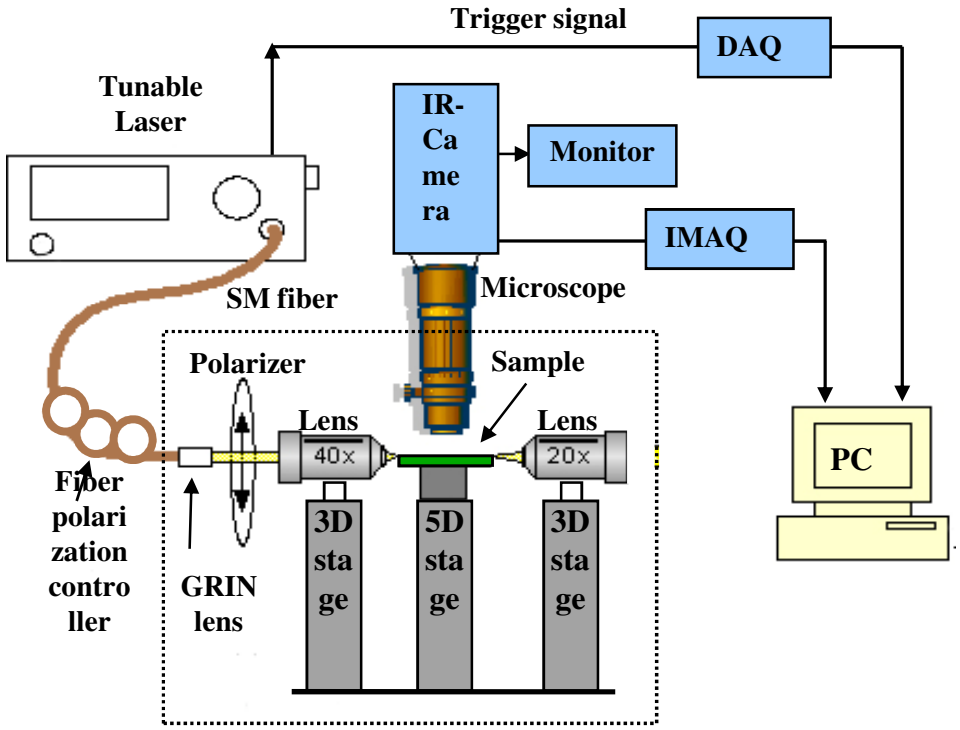

81 Resonances found in one FSR




Wavelength spacing~ 0.621 nm

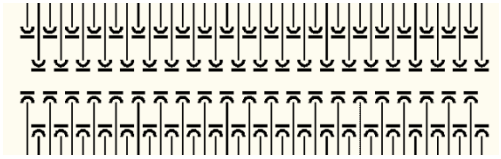
# Characterization

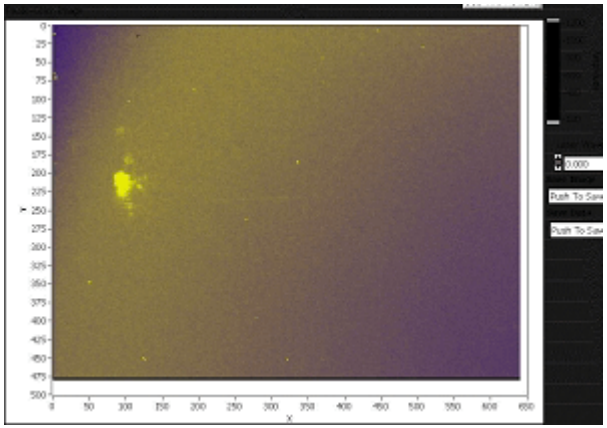
## Top View Imaging




Experimental Setup

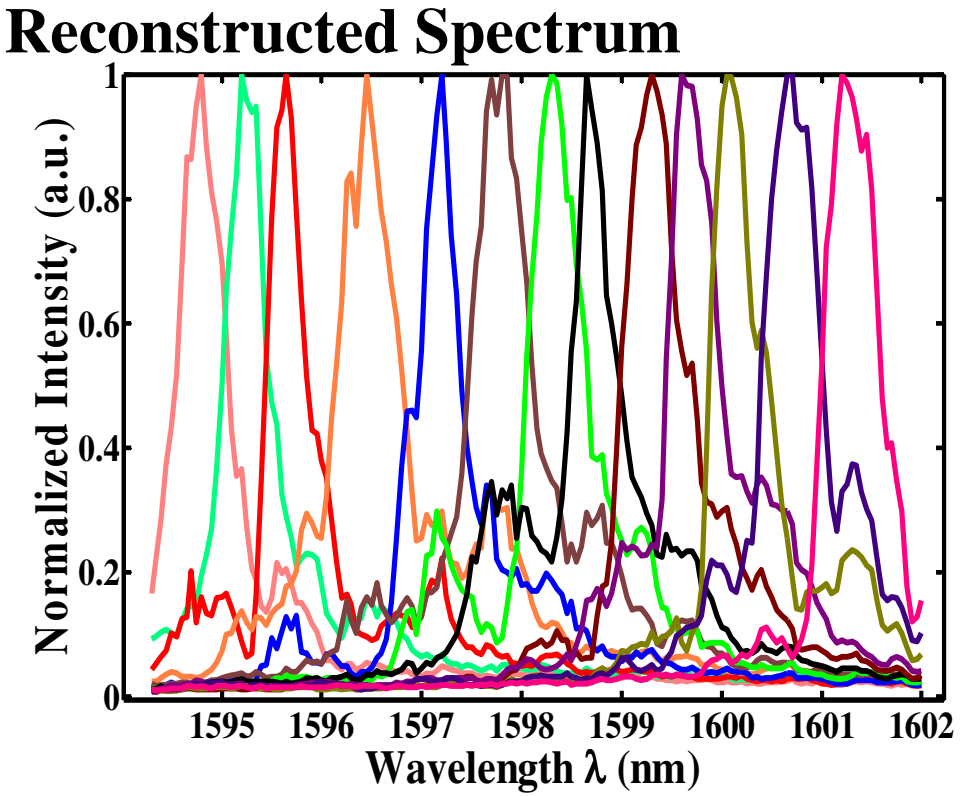
### Scatterer Array





Top View image evolution as the wavelength scans from 1550.0 nm to 1601.30 nm

# Characterization

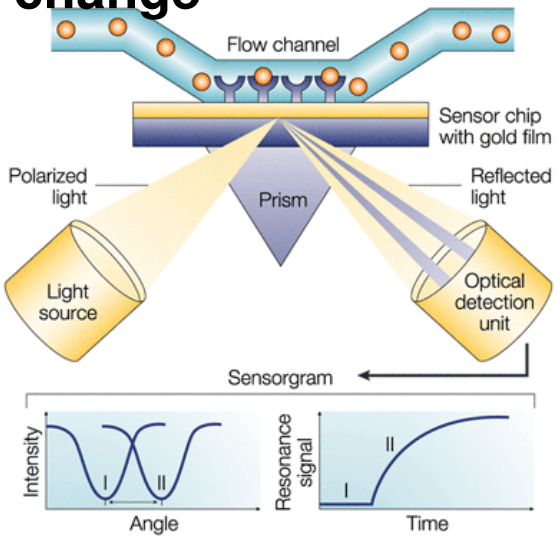



**Responses of 13 Channels**

- **Resolution~ 0.6 nm**
- **Crosstalk ~ -10 dB**

# Label-free Refractive Index Sensing

- Target molecule binding on surface → $n_{eff}$ changes → phase change

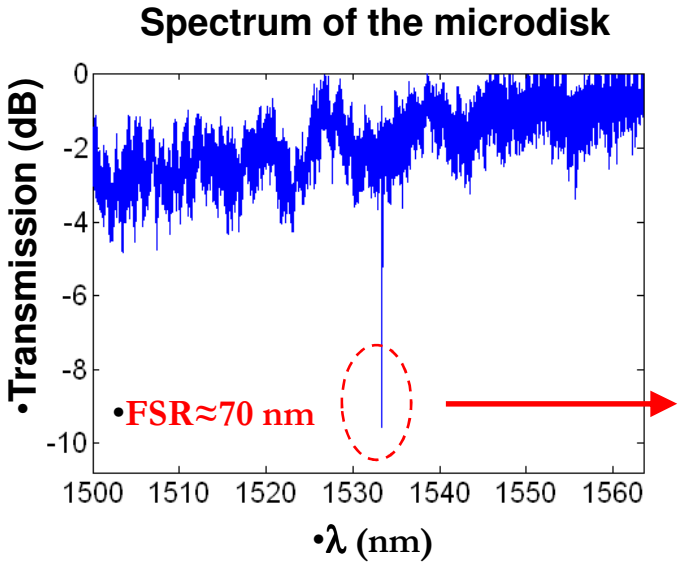


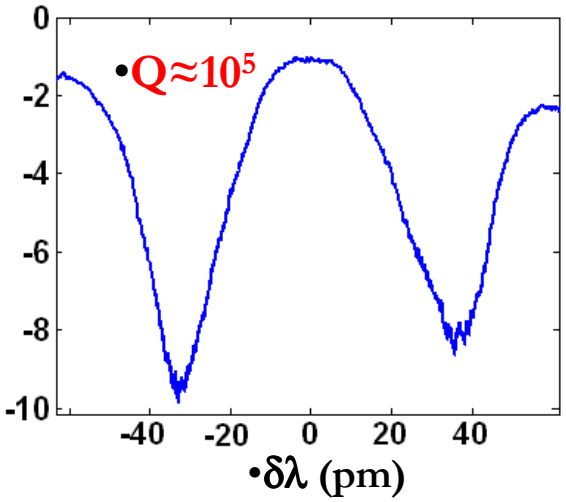


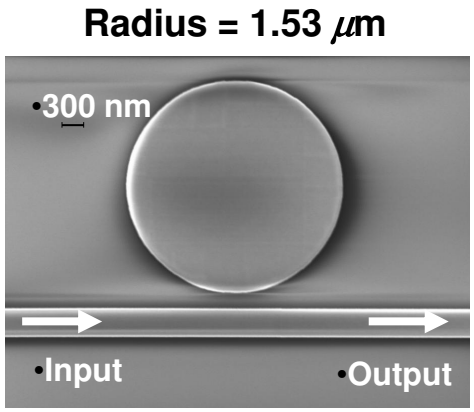

•Reference

- Surface Plasmon Resonance
  - Commercial system (e.g. BIAcore)
  - Bulky external optics
  - Typical protein detection sensitivity ~ *50 ng/mL*
- Mach Zehnder Interferometer
  - Long interaction length (cm) to enhance phase sensitivity
  - Typical protein detection sensitivity ~ 5 ng/mL

# Scaling of Microresonators: High Q and Low Mode Volume



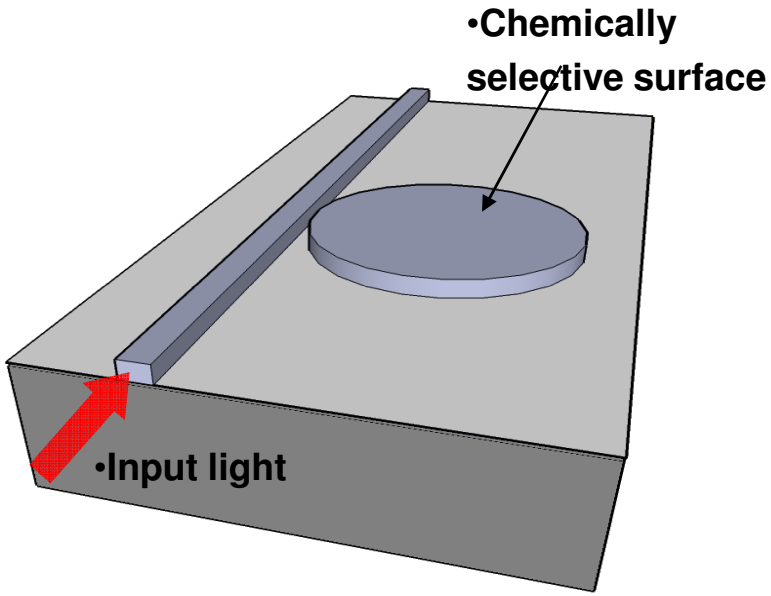




❑ Q~100,000 and mode volume $0.15(\lambda_0)^3$ was observed.

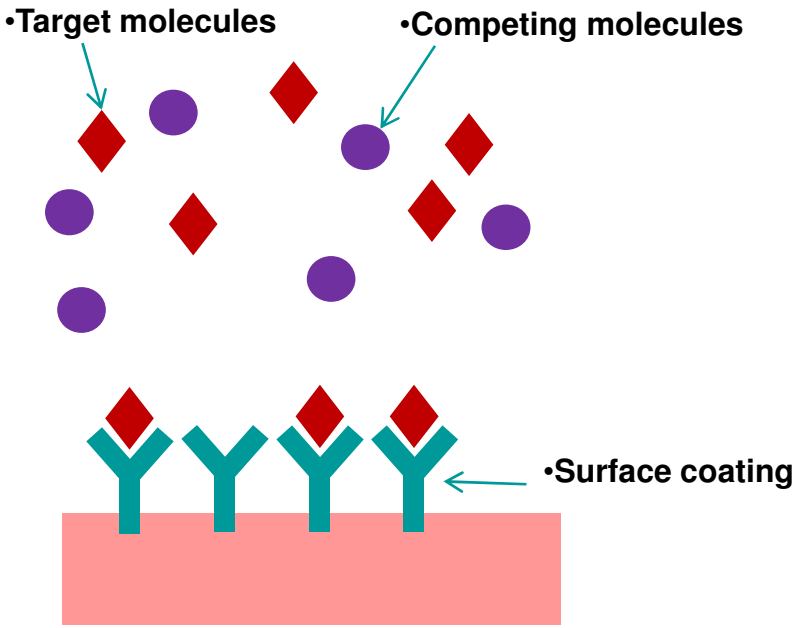
•A microdisk with a radius of 2 μm showed a Q~150,000

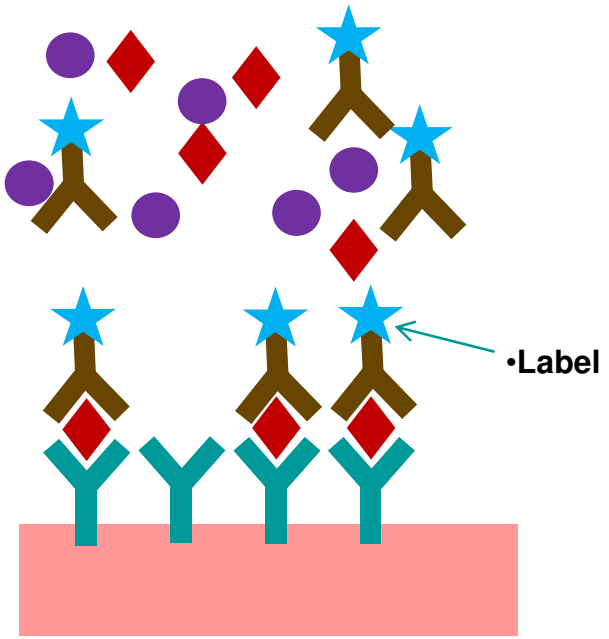
# Integrated Photonic Sensing

- Integrated optical sensors for bio and gad detection
- Applications
  - Hazard detection
  - Biomolecule sensing
  - Environmental sensing
- Advantages
  - Compactness
  - High sensitivity (field enhancement)
  - Minimal amount of specimen requirement



# Optical Sensing Modes

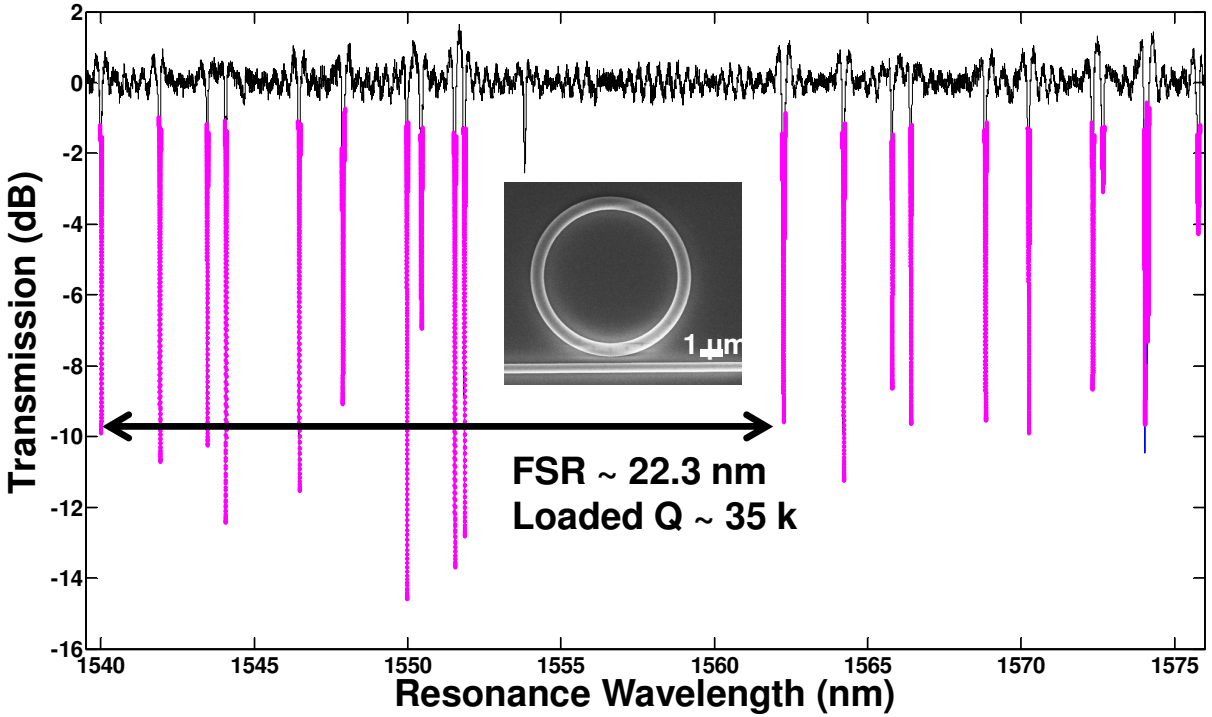



- **Label-free detection**
- ***Refractive Index***
- ***Raman***
- ***Optomechanical***

- **Labeled sensing principle**
- ***Fluorescence***

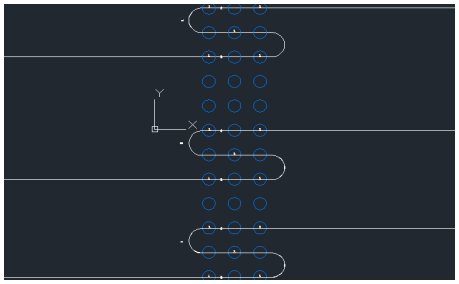
# Sensing Element: Compact Microring Resonator

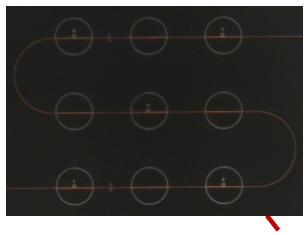


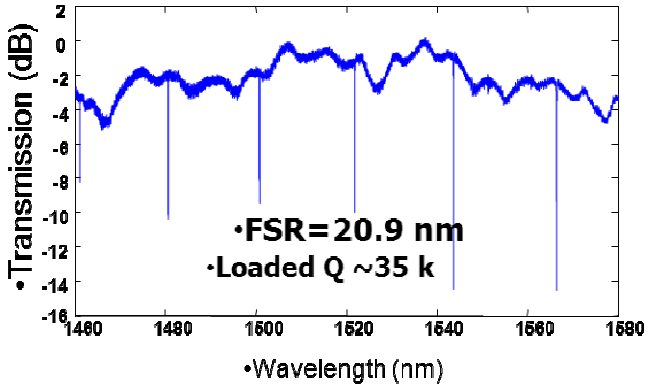

**Transmission of an array of 10 microring resonators under TM polarization**

High Quality factor (35,000) → High detection resolution
Compact resonator (radius ~ 4 um) → Large free spectral range (FSR) → high multiplexing
TM polarization → High sensitivity

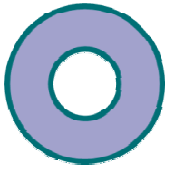
# Selective Coating of Sensing Resonators with Different Polymers



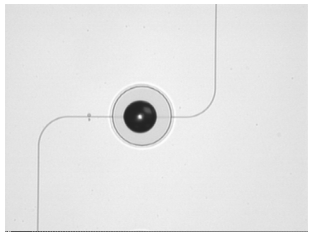






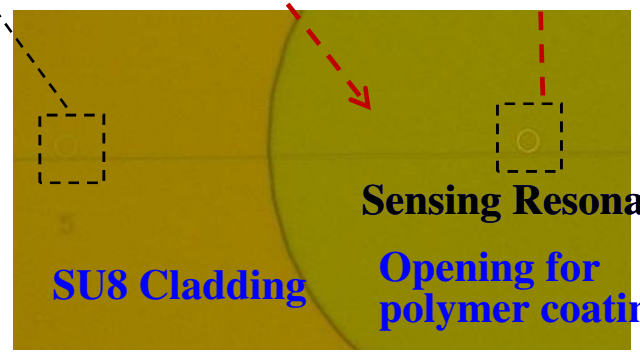



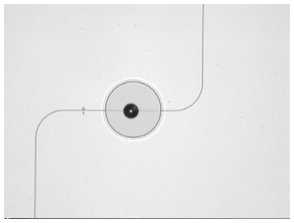
Outer radius ~ 4.3 µm
Inner radius ~3.6 µm
Thickness ~250 nm



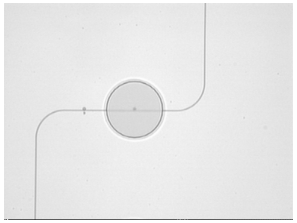
Right after drop coating

Ref. Resonator



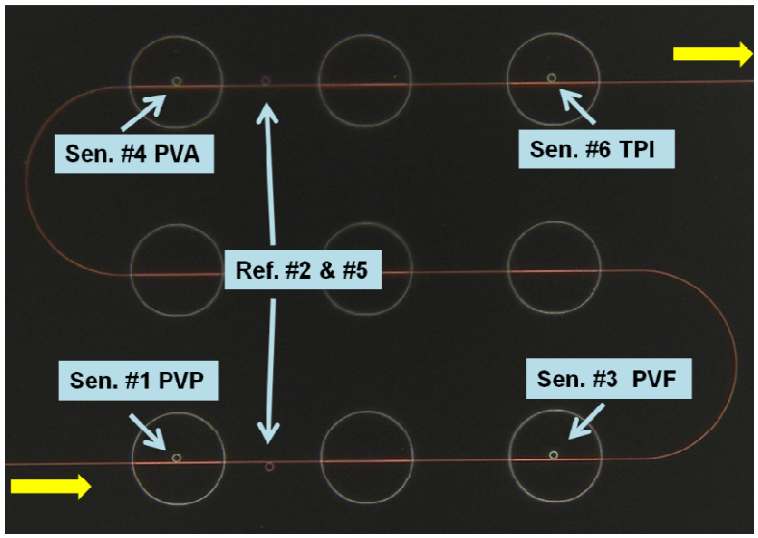



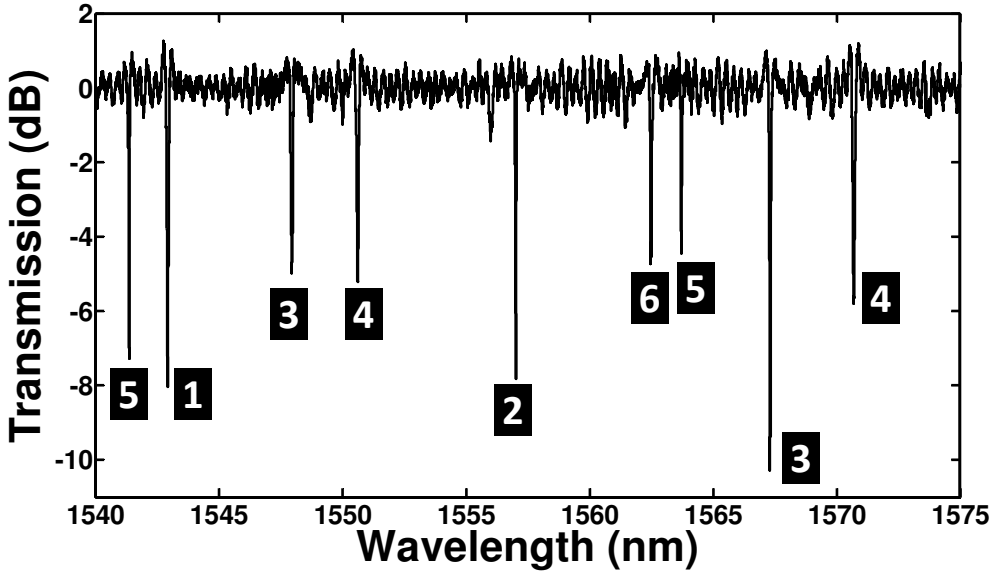
Solvent is in evaporation



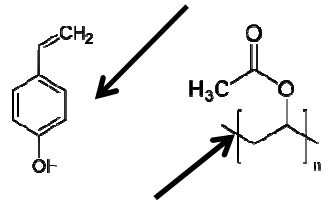
Evaporation is complete

# Resonator Array After Polymer Coating



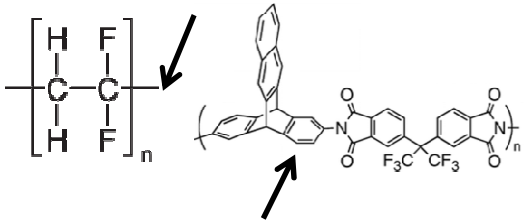




**PVP** Poly(4-vinyl phenol)



**PVA** Poly(Vinyl acetate)

**PVF** Poly(vinylidene fluoride)



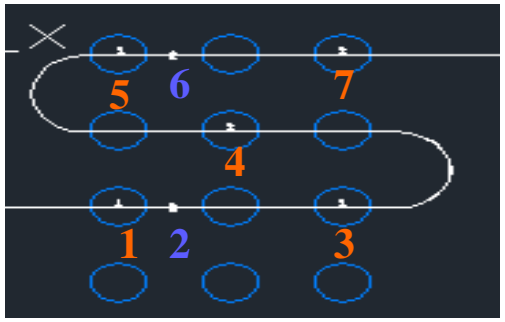
**TPI** Triptycene Polyimides

Four different polymers are selected to coat the resonators individually;

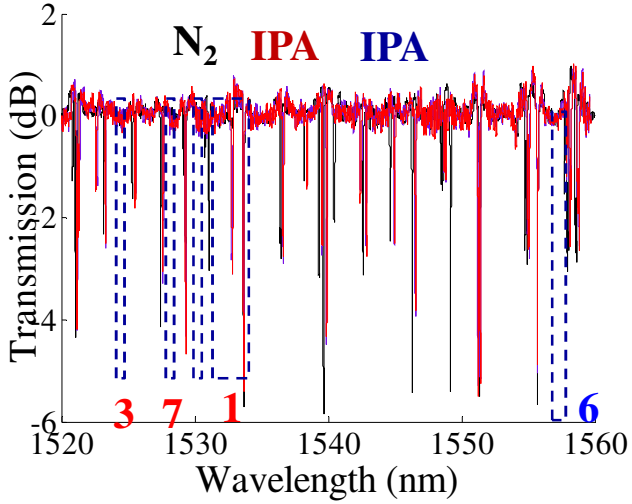
The resonances of the sensing elements are first Identified in the calibration prior to the gas sensing experiment;

Resonators #2 and #5 are designed to compensate the adverse environmental effects;

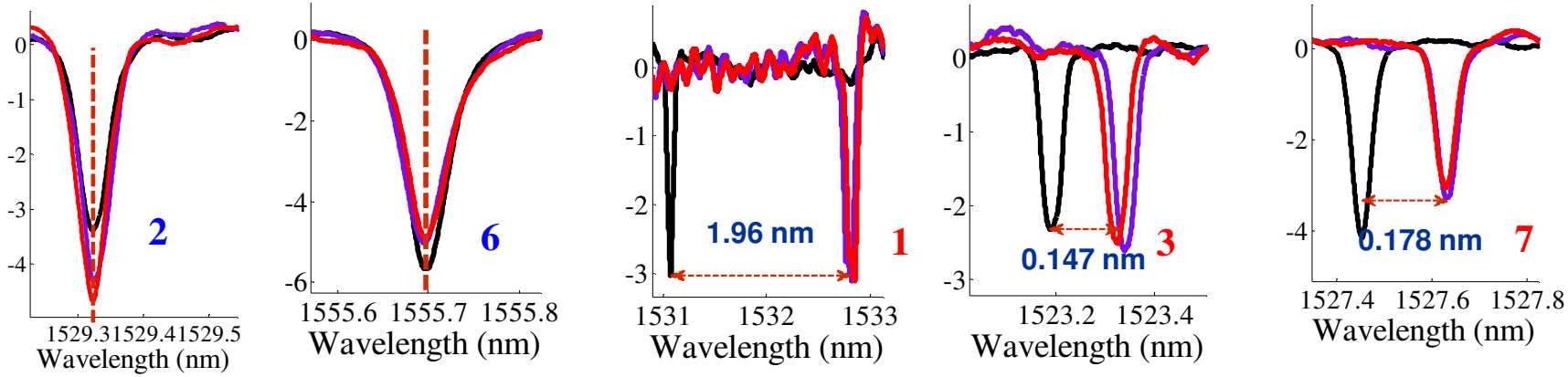
# Multiplexed Gas Sensing with On-chip References




**1: Poly(4-vinyl phenol)**
**3: Poly(vinylidene fluoride)**
**4: No coating**
**5: Poly (Vinyl acetate)**
**7: TPI 1 from MIT**

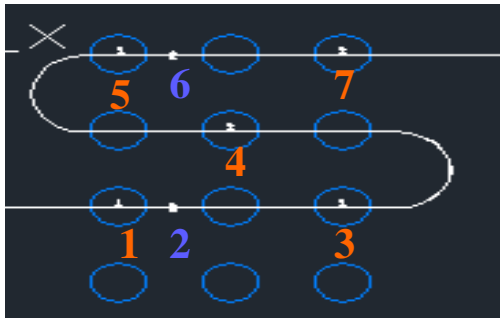



**IPA**

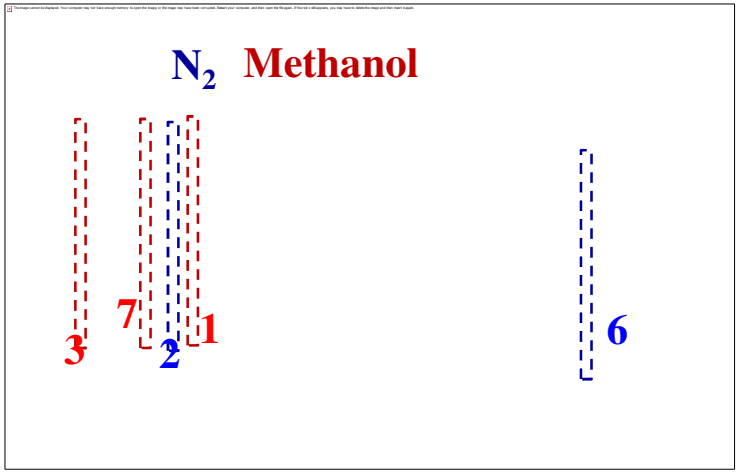



- **Different coatings respond differently to different analytes**
  - Use reference resonator to correct for temperature bias and drift
  - Use differential measurement to detect different analytes in a mixture

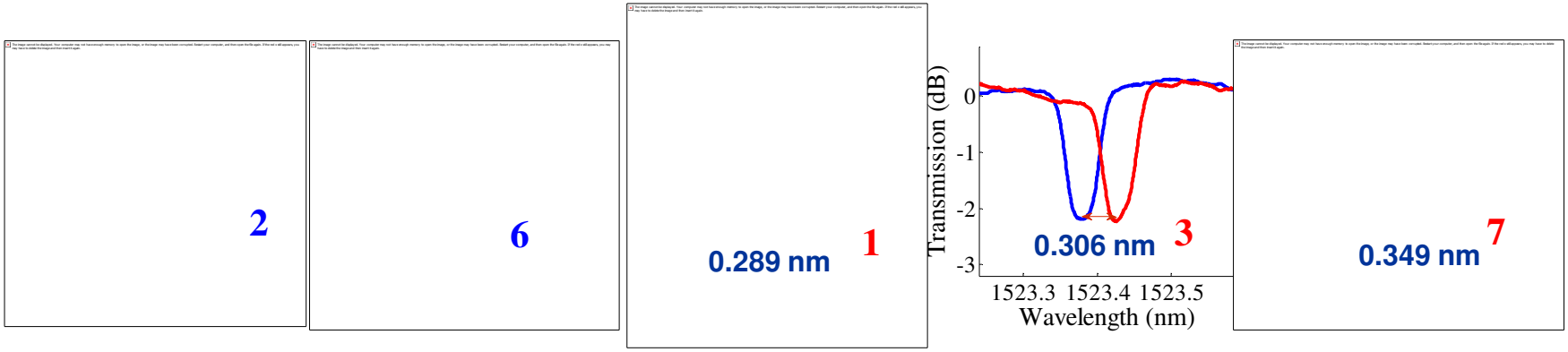
# Multiplexed Gas Sensing with On-chip References



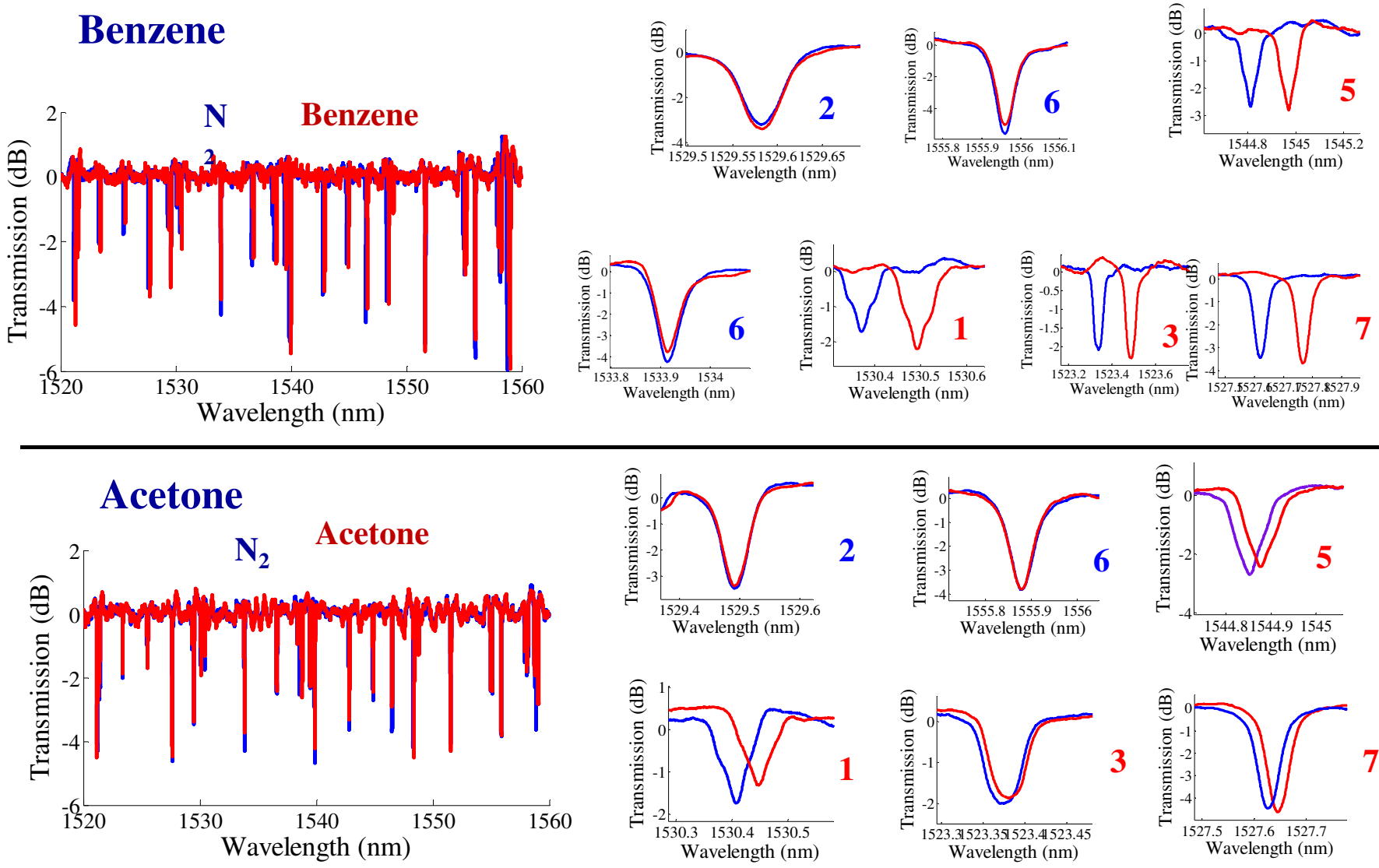

1: Poly(4-vinyl phenol)
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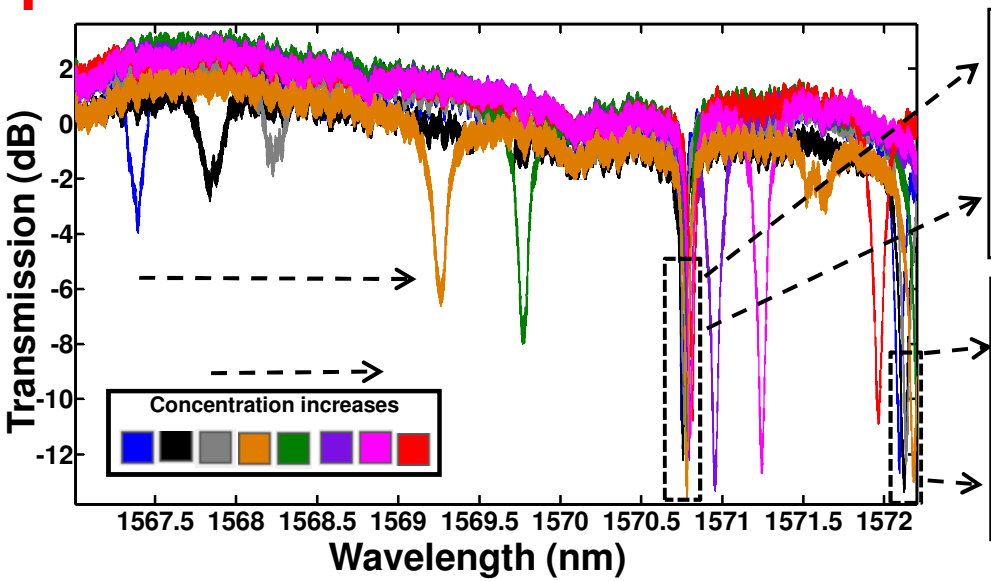

## Methanol

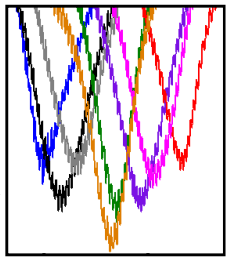


# Multiplexed Gas Sensing with On-chip References



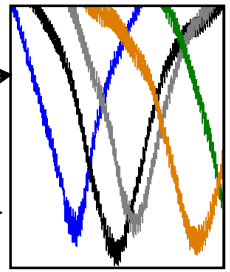
# High-sensitivity Demonstration of IPA Sensing with PVP-coated Resonators



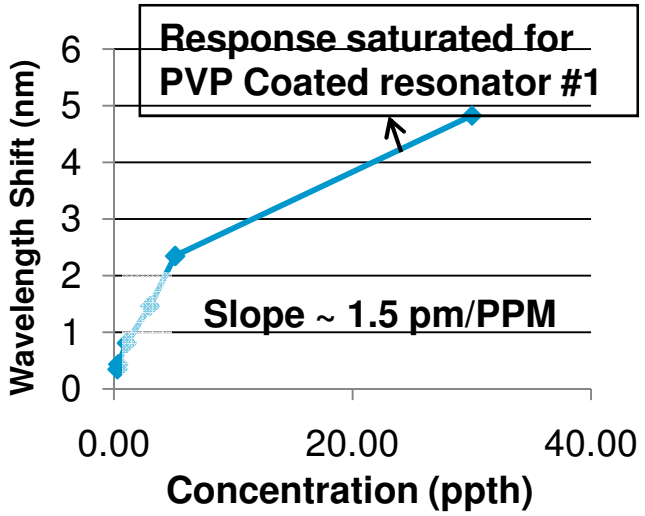
**Ref. Resonator #5**

Resonance wavelength drifting of the Ref. resonator shows the temperature variation during the sensing test.



**Sensing Resonator #4 with PVA**

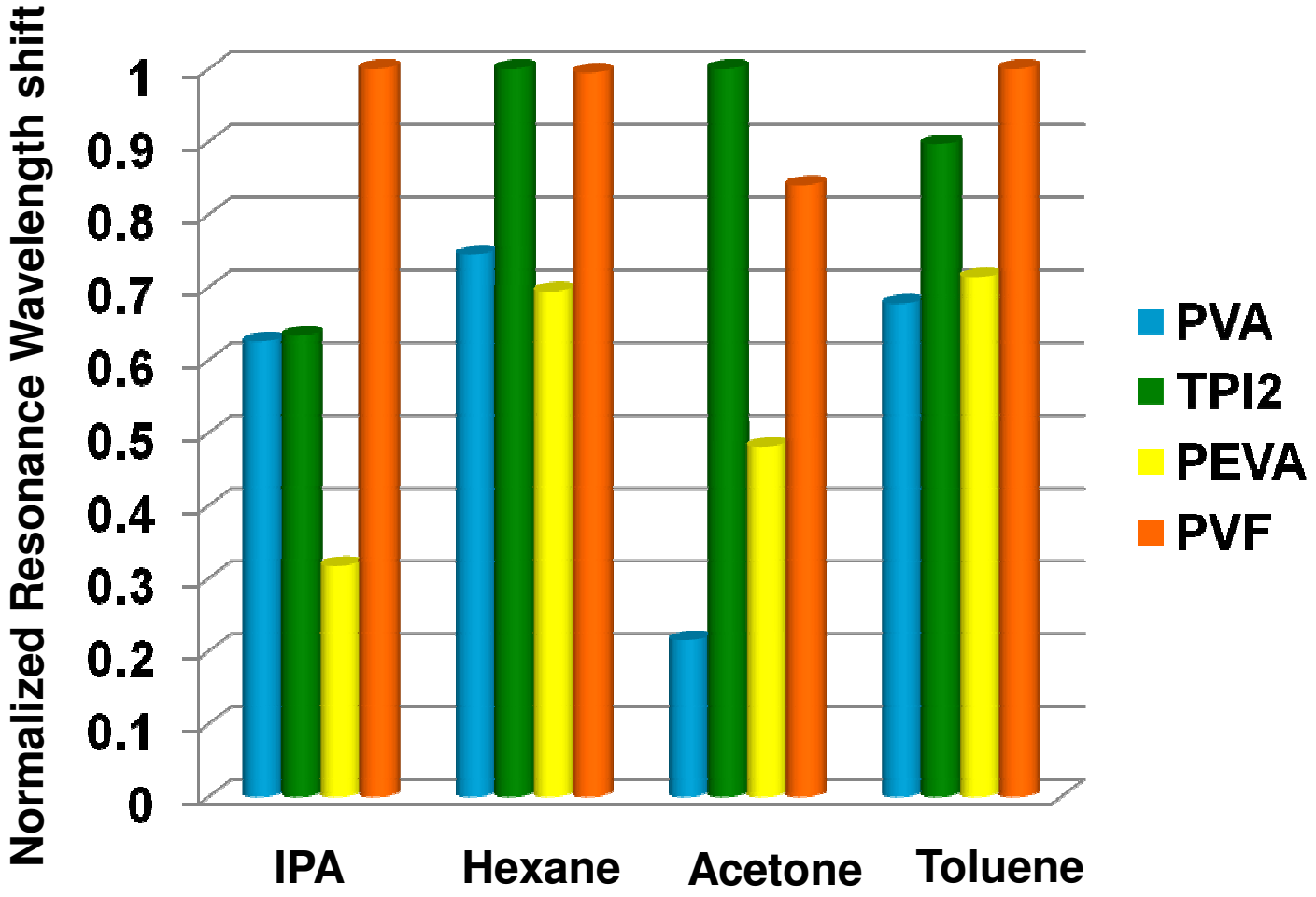
Resonance wavelength is increasing, but much slower than Res. #1 coated with PVP.




Resonance wavelength of PVP coated resonator #1 increases dramatically as the concentration of incoming IPA vapor increases

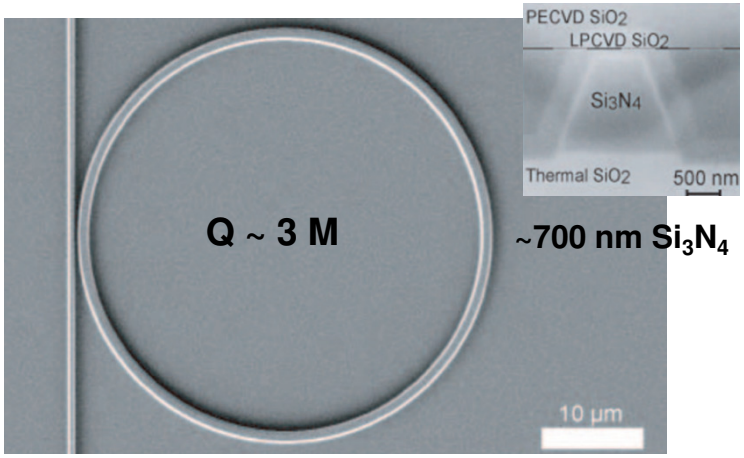
- With optimized polymer coating and optical design, Res. #1 shows high sensitivity under TM polarization;
- Extinction ratio of Res. #1 changes gradually as a result of the increase in the refractive index of polymer cladding with loaded vapor molecules;
- Calculated sensitivity is ~ 1.5pm/PPM for IPA, showing the capability of detecting at sub-PPM range with 1pm detecting resolution;

# Multiplexed VOC Vapor Sensing



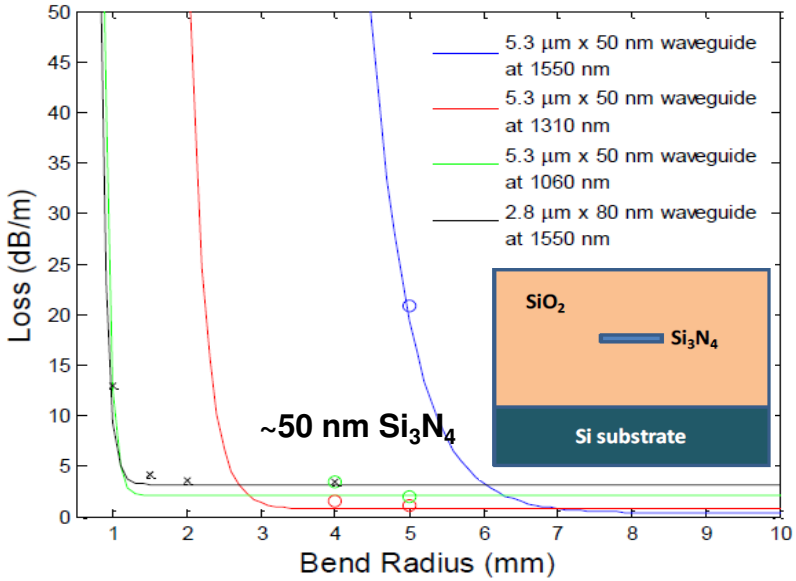

- The diversity of the response of different polymers to different gases enables multiplexed gas sensing.

# High-Q/Low-loss SiN Devices




**Michal Lipson, et al., Cornell (2009)**

Thick $Si_3N_4$ layer allows compact microresonators but the propagation loss is relatively high (>0.1 dB/cm)



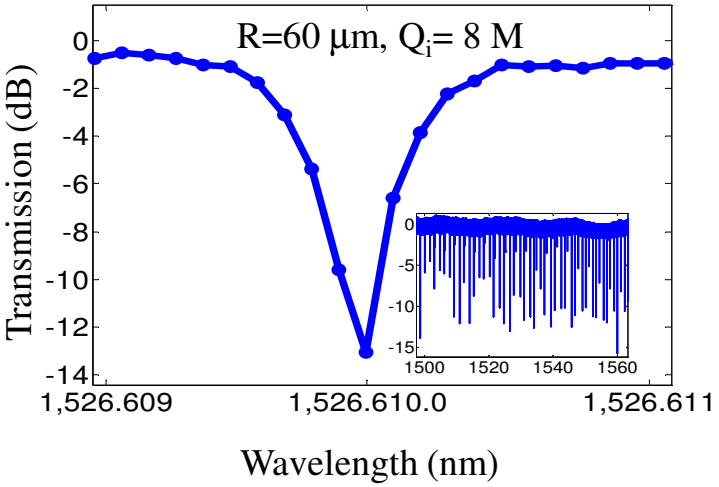

**John E. Bower, et al., UCSB (2011)**

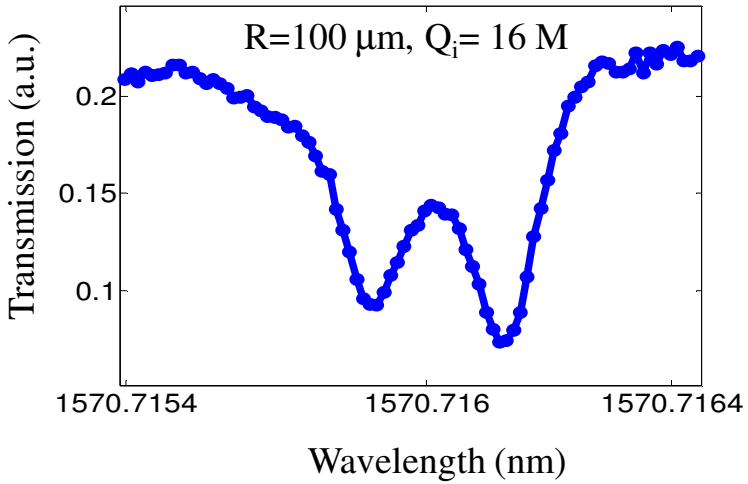
Thin $Si_3N_4$ layer: low loss (~ 0.1dB/m) but weak guiding capability.

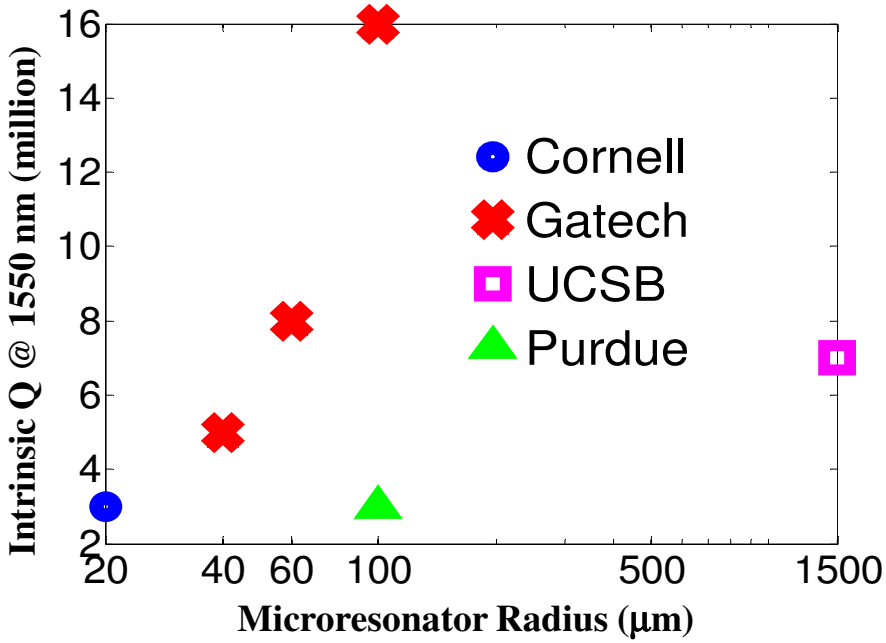
Realize compact, yet high Q SiN resonators based on a trade-off between the size and quality factor

# Compact and High Q $Si_3N_4$ Resonators

- Q and Q/V matter in different applications



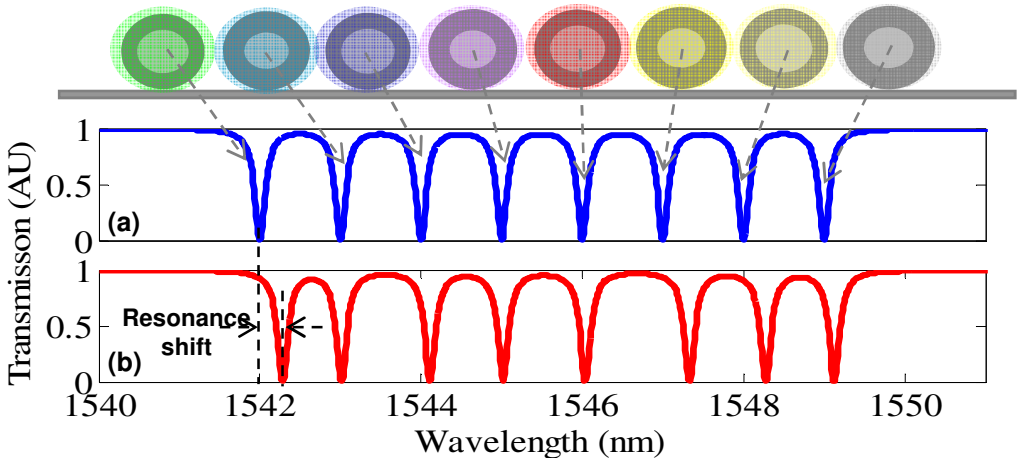




Achieved highest Q to-date and low mode-volume SiN resonators

# Multiplexed Gas sensing with polymer cladding

- **Challenge:** Lacking of lock-and-key mechanism in gas sensing, high sensitivity techniques do not provide good specificity
- **Approach:** Multiplexed gas sensing with a polymer coated optical resonator array

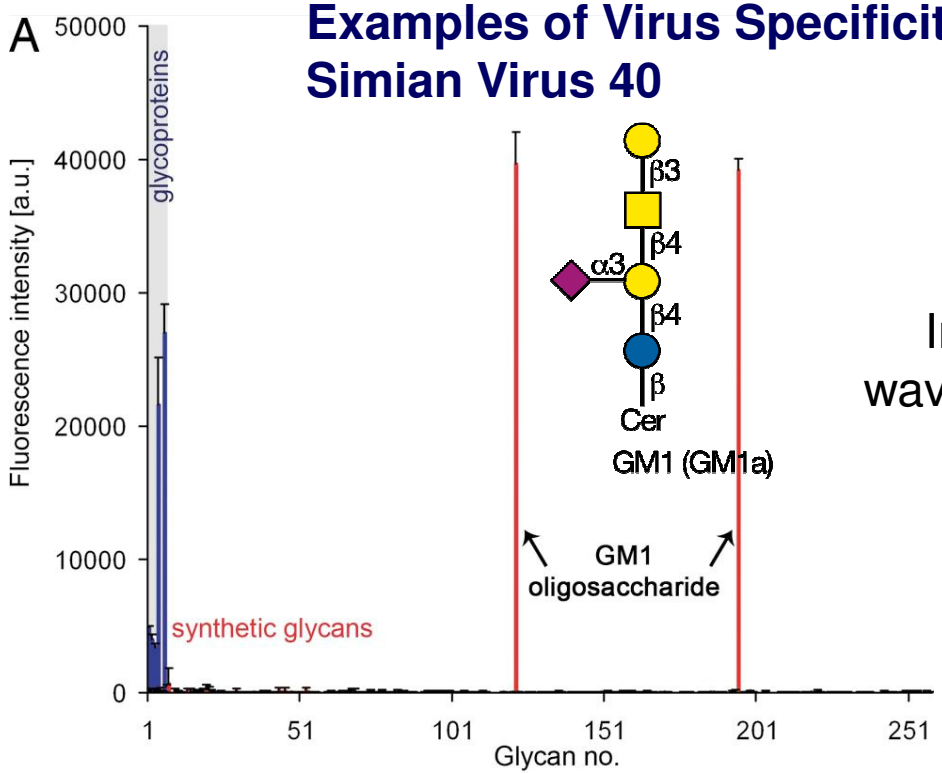


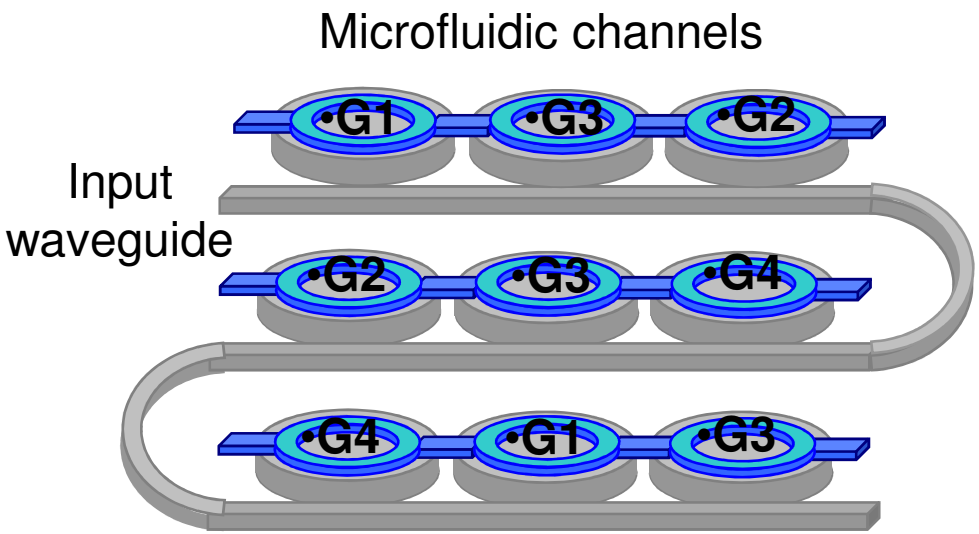

- Different resonators in the array coated with different polymers respond differently to the vapor analyte of interest
- Obtained response matrix is used for the inverse problem to acquire the info of the sample analyte.

# Bio-Receptor Encoding for Multiplexed Sensing

- Each pathogen can be detected by binding to a unique set of glycan elements
- For any class of target pathogens, a specific set of elements will be selected that can distinguish different pathogens in that class

**Examples of Virus Specificity:**
**Simian Virus 40**



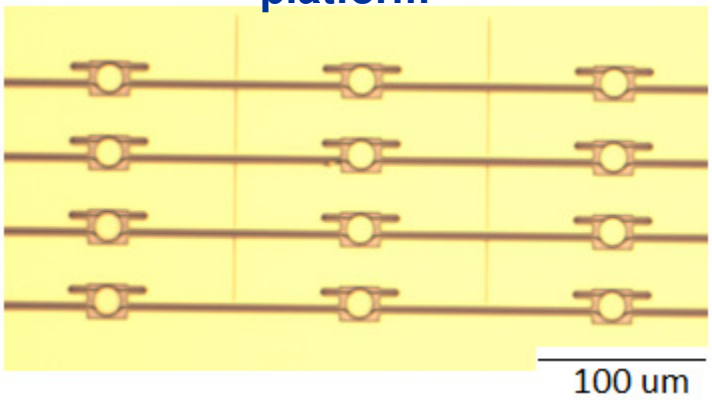




•***From*** **Neu et al (2008)** ***PNAS*** **105(13):5219-5224**

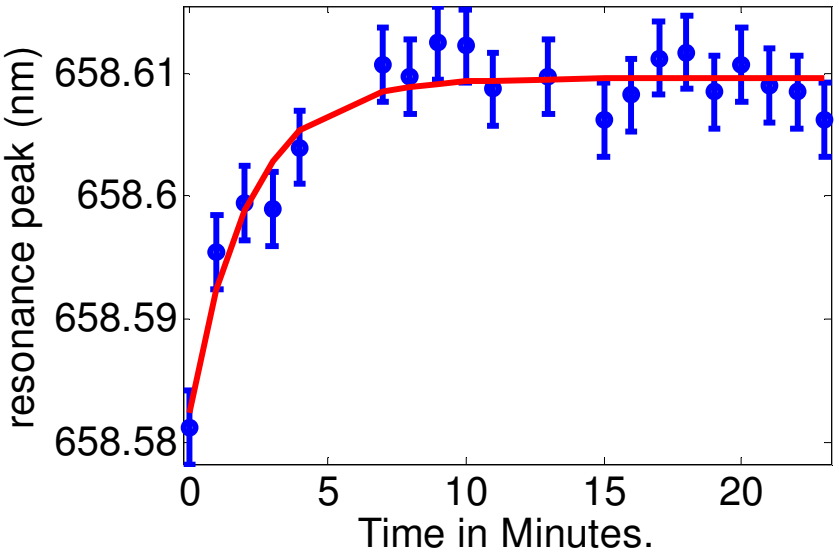
# High-Q Resonator Arrays for Multiplexed Sensing: Glycan Example

- Large multiplex arrays by a combination of spatial and spectral multiplexing
- Precise selective coating of different resonator using Bioforce system
- Low non-specific binding using a PEG-NHS chemistry to bind glycan to the sensor surface

**Multiplexed sensor array in SiN platform**



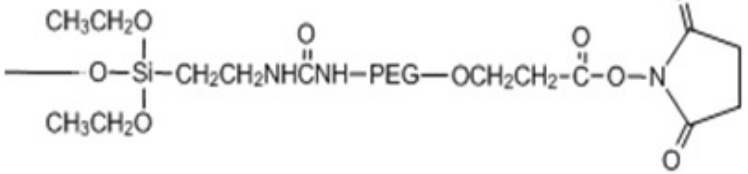

Resonator Response. Man5 and ConA




•**Glycan binding kinetics**

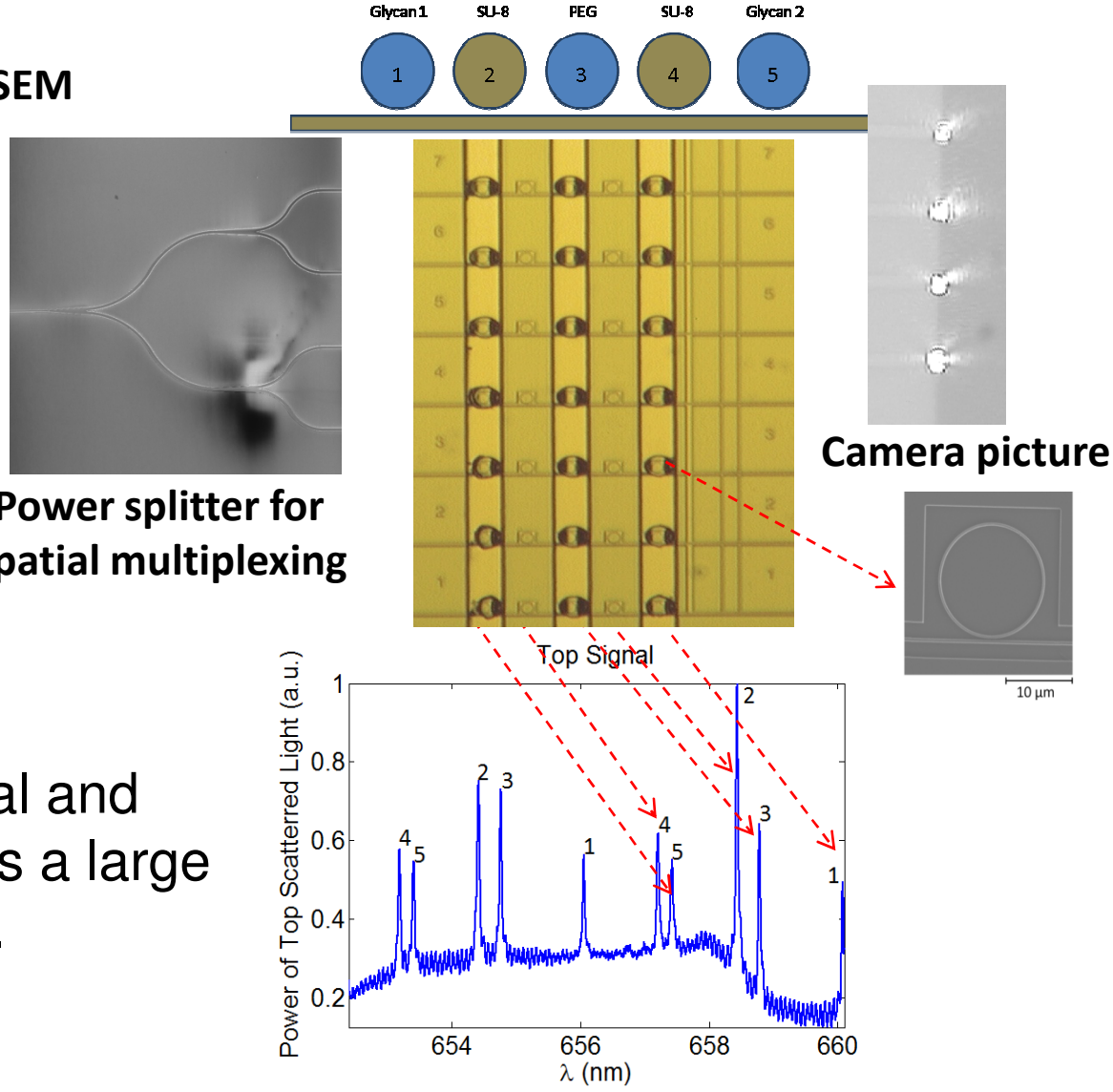
SiN

Silane-PEG-NHS



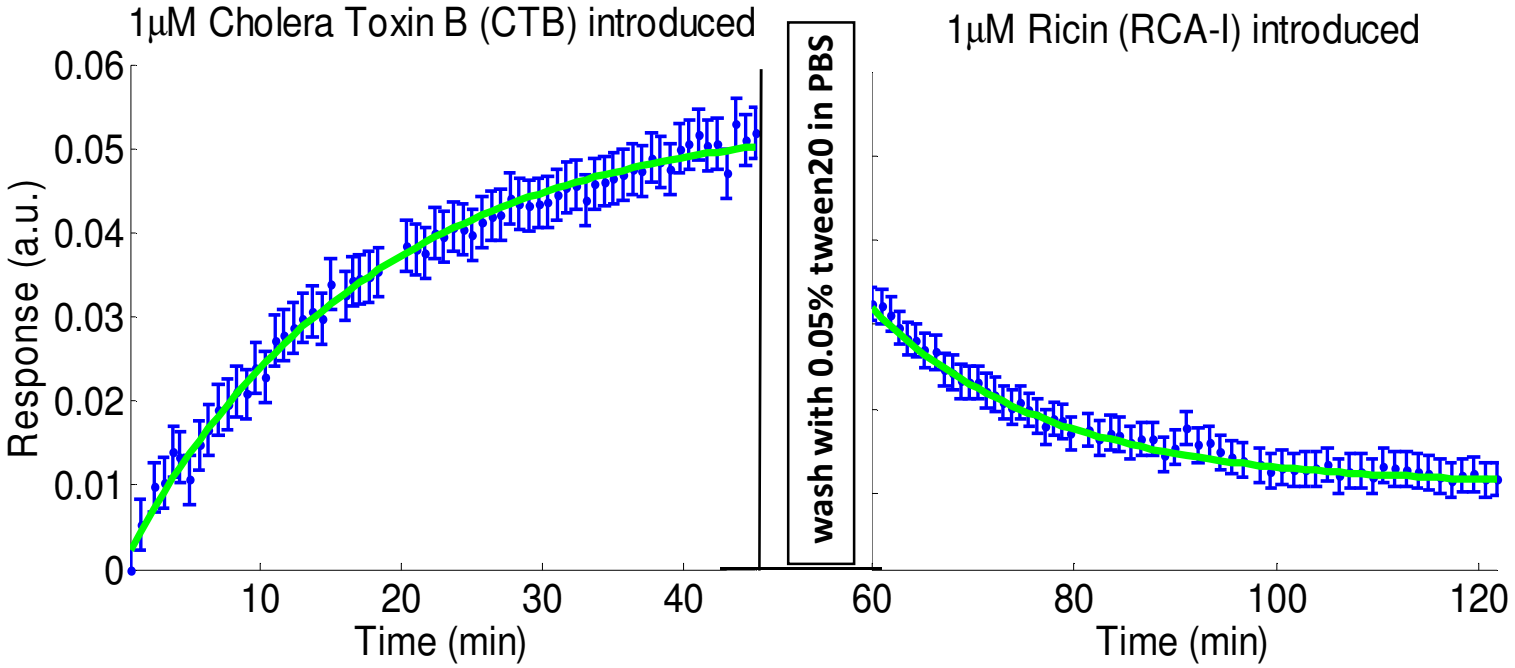
# High-Q Resonator Arrays for Multiplexed Sensing: Spectrally and Spatially Multiplexed Devices

Precise selective coating of different resonators

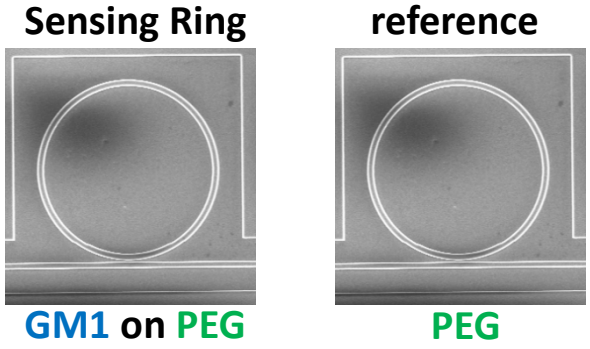



- Combination of spectral and spatial sensing enables a large degree of multiplexing.

# Toxin Detection Using Referenced Sensors




**Sensing resonance shifts about 50pm with respect to reference (a resonator with PEG but no Glycan coating).**



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