# Photonic Ring Resonators for Cosmology and HEP applications


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## Two applications in this talk

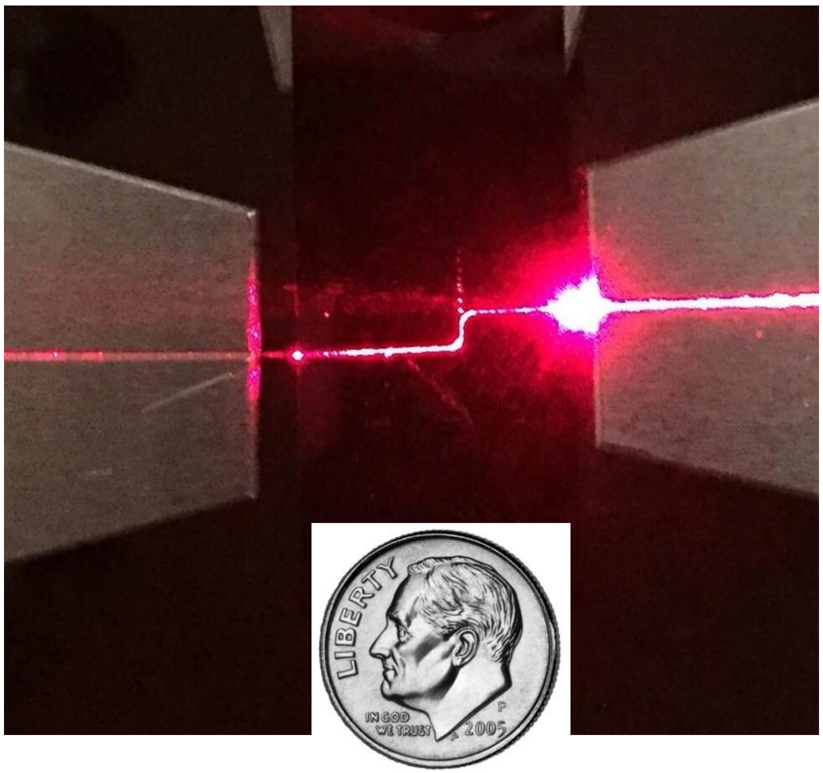
**Notch filters to greatly reduce sky background for near-infrared measurements**

**Mimic use in telecommunications for particle tracking detectors/triggers**

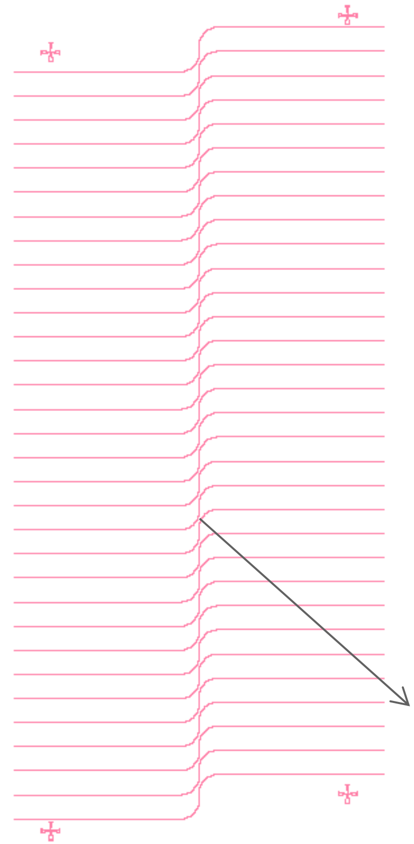
# Optical/Infrared  Silicon Waveguides (<1um wide/tall)

## Difference in index of refraction of silicon with surrounding material

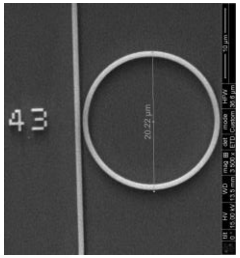
Our test-stand, optical fiber input and output,  tunable and fixed red and IR lasers




Design file with 32 independent devices



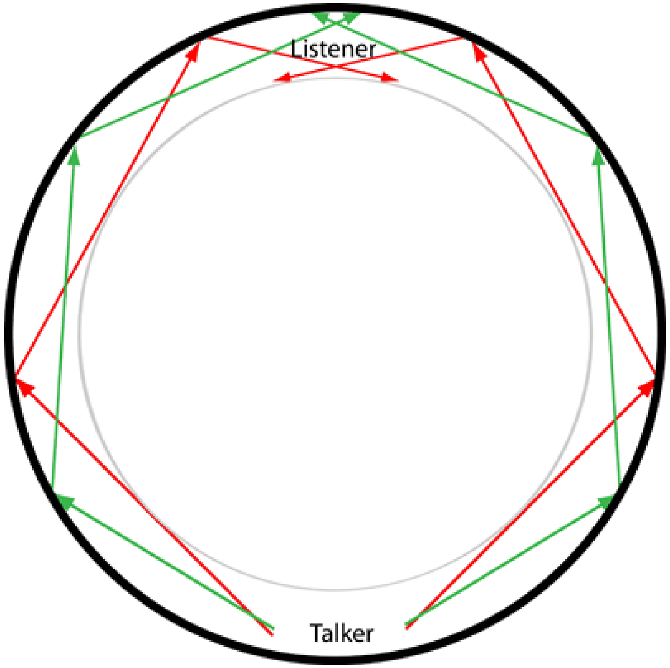
10um Ring in middle (SEM pic)



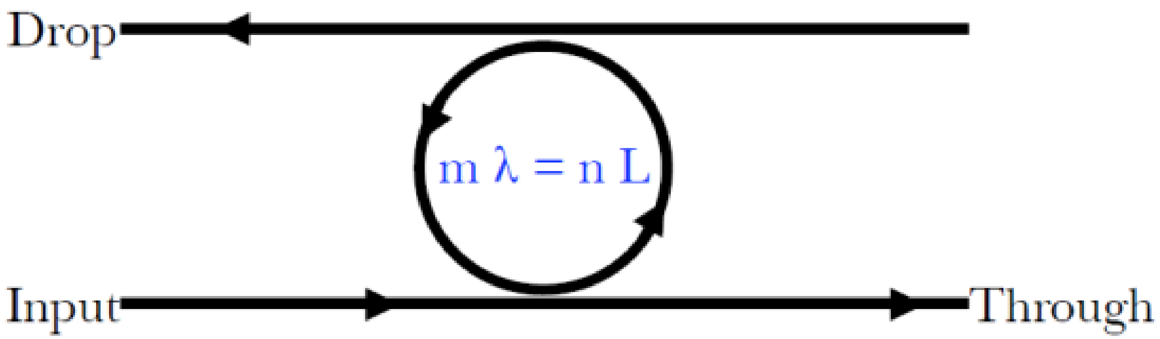
# Optical Ring Resonators:   Resonant cavities on a chip

## St. Paul's Cathedral, London

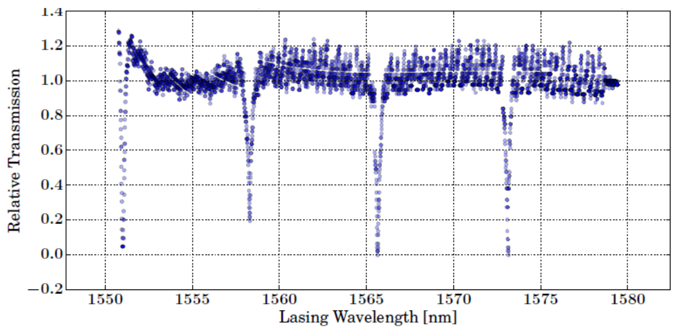
## The Whispering Gallery



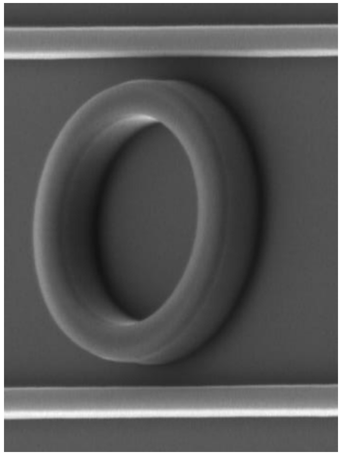
# How do Ring Resonators Work?




25um single SiN ring with different modes (7nm gaps)



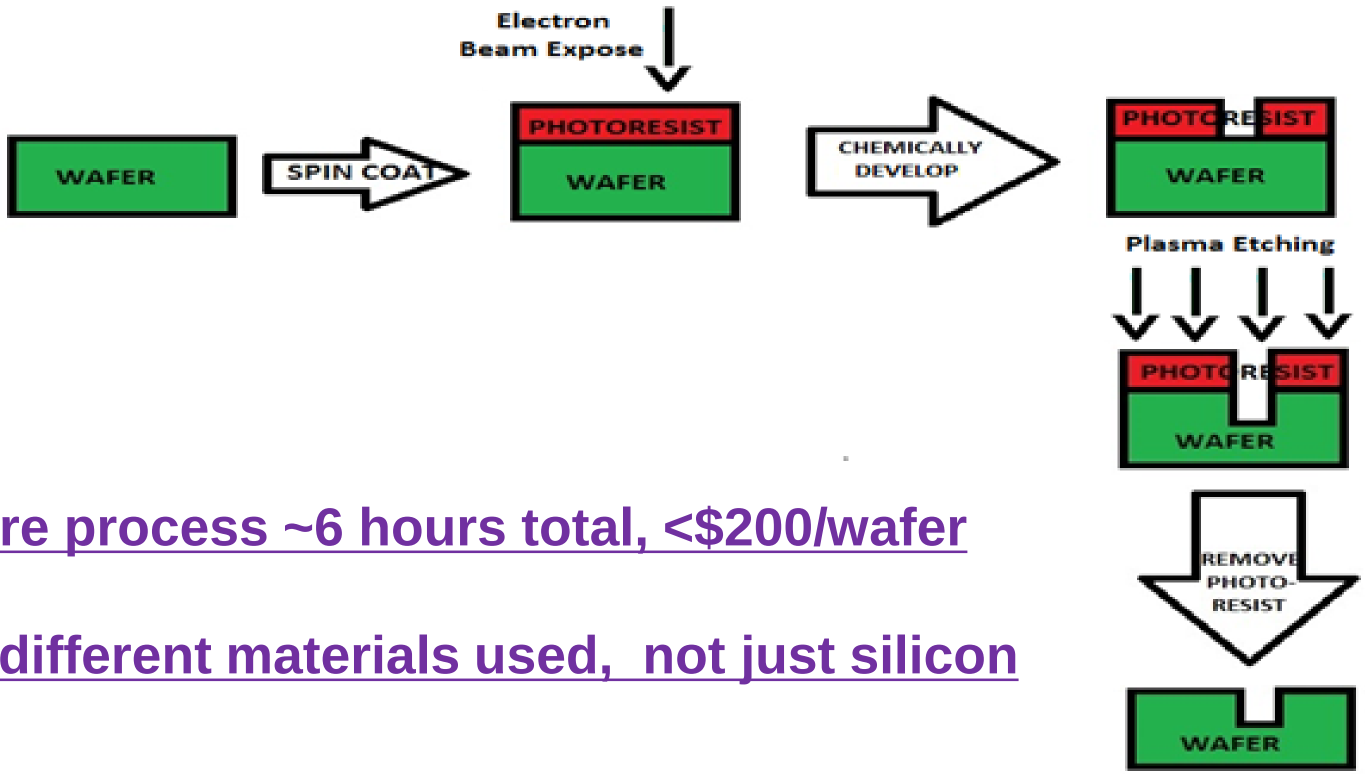

Silicon ring and waveguides fabricated at Argonne



SEM pic: 3um scale

# Nanofabrication Steps With UV Lithography (<100nm process) or more precise Electron Beam Lithography

**Start with 3-layer wafer: a) Si substrate, b) SiO2, c) Silicon device layer**

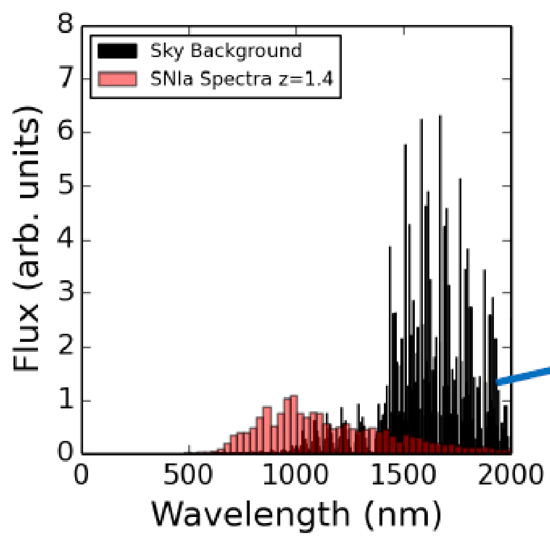



**Entire process ~6 hours total, <$200/wafer**

**Many different materials used, not just silicon**

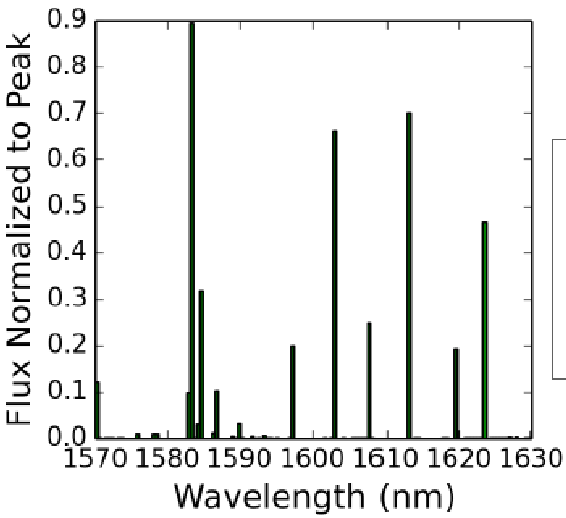
# Cascaded ring resonators as multi-notch filters

## Revolutionize Infrared Astrophysics by removing sky background spikes

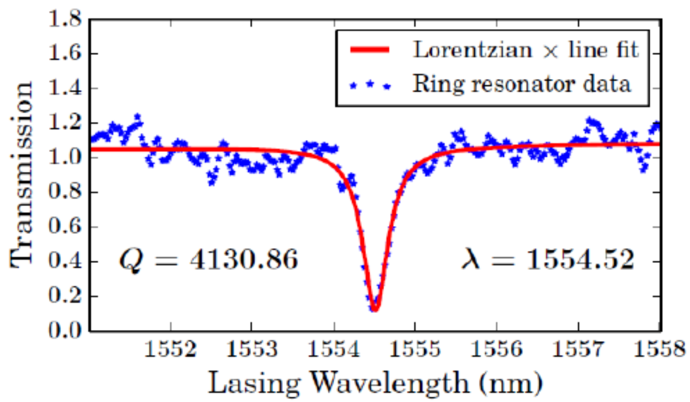



ZOOM 1600nm

Even with only 6 notches over 60nm window, can improve SNR from 1 to 5




Background spikes are <0.2nm wide separated by 5-10nm.

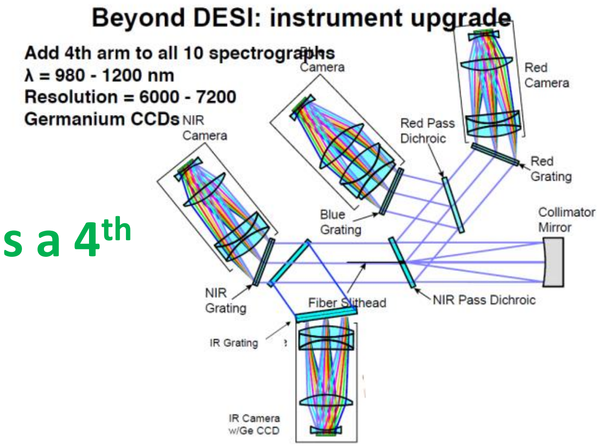



**Need a series of rings on a single waveguide, each with a different radius, tuned to the sky background wavelengths**

# Optical ring resonators for Cosmology

- What is the Science?
  - All ground-based near-infrared probes of cosmic acceleration
    - Supernovae
      - Redshift>1 SNe smothered by sky lines
      - All redshift SNe near-infrared insensitive to dust, may be dominant systematic for LSST
      - Redshift<1 SNe near-infrared provides much better standard candle with no corrections
      - Game-changer for ground-based supernova science, only hope for 100% LSST NIR follow-up
    - Galaxies redshift>1
      - Southern Spectroscopic Instrument being discusses
      - New $10-$100M instrument to follow-up and enhance LSST /DESI/CMBS4
      - Focus on pushing into near-infrared for almost all options
      - OH sky background increases costs, limits wavelength ranges, and degrades performance without suppression technology
    - Reionization galaxies redshift>7
      - New thirty-meter telescopes

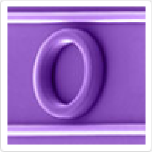
**Proposed DESI upgrade is a 4$^{th}$ NIR arm (D. Schlegel)**



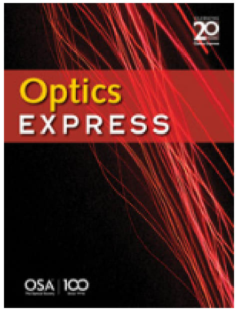
# Detailed Specifications and Early Test Results in Recent Pub.

OSA Publishing > Optics Express > Volume 25 > Issue 14 > Page 15868

Journal Home | About | Issues in Progress | Current Issue | All Issues | Feature Issues



## Photonic ring resonator filters for astronomical OH suppression

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# Recent Milestones

First working devices in red wavelengths Feb 2016

First working devices (and test-stand) in infra-red  June 2016

Northwestern Nano-photonics graduate student

**Pufan Liu** starts January 2017

(One specification met and 16 working devices at this time, 10% yield)

Five of our six specifications satisfied September 2017,

132 working devices, 90% yield

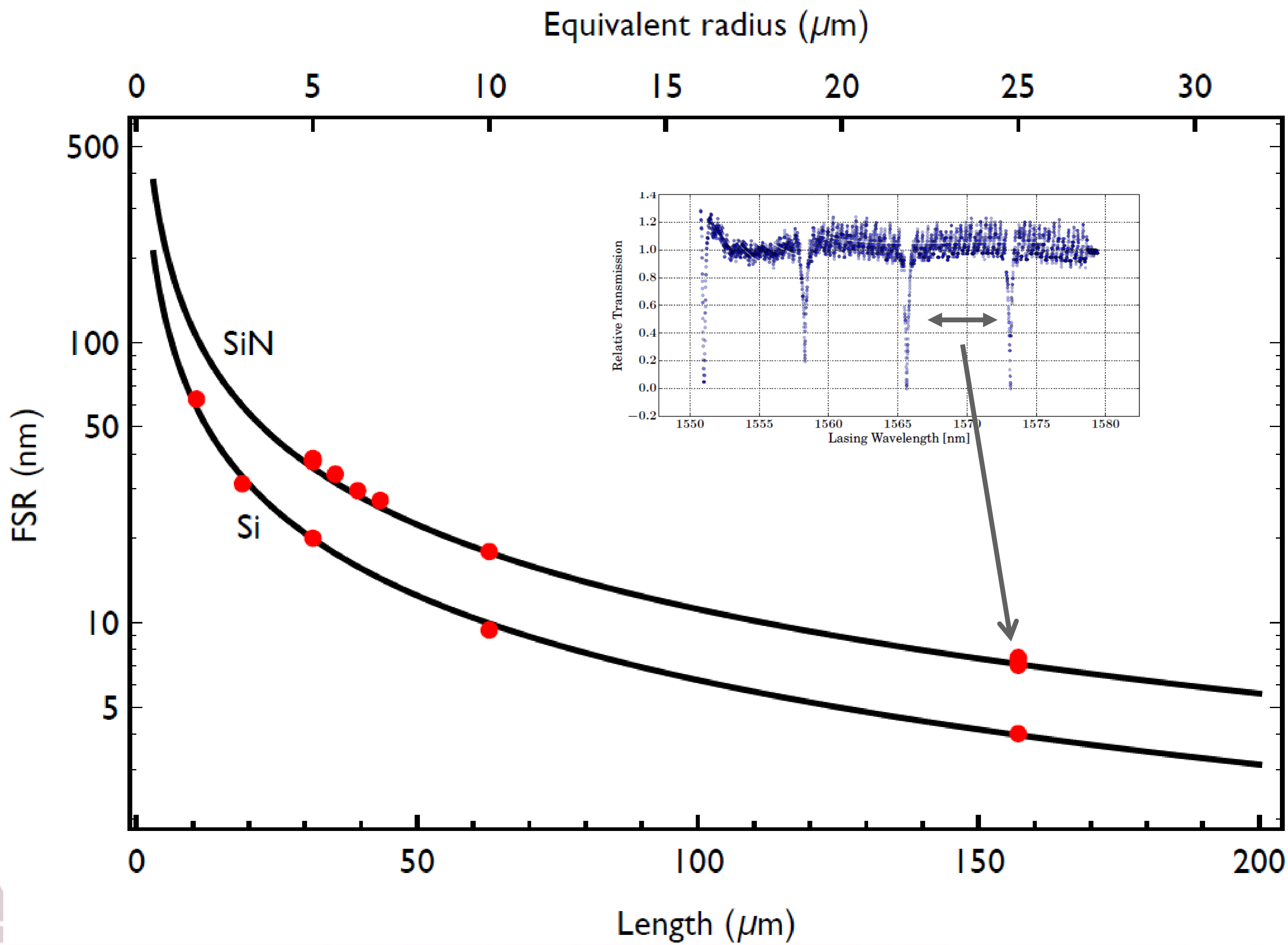
# Specs needed for a on-sky engineering test and science…

1. Free spectral range > 30nm (FSR,  gaps between resonator modes) ✓
2. Notch width < 0.4nm ✓
3. Polarization-independent enough to not ruin other specs ✓
4. Notch depth > 20dB ✓
5. >5 notches per chip at correct wavelengths ✓
6. Transmission enough to significantly improve signal-to-noise (~50%)

✓ = Specs currently satisfied

**Most challenging ones #1,5,6 discussed next…**

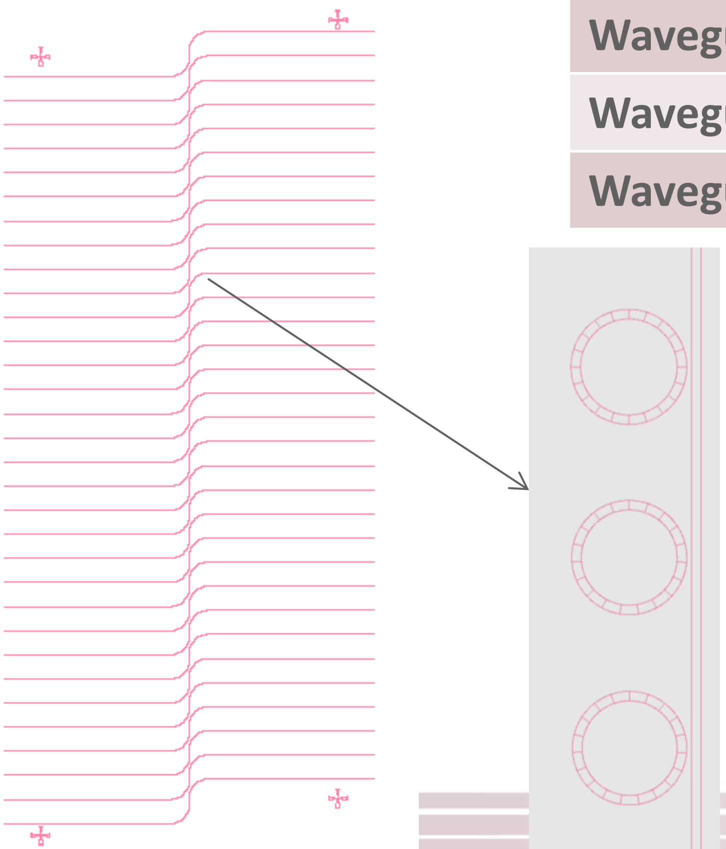
# Summary plot of Free Spectral Range (FSR, gaps between modes)
## 132 devices have been fabricated and demonstrated suppression



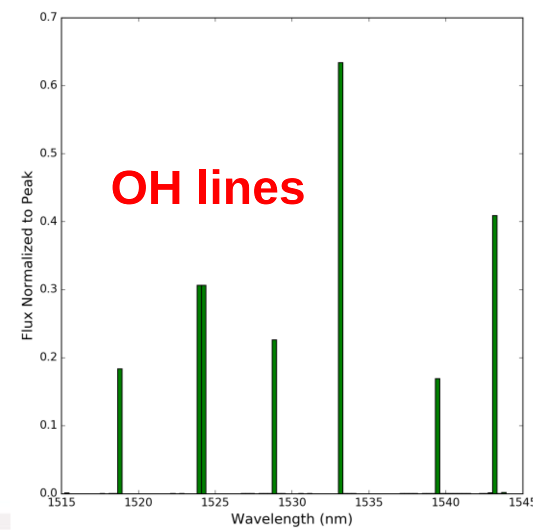
# 5 triple-ring systems each targeting 3 OH lines

## Initial fabrication brings within 2nm, iterative tuning and retesting brings wavelengths within 0.2nm spec

| OH Line (nm) | 1518.71 | 1524.09 | 1528.78 |
|---|---|---|---|
| Waveguide #25 – OH Line (nm) | -0.16 | -0.2 | 0.09 |
| Waveguide #27 – OH Line (nm) | 0.04 | 0.04 | 0.01 |
| Waveguide #28 – OH Line (nm) | -0.18 | 0 | 0.15 |
| Waveguide #29 – OH Line (nm) | -0.05 | -0.07 | -0.06 |
| Waveguide #30 – OH Line (nm) | -0.04 | 0.21 | -0.06 |

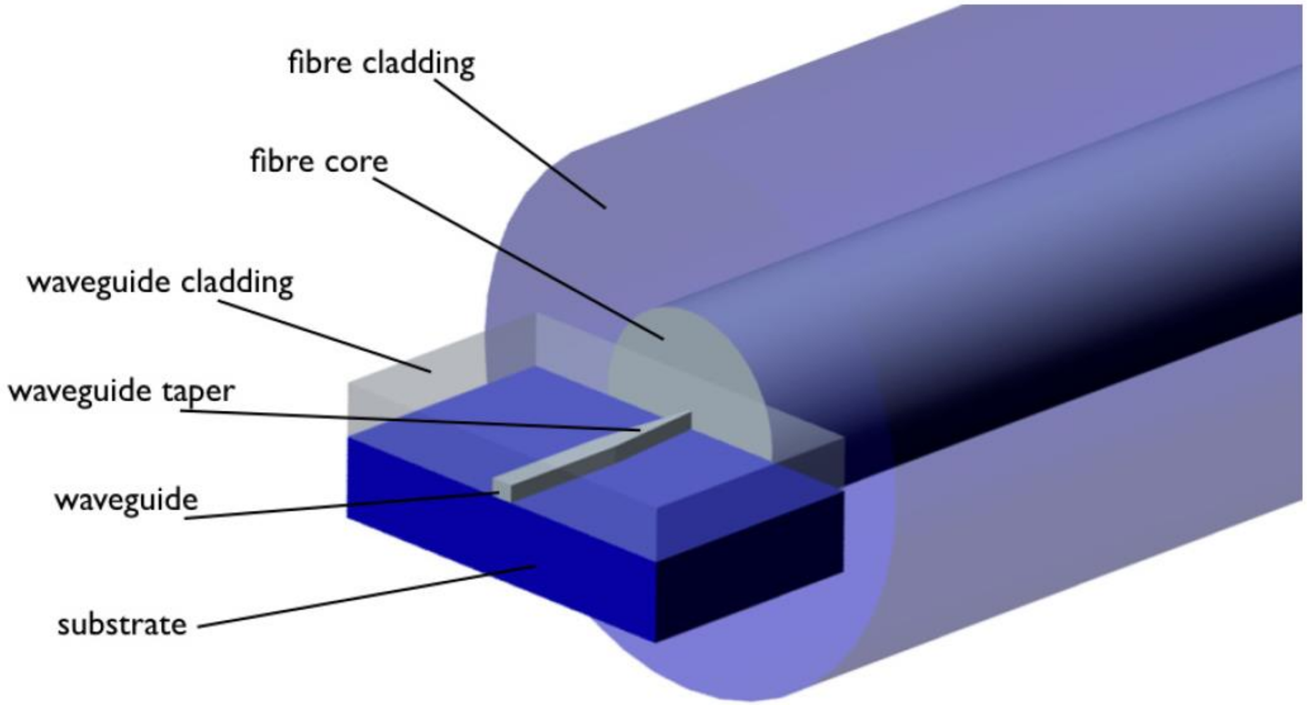


3 rings, radii differ by 20nm

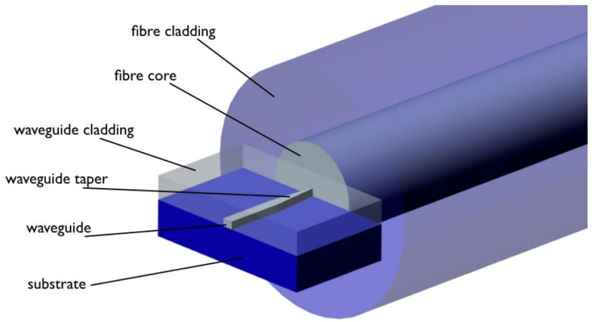


# Coupling light from fiber to silicon

## Not to scale, fiber core x80 larger than tapered waveguide



# Coupling light from fiber to silicon




**Many papers have solved this with better than 90% coupling, starting in 2003. Google search gives 506,000 results.**

**We are starting to implement those ideas**

## Ultra-low loss photonic integrated circuit with membrane-type photonic crystal waveguides


**Sharee J. McNab, Nikolaj Moll*, and Yurii A. Vlasov**

*IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*
**IBM Zurich Research Laboratory, Rueschlikon, Zurich, Switzerland*
yvlasov@us.ibm.com



**Abstract:** We report the design and testing of an SOI-based photonic integrated circuit containing two-dimensional membrane-type photonic crystal waveguides. The circuit comprises spot-size converters to efficiently couple light from a fiber into single-mode strip waveguides and butt-couplers to couple from strip waveguides to photonic crystal waveguides. Each optical interface was optimized to minimize back-reflections and reduce the Fabry-Perot noise. The transmission characteristics of each component are measured and record low propagation losses in photonic crystal waveguides of 24dB/cm are reported. The combination of an efficient two-stage coupling scheme and utilization of ultra-long (up to 2mm) photonic crystal waveguides reduces the uncertainty in determining the loss figure to 3dB/cm.





**OCIS codes:** (230.7370) Waveguides; (250.5300) Photonic integrated circuits



**1302** OPTICS LETTERS / Vol. 28, No. 15 / August 1, 2003


## Nanotaper for compact mode conversion


**Vilson R. Almeida, Roberto R. Panepucci, and Michal Lipson**

*School of Electrical and Computer Engineering, Cornell University, 411 Phillips Hall, Ithaca, New York 14853*



Received December 13, 2002



We propose and demonstrate an efficient coupler for compact mode conversion between a fiber and a submicrometer waveguide. The coupler is composed of high-index-contrast materials and is based on a short taper with a nanometer-sized tip. We show that the micrometer-long silicon-on-insulator-based nanotaper coupler is able to efficiently convert both the mode field profile and the effective index, with a total length as short as 40 $\mu$m. We measure an enhancement of the coupling efficiency between an optical fiber and a waveguide by 1 order of magnitude due to the coupler. © 2003 Optical Society of America



*OCIS codes:* 130.3120, 250.5300, 230.3120, 230.7380, 230.7390.

# Silicon photonics emerging technology in telecommunication and computing

**First major US silicon photonics foundry opened last year in Rochester**

**$610M facility, $500M industry, $110M DOE and DOD**

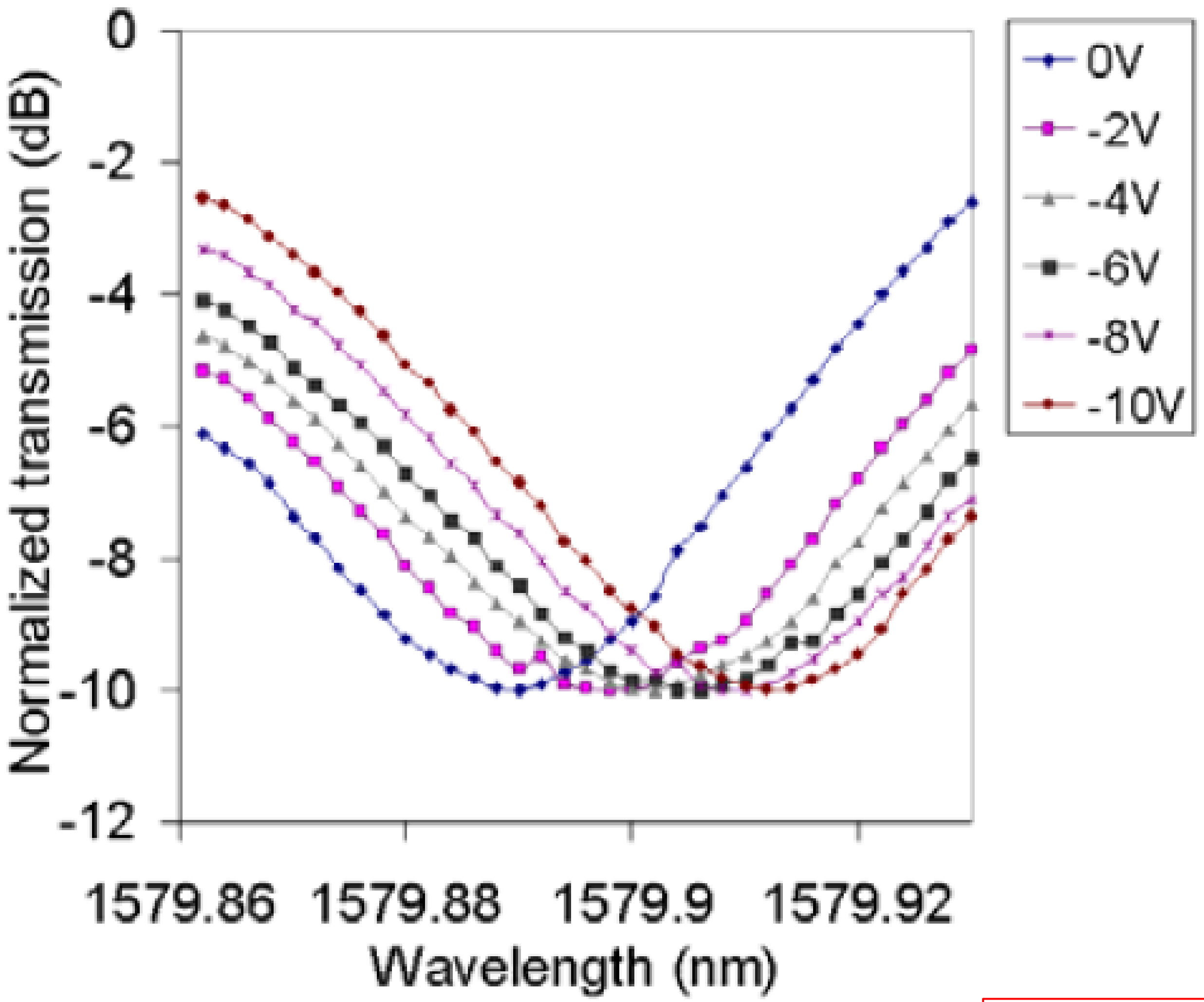
AIM photonics
AMERICAN INSTITUTE for MANUFACTURING INTEGRATED PHOTONICS


US VICE PRESIDENT JOE BIDEN (CENTER) MEETS SUNY POLYTECHNIC INSTITUTE'S FOUNDING PRESIDENT AND CEO DR. ALAIN KALOYEROS (FAR LEFT) AND NEW YORK STATE GOVERNOR ANDREW CUOMO (RIGHT OF CENTER) DURING THE OFFICIAL ANNOUNCEMENT OF THE AIM PHOTONICS HUB IN ROCHESTER, NY, ON JULY 27, 2015.

**IBM 2012 press release:**
**"Silicon Nanophotonics is Ready for Development of Commercial Applications"**

**Typically using voltage modulation of ring wavelengths**

# Example of Ring Resonator Wavelength Modulation with Voltage

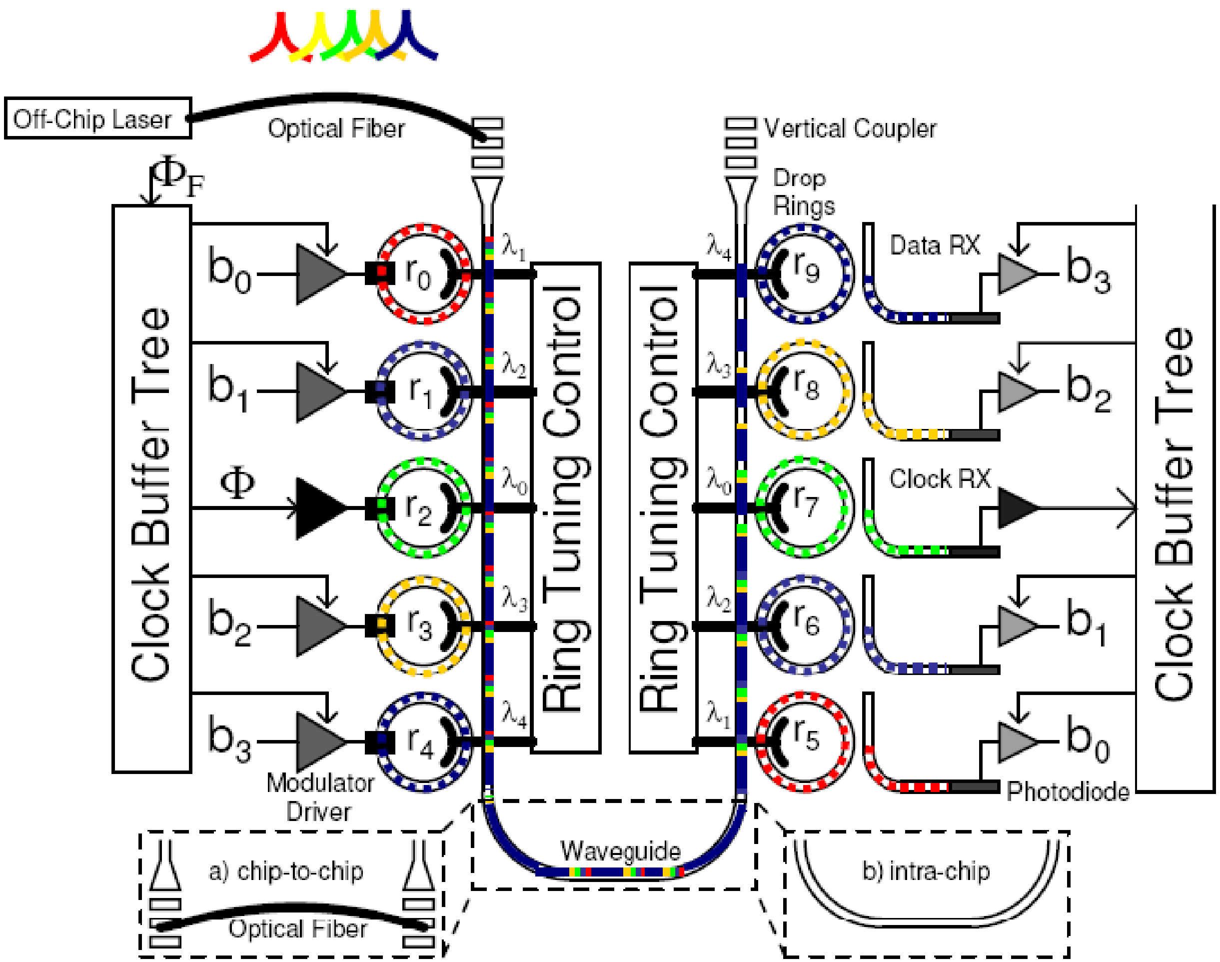



Gardes et al., 2009

Integrated pixel detector/pre-amp and ring resonator chip

1 PIXEL Voltage → 1 Ring illuminated with CW laser/LED, changes output wavelength, measured off the detector to give a “hit”

- **Low Mass: Integrated with pre-amp, possibly nothing else on detector**
- **Low power ~1uW/channel (Pradhan et al., 2005)**
- **Compact: ~5um/channel (ring diameter + light wavelength)**
- **Fast: >165 GHz (Bortnik et al., 2007)**
- **Modulation with rad-hard pn diode**




- Each λ carries one bit of data
→Bandwidth Density achieved through DWDM
→Energy-efficiency achieved through low-loss optical components and tight integration

**Stojanovic (MIT)**

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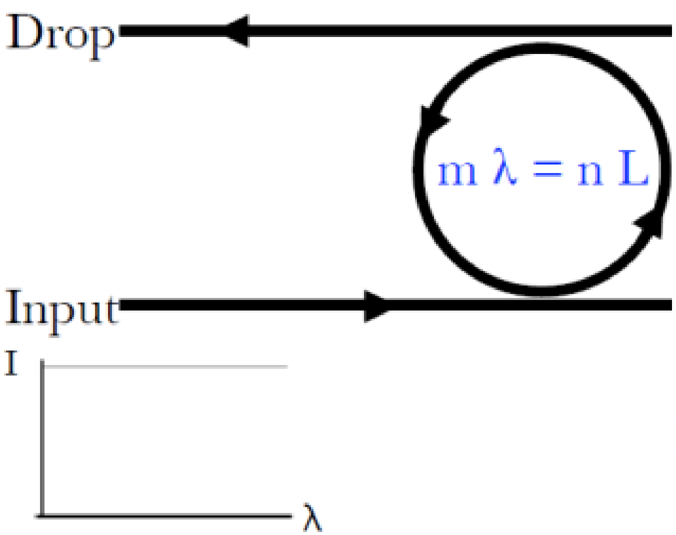
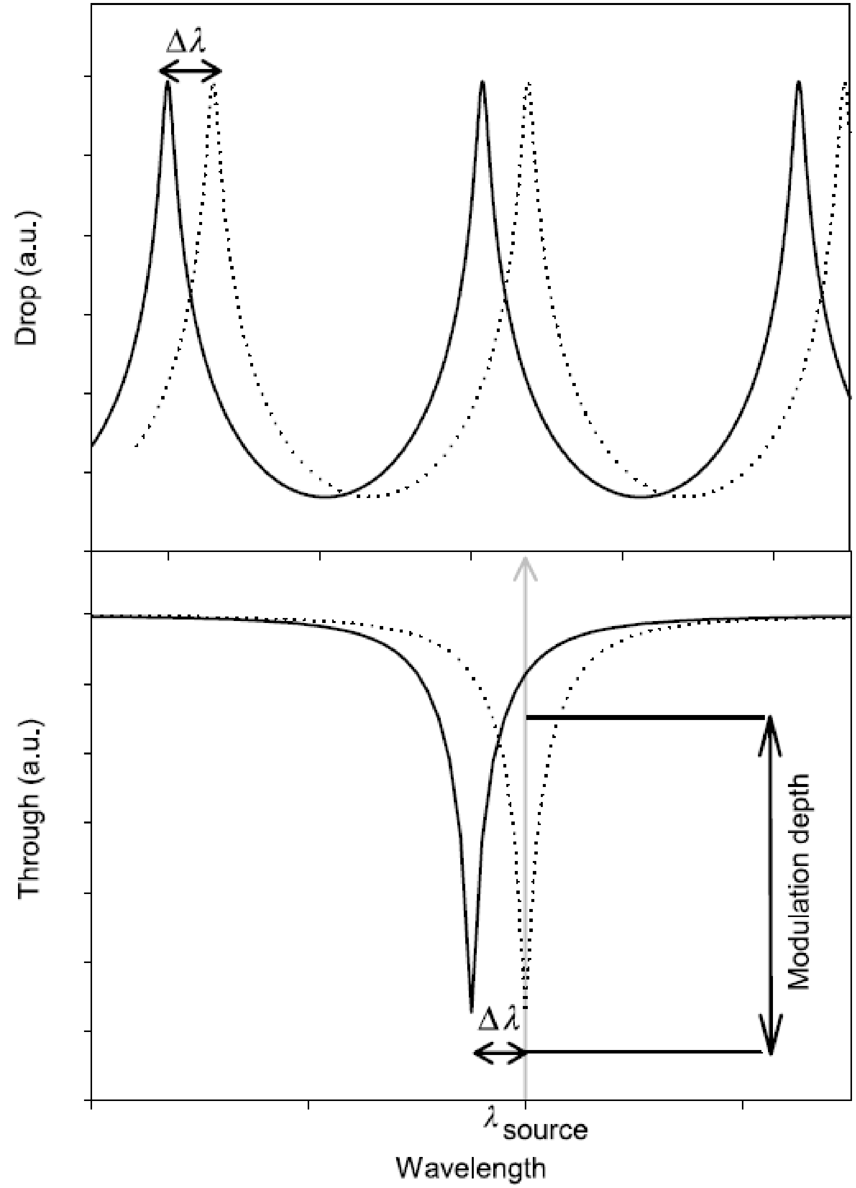
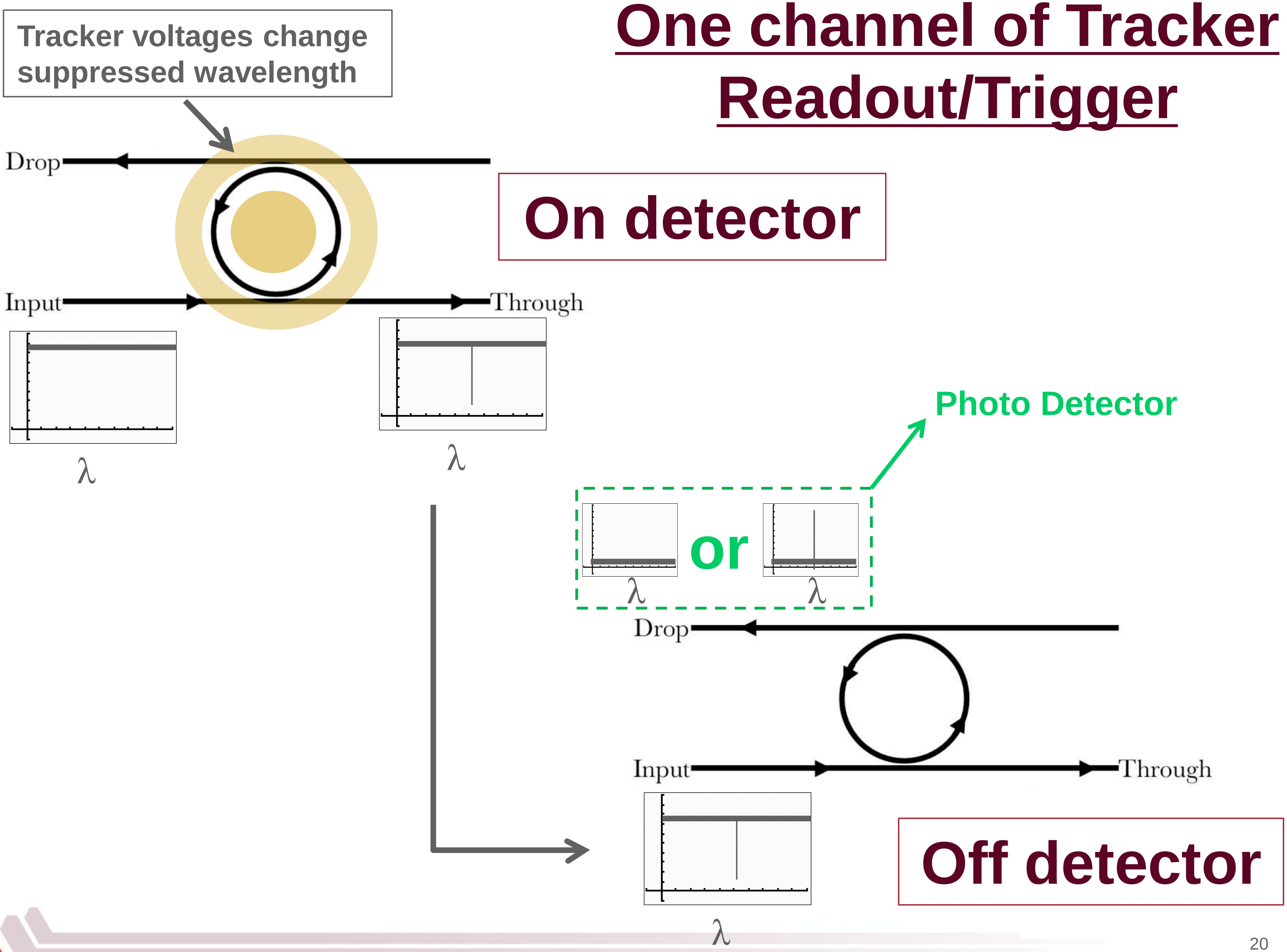

Drop
m λ = n L
Input
I
λ


Δλ
Drop (a.u.)
Through (a.u.)
Modulation depth
Δλ
λ source
Wavelength

# One channel of Tracker Readout/Trigger



# Summary

Silicon Photonics an Emerging Technology, new to US HEP

Possible high-impact applications in Cosmology and HEP TDAQ

Notch filters for background removal in near-infrared cosmology advancing quickly,  with planning underway for an on-sky test

Industry-like TDAQ application will be addressed next

Technologies and techniques similar for all applications