Nanophotonics

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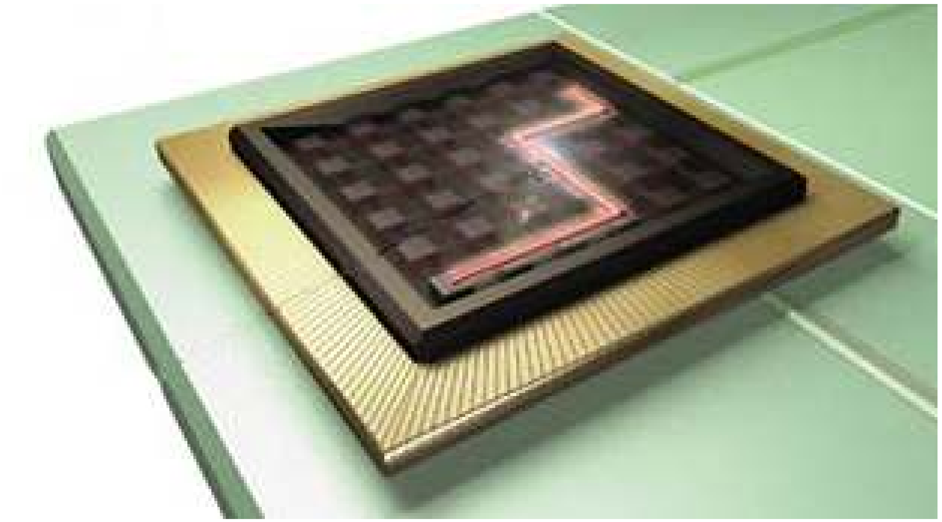
Cornell University

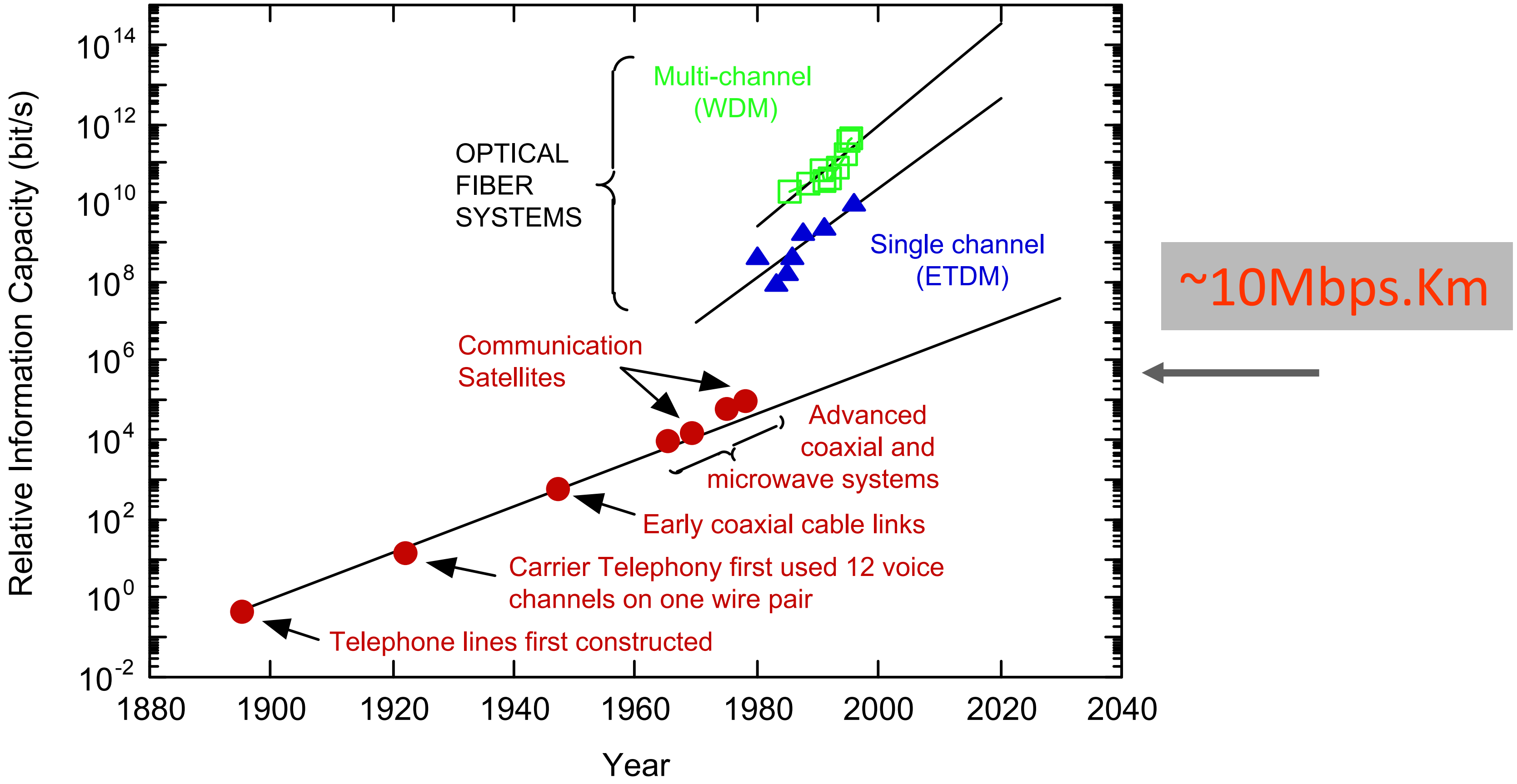


Outline

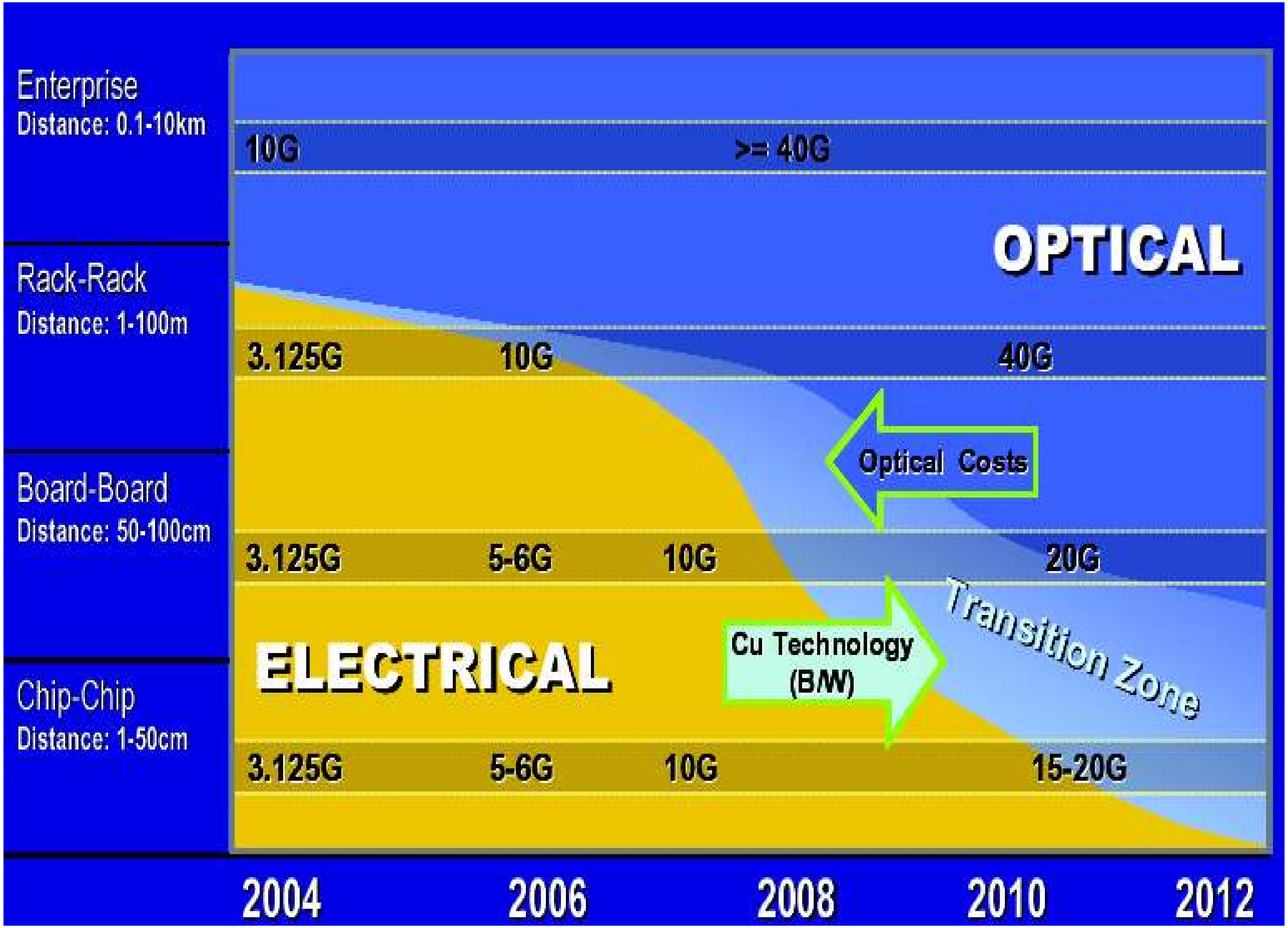
- Motivation for Silicon Photonics
- Wave Guiding Theory
- Ultra Low Loss Waveguides and Ring Resonators
- Electro-Optics Modulation
- Integrating Silicon Photonics with CMOS
- Athermal Photonic Devices

Motivation for Silicon Photonics

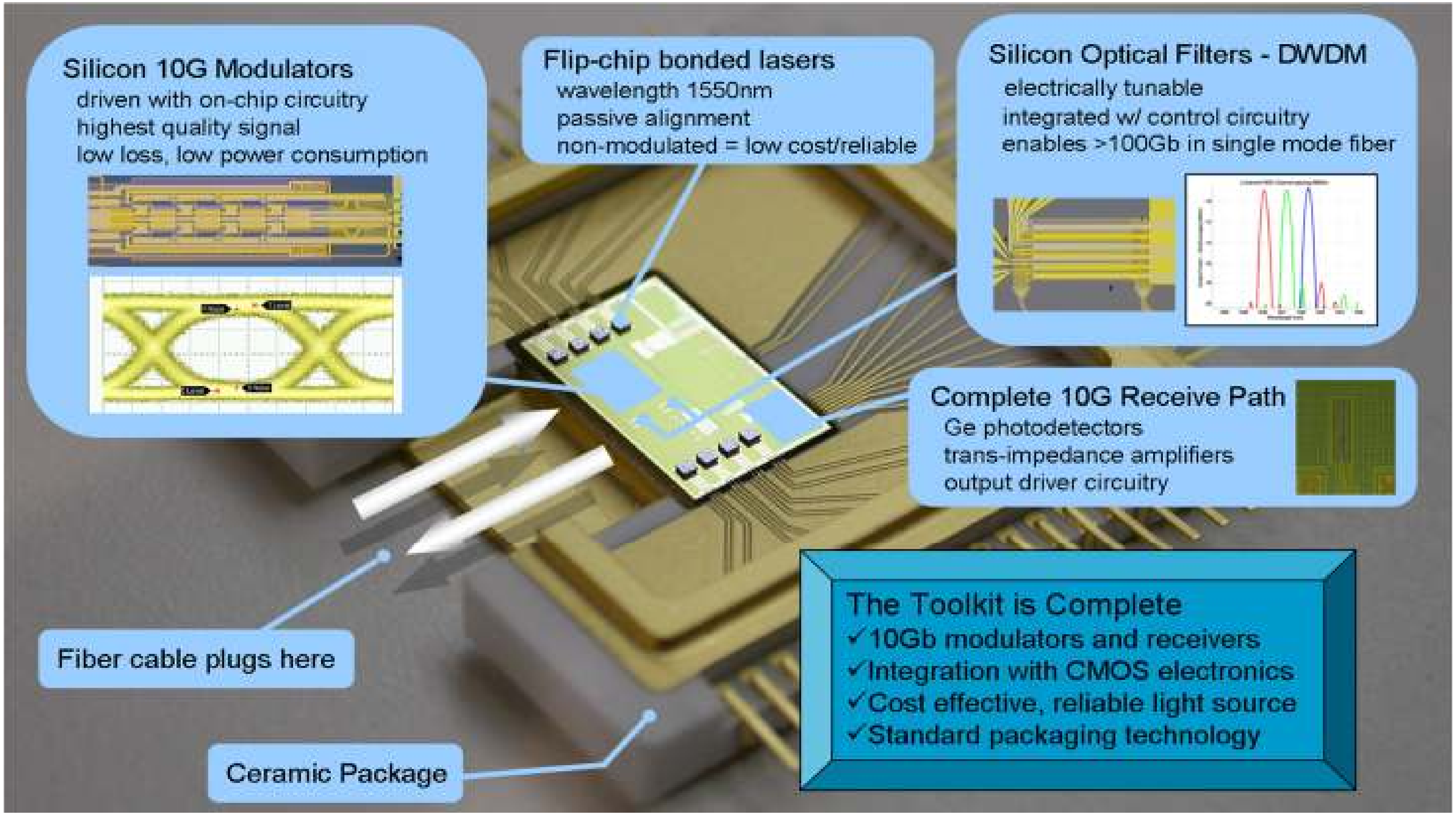
Photonics drives telecom



We are experiencing this drive on-chip!

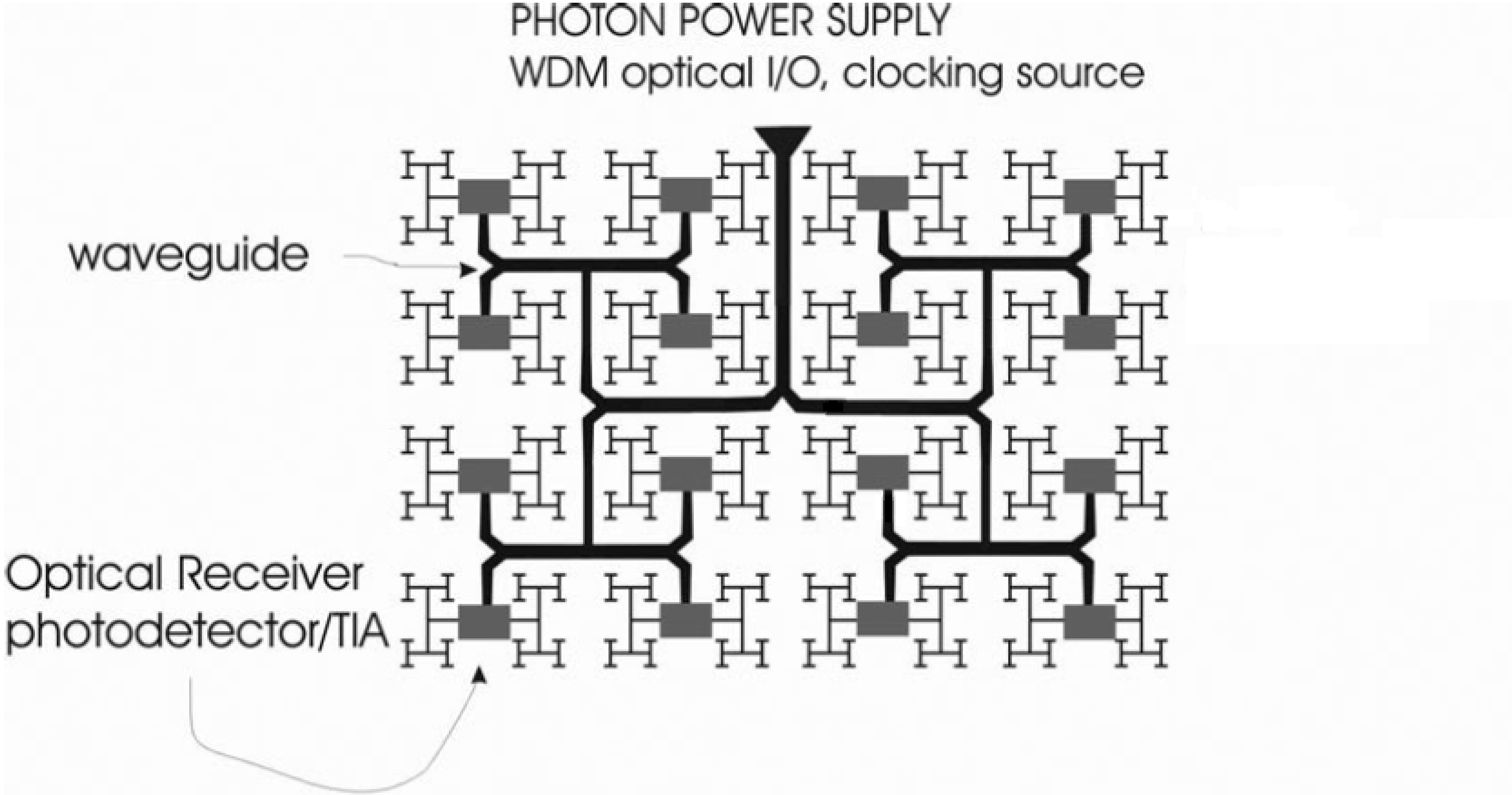

Enterprise
Distance: 0.1-10km
Rack-Rack
Distance: 1-100m
Board-Board
Distance: 50-100cm
Chip-Chip
Distance: 1-50cm
10G
>= 40G
OPTICAL
3.125G
10G
40G
Optical Costs
3.125G
5-6G
10G
20G
Transition Zone
Cu Technology
(B/W)
ELECTRICAL
3.125G
5-6G
10G
15-20G
2004
2006
2008
2010
2012

Luxtera CMOS photonics technology

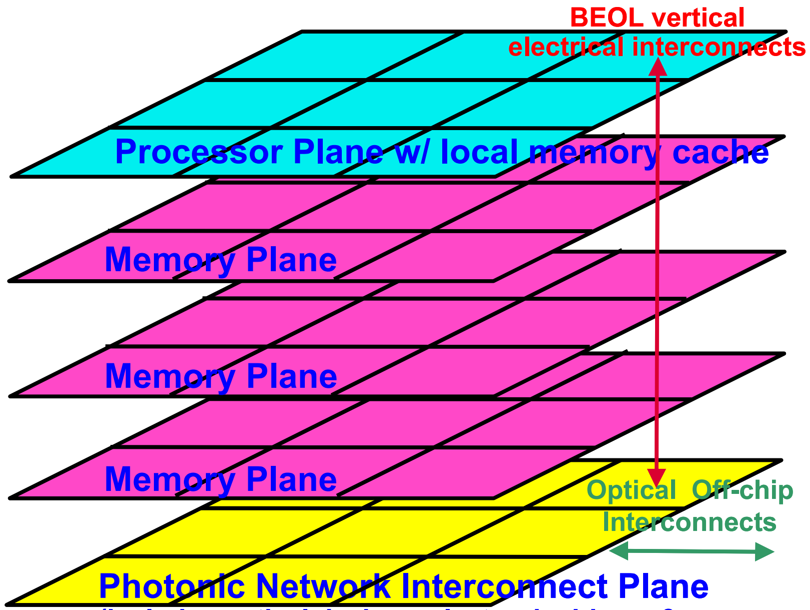


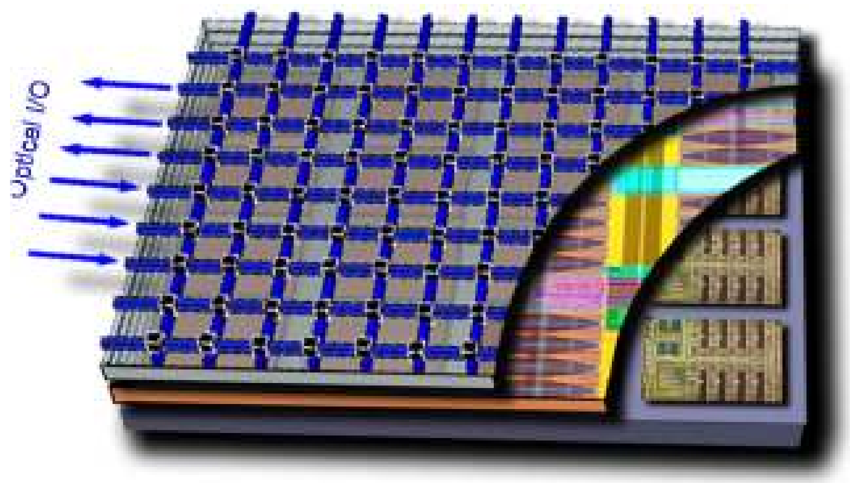
Silicon photonics on-chip

Kimerling, 1997



Silicon photonics for multi-core interconnect



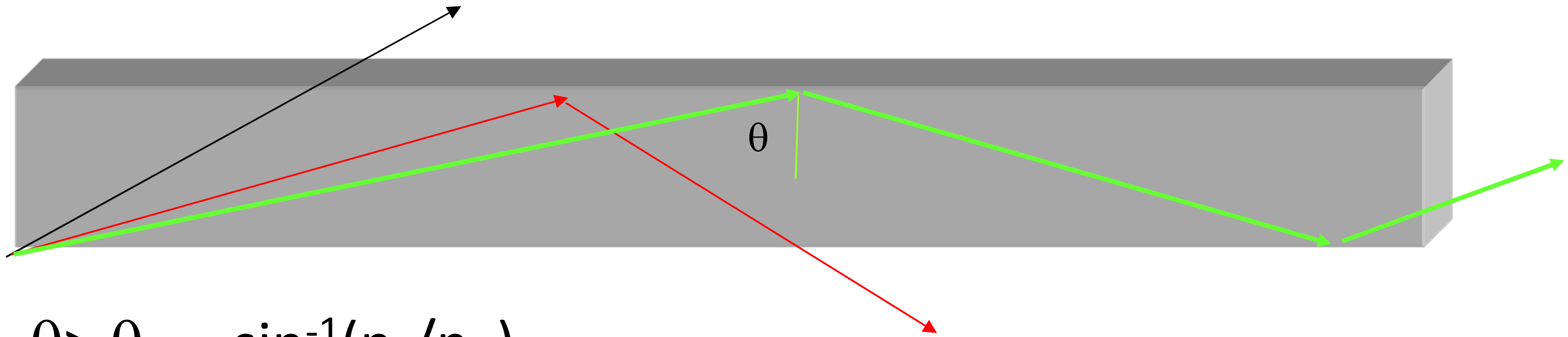


Bergman-Columbia, J. Kash, IBM

Wave Guiding Theory

How is light guided?

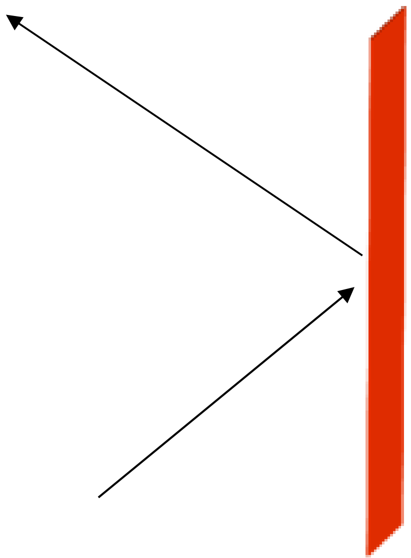
Total internal reflection!



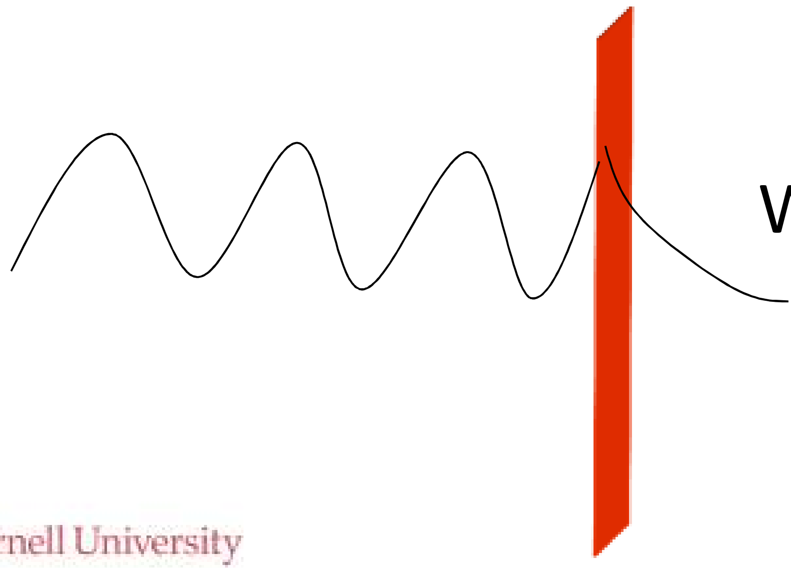
$\theta > \theta_{crit} = \sin^{-1}(n_L/n_H)$

The larger is the index-the easier it is to guide.

Is it a ray or is it a wave?



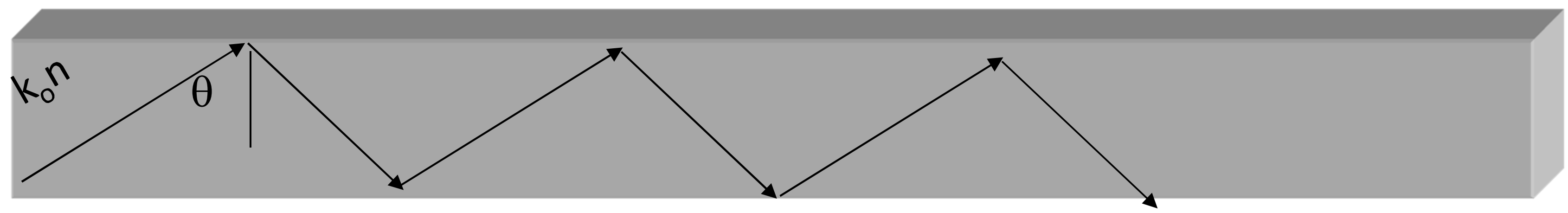
Ray picture



Wave picture

$E \sim e^{-\gamma x}$

Why not every angle (wavevector) can propagate?



$2k_onh\cos\theta+Ø_{down}+Ø_{up}=q2\pi$ q=1,2,3.....

or $\cos\theta \sim q\,\pi/nk_oh$

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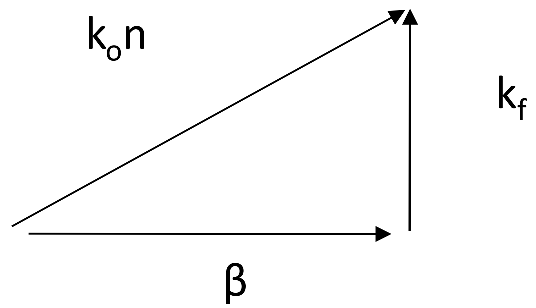
Wavector of propagation

Light propagating in a medium with index n:

$v_p = c/n$

$\lambda = \lambda_o/n$



$\beta^2 = (k_o n + k_f)^2$

$\beta \equiv k_o n_{eff}$

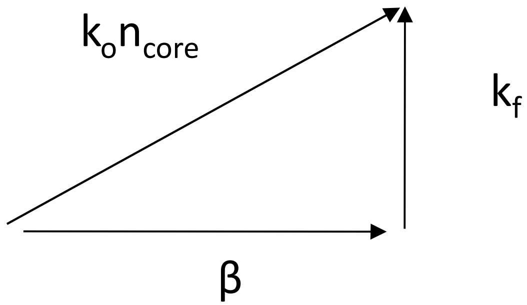
Different modes in a waveguide

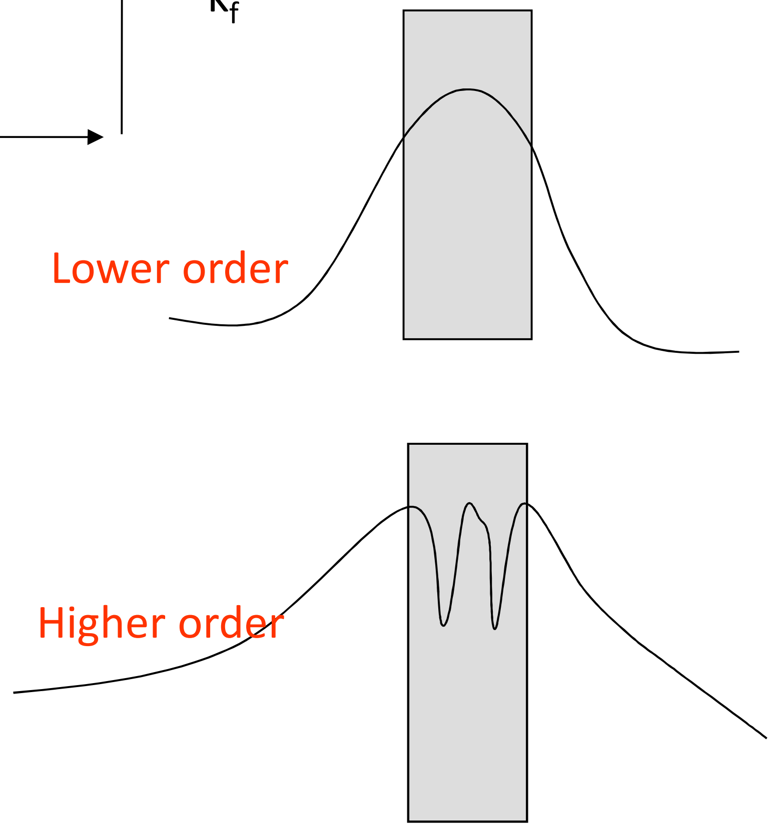
$\beta^2 = (k_o^{\,2} n^2_{core} - k_f^{\,2})$

$\beta = k_o n_{eff} > k_o n_{cladd}$ and $< k_o n_{slab}$

$E \sim \cos k_f x \; e^{-\gamma x}$

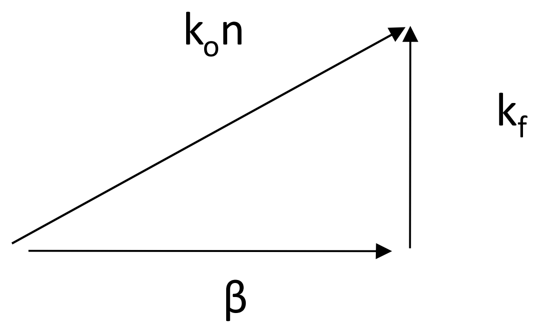
$\gamma \;\; = \mathrm{sqrt}(\beta^2 - k_o^{\,2} n_{clad}^{\,2})$

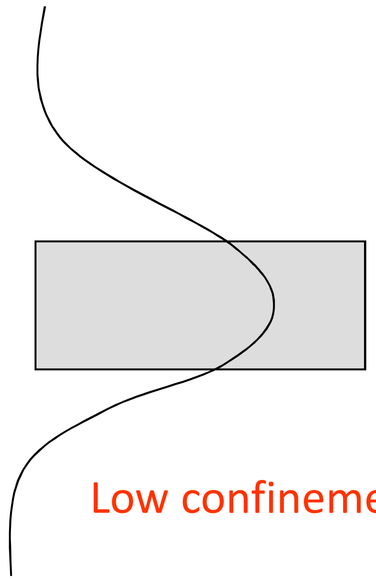




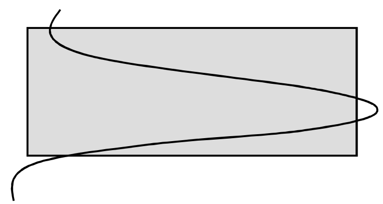
High index contrast leads to high confinement

$\gamma \quad = \mathrm{sqrt}(\beta^2 - k_o^2 n_{cladd}^2)$



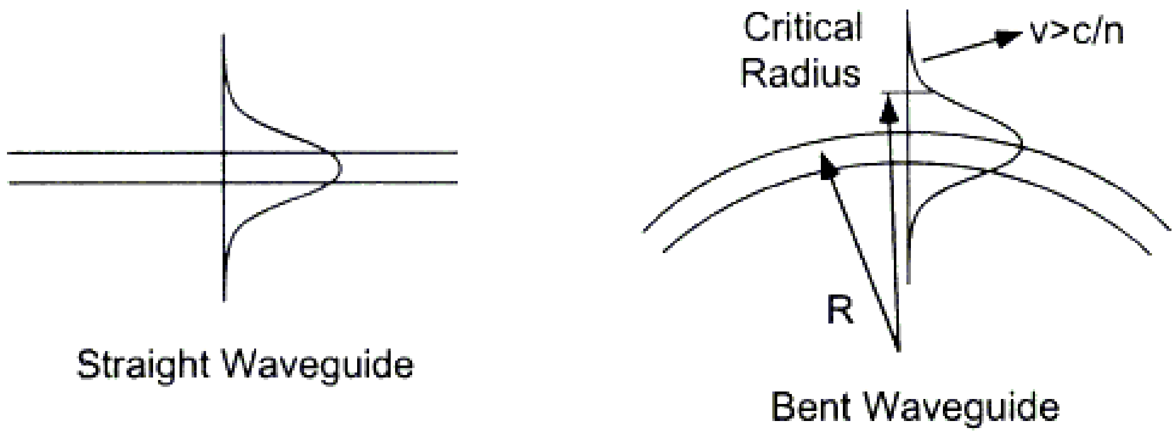


Low confinement



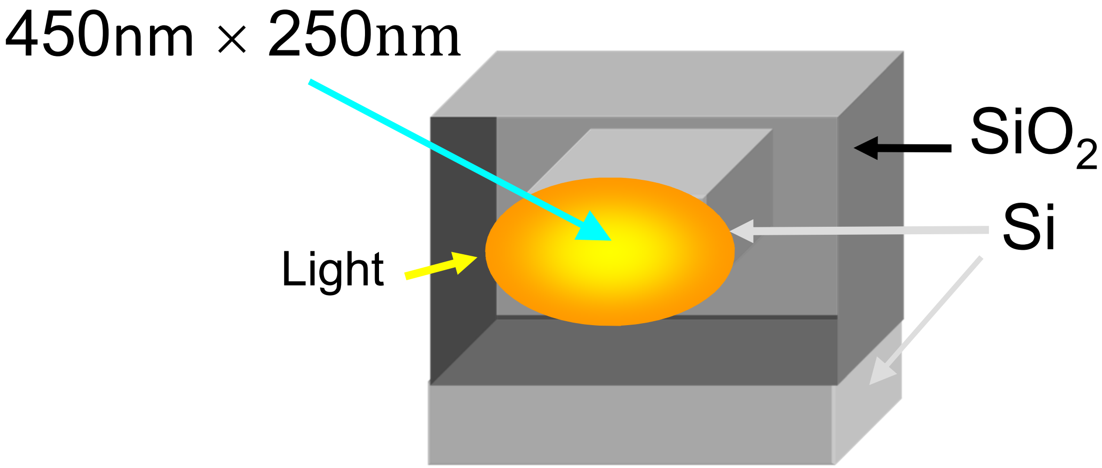
High confinement

Bending light on-chip



Work only with high confinement, single mode waveguides!

High confinement waveguides for functional devices

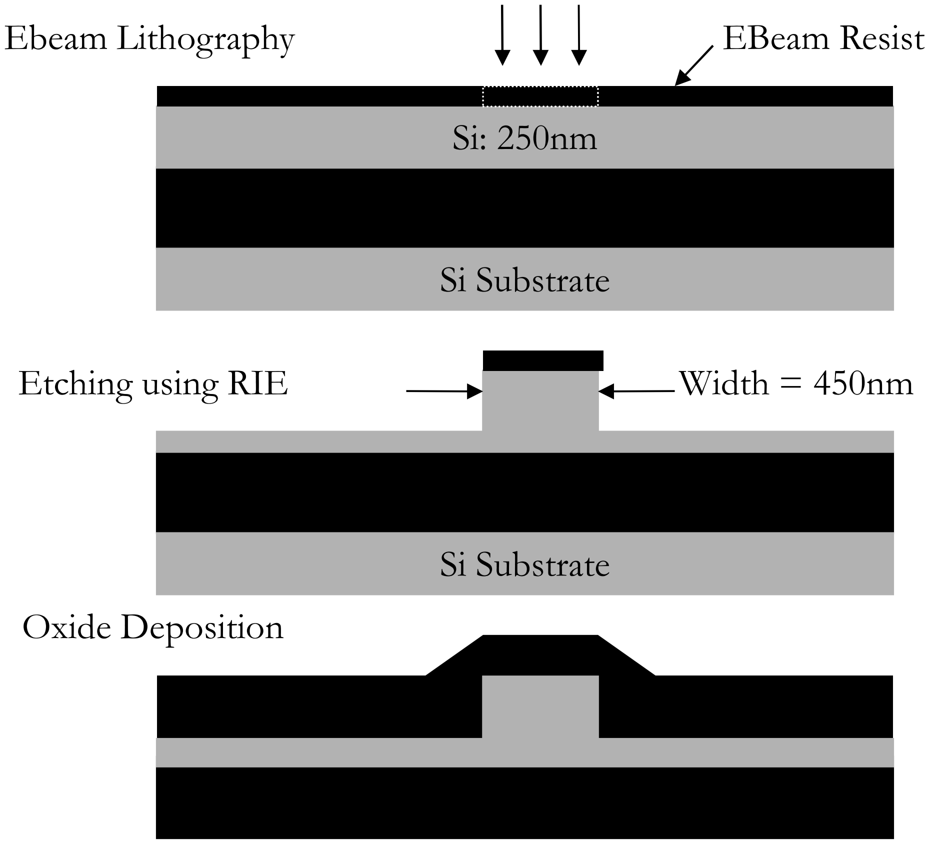


- Intensity in the waveguides can be orders of magnitude higher than the intensity in the core of single mode optical fiber.
- Nonlinear optical effect can be excited with moderate optical power in short distances.

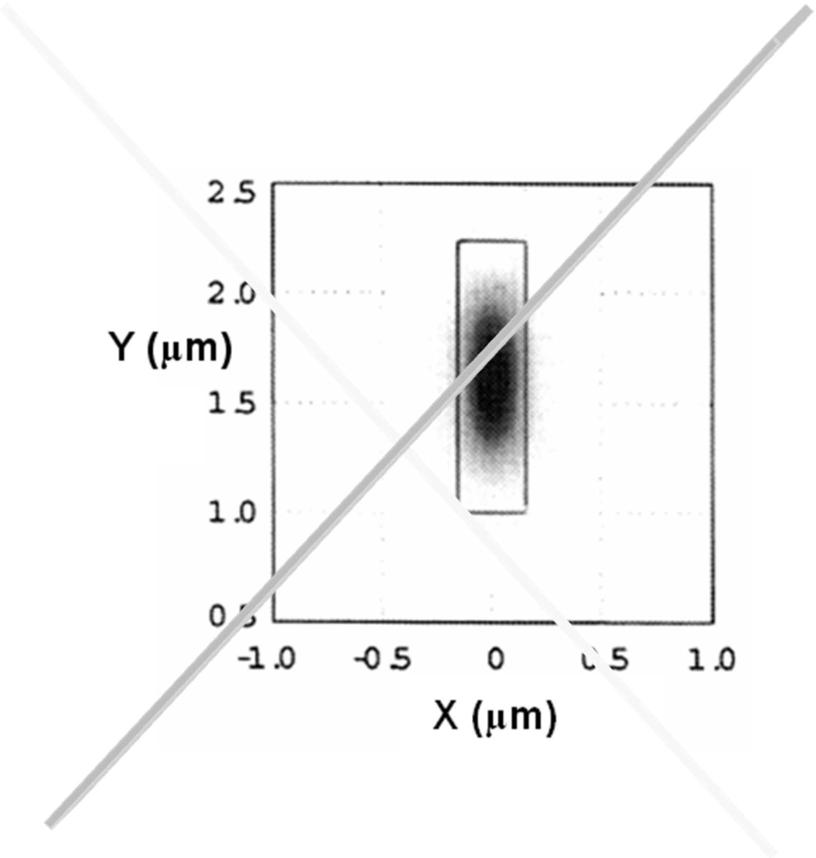
Silicon waveguides:

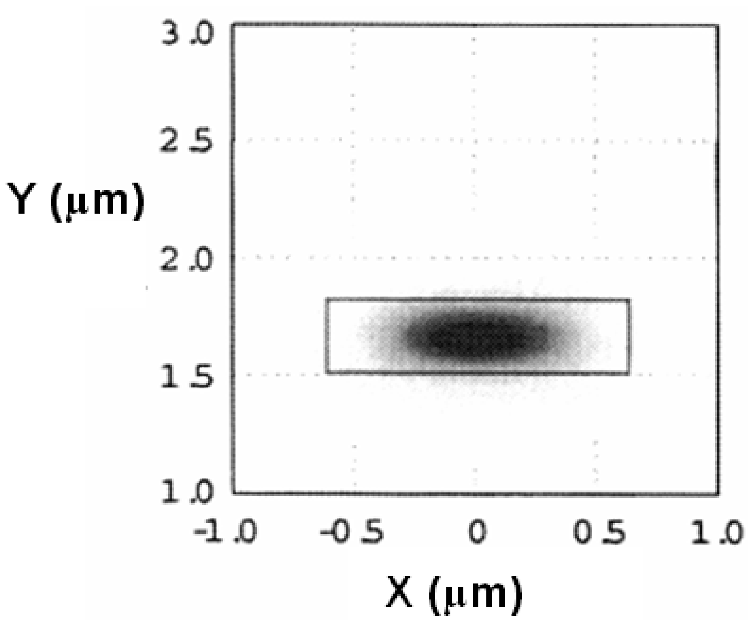
•High index contrast (very small waveguides: 3 orders of magnitude light enhancement when compared to fibers)
•Compatible with CMOS microelectronics.
•Ability of large-scale integration.

Fabrication

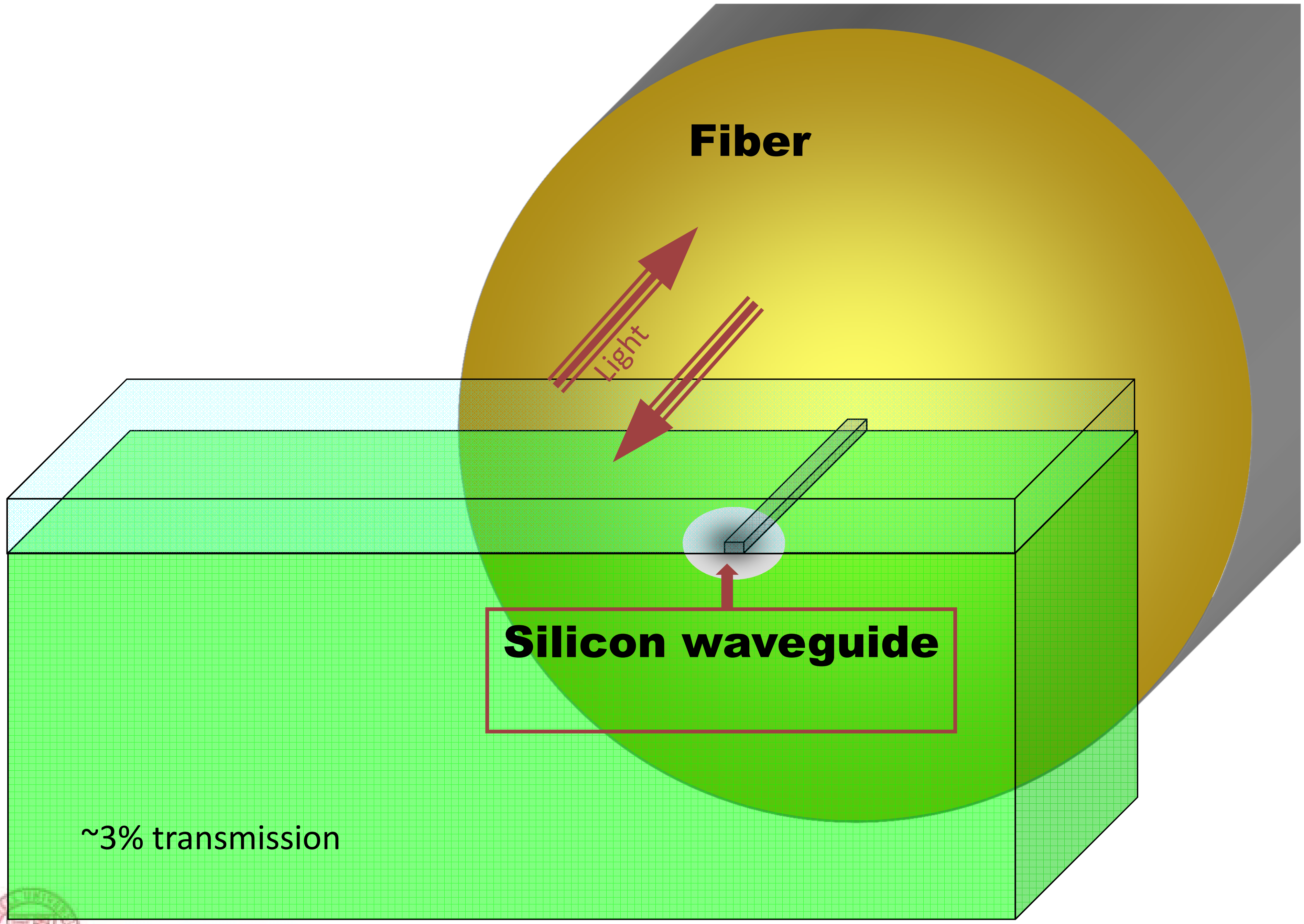


Orientation of the waveguides

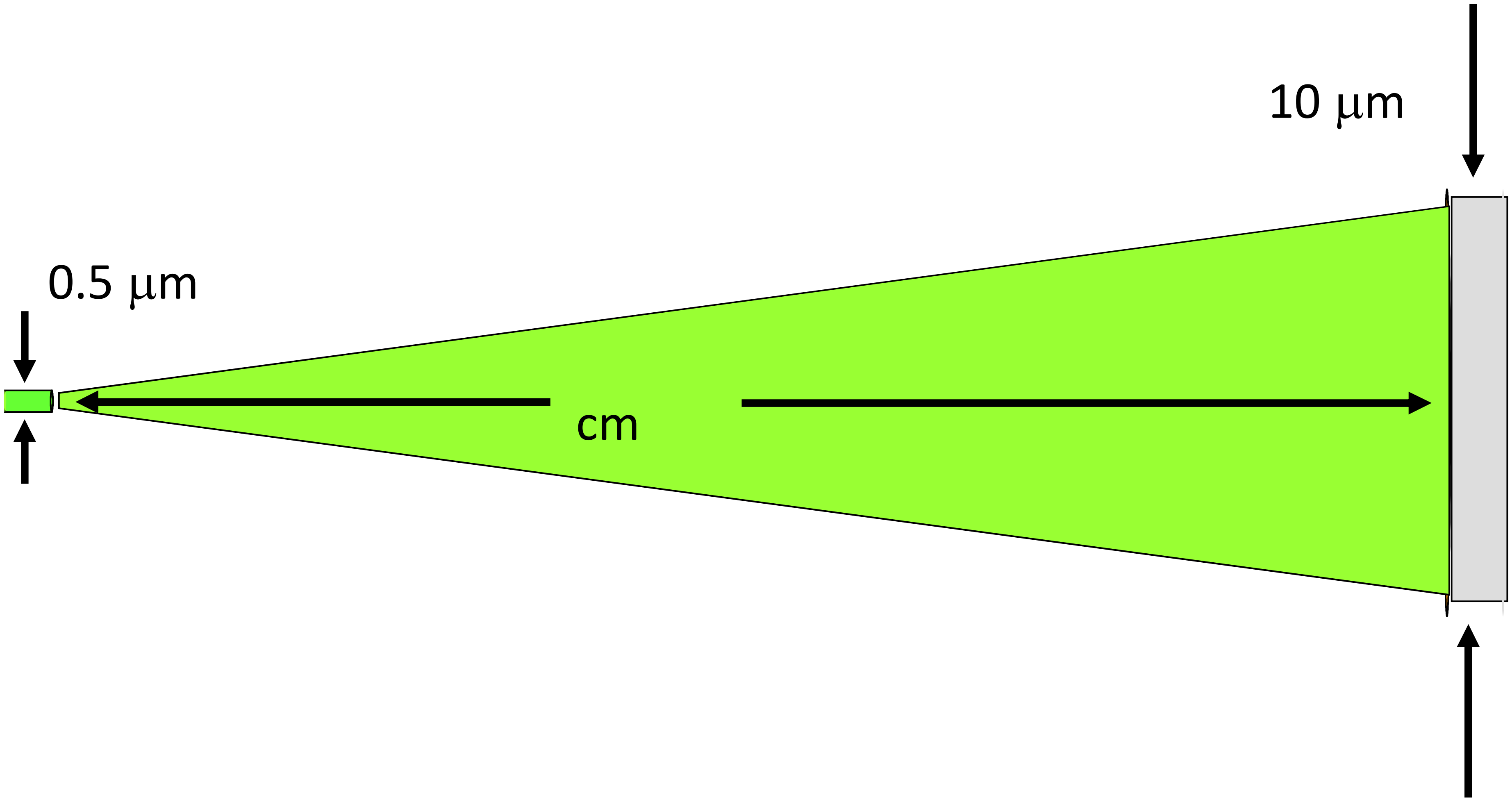




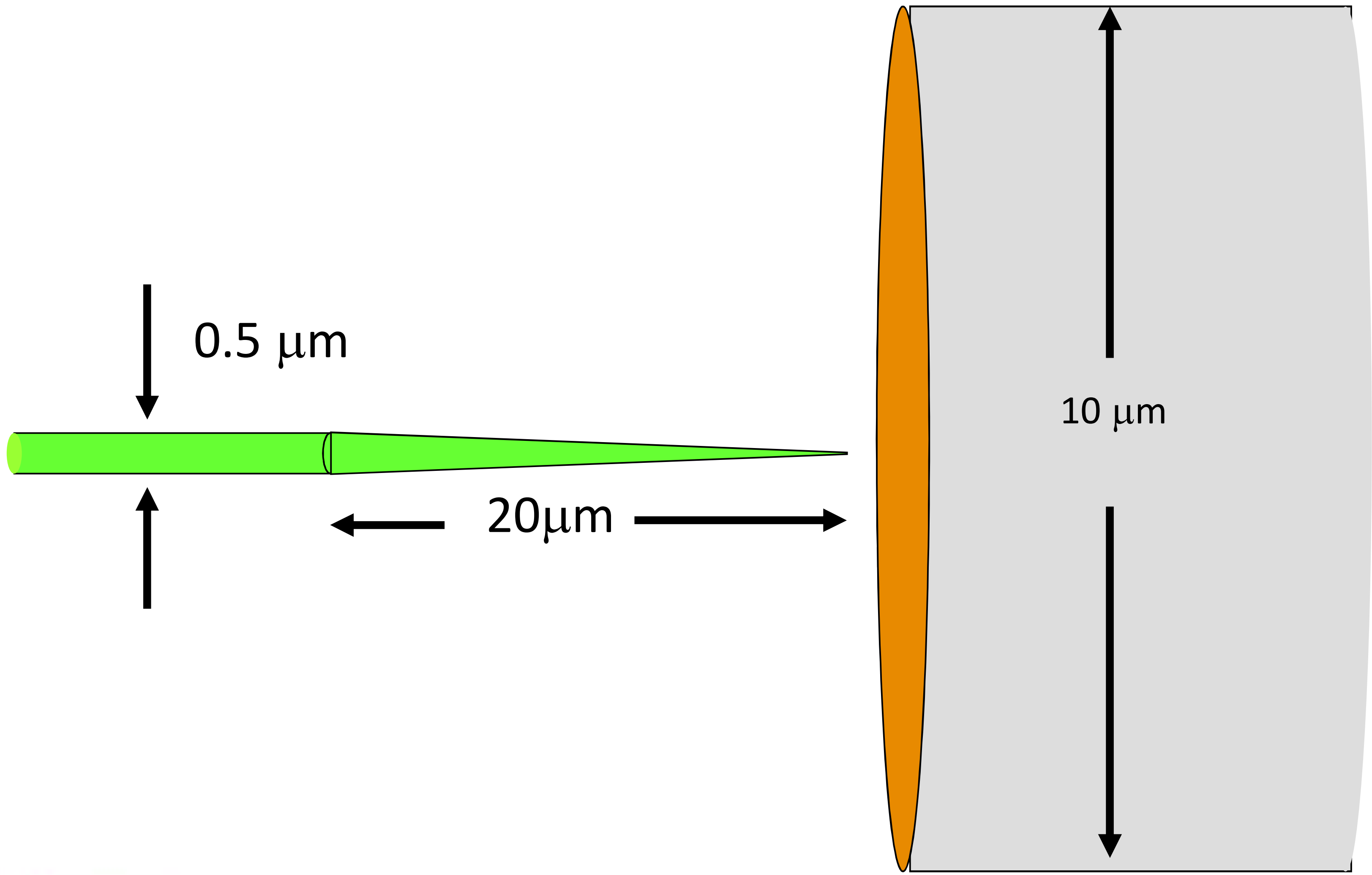
Highly polarization dependent


Fiber
Light
Silicon waveguide
~3% transmission

Naive solution



Inverse taper



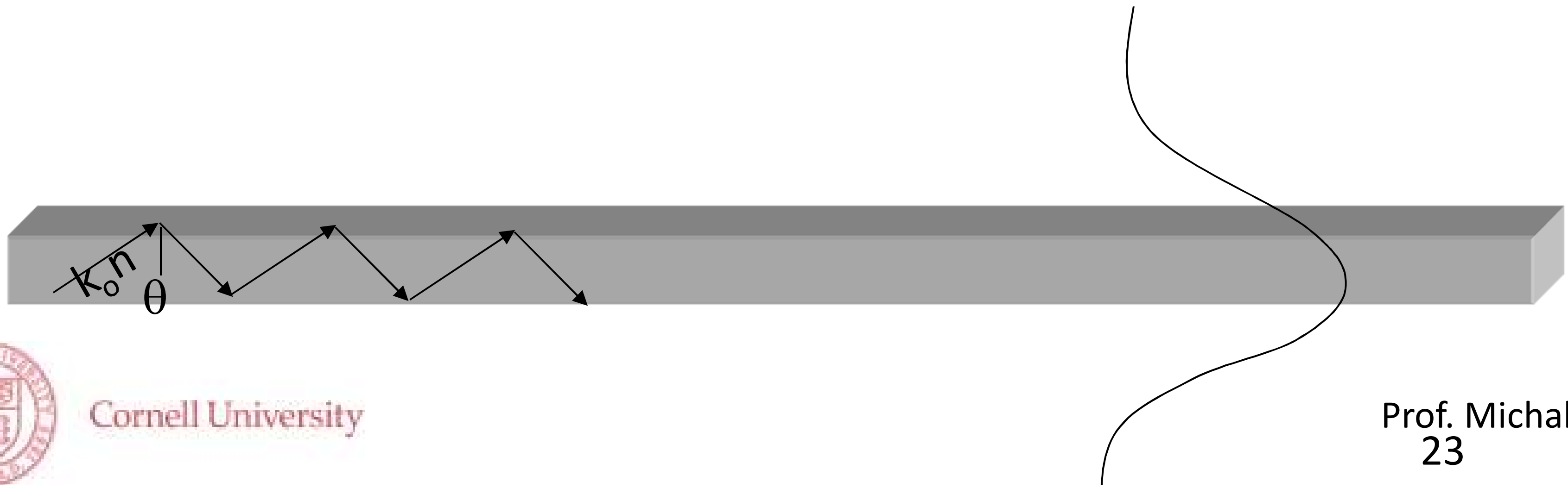
NTT, IBM

A very small waveguide

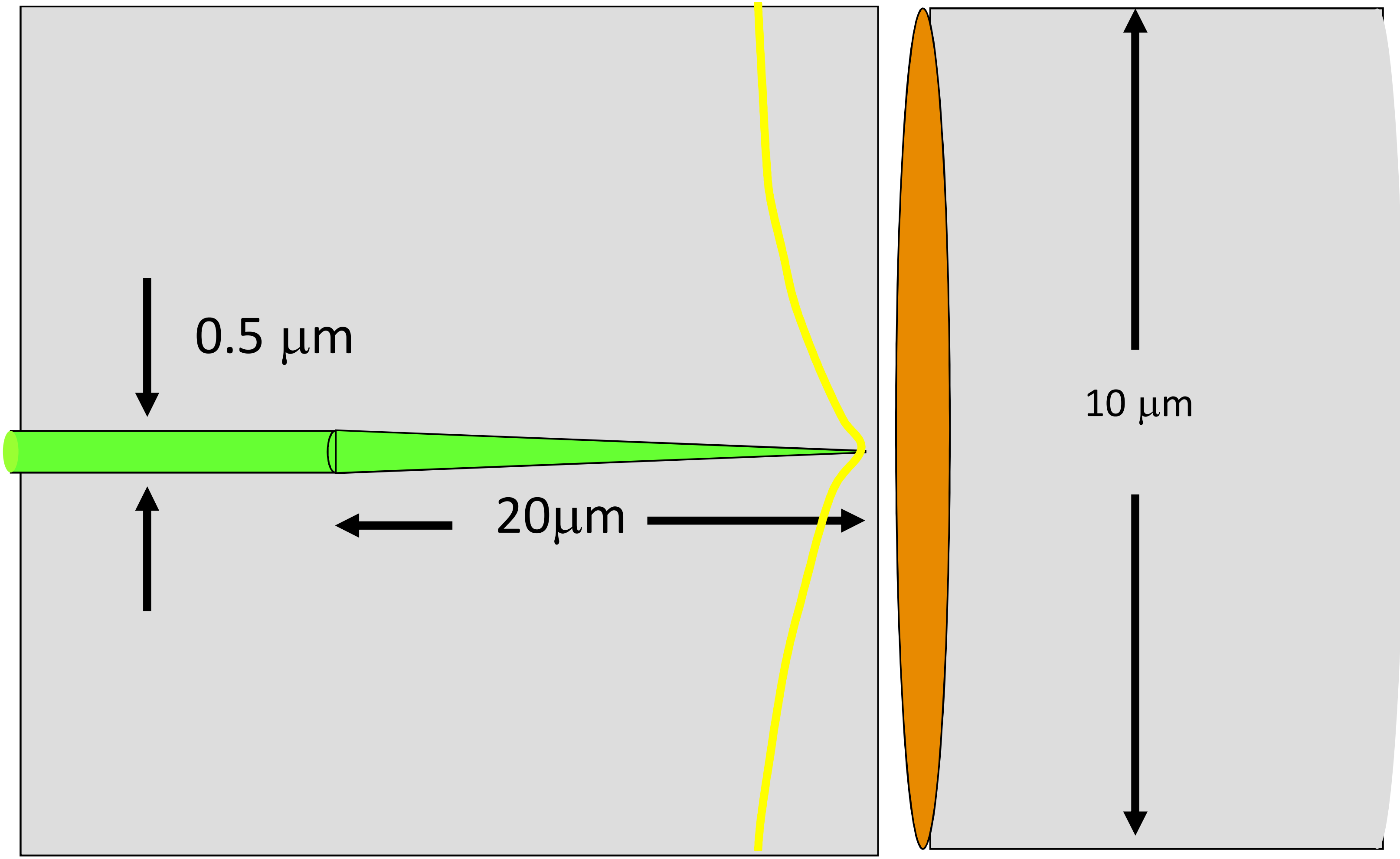
cos θ~q π/nk$_o$h

If q=1 and h small
cos θ~ π/nk$_o$h is large (small angle)

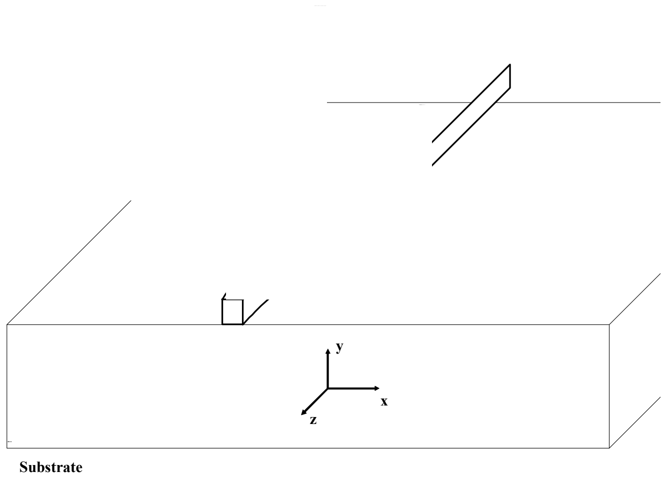
Small angle means very large evanescent field!

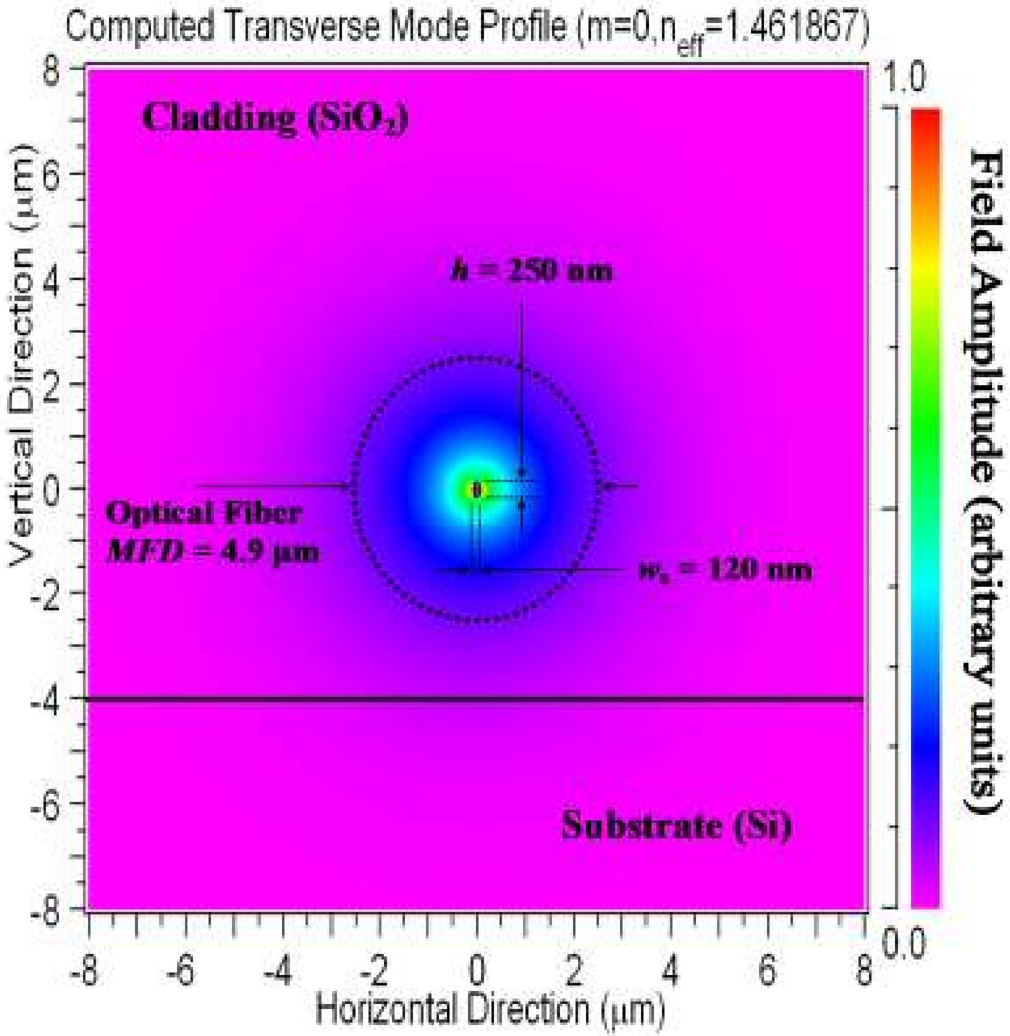


Inverse taper



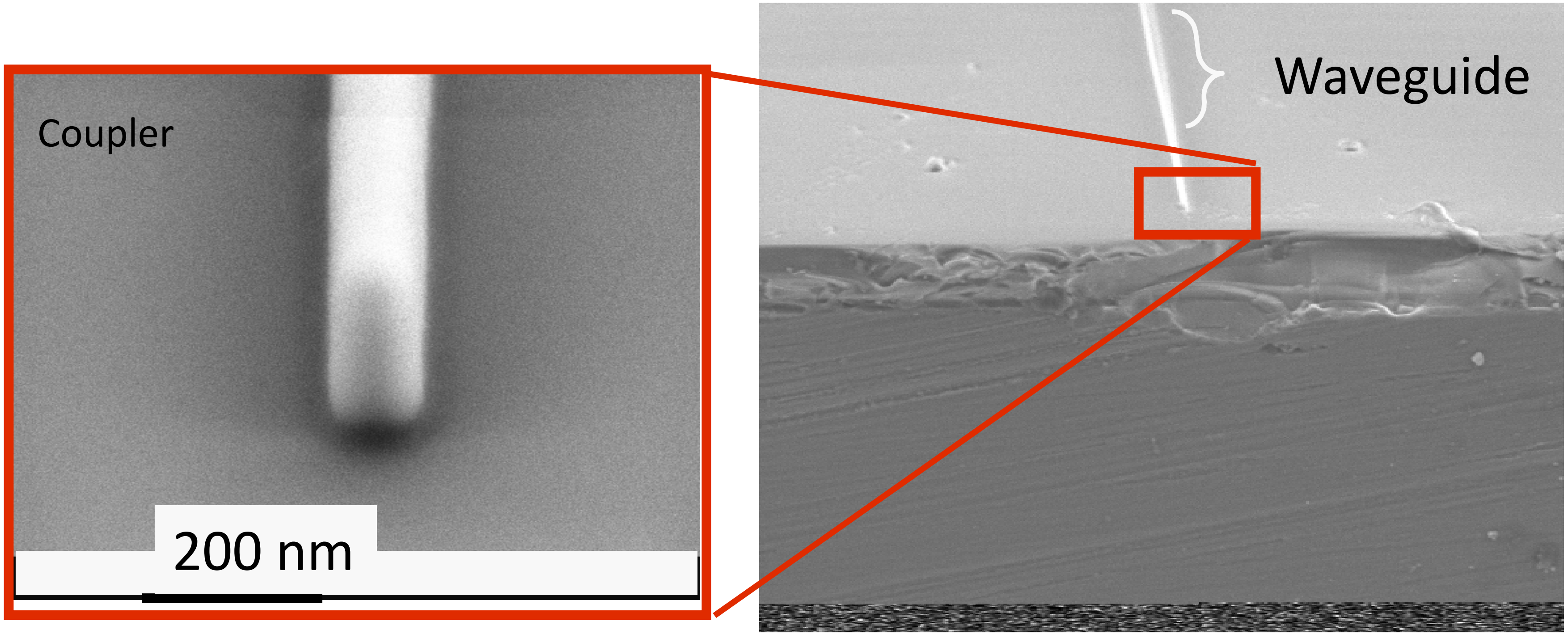
Simulations





95% efficiency

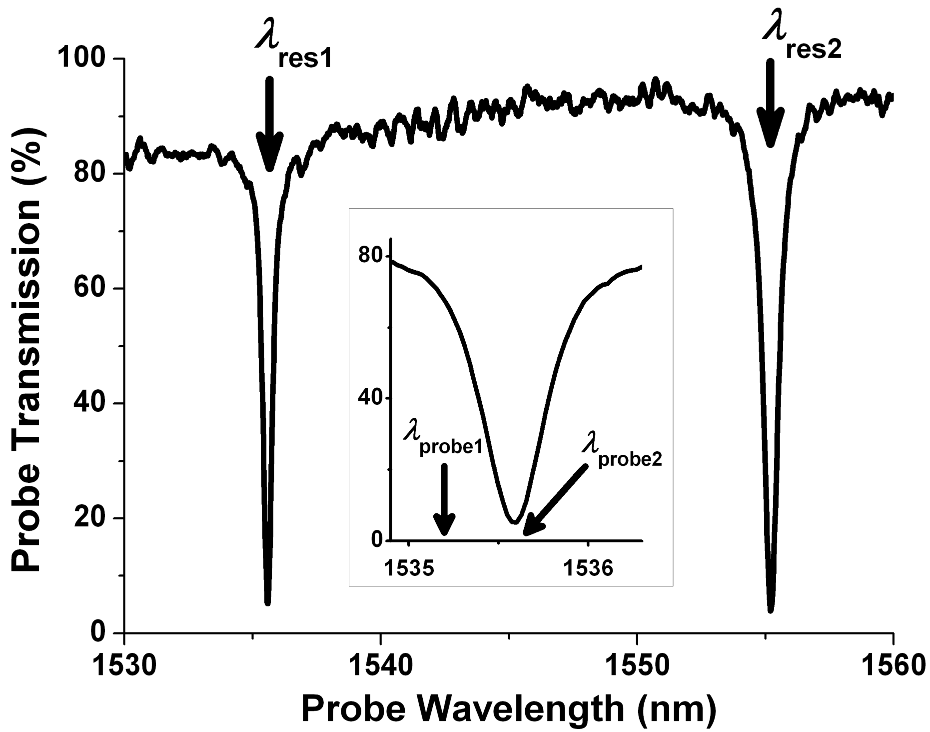
Fabrication



<1dB losses

Almeida, V. R., Panepucci, R. R., and M. Lipson, Optics Letters, 28, 1302 (2003).

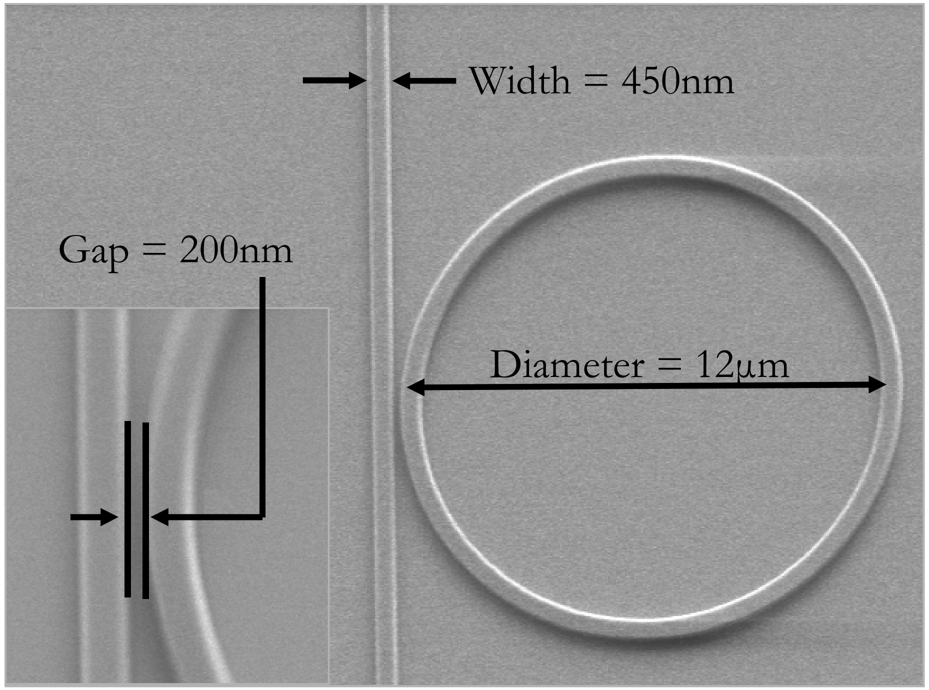
Strong light confining structures

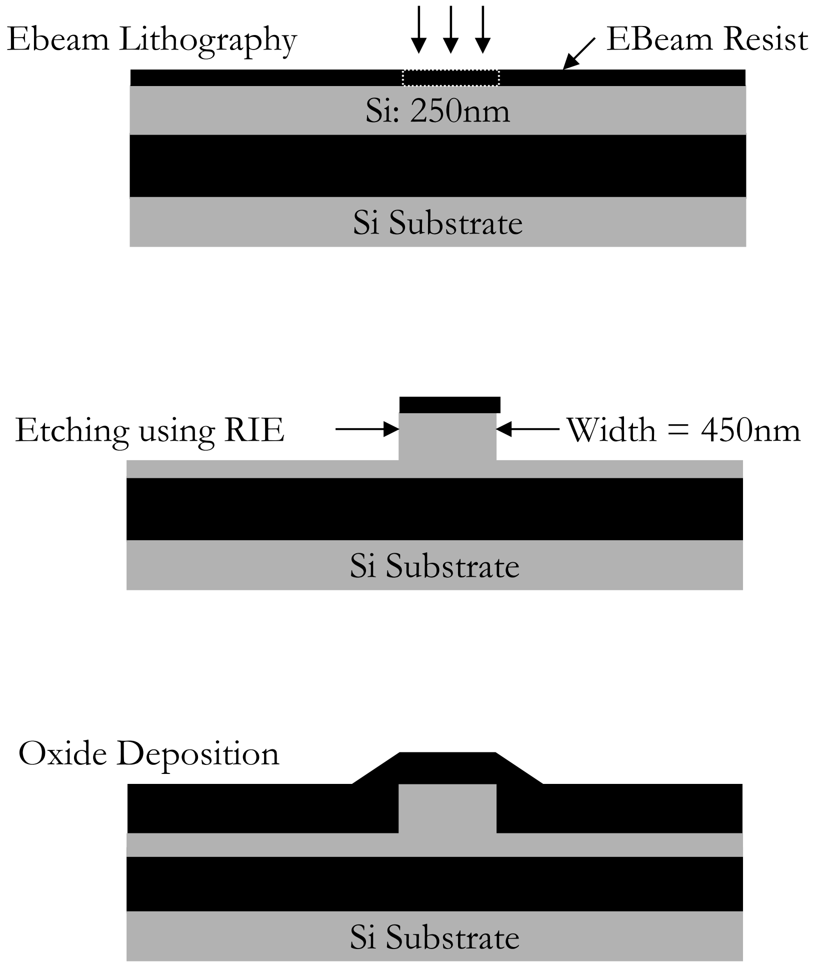


Device is very sensitive to small perturbations in the Silicon

Fabrication

Scanning electron micrograph of a ring resonator





Ultra Low Loss Waveguides and Ring Resonators

State of art

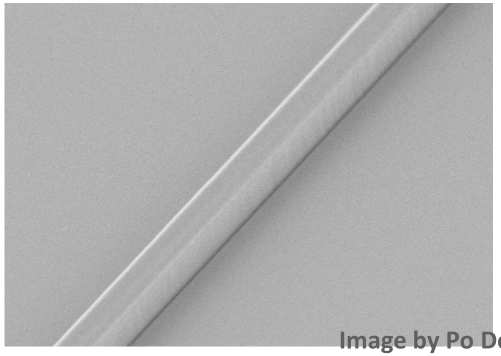
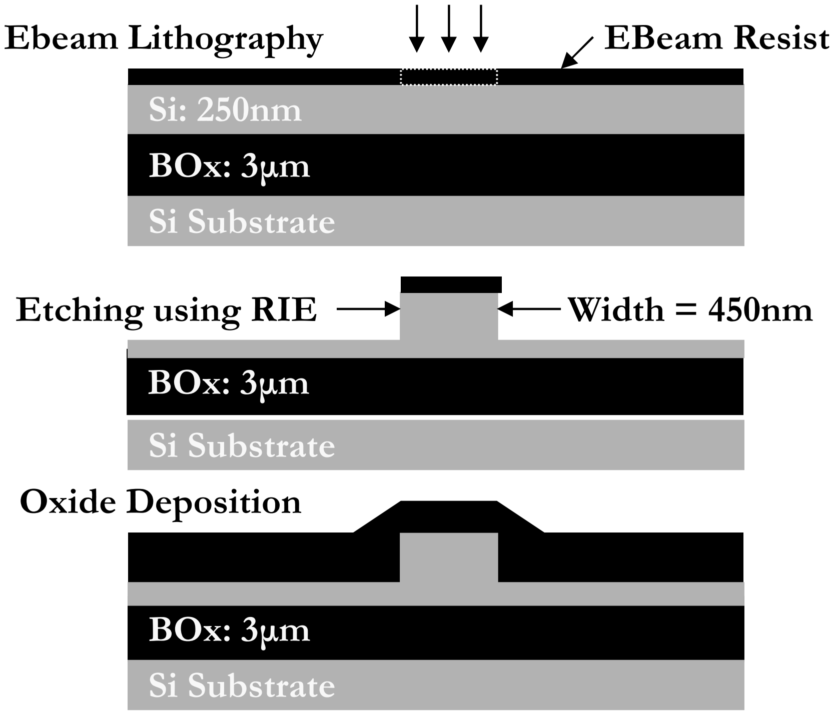


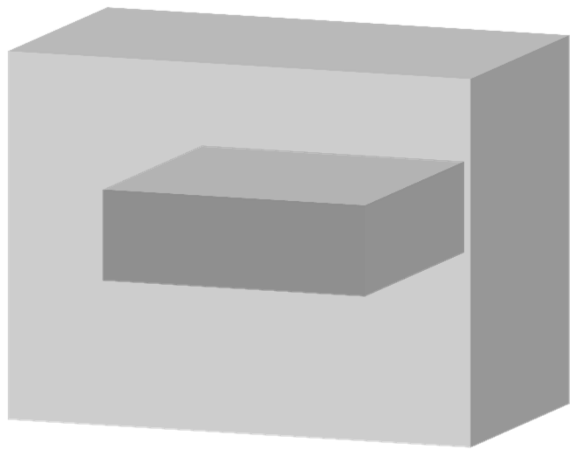
Image by Po Dong



Jaime Cardenas, Carl B. Poitras, Jacob T. Robinson, Kyle Preston, Long Chen, and Michal Lipson, "Low loss etchless silicon photonic waveguides," Opt. Express **17**, 4752-4757 (2009) Maziar P. Nezhad, Olesya Bondarenko, Mercedeh Khajavikhan, Aleksandar Simic, and Yeshaiahu Fainman, "Etch-free low loss silicon waveguides using hydrogen silsesquioxane oxidation masks," Opt. Express **19**, 18827-18832 (2011)
Boris Desiatov, Ilya Goykhman, and Uriel Levy, "Demonstration of submicron square-like silicon waveguide using optimized LOCOS process," Opt. Express **18**, 18592-18597 (2010)

Decreasing Losses in Silicon Waveguides

Etched Channel Waveguide: 1 – 2 dB/cm

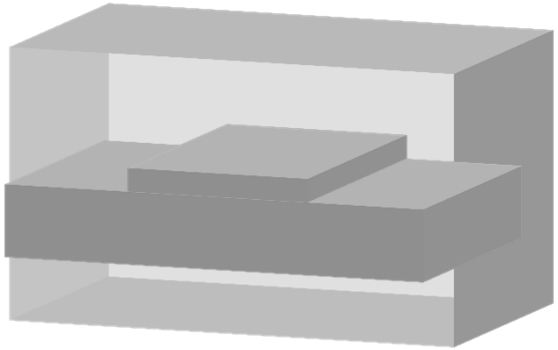


F. Xia, L. Sekaric, and Y. Vlasov, "Ultracompact optical buffers on a silicon chip," Nat. Photonics 1, 65-71 (2007)

M. Gnan, S. Thoms, D. S. Macintyre, R. M. De La Rue, and M. Sorel, "Fabrication of low-loss photonic wires in silicon-on-insulator using hydrogen silsesquioxane electron-beam resist," Electron. Lett. 44, 115-116 (2008)

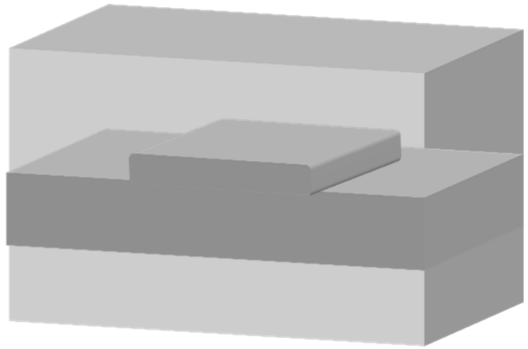
Decreasing Losses in Silicon Waveguides

Shallow Etch Rib: 0.3dB/cm



Po Dong, Wei Qian, Shirong Liao, Hong Liang, Cheng-Chih Kung, Ning-Ning Feng, Roshanak Shafiiha, Joan Fong, Dazeng Feng, Ashok V. Krishnamoorthy, and Mehdi Asghari, "Low loss shallow-ridge silicon waveguides," Opt. Express **18**, 14474-14479 (2010)

Oxidized Shallow Rib: 0.4dB/cm



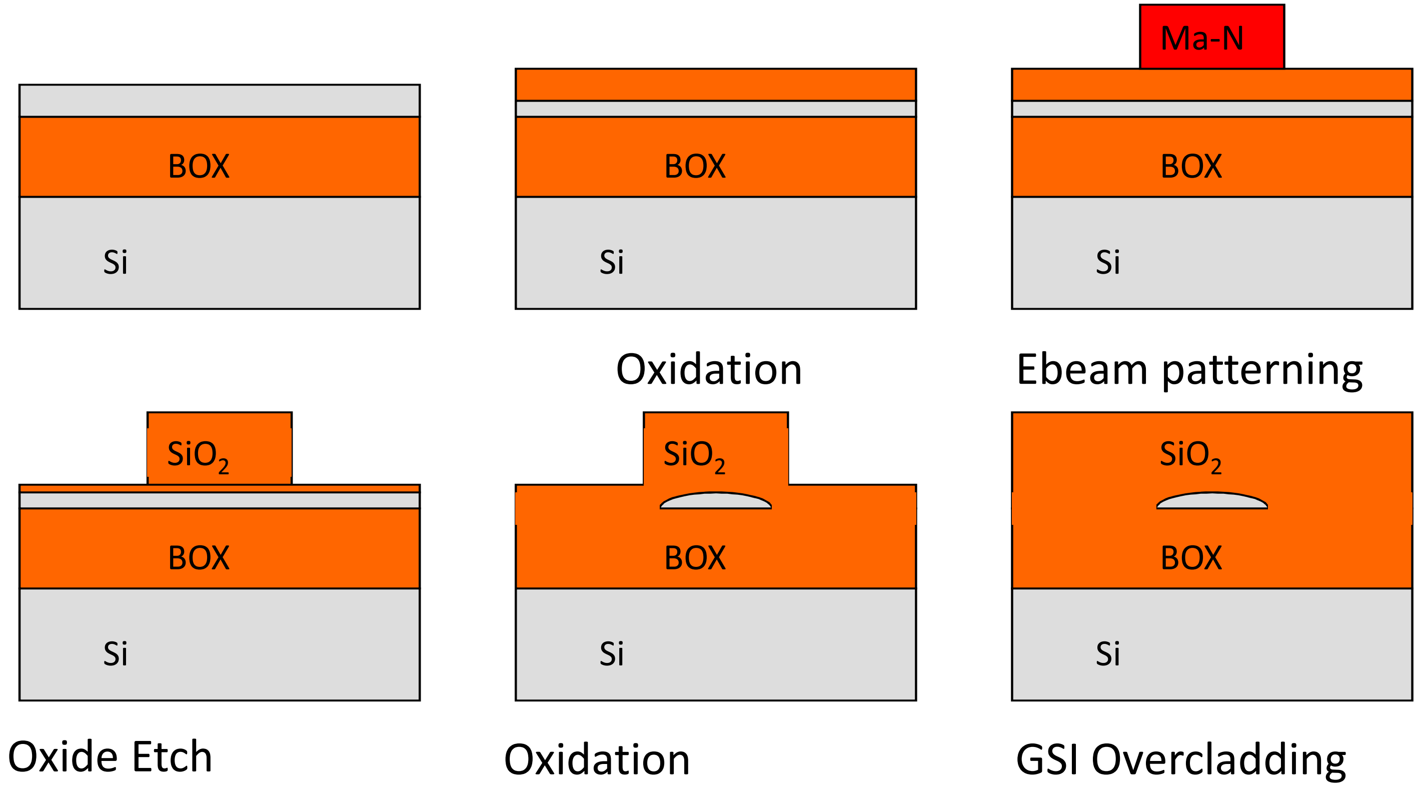
R. Pafchek, R. Tummidi, J. Li, M. A. Webster, E. Chen, and T. L. Koch, "Low-loss silicon-on-insulator shallow-ridge TE and TM waveguides formed using thermal oxidation," Appl. Opt. **48**, 958-963 (2009)

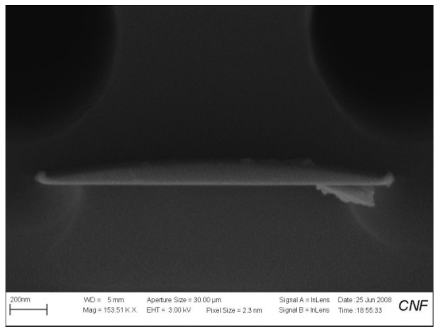
Cornell University

Prof. Michal Lipson

Prof. Michal Lipson

Etchless waveguides



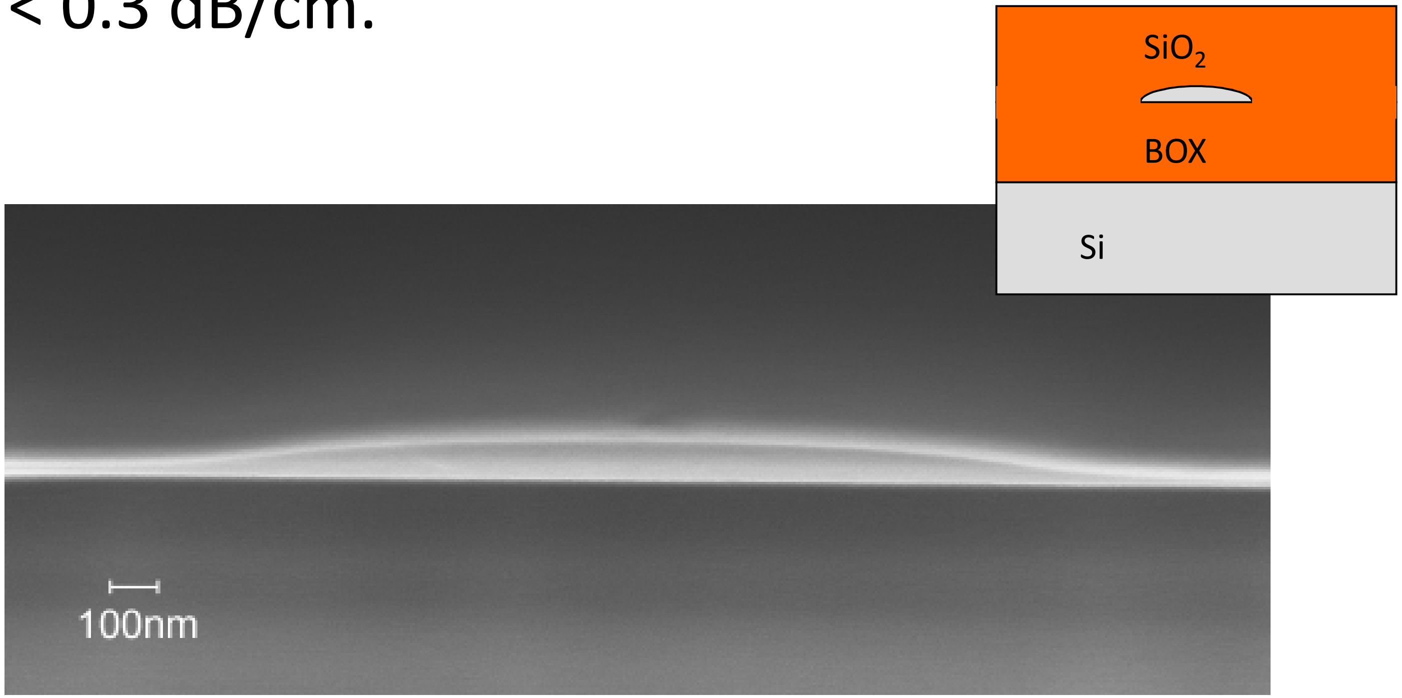


Cardenas, J., Poitras, C.B., Robinson, J.T., Preston, K., Chen, L. and Lipson, M., *Low loss etchless silicon photonic waveguides, Optics Express, Vol. 17, No. 6, 4752, 16 Mar. 2009.*

Etchless waveguides

Waveguides dimensions: 315-nm high by 1-μm wide.

Losses < 0.3 dB/cm.



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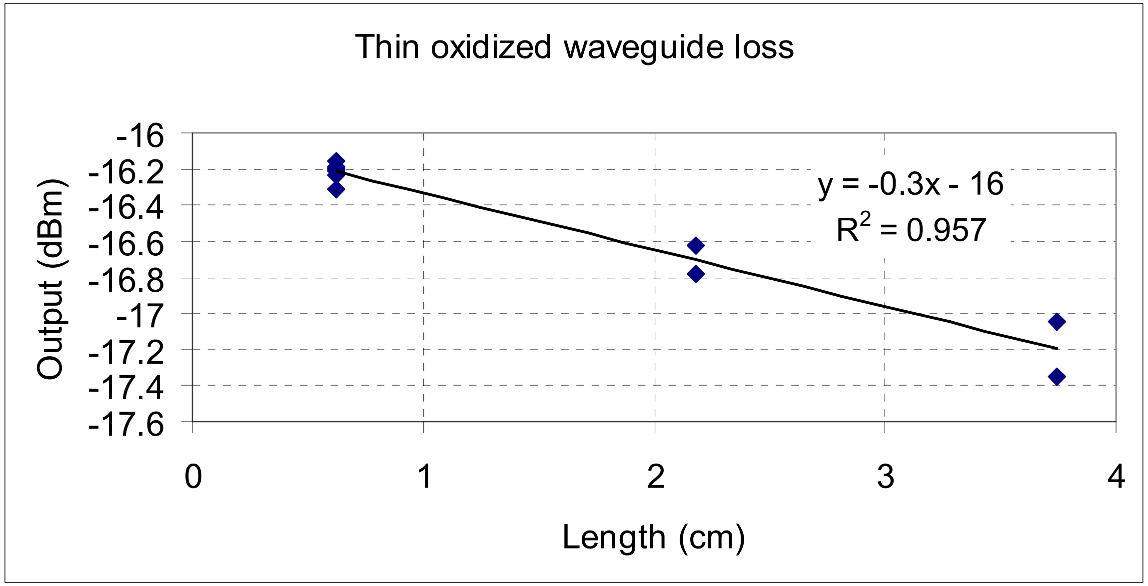
Results

- Etchless waveguide has a loss < 0.3 dB/cm.
- Waveguide is 1-μm wide by 70-nm high with an 8-nm slab.



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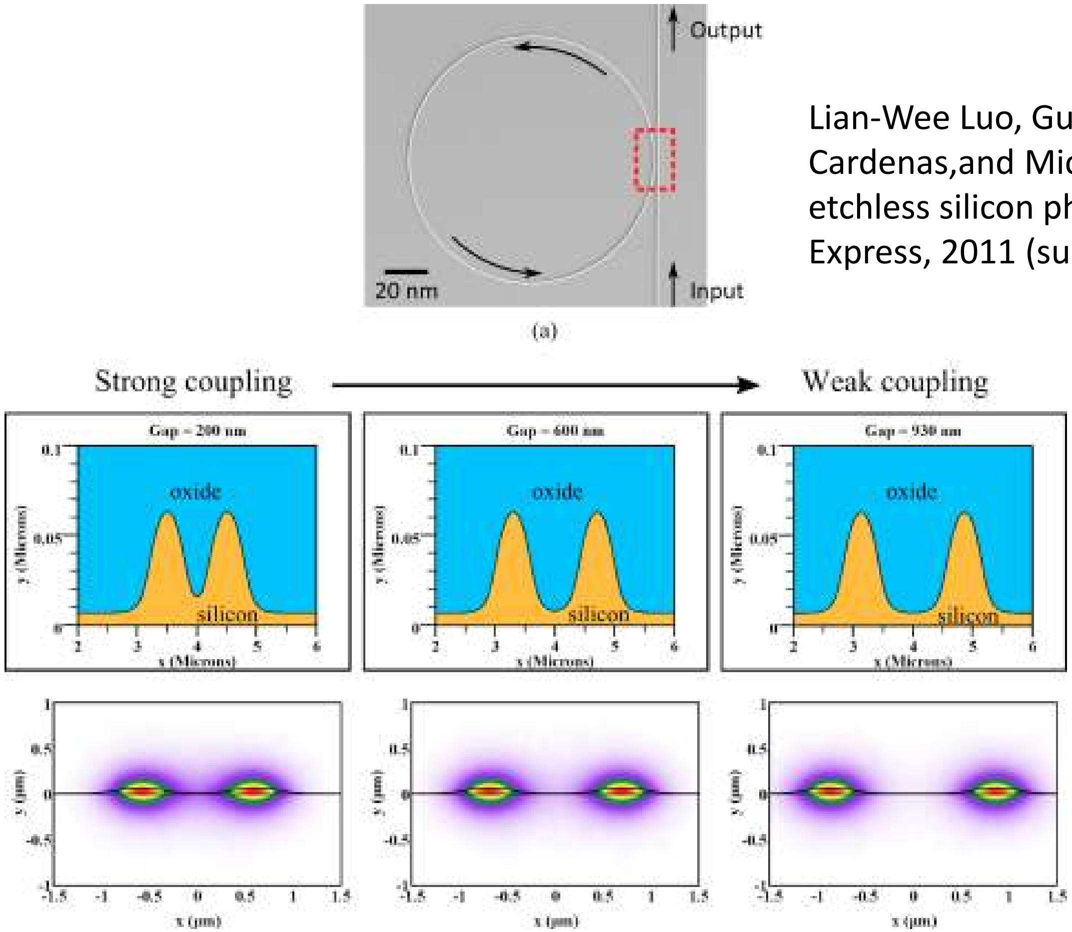
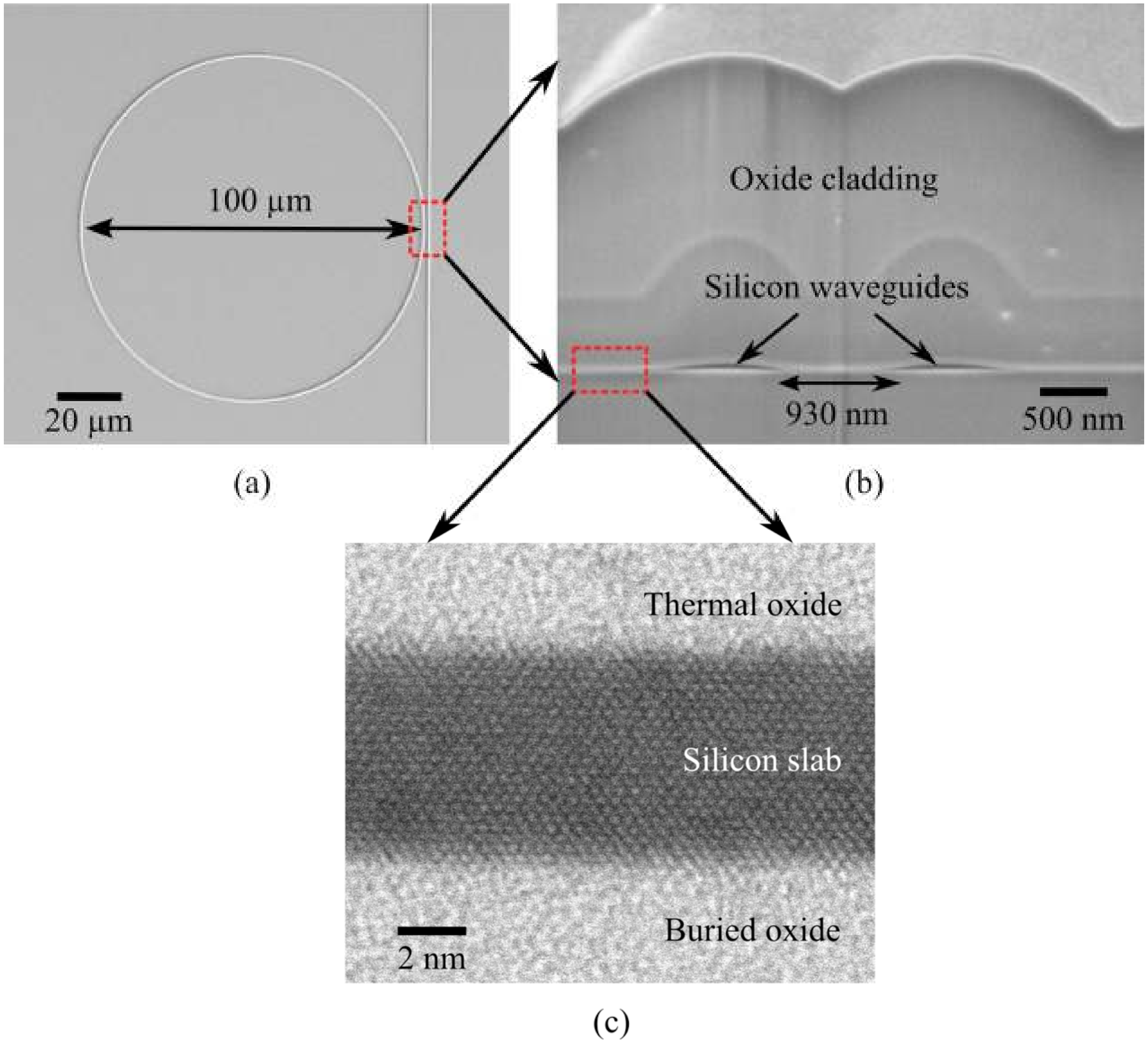
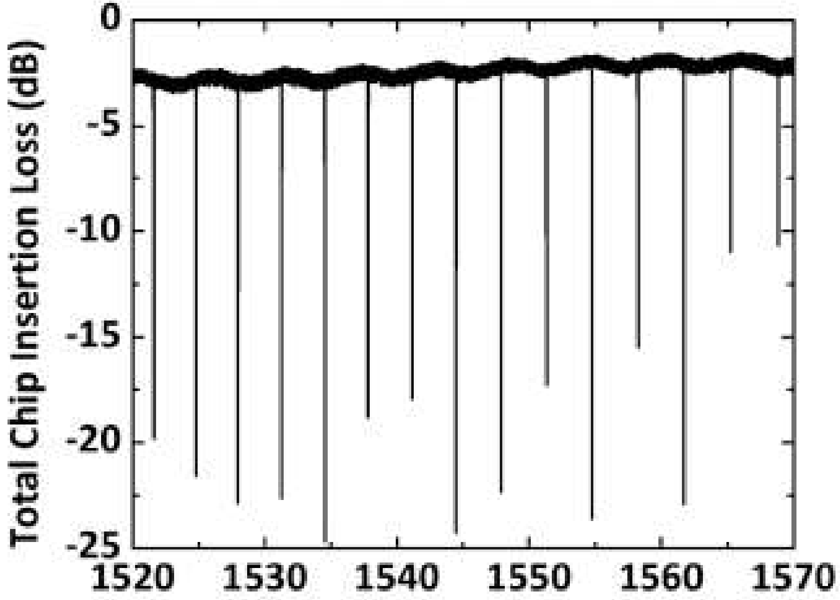
Etchless cavities

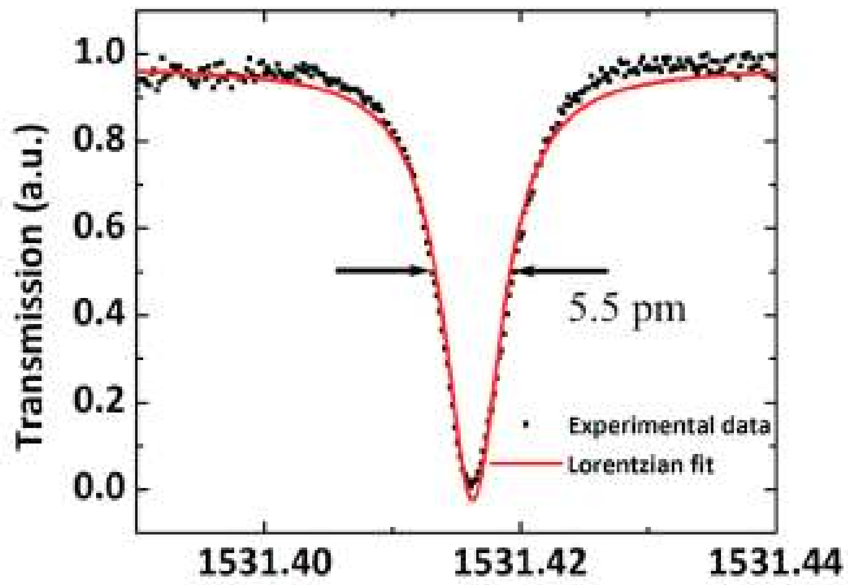


(b)

Lian-Wee Luo, Gustavo S. Wiederhecker, Jaime Cardenas,and Michal Lipson, High quality factor etchless silicon photonic ring resonators, Optics Express, 2011 (submitted)


100 µm
20 µm
(a)
Oxide cladding
Silicon waveguides
930 nm
500 nm
(b)
Thermal oxide
Silicon slab
Buried oxide
2 nm
(c)





Q~1M

Lian-Wee Luo, Gustavo S. Wiederhecker, Jaime Cardenas,and Michal Lipson, High quality factor etchless silicon photonic ring resonators, Optics Express, 2011 (submitted)

Electro-Optics Modulation

Overview

Electro-optical modulation in pure-silicon platform relies on free carrier dispersion (FCD)

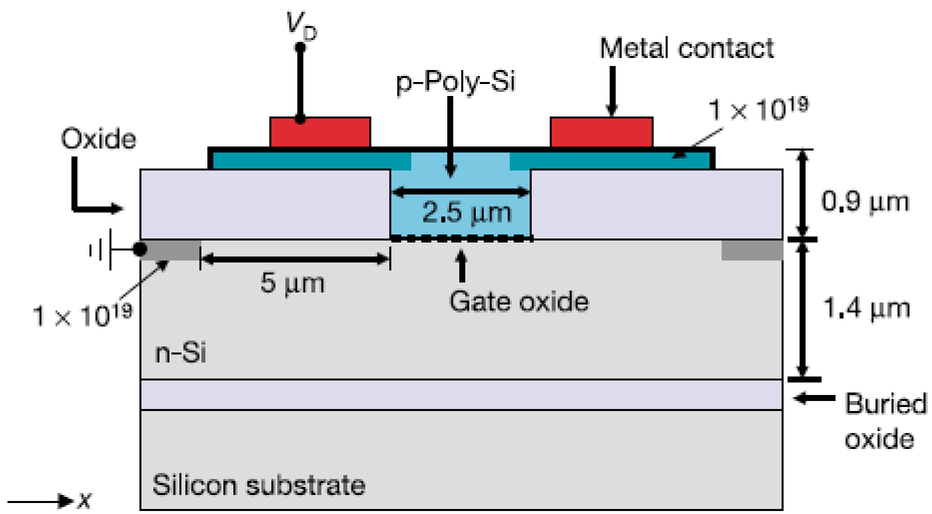
FCD is a change in refractive index of a material due to change in free carrier density within the material.

FCD always comes with free carrier absorption(FCA), due to Kramers-Kronig relation.

MOS Modulators

First all-silicon modulator with >1GHz BW

Changes carrier density in optical region by using the accumulation layer modulation in a MOS channel area.



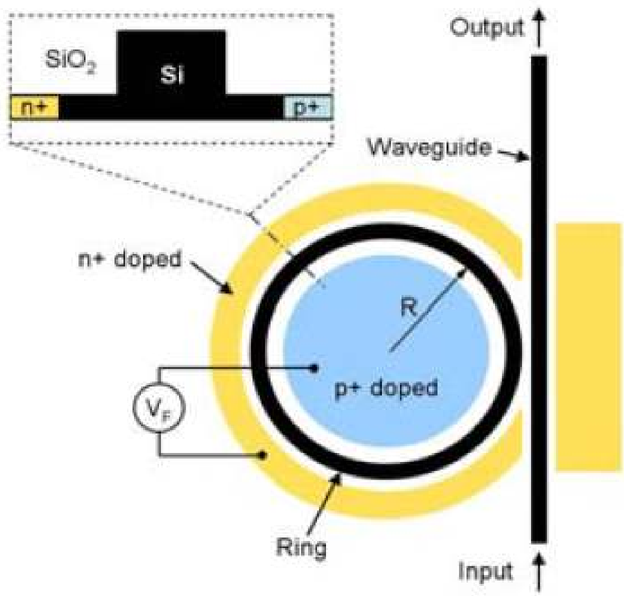
Paniccia, M. et al., "A high-speed silicon optical modulator based on a metal-oxide-semiconductor capacitor"(2004)

Forward PIN

Based on injection of carriers in a forward bias diode operation.

Can achieve very high index change per applied voltage due to exponential I-V characteristic of a diode.

Limited in speed due to carrier dynamics



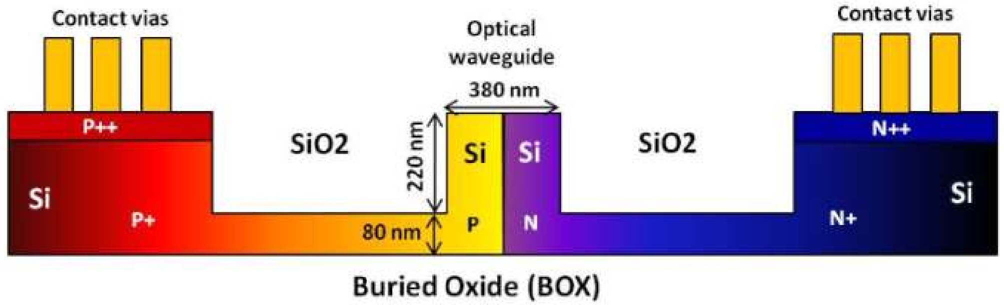
Manipatruni, S. et al., “High speed carrier injection 18 gb/s silicon micro-ring electro-optic modulator” (2007)

Reverse PN

Based on depletion width modulation in reverse bias of a PN junction

– Number of free carriers are lower in depletion region, resulting in index change

Carrier dynamics permit much faster operations, into > 40GHz.



Li, G. et al., "25 Gb/S 1V- driving CMOS ring modulator with integrated thermal tuning" (2011)

Implemented structures

FCD induces refractive index change, which changes the phase of an optical signal.

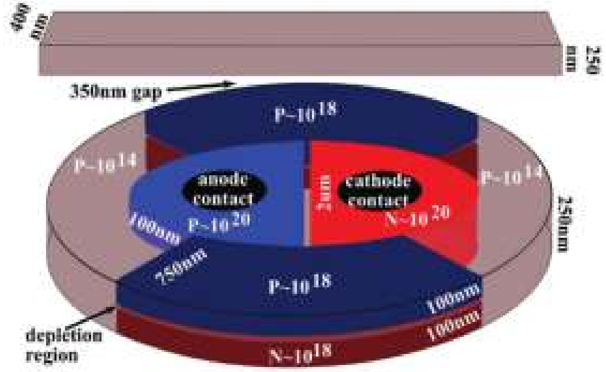
- This phase modulation needs to be converted to amplitude modulation for On-Off-Keying (OOK) signal.

Two common structures are :

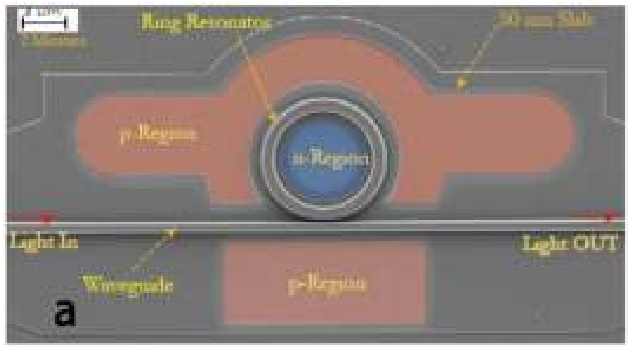
- Microring / Microdisk resonators
- Mach-Zehnder Interferometer

Microring/Disk Modulator

- Leverages the resonant transfer function to convert small change in index to large change in amplitude.
- Allows for very small foot print (<20um in diameter)
- Temperature sensitivity is a parasitic effect that needs to be controlled.



Watts, M. R. et al., “Vertical junction silicon microdisk modulators and switches” (2011)



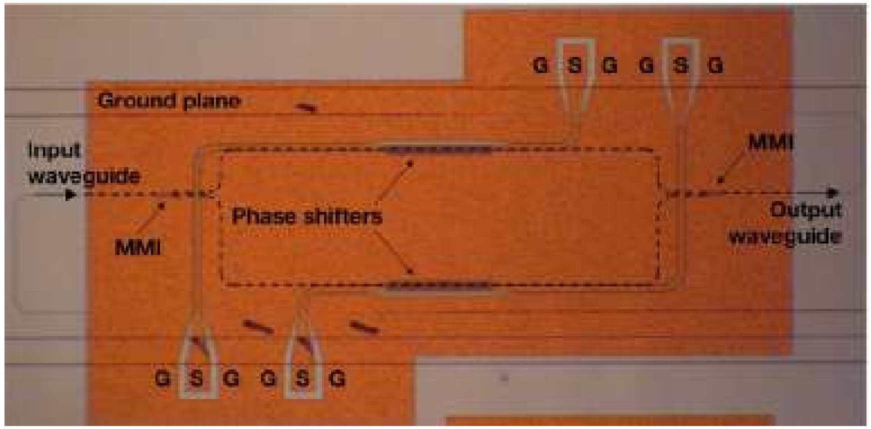
Manipatruni, M. et al., “Ultra-low voltage, ultra-small mode volume silicon microring modulator” (2010)

Mach-Zehnder Modulator

Uses MZI's sinusoidal transfer function of phase to modulate amplitude.

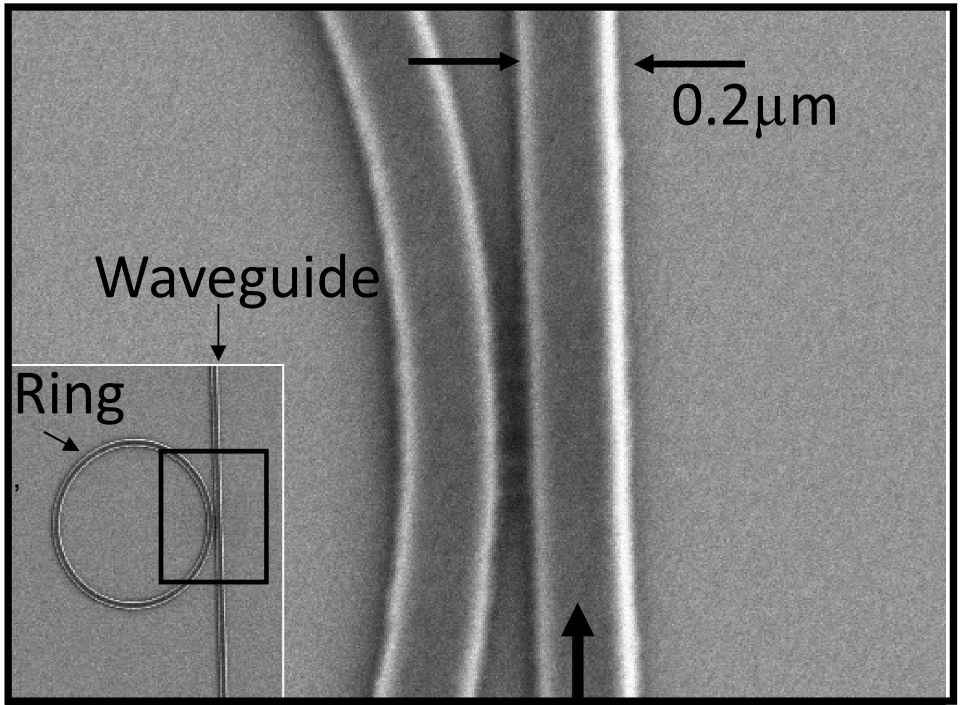
Relatively big, due to large phase shift requirement.

Non-resonant and differential, eliminating temperature sensitivity.



Thomson, D.J. et al. , "High contrast 40 gbits/s optical modulation in silicon" (2011)

Compact all-optical modulator on Silicon (carrier injection)



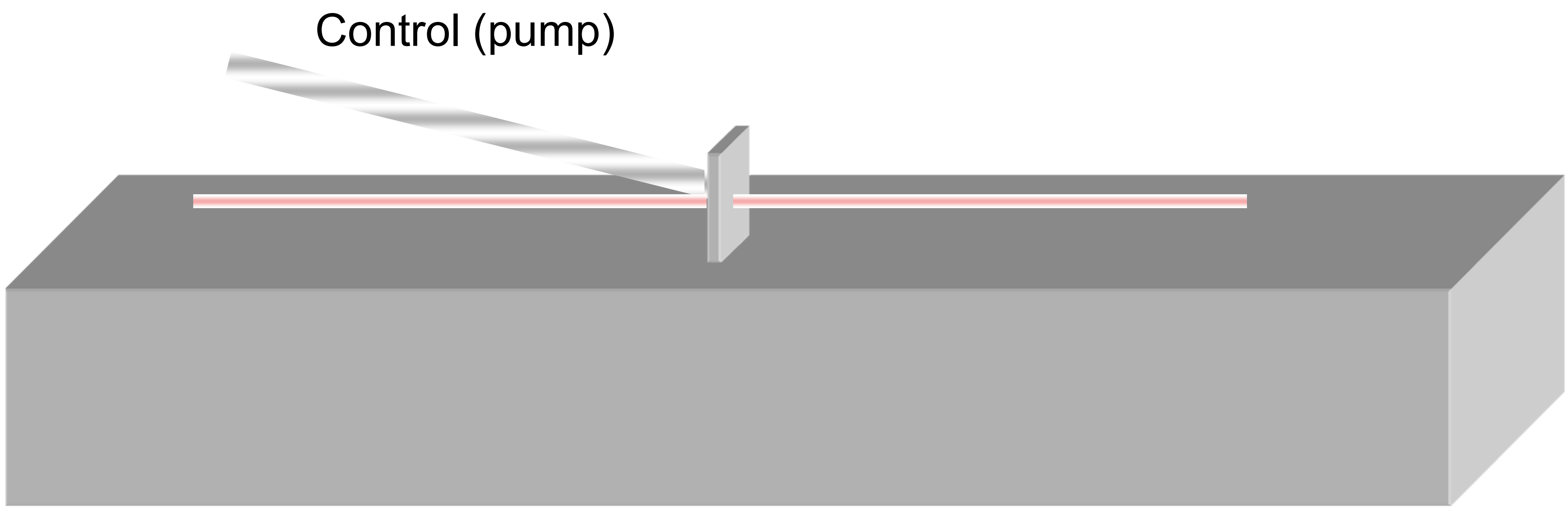
Pump+probe (λ_{probe}~ λ_{pump}~1.5μm)

High confinement waveguides: Enhancement of the two-photon absorption

High Q cavity: Increase in sensitivity of the device to small index changes

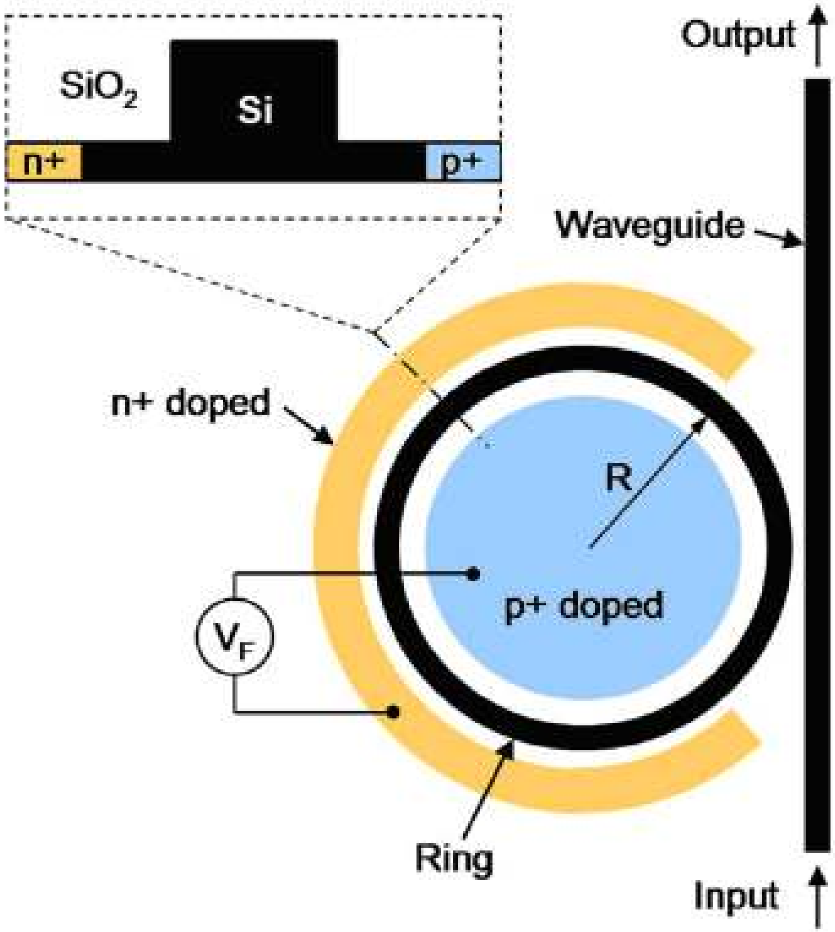
Almeida, V. R., Barrios, C. A., Panepucci, R. R., Lipson, M., "All-Optical control of light on a Silicon chip", Nature, pp1081-1084 (Oct 28th, 2004)
Almeida, V. R., Barrios, C. A., Panepucci, R. R., Lipson, M., Foster, M.A., Quzounov, D. G., and A. L. Gaeta, "All-optical switching on a silicon chip", Optics Letters 29 (Dec. 2004)

All-optical modulation



Opening gate: from opaque to transparent

Ring resonator based electro-optic modulator on silicon-on-insulator-microns in size

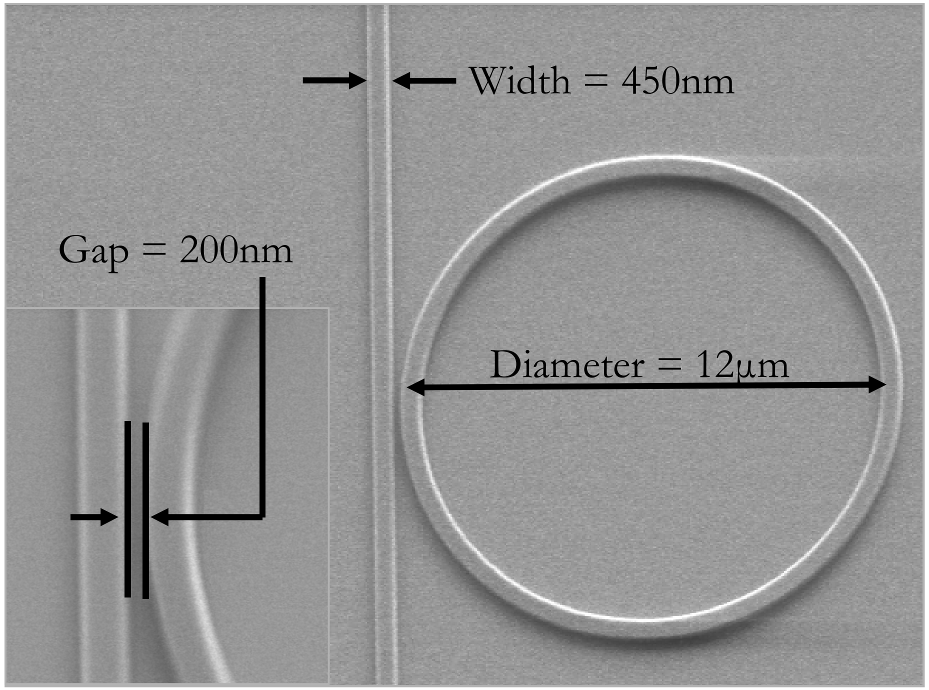


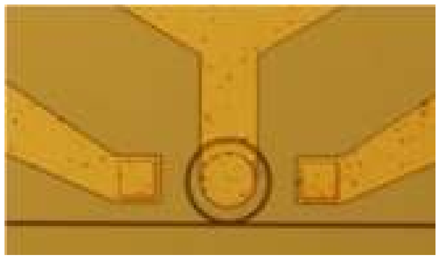
Liu, A. et al. Nature 427, 615 (2004)

Q. Xu, B. Schmidt, M. Lipson, Nature, May 19 March 2005

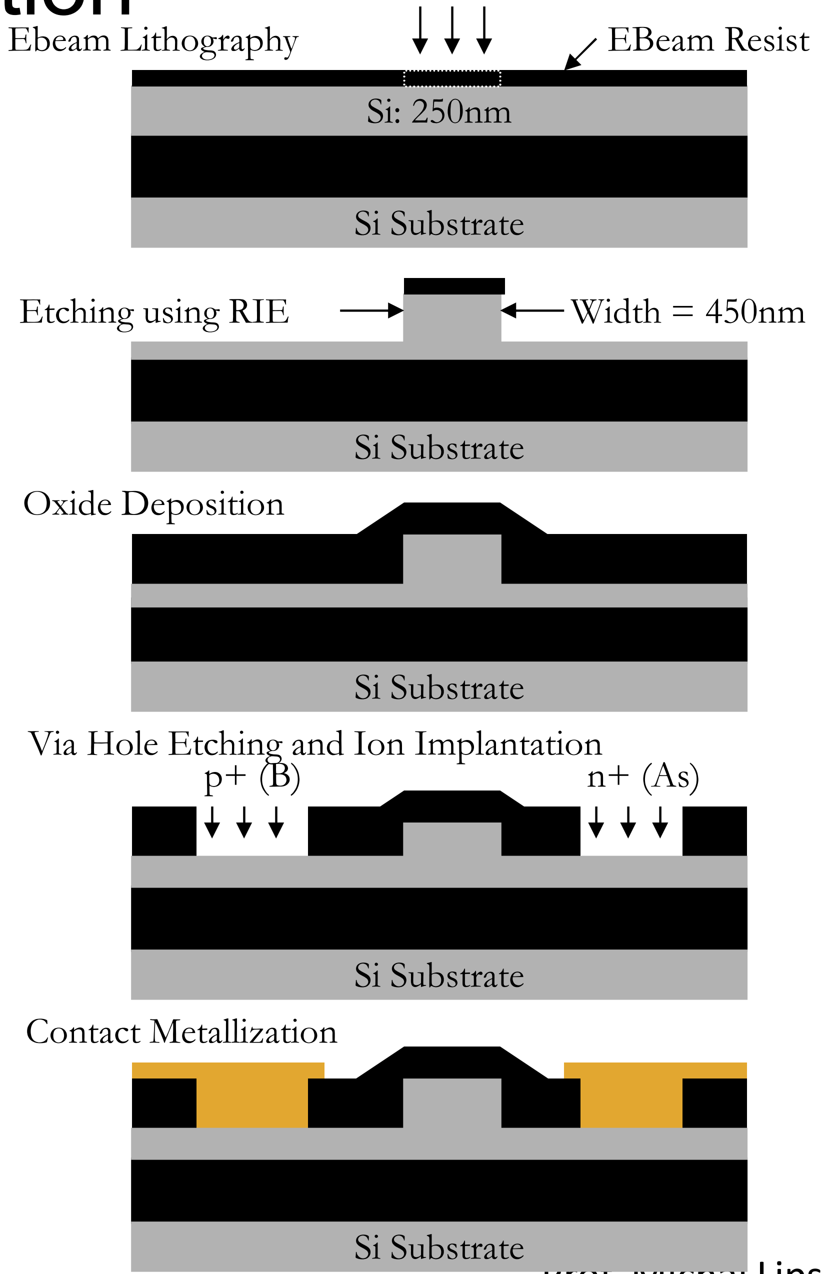
Fabrication

Scanning electron micrograph of a ring resonator

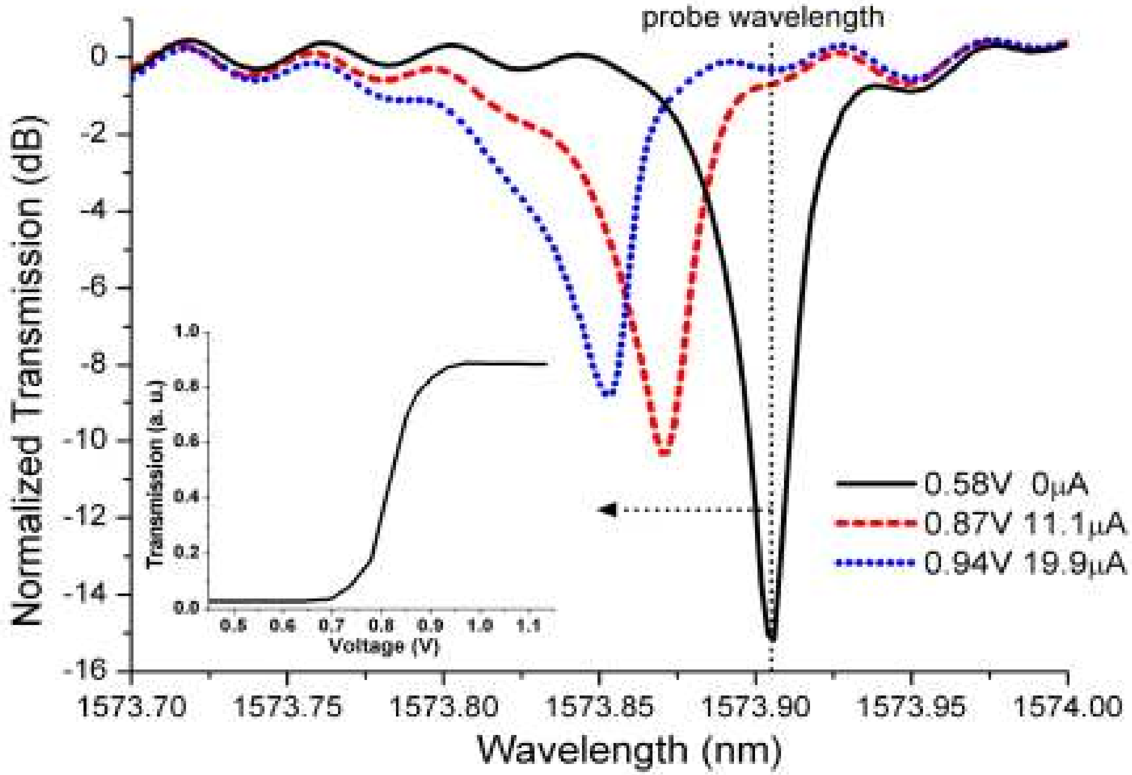




Microscope image of fabricated optical modulator with electrical contacts

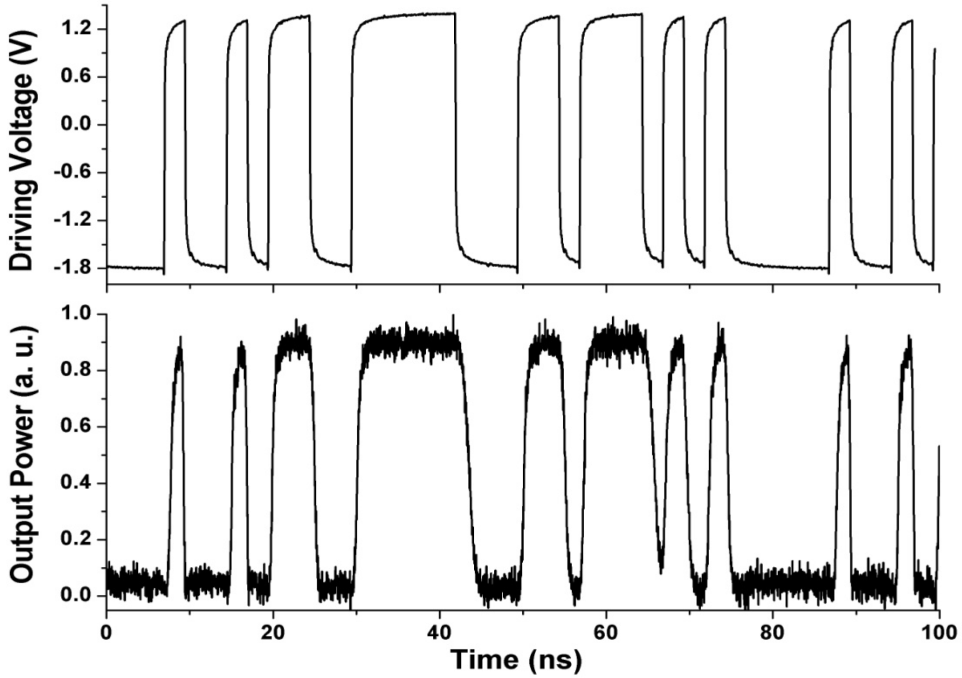


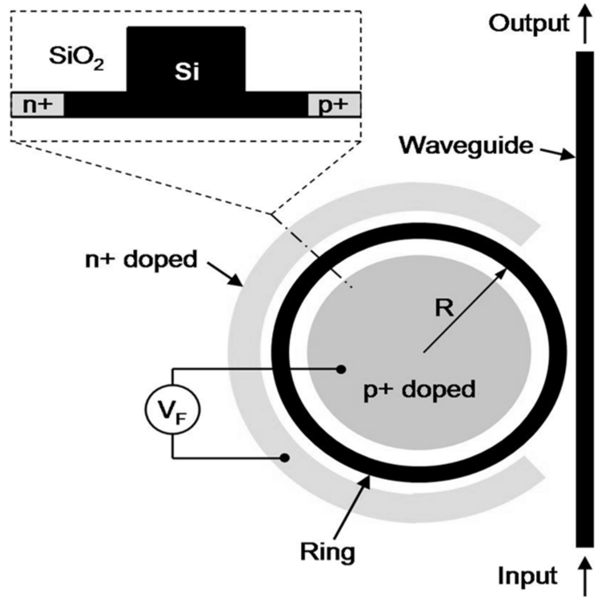
Modulation results (DC)



Dynamic response

0.4 Gbit/s generated with 3.3 Vpp in micron-size device!





Lifetime under junction: 0.2nsec

Q. Xu, B. Schmidt, M. Lipson, Nature, May 19 March 2005

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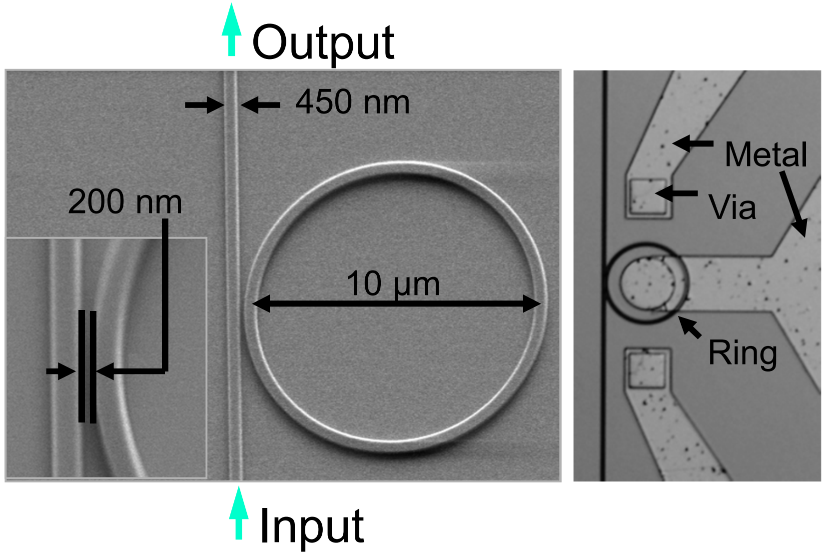
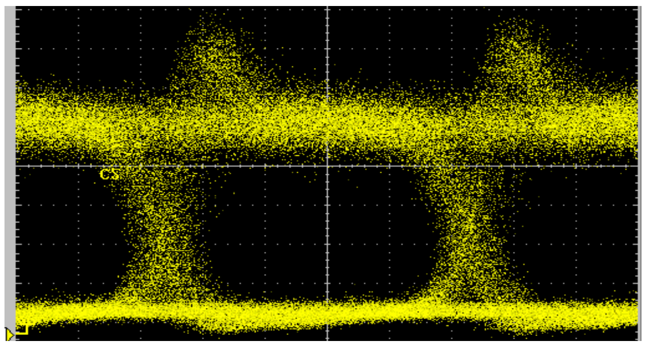
Microring modulator : experiments

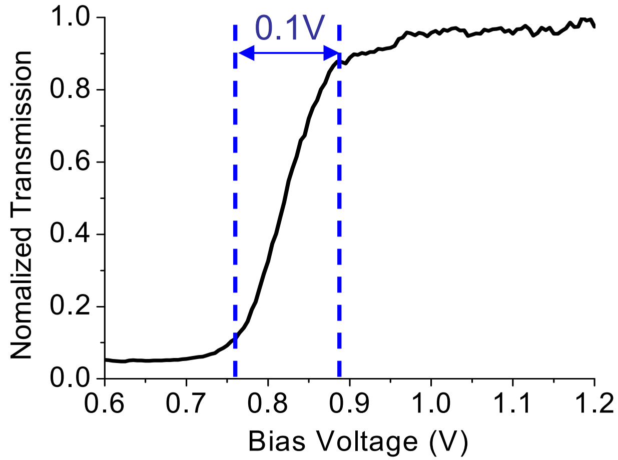


Gate-like transfer function.

Gb/s modulation with over-drive.

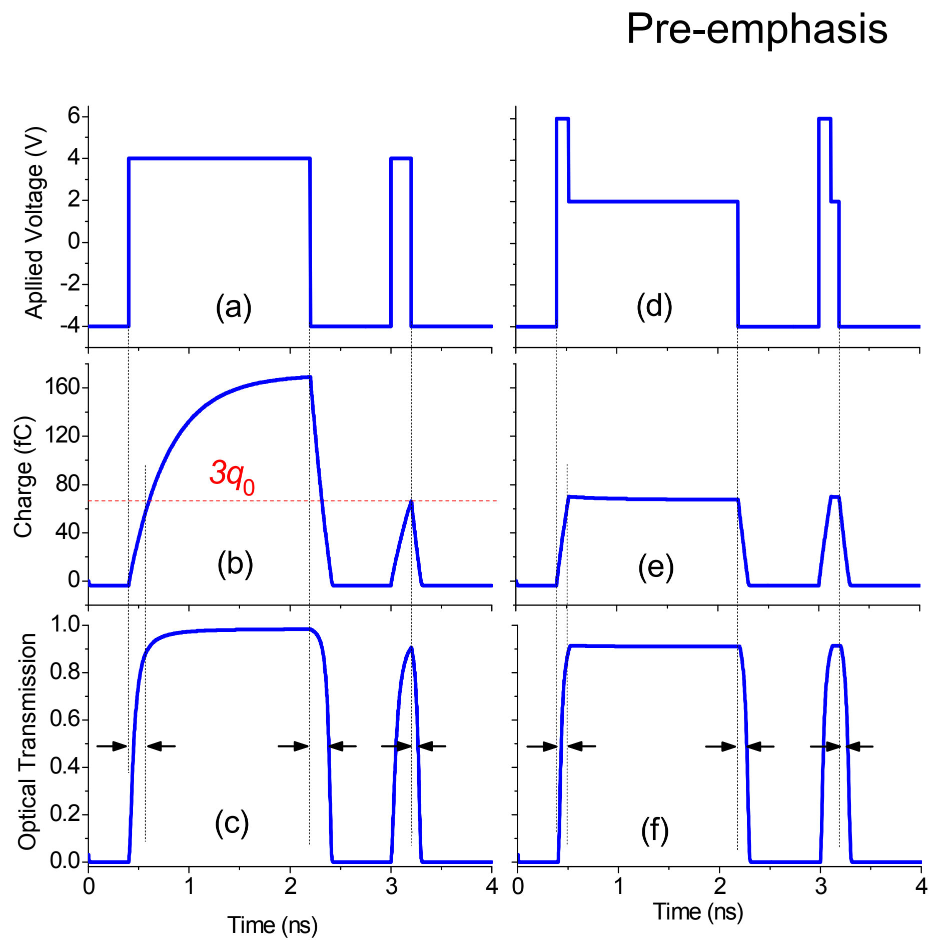
4 Gbit/s NRZ





Q. Xu, B. Schmidt, S. Pradhan, & M. Lipson, *Nature* 435, 325 (2005)

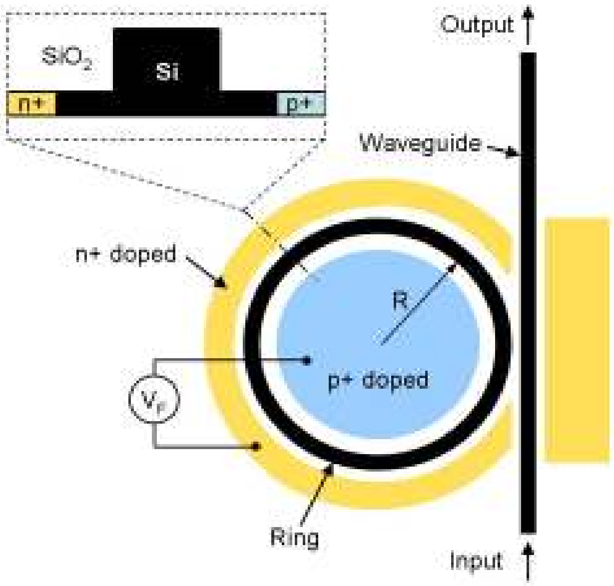
Increasing the modulation speed

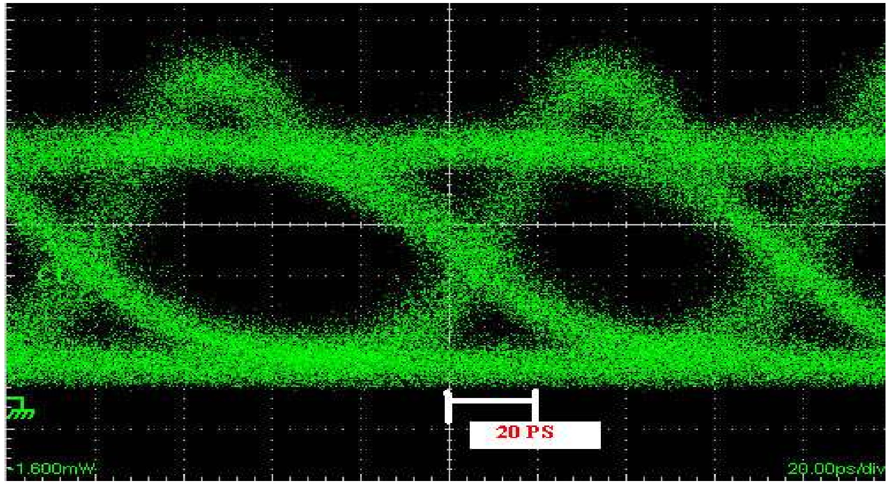


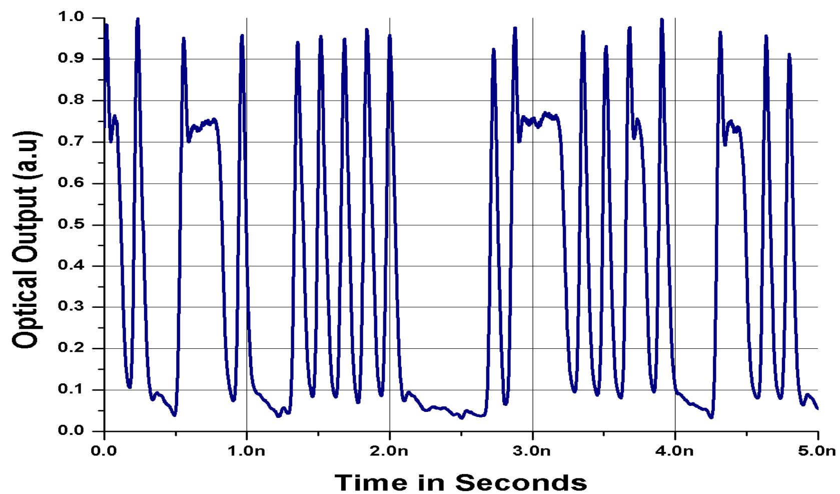
Q. Xu, B. Schmidt, S. Pradhan, & M. Lipson, *Nature* 435, 325 (2005)

Q. Xu, S. Manipatruni, B. Schmidt, J. Shakya, & M. Lipson, *Opt. Express* 15, 430 (2007)

Micrometer Scale Silicon Electrooptic Modulator At 20 gbps







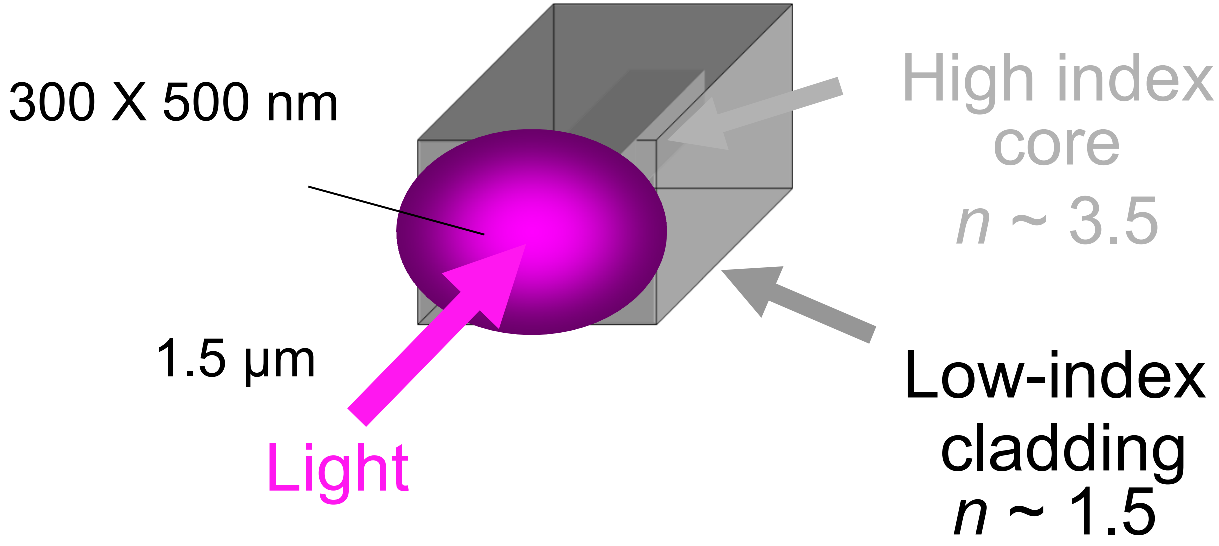
PRBS 2^{10}-1

>9dB modulation depth!

Q. Xu, M. Lipson, Optics Express Feb 2007

Nonlinear interactions in Si structures

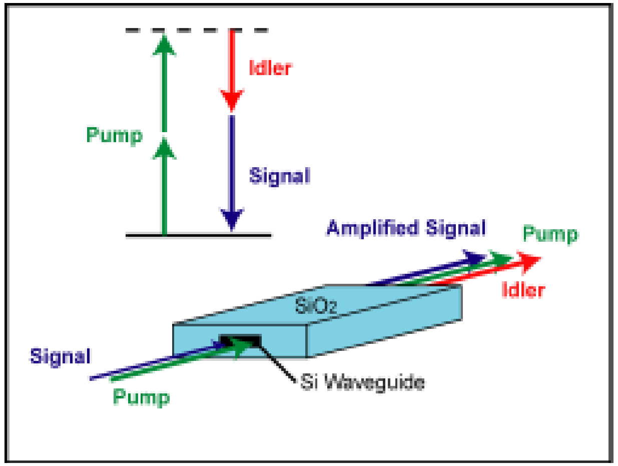
- High index contrast – tight optical confinement
  - compact structures, much smaller than the wavelength
  - enhanced nonlinearity (100X silica)
  - dispersion engineering
- Massively parallel devices enable ultrahigh bandwidth processing



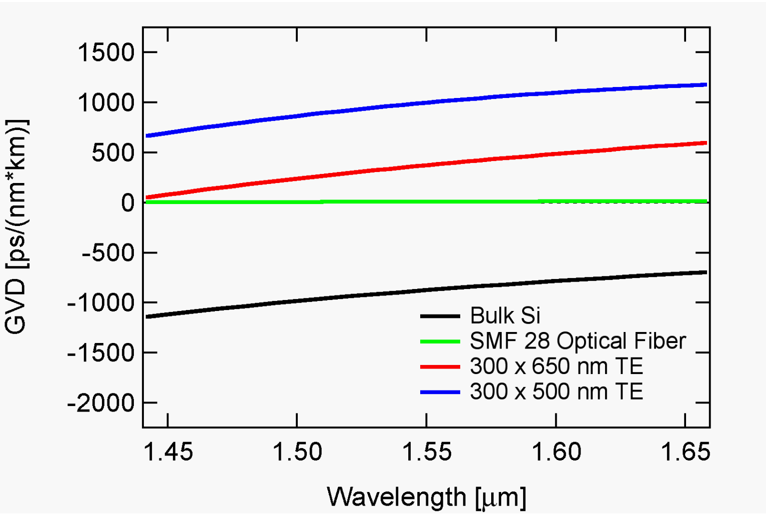
Dispersion control in Si waveguides

Intel, IBM, Columbia, NTT, UCLA (all narrow band or no amplification)

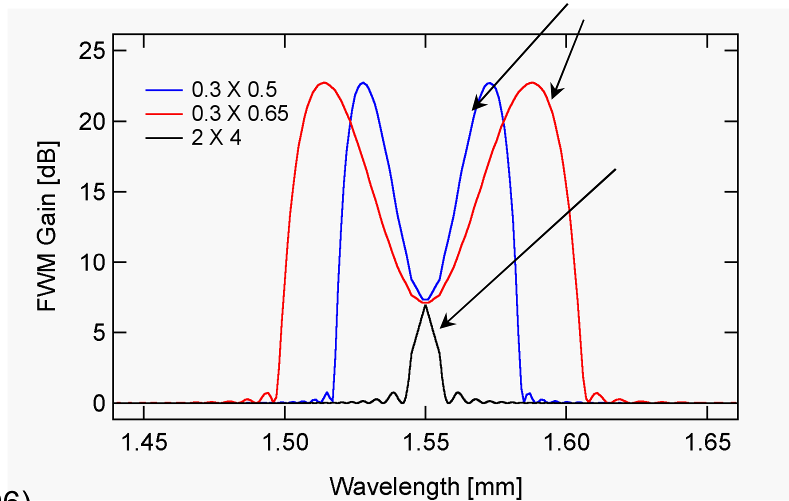
- Waveguide Group Velocity Dispersion (GVD) can be tuned/tailored by controlling shape and size.



Simulated dispersion



Simulated Gain/Conversion Curves

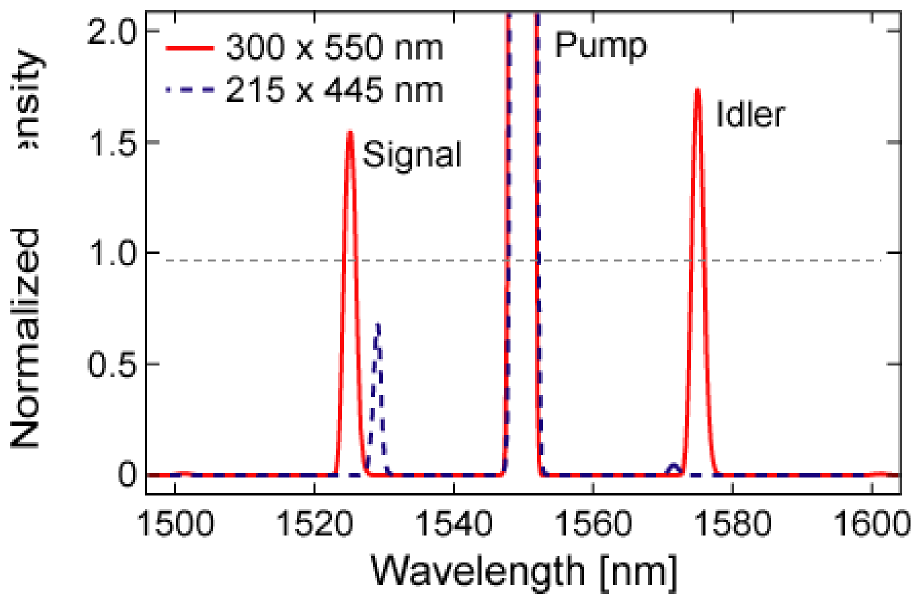


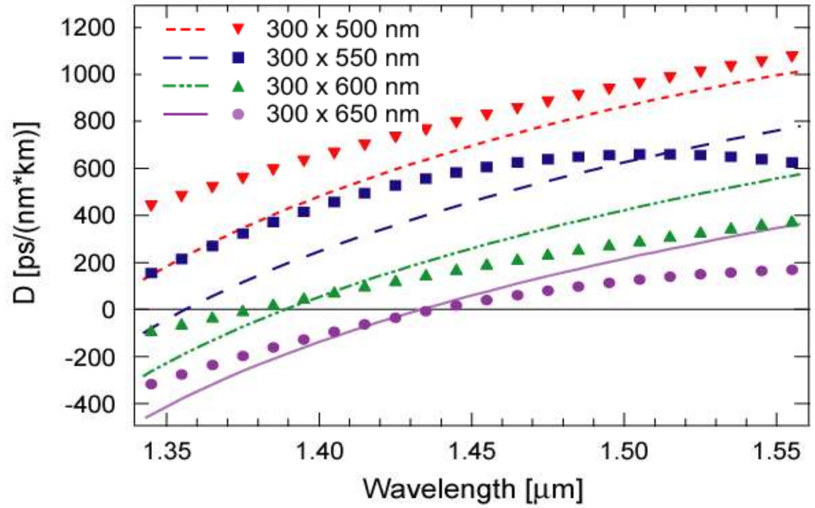
Turner, Foster, Sharping, Schmidt, Lipson, and Gaeta, *Opt. Express* (2006).

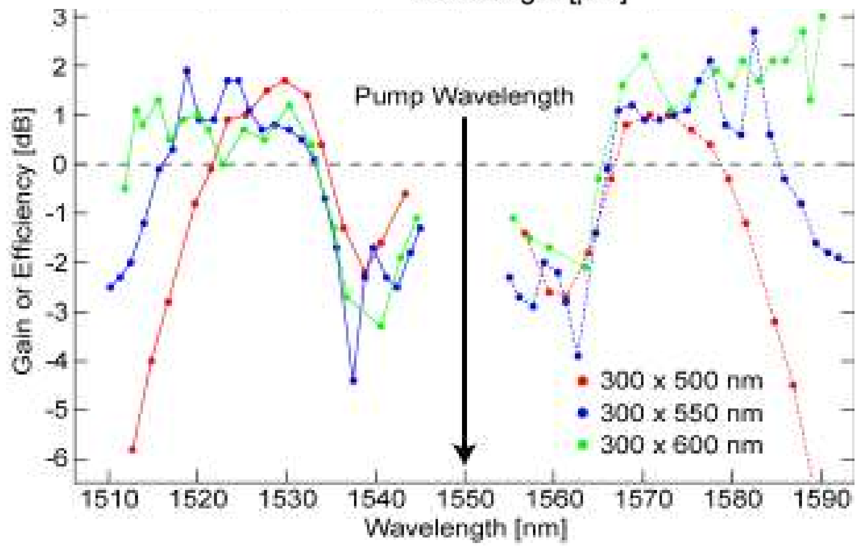
Broad-band gain and efficient wavelength conversion

- Fabricate waveguides with dispersion
- Large increase in FWM efficiency.
- First observation of broadband gain in Si

anomalous GVD
normal GVD





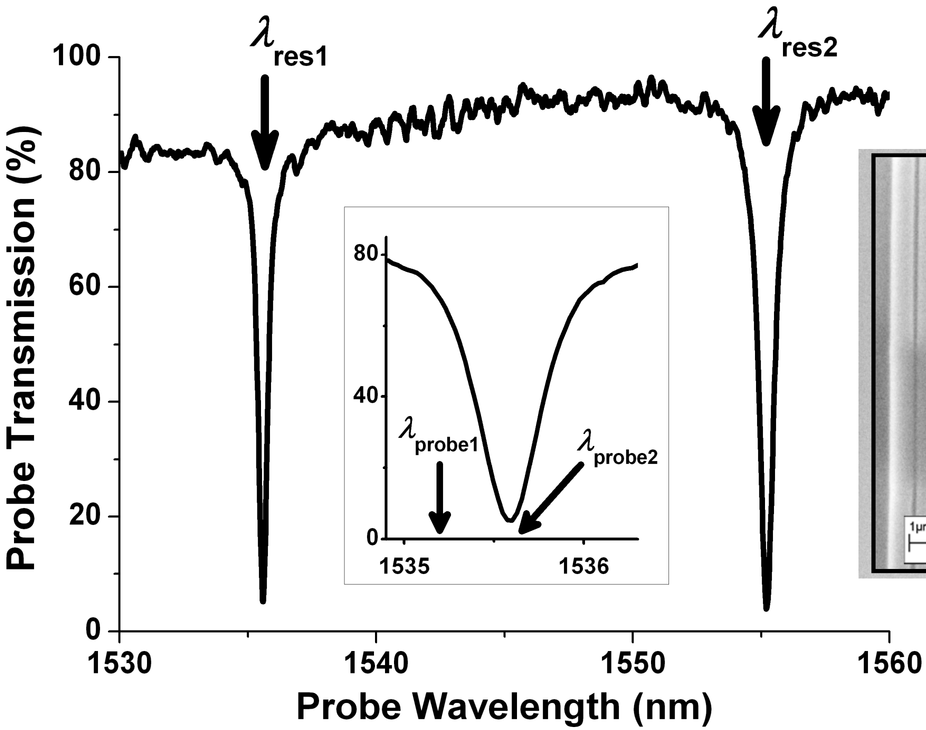


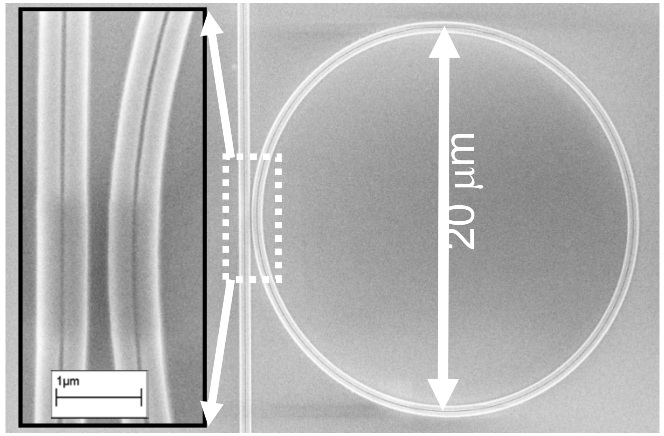
amplification | wavelength conversion

Foster, Turner, Sharping, Schmidt, Lipson, and Gaeta, *Nature* 441, 960 (2006).

Cornell University

Strong light confining structures



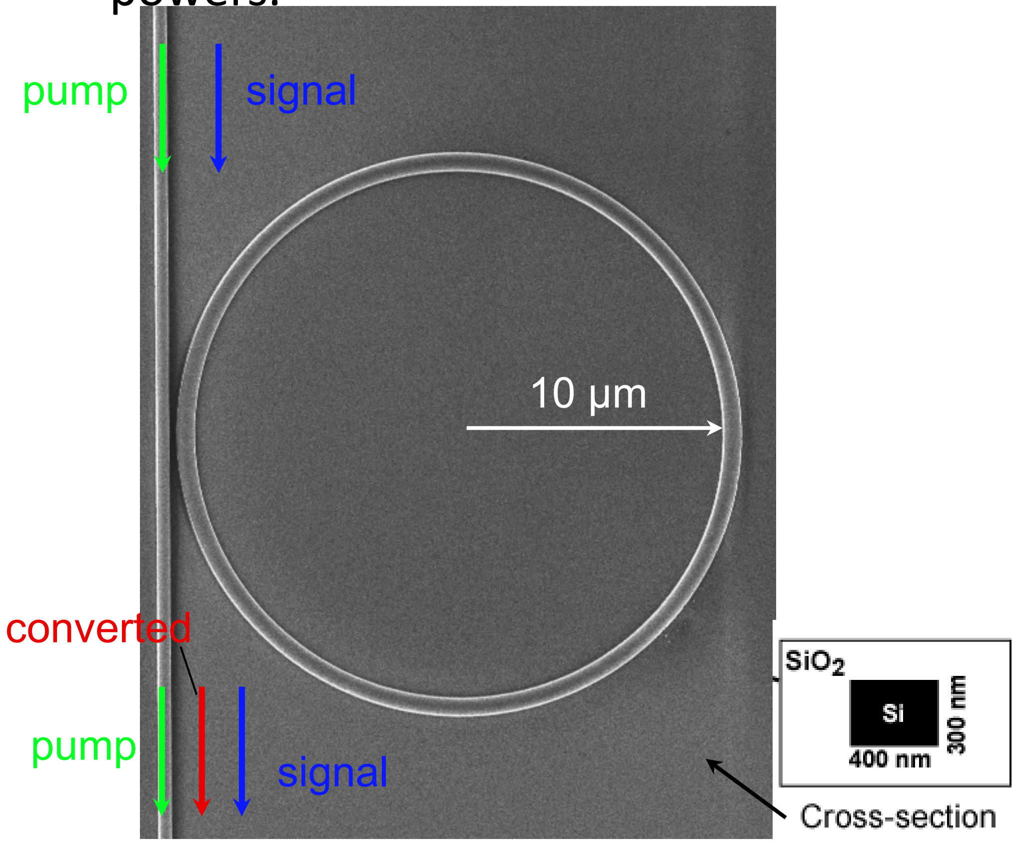


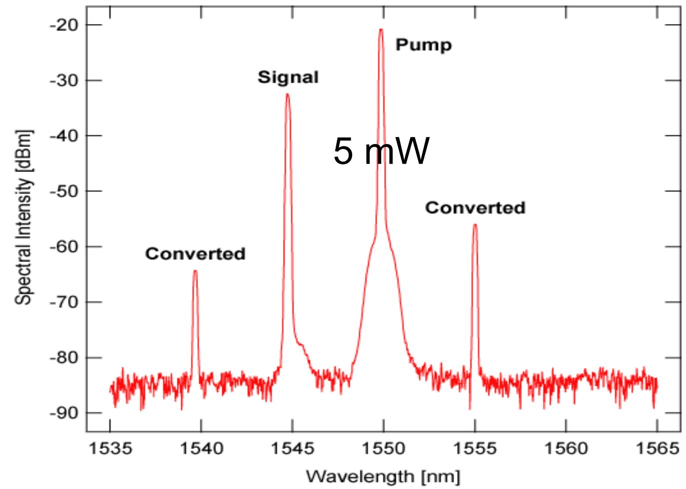
Q~2300

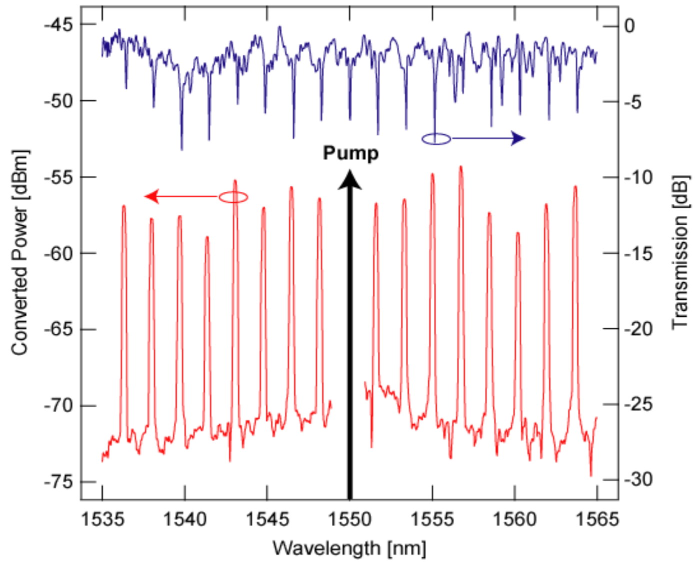
Device is very sensitive to small perturbations in the Silicon

Ultra-low power frequency conversion

- Use ring resonator to enhance efficiency of Four Wave Mixing process.
- Frequency conversion w/ mW cw powers.

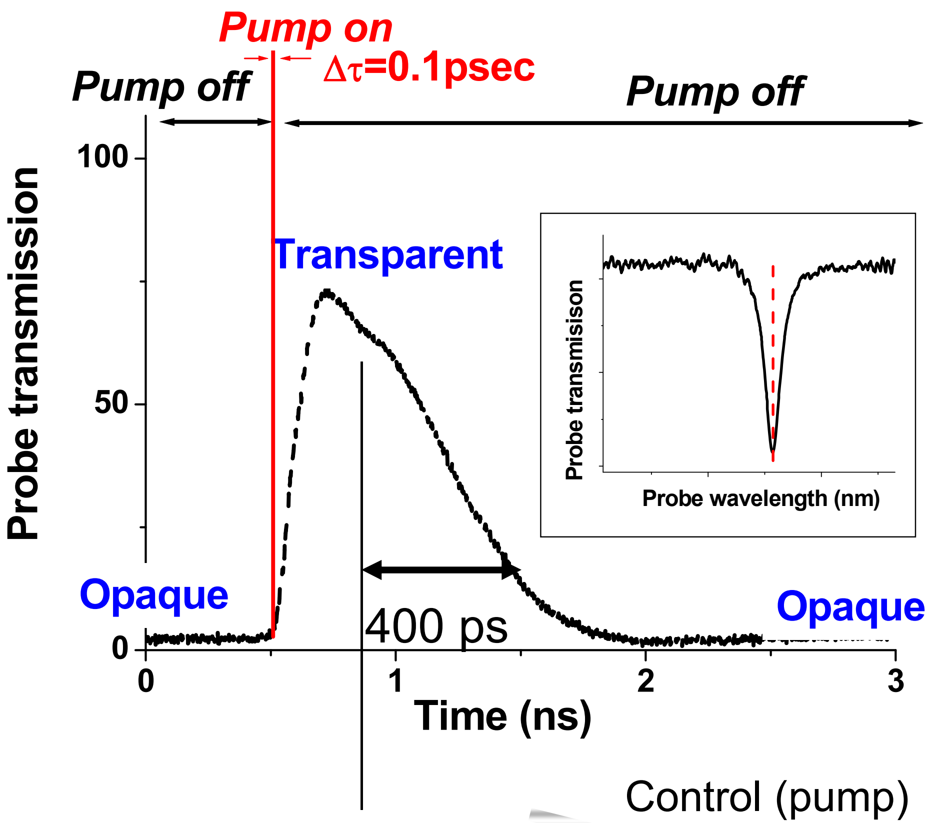


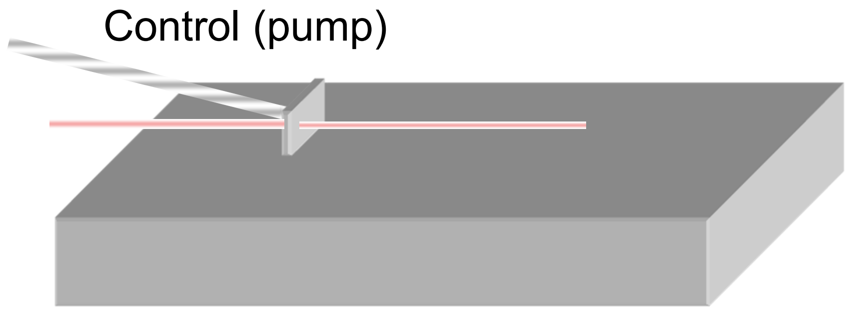




Turner, Foster, Gaeta, and Lipson, *in preparation* (2007).

Demonstration of Switch: Opening Gate



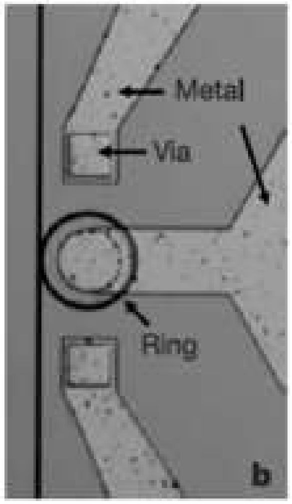


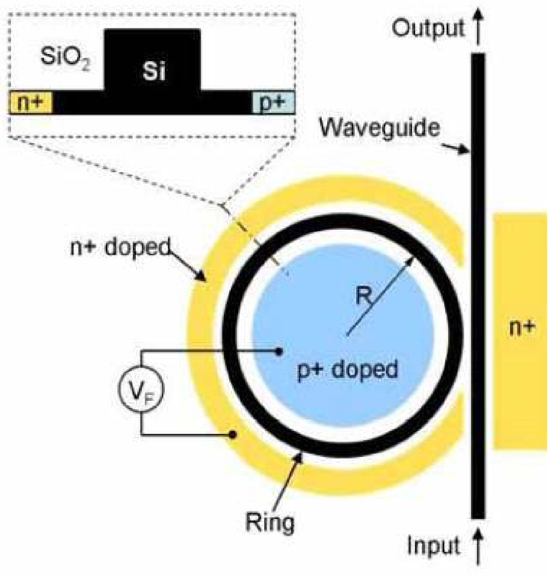
fJ power consumed

Almeida, V, Lipson, M., Nature, p1081 (Oct, 2004)

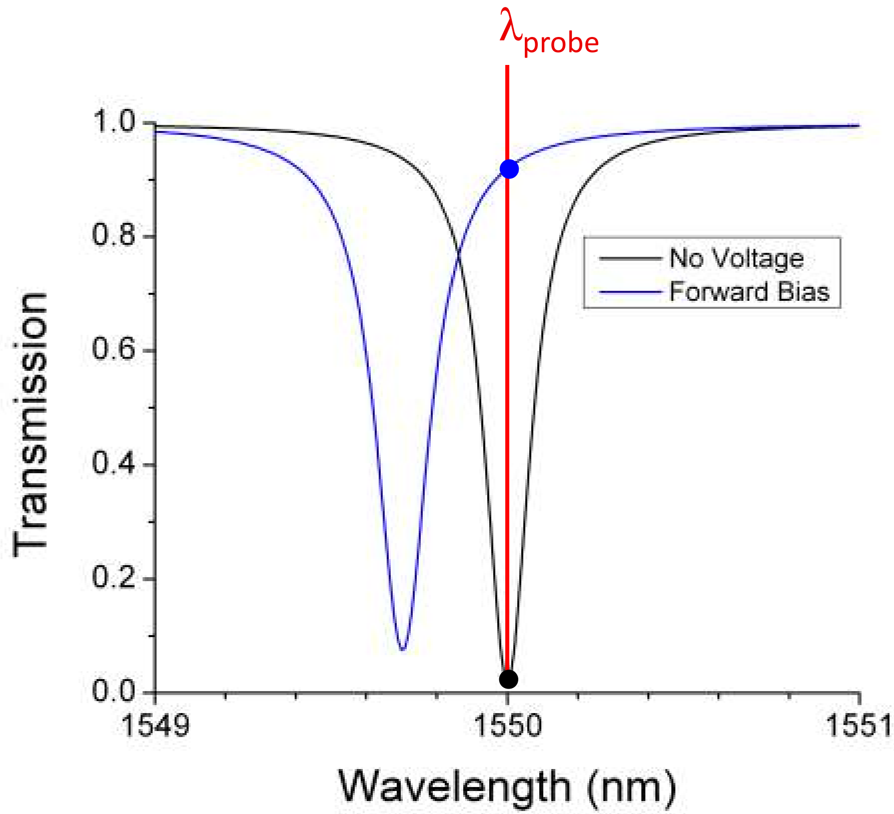
Micrometer-scale devices

<u>Si Ring Resonator PIN Modulator</u>





Top view

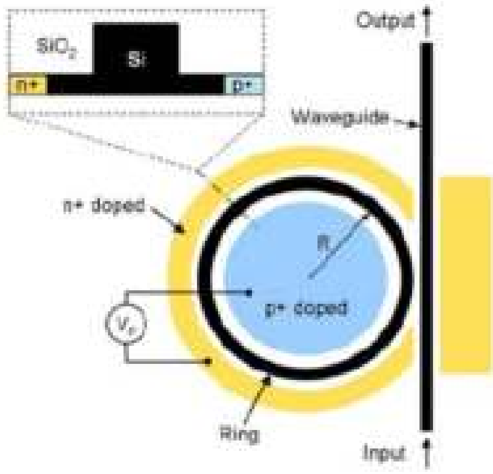


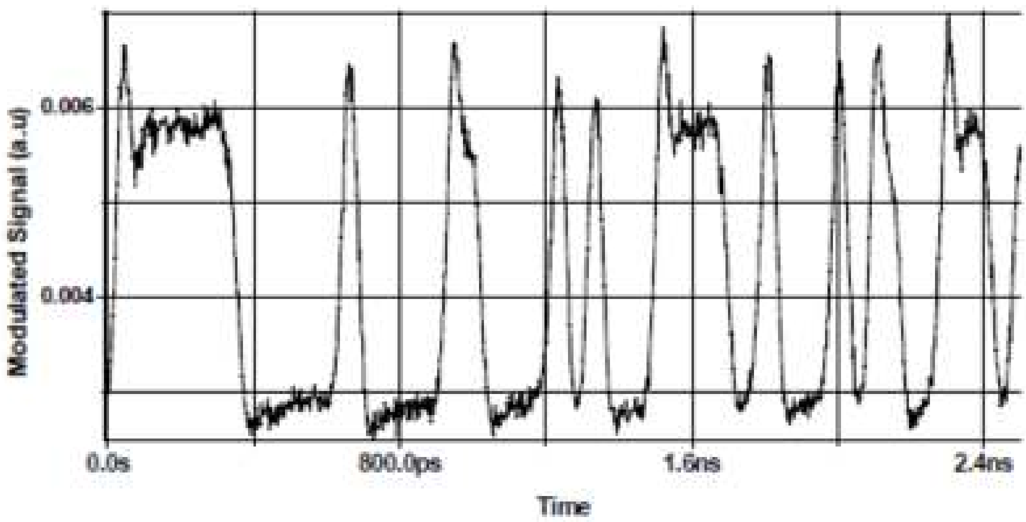
<u>State of the art</u>: 18 Gbps

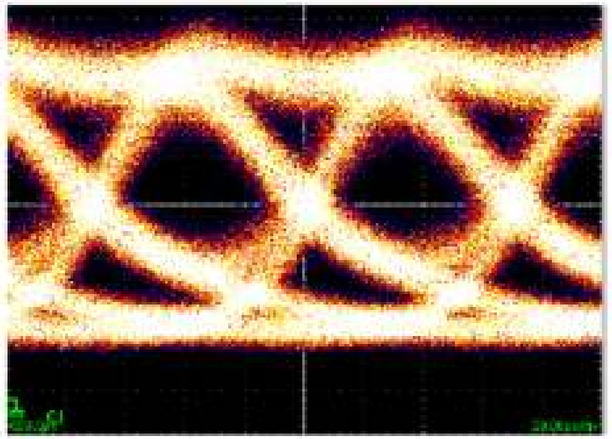
S. Manipatruni, M. Lipson, et al., *LEOS* 2007

1. Xu, Q., Schmidt, B., Pradhan, S., and Lipson, M., "Micrometer-scale Silicon Electro-Optic Modulator," **Nature**, Vol. 435, pp. 325-327, June 2005.

18 Gbps modulator







S. Manipatruni, M. Lipson, et al., *LEOS* 2007

Integrating Silicon Photonics with CMOS Microelectronics

Cornell University

Prof. Michal Lipson

Overview

There are three distinct approaches to combining photonics and electronics

- 'Traditional' SOI photonics by IBM, Luxtera, etc
- 'Photonic Bridge Chip' (e.g. by Oracle)
- 'Localized Substrate Removal (LSR)' bulk CMOS photonics (e.g. by MIT)
- 'Deposited optics multi-chip module (MCM)' (e.g. by Cornell)

Pros and Cons of each approach is discussed.

'Traditional' SOI photonics

This platform chooses the SOI based CMOS, in which one incorporates both the electronics and optical devices in the same layer

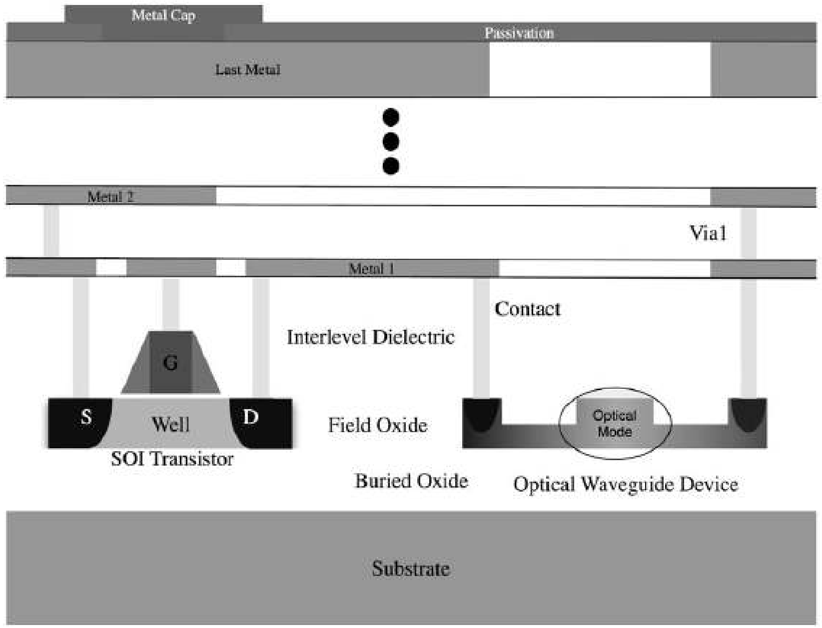


Figure 1. Schematic cross-section of SOI CMOS Photonics process

Pinguet, T et al., "Monolithically integrated high-speed CMOS photonic transceivers" (2008)

‘Traditional’ SOI photonics

Pros :

-tightest integration (physically on same layer)

-no need for any post processing / packaging

‘Traditional’ SOI photonics

Cons :

-Electronic real estate taken up by comparatively ‘large’ optical devices (sub 100nm vs greater than 400nm)

-waveguide routing becomes difficult due to lack of multiple optical layer

-Buried oxide needs to be thick enough(~1um minimum) to prevent excessive optical leakage into substrate. This is directly against requirement for advanced SOI fets (PD or FD) that requires BOX to be 100’s of nm or thinner.

-Cannot form optically connected multi-chip module

-requires some modification of CMOS fabrication process

Photonic Bridge Chip

This platform builds electronics and photonics on separate chips, than uses solder bumps to flipchip mount photonics on top of VLSI die.

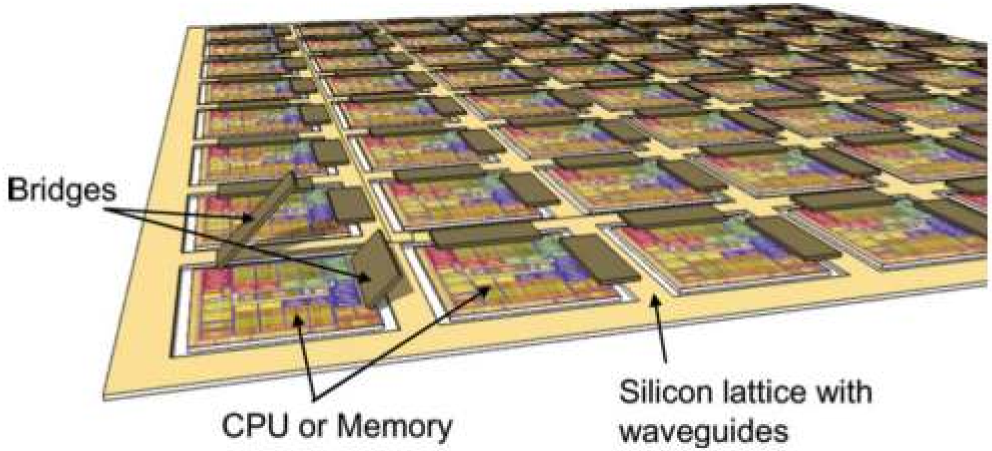


Fig. 1. Macrochip is a logically contiguous piece of densely interconnected silicon that integrates CPUs, memory, and a systemwide optical interconnect.

Cunningham, J.E et al., "Integration and Packaging of a Macrochip with silicon nanophotonic links" (2011)

Photonic Bridge Chip

Pros :

-Separate, optimized process for electronic and photonics

-allows optically connecting discrete electronic dies

-can potentially reuse die resulting from a faulty flipchip processing to increase effective yield

Photonic Bridge Chip

Cons :

-Requires nontrivial precision alignment and solder bumping process

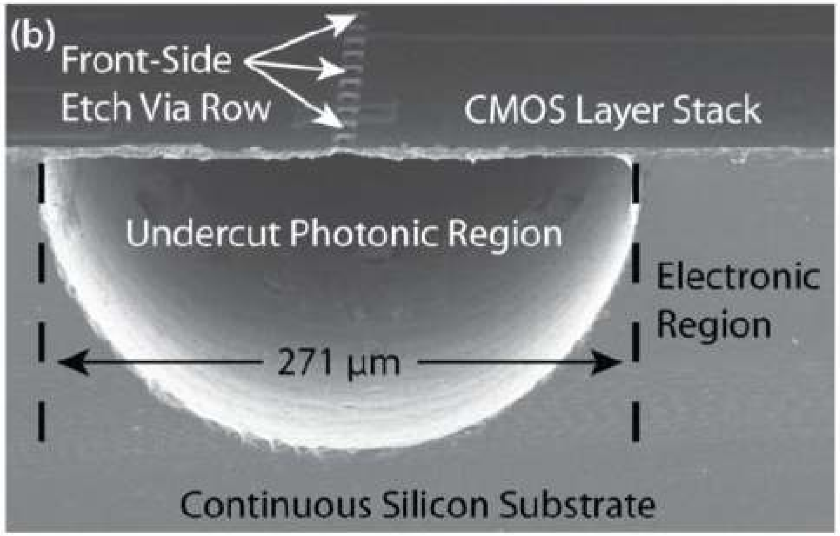
-Solder bumps adds non-negligible parasitics (~25fF)

-Optical connectivity limited to point-to-point between nearest neighbors

-Potential mechanical stability issues

Localized Substrate Removal (LSR) bulk CMOS photonics

This platform uses polysilicon gate material in bulk CMOS to form optical devices. The silicon bulk underneath the photonic device is removed through post processing to enable waveguiding.



Orcutt, J.S. et al., "Nanophotonic integration in state-of-the-art CMOS foundries" (2010)

Localized Substrate Removal (LSR) bulk CMOS photonics

Pros:

-Leverages bulk CMOS technology, which accounts for a majority of CMOS logic production.

-Requires no changes to CMOS process

-Optical devices are very close to transistors, reducing electrical parasitics

Localized Substrate Removal (LSR) bulk CMOS photonics

Cons:

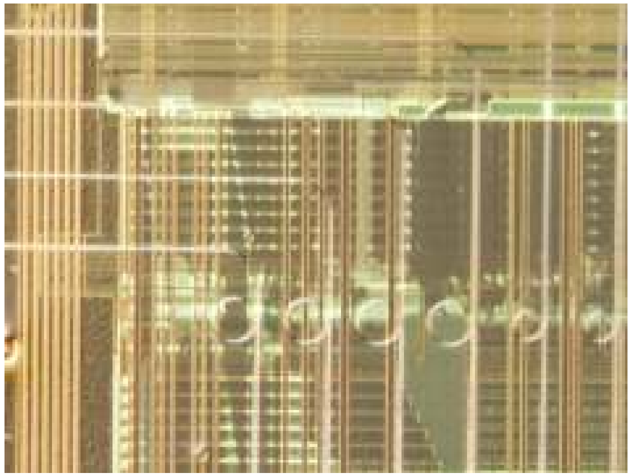
-Photonics and transistor compete for valuable front-end silicon real estate.

-waveguide has relatively high loss

-Substrate removal may have negative effect in reliability

Deposited optics Multi Chip Module (MCM)

This platform takes multiple dies and securely attaches them onto a carrier substrate, on which multiple optical layer is deposited to enable intra- and inter- die connectivity



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Lee, Y.H.D. "Backend monolithic integration of passive optical devices on 90nm bulk CMOS chip" (2012)

Deposited optics MCM

Pros :

-CMOS process is untouched

-Discrete dies can be optically connected with ease.

-Allows multiple optical layers (passive and / or active)

+Leaves valuable front-end silicon for transistors

-Mechanically robust

-Completely based on planar processing

Deposited optics MCM

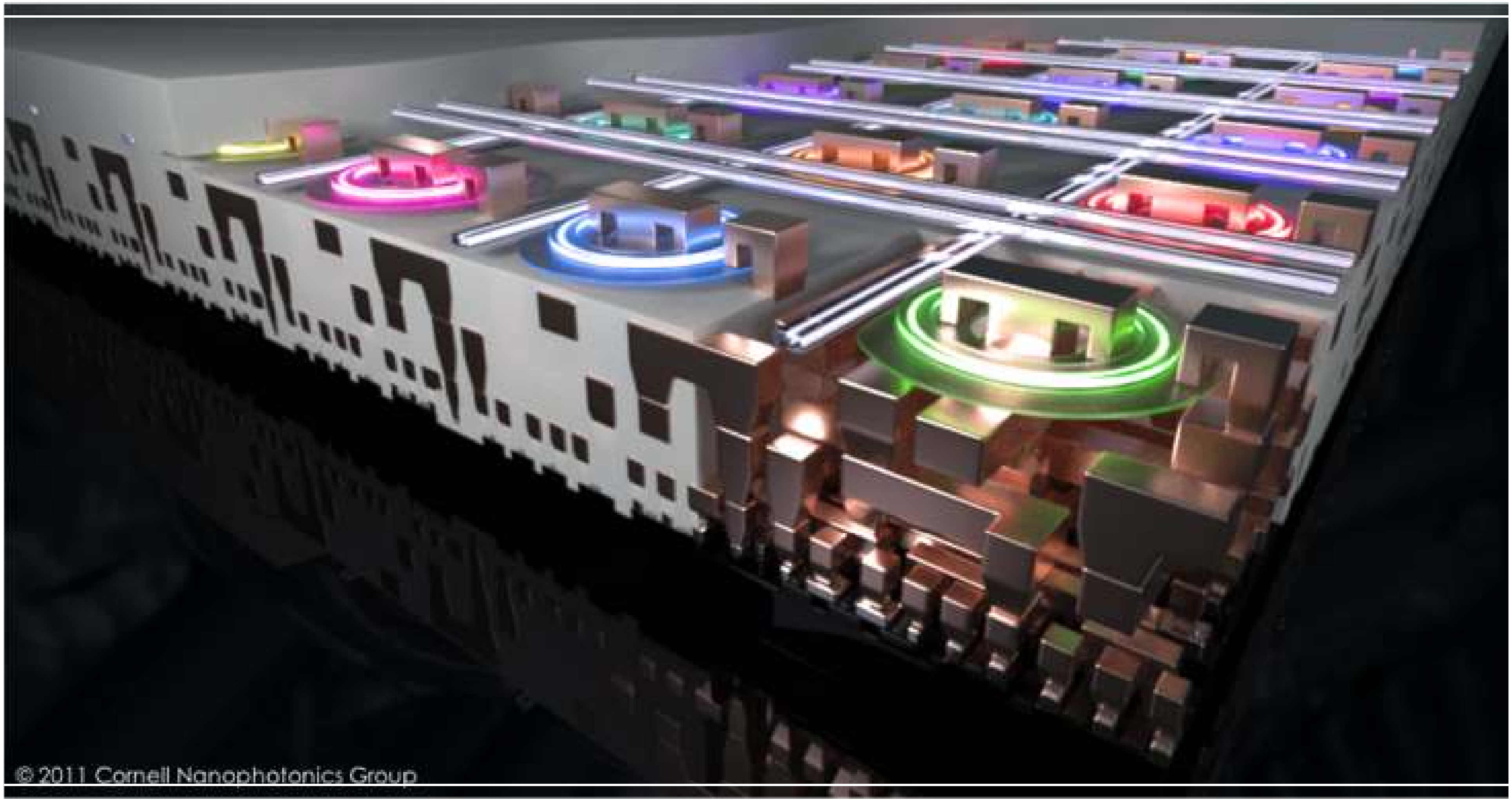
Cons :

-optical devices are not as ideal as SOI variants due to use of poly-Si

-relatively low process thermal budget of ~450C, limiting optical process flexibility

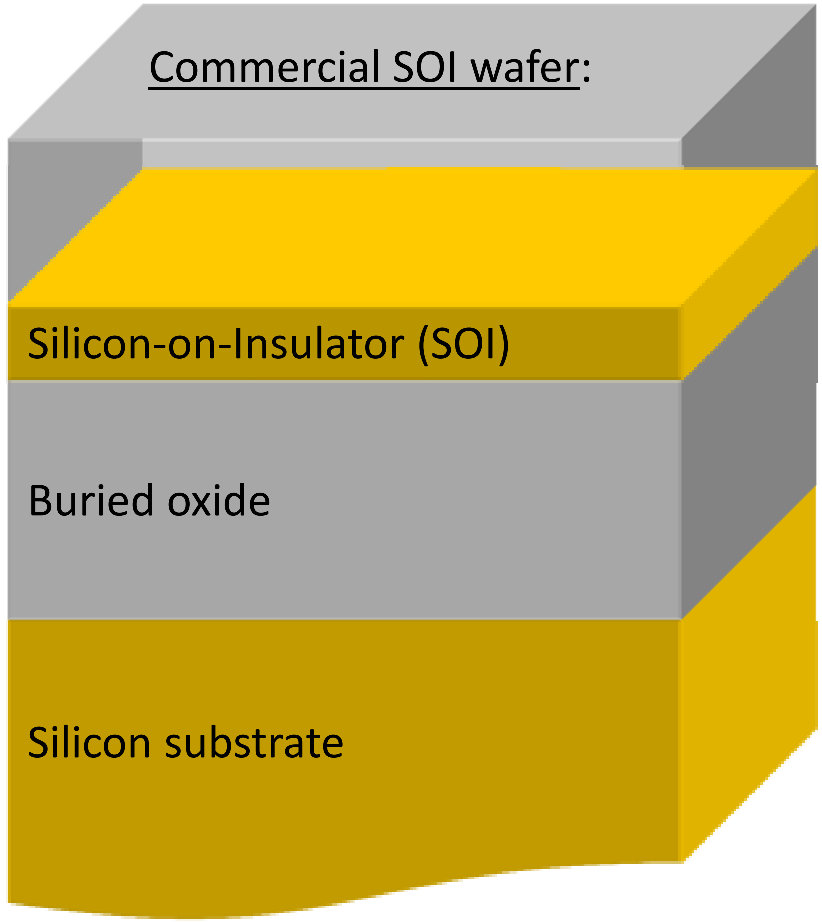
-reprocessing of dies is not easy if optical layer is tested to be faulty during processing.

Deposited Silicon



Silicon photonics

Chip-scale optical data communication

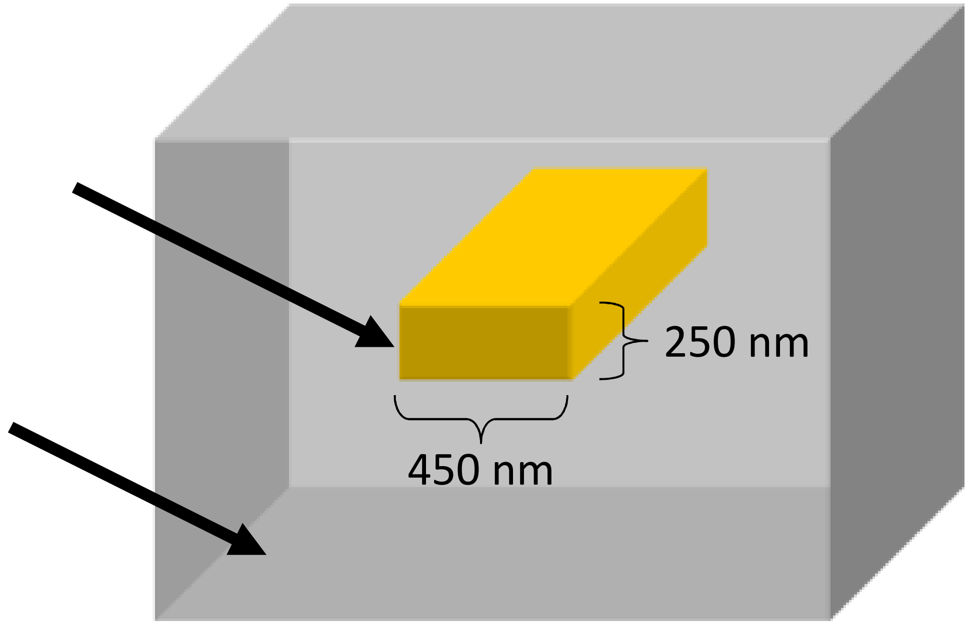


Silicon photonics

Chip-scale optical data communication

Crystalline Silicon (n = 3.5)

Silicon Dioxide (n = 1.5)

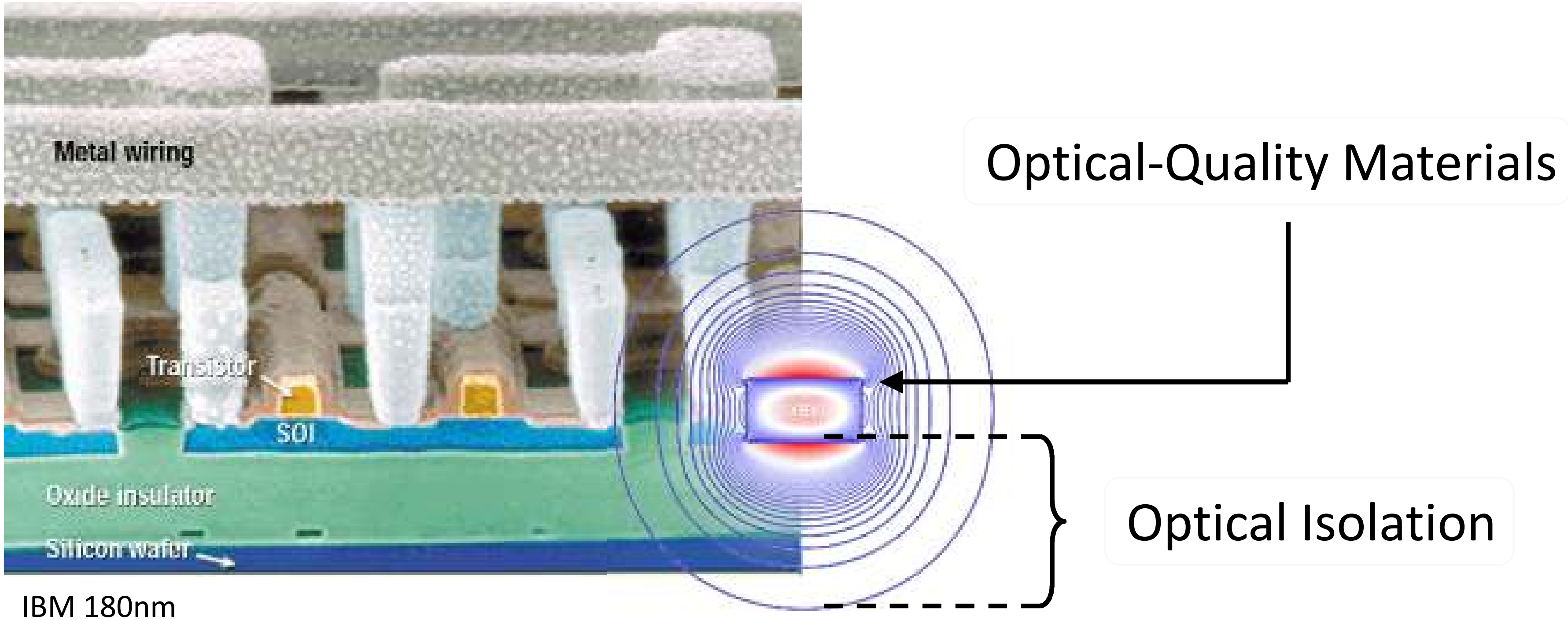


Want electro-optic devices that are *fast*, *small*, and *closely integrated with silicon microelectronics*

Cornell University

Prof. Michal Lipson

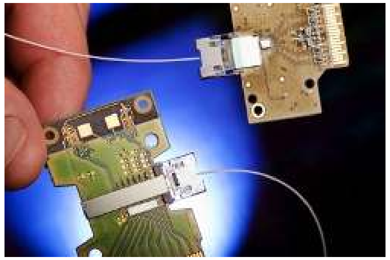
Requirements of photonics



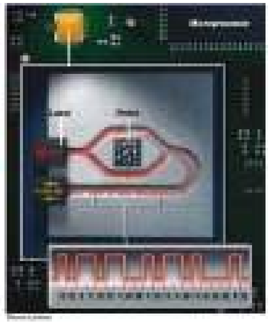
IBM 180nm

No Real-Estate Available in the Front-End!

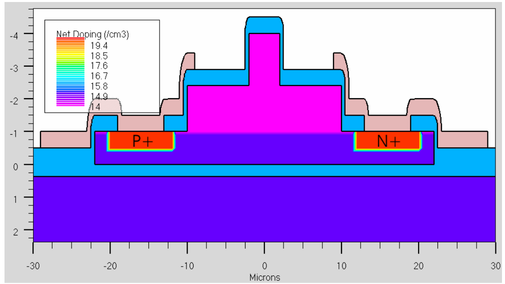
Silicon photonics integration



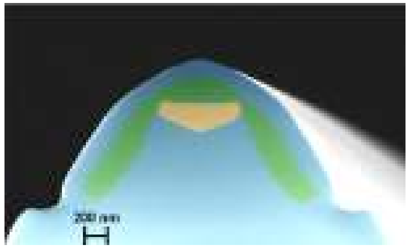
Intel 2010



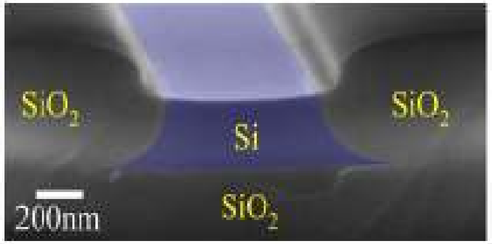
Luxtera 2005



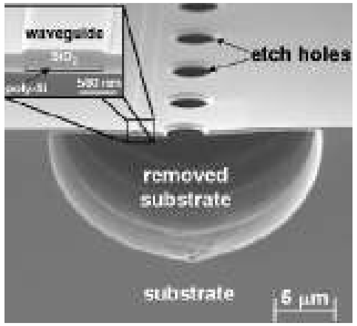
Kotura 2008



Cornell 2010



HUJI 2010



MIT 2008

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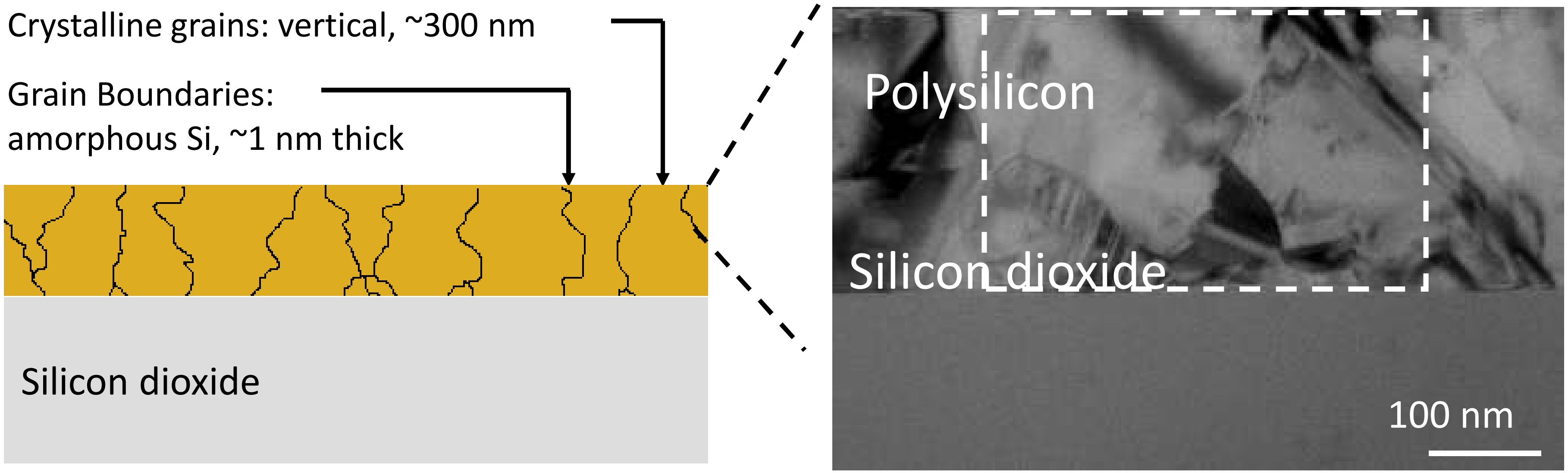
Deposited Silicon



Side view

Cross-section TEM of crystallized LPCVD film

Grain size ≈ Device size

Deposited optical materials

<u>Waveguides</u>: PECVD silicon nitride

Intel, GT

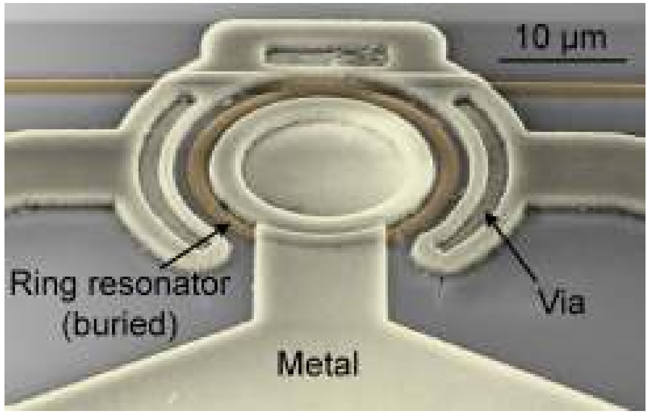
<u>Modulator:</u> Electro-optic polymers

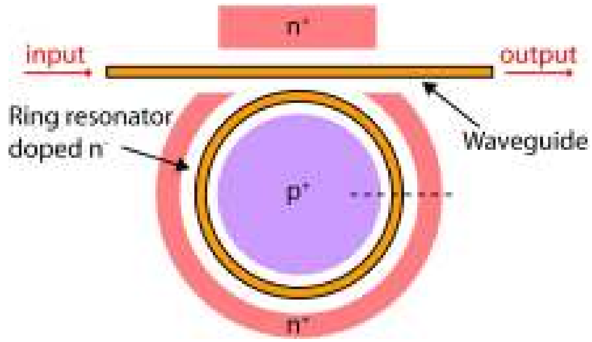
Block, Young et al. (Intel)
Hochberg et al. (U.Wash)
others

Polycrystalline silicon

Lipson et al. (Cornell)
Ram et al. (MIT)
Kwong et al. (A*STAR)

Polysilicon ring resonator modulator
Preston et al., *OpEx* 2009





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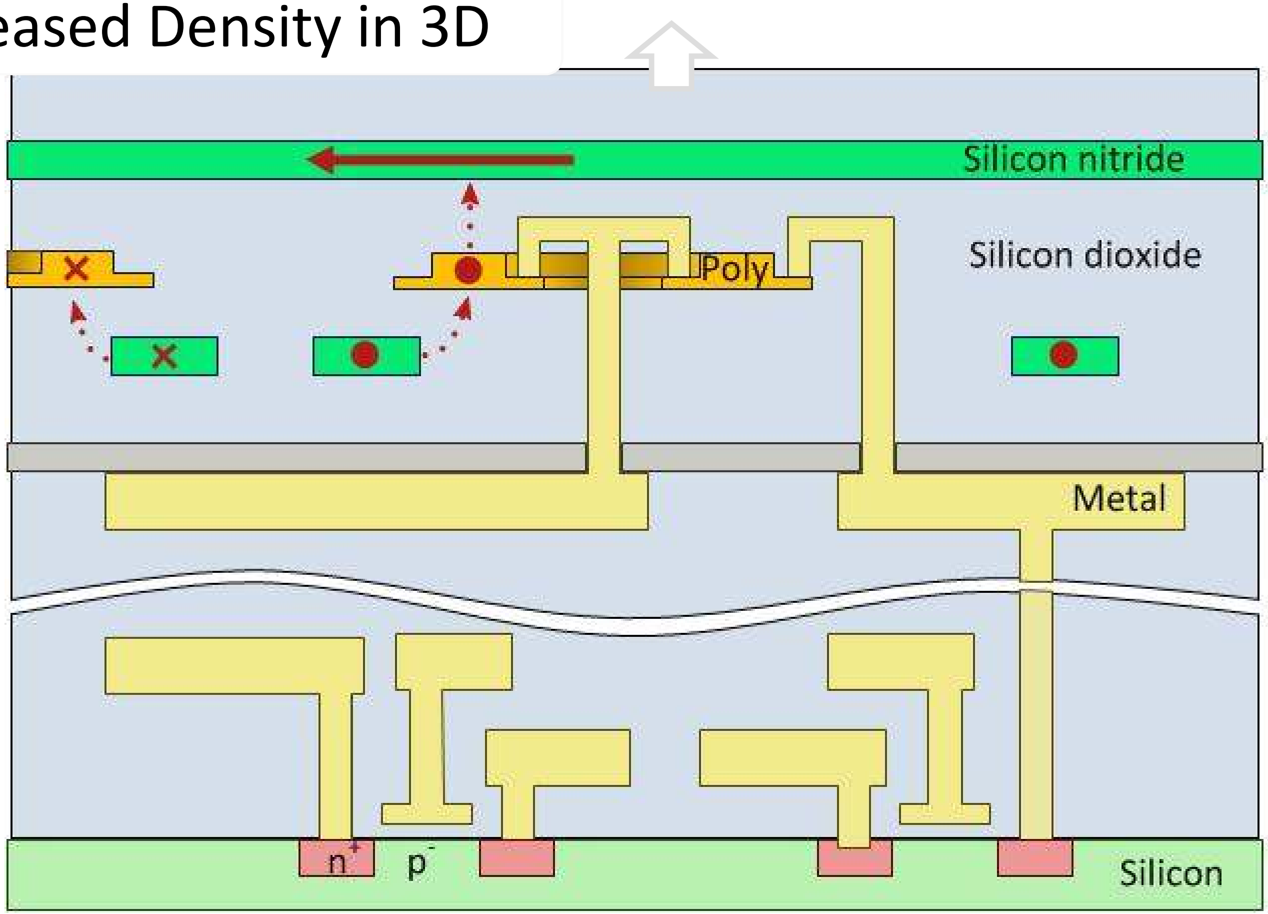
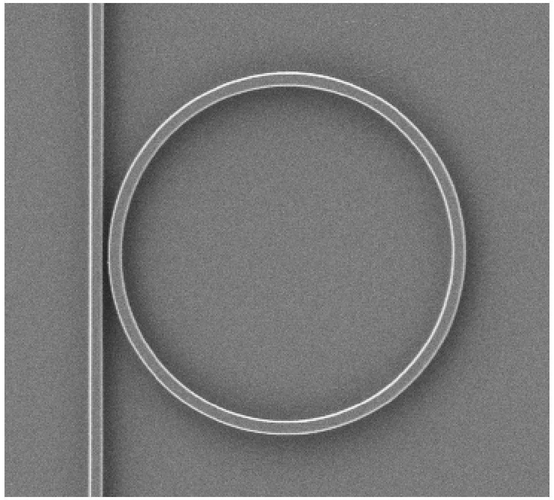
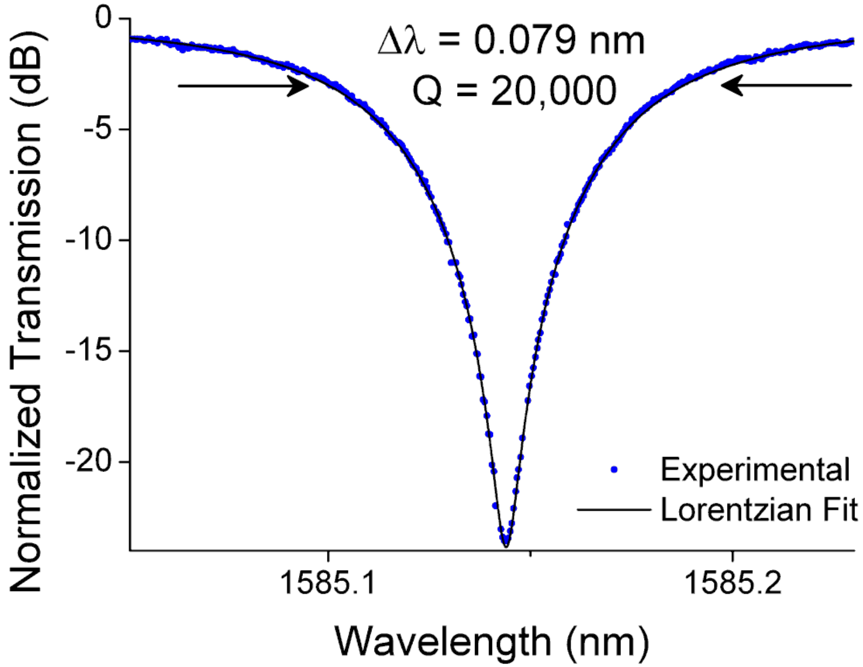
Backend photonics

Increased Density in 3D



Poly rings



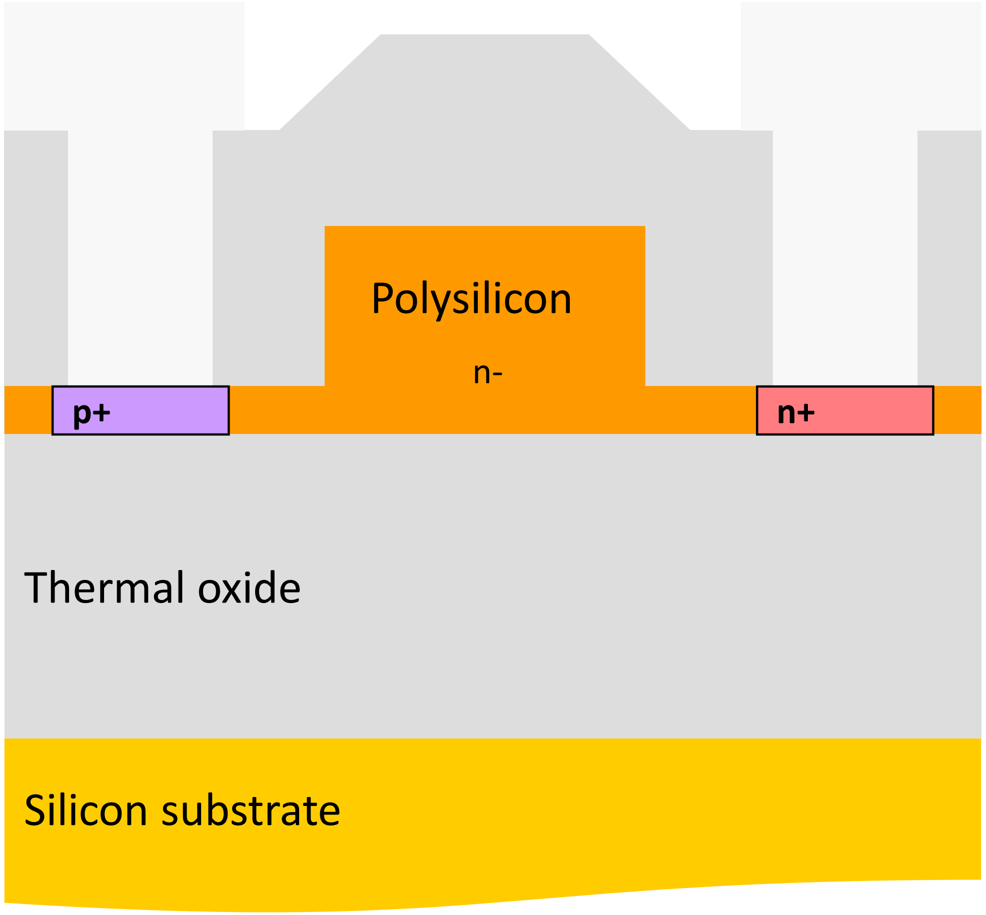


Q = 20,000

$\alpha \approx 15$ dB/cm

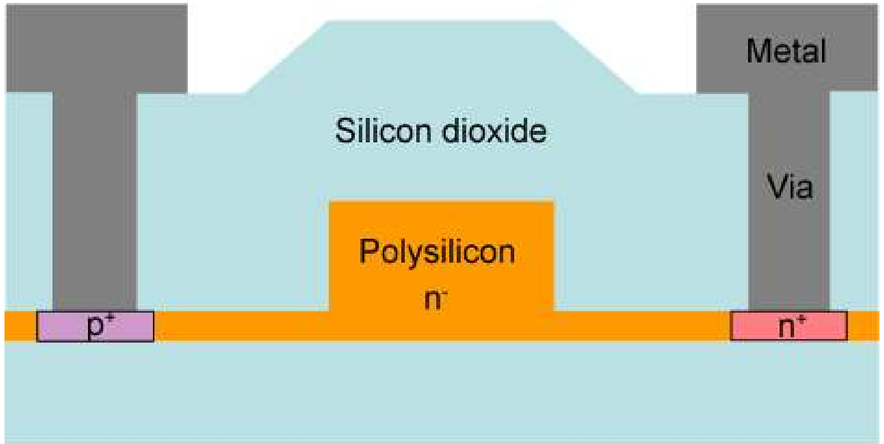
K. Preston, M. Lipson, et al., *Opt. Exp.* 2007

Fabrication

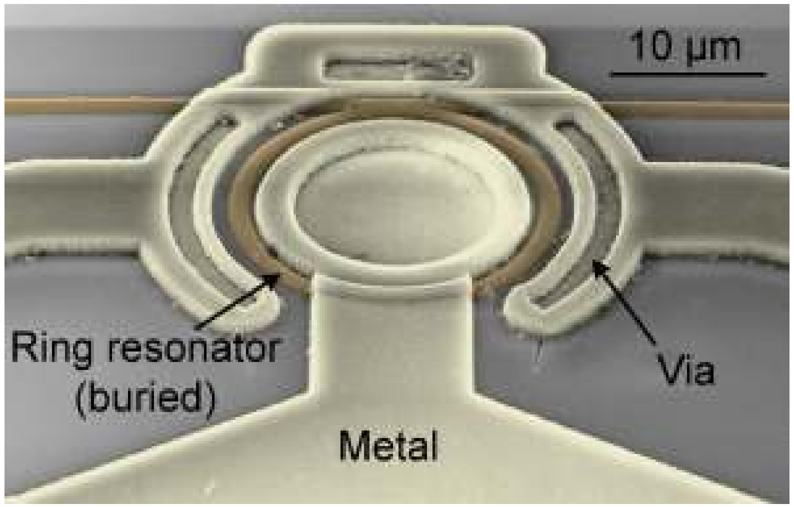


Cross-section (not to scale)

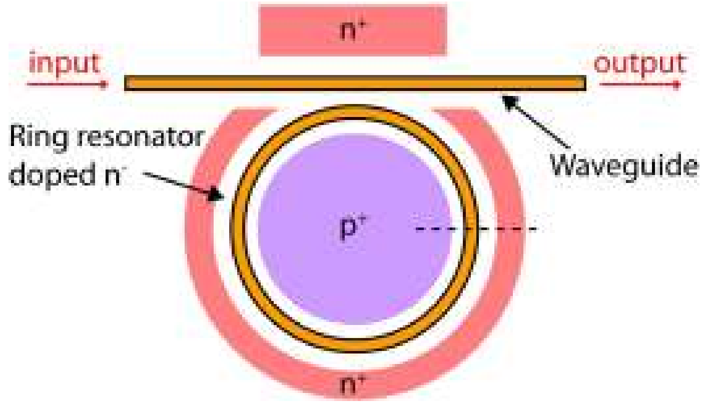
Fabrication



Cross-section (not to scale)

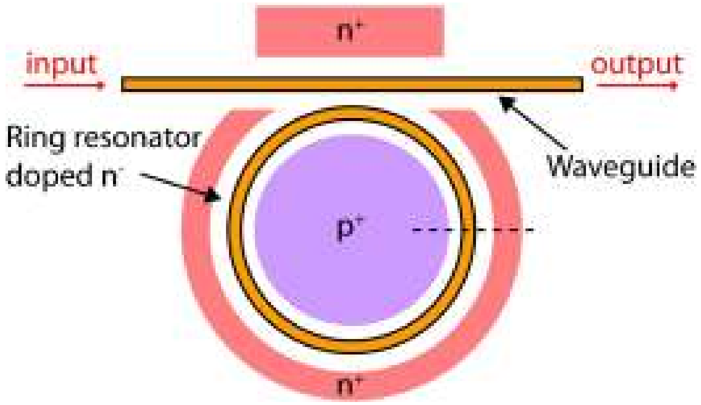


Top view (microscope)

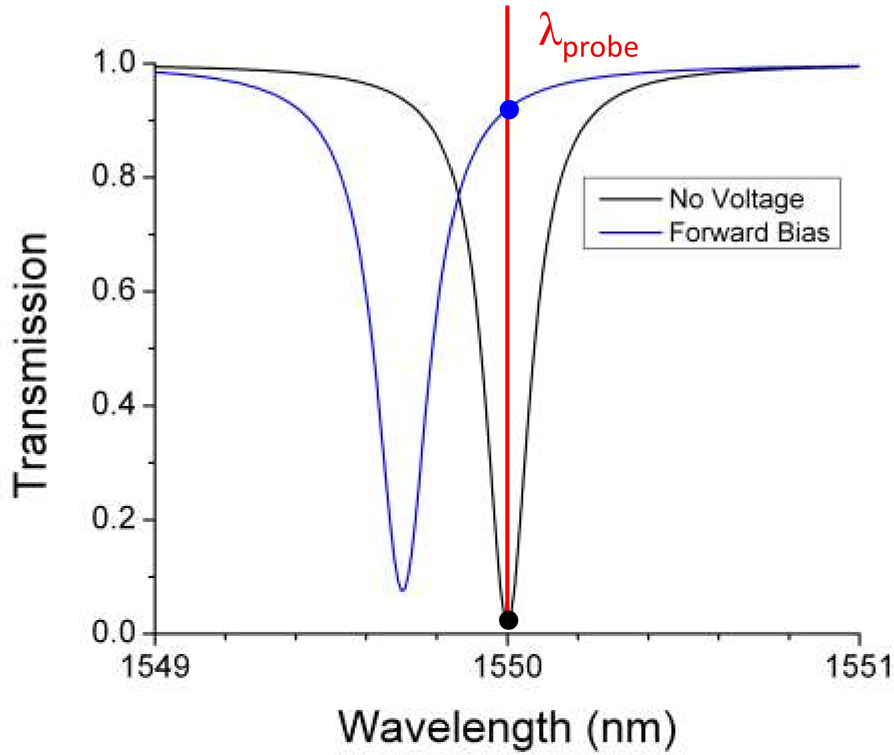


Schematic

Resonator electro-optic modulation



Schematic

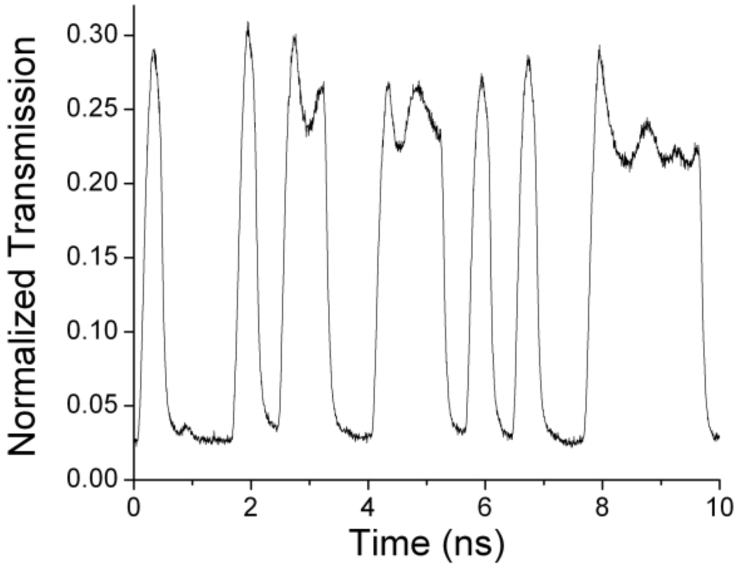


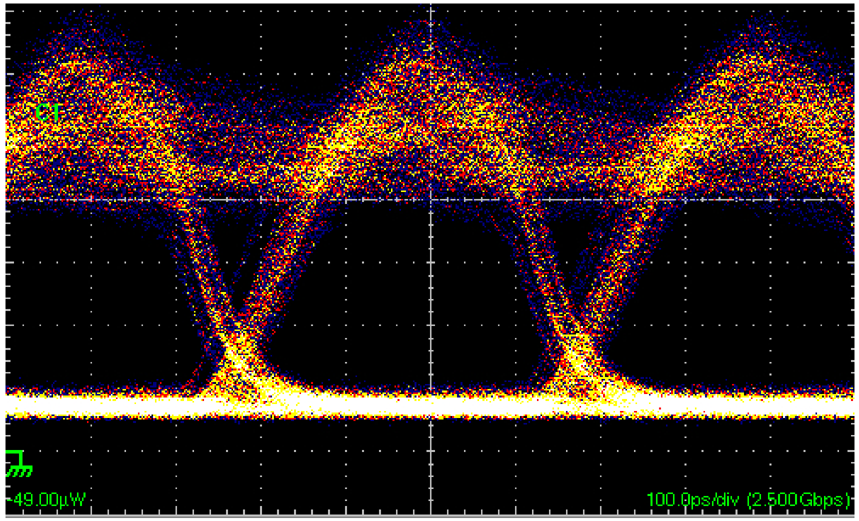
<u>Expected changes in polysilicon material system:</u>

- Moderately lower *Q*
- More forward bias voltage (higher resistance)
- Less reverse bias voltage (faster carrier recombination)

Polysilicon electro-optic modulator

10 micron device:





2.5 Gb/s NRZ 2^7-1 PRBS electrical signal applied, ±4 V swing, 4 V DC bias

- 10 dB modulation depth
- No reverse bias (fast recombination)
- Power consumption ~ 2 mW (<1 pJ/bit)

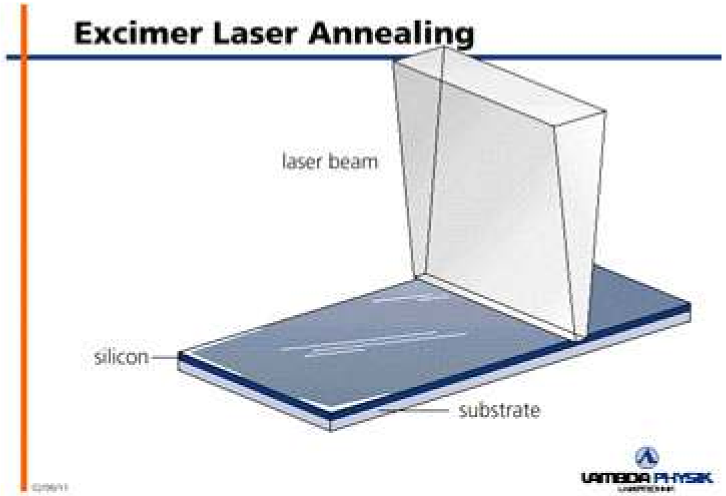
K. Preston, M. Lipson, et al., *Opt. Express* Vol. 17, No. 7 (2009)

LCD Industry: laser annealing

Deposit low-temperature amorphous-Si

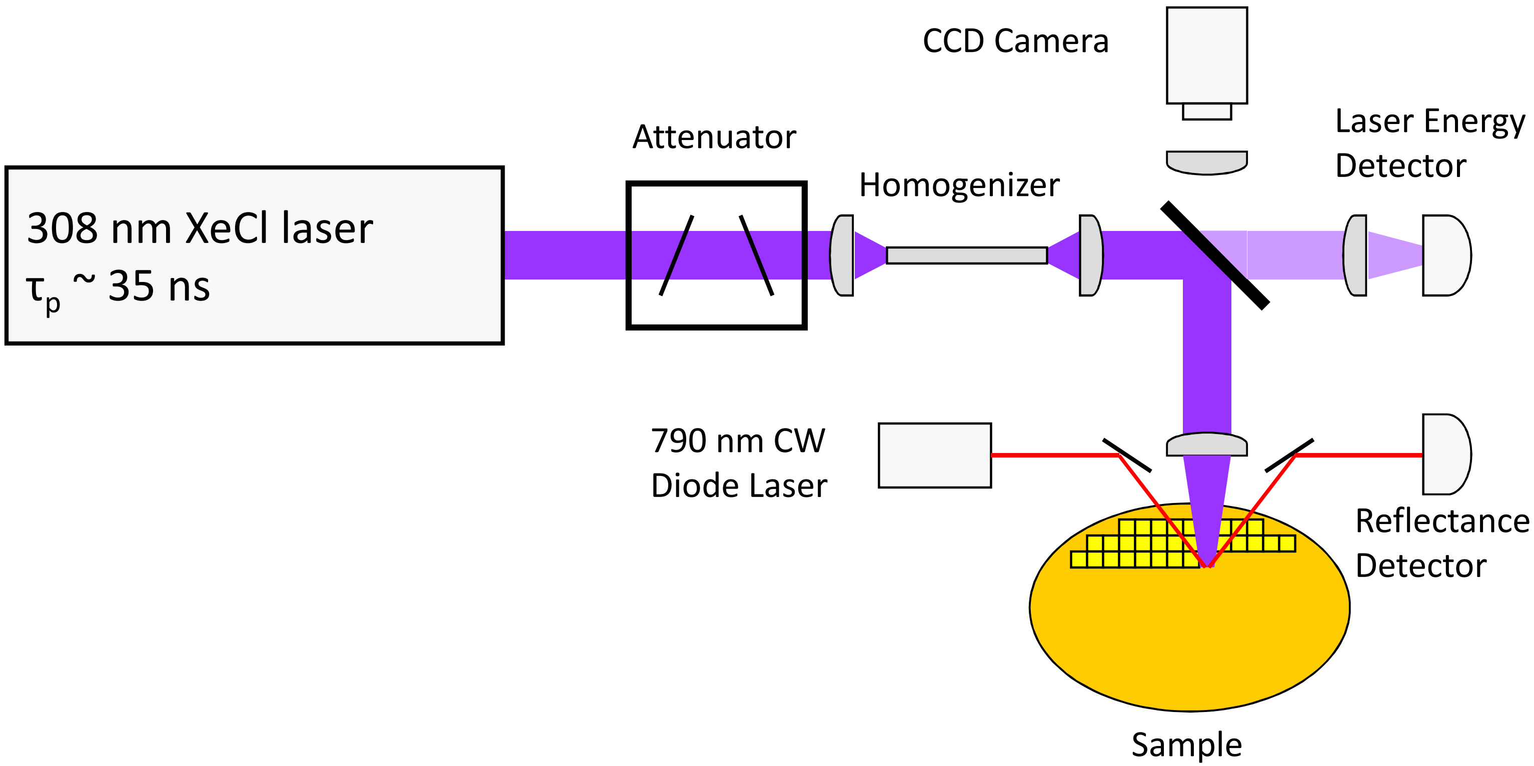
Melt and crystallize Si with fast laser pulse

Currently used in mass production for high quality TFT-LCD displays



Sumitomo

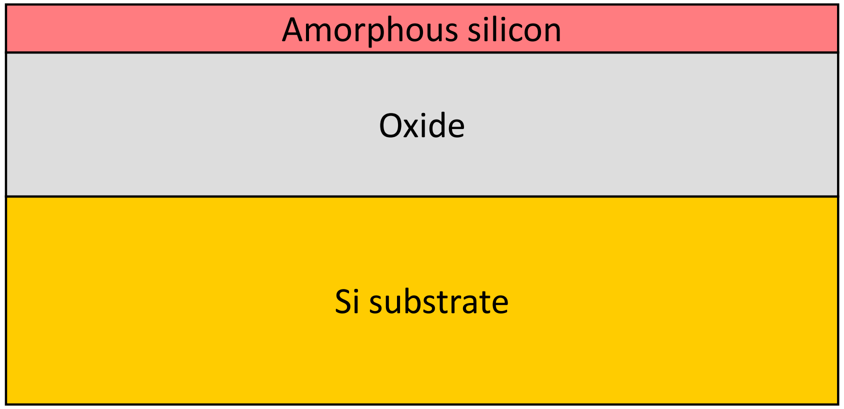
Excimer laser annealing



- Analogous to stepper photolithography
- Homebuilt system: 3.5 mm spot size, 10 Hz fire rate
- Transient reflectance for surface melt detection

Fabrication

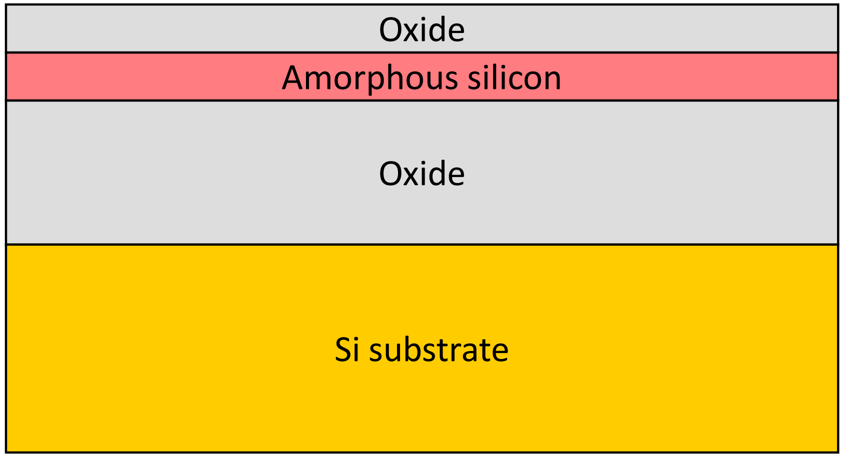
Deposit 150 nm amorphous silicon:
e-gun evaporation at room temperature



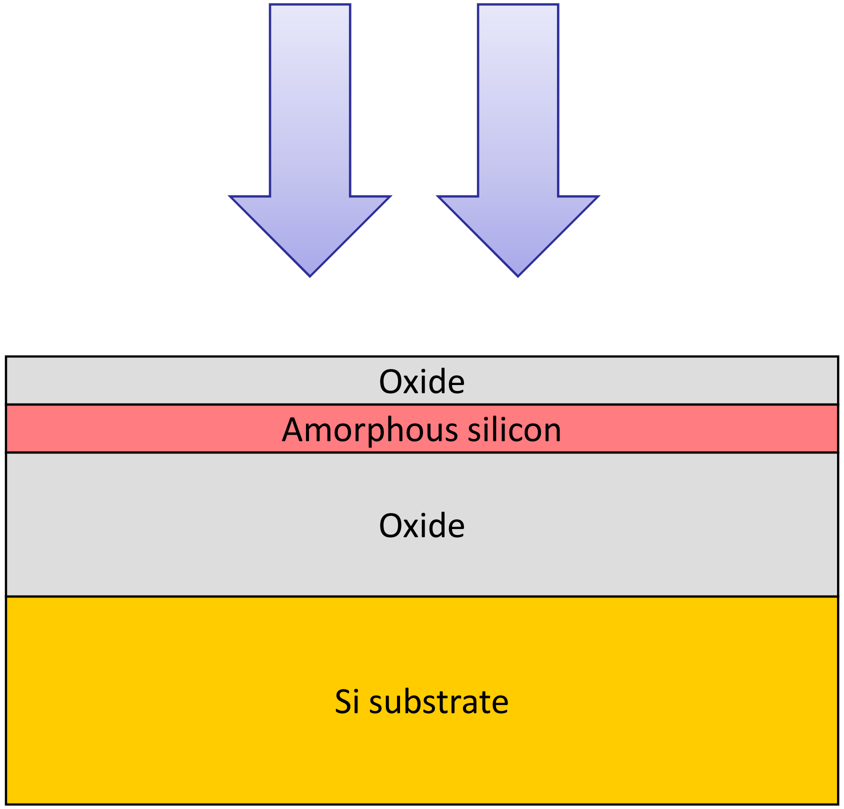
Fabrication

Deposit PECVD oxide capping layer: 150 nm

- Antireflective coating for λ = 308 nm
- Stabilizes top surface of silicon

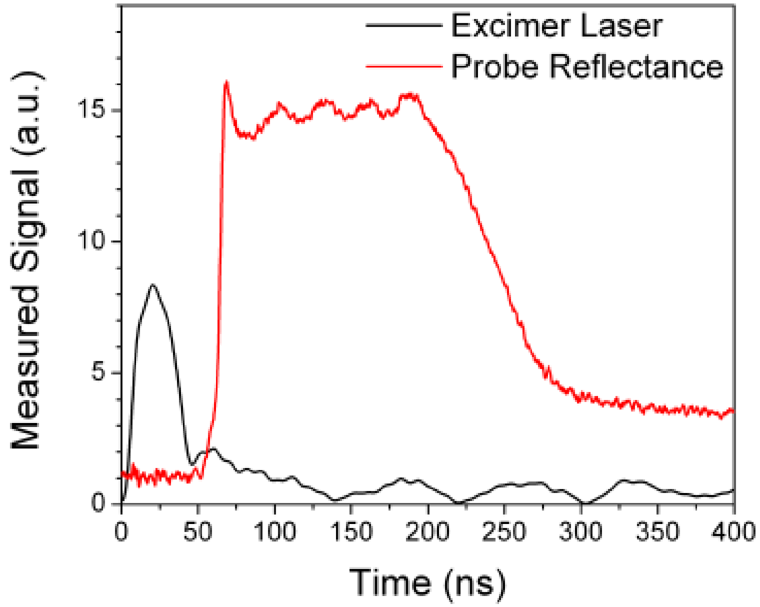


Fabrication



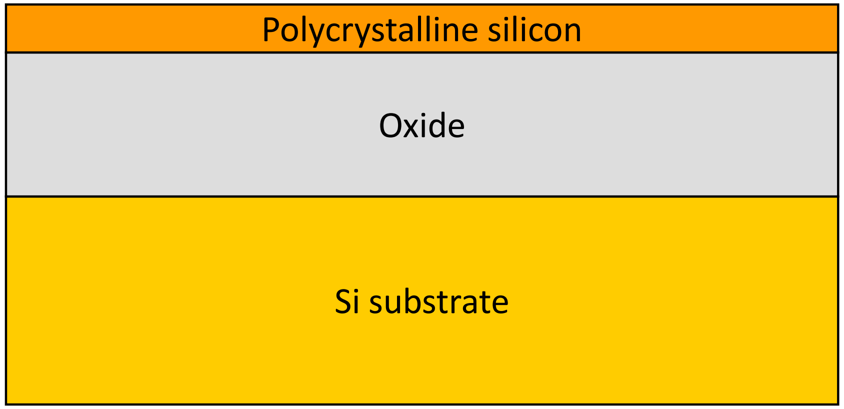
Excimer laser anneal

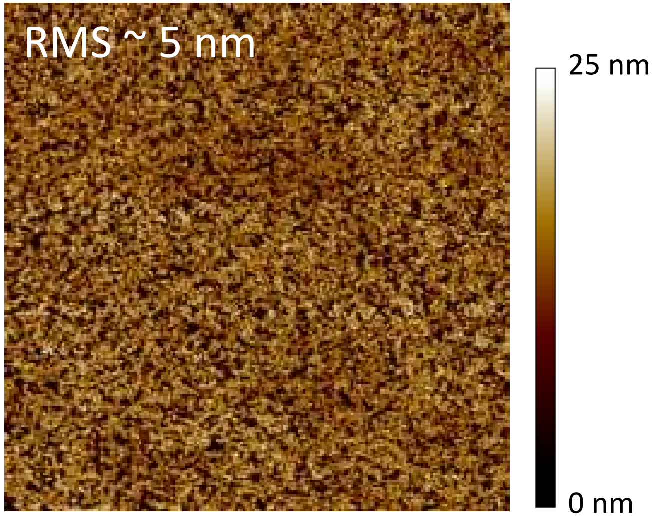
- Pulse absorbed in top 10 nm
- Silicon melts down from top
- Crystallizes back up from bottom



Fabrication

AFM: Roughness ~ 5 nm r.m.s.

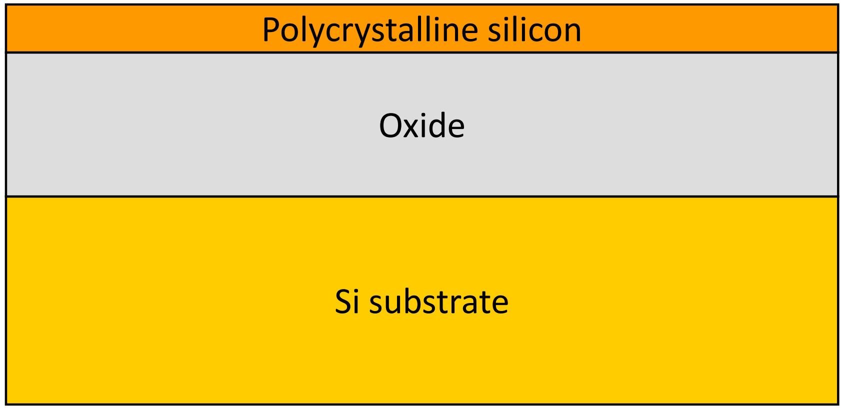




5x5 μm

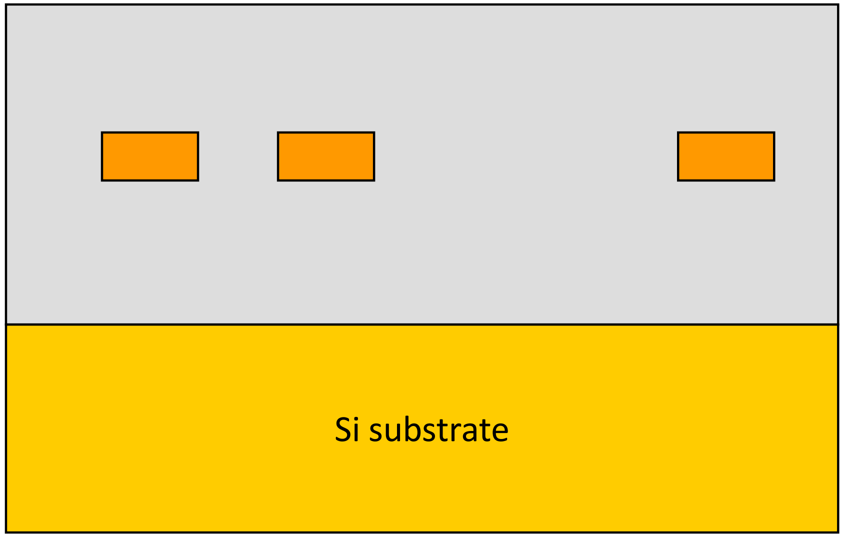
Fabrication

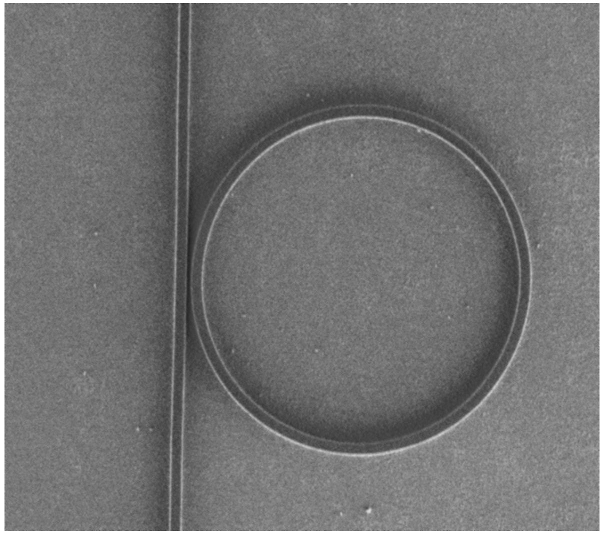
AFM: Roughness ~ 5 nm r.m.s.
Reduce to ~ 1 nm with CMP



Fabrication

E-beam lithography
Chlorine-based ICP-RIE etch
PECVD oxide deposition





SEM

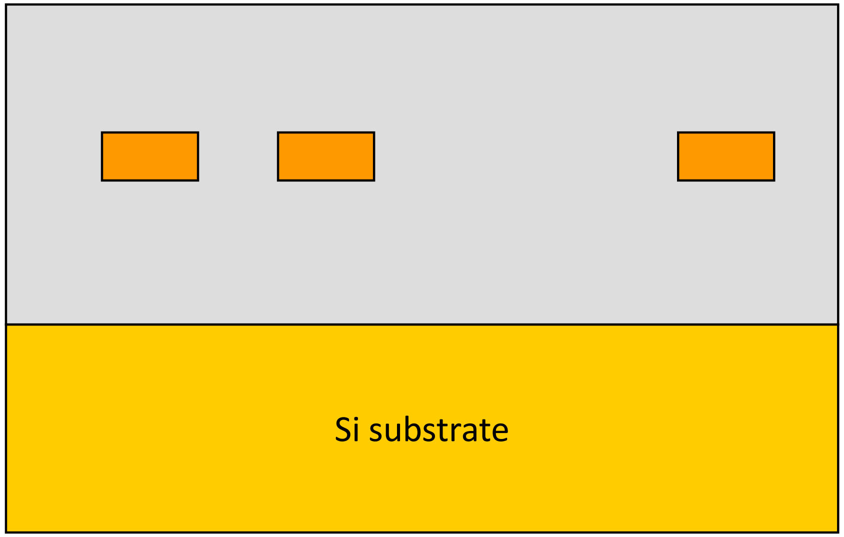
Thin devices

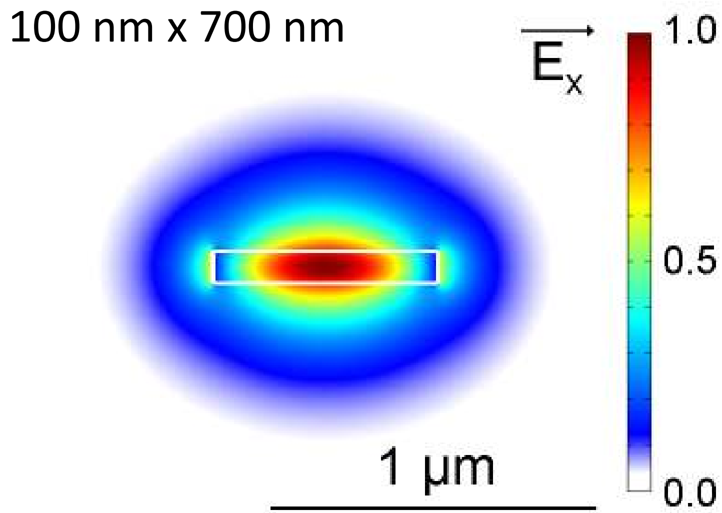
Thinner silicon layer

→ lower UV pulse energy

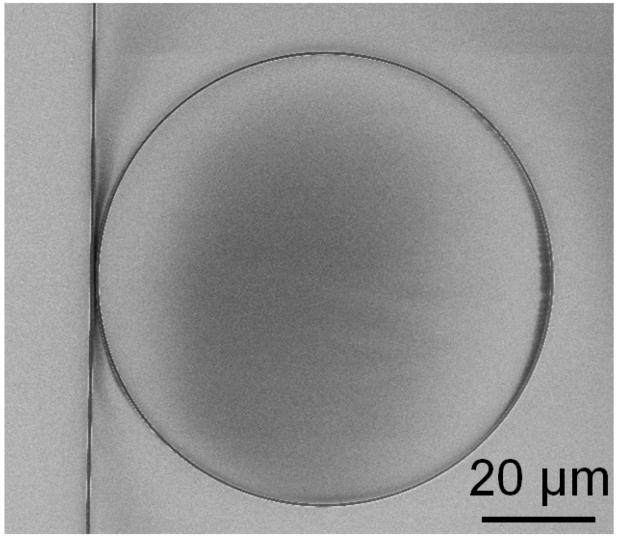
→ lower transient temperature for complete melt

→ don't require ultra-pure a-Si material

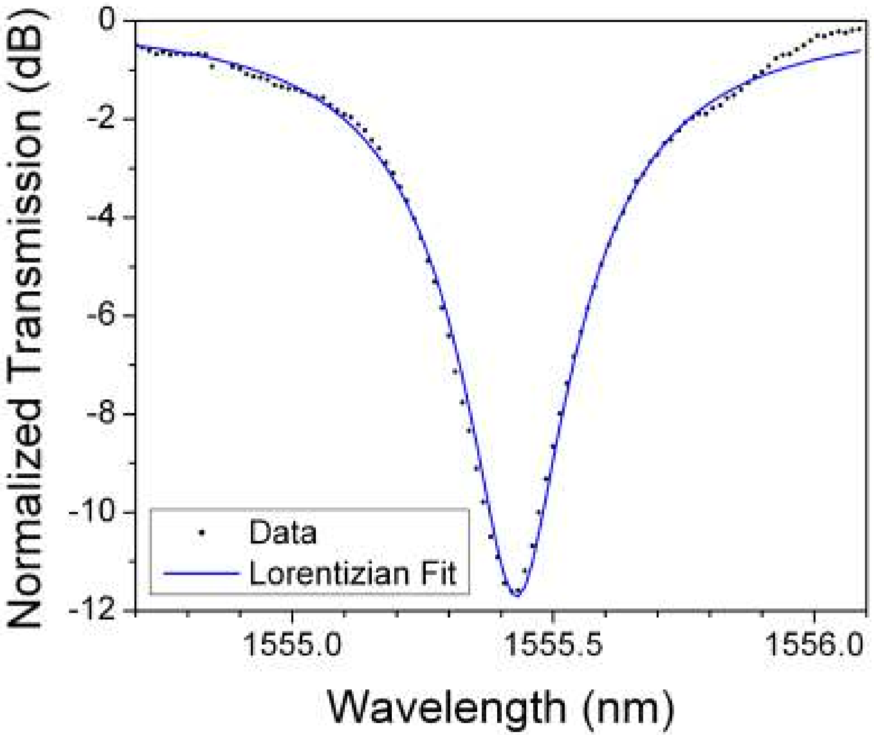




Polysilicon ring resonator



700 nm waveguide width, 40 µm radius



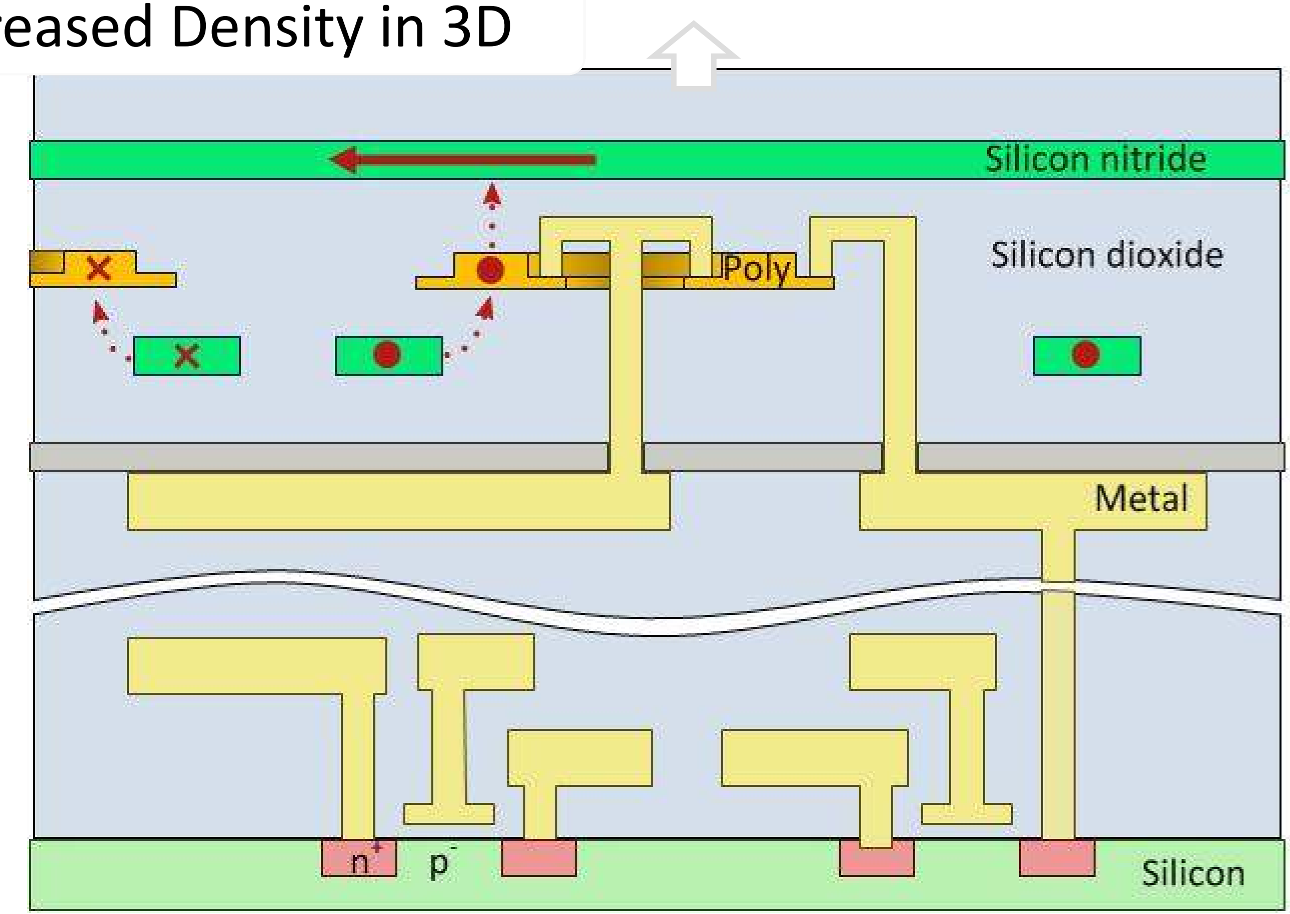
Q = 3000, good for high-speed electro-optic modulation

Preston et al., *OpEx* 2009

Low temperature fabrication < 400 °C

Passive SiN waveguides

Increased Density in 3D



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Silicon Nitride

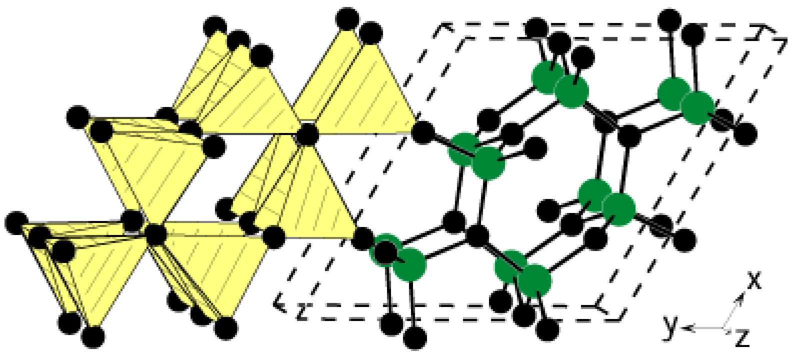
Silicon Nitride, Si_3N_4

n=2

λ>400nm

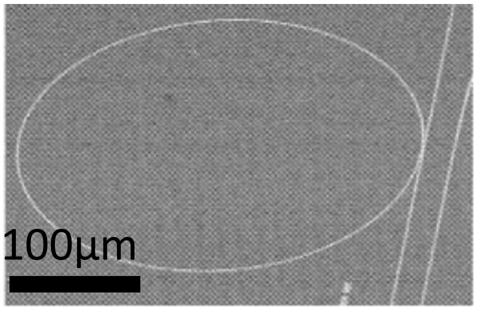
Propagation Losses <0.1 dB/cm

Low nonlinear absorption



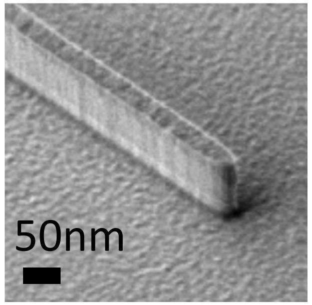
Riedel, 2004

Previous work



Q~240,000
200nm

IR C. T. Sullivan, Sandia, 2004

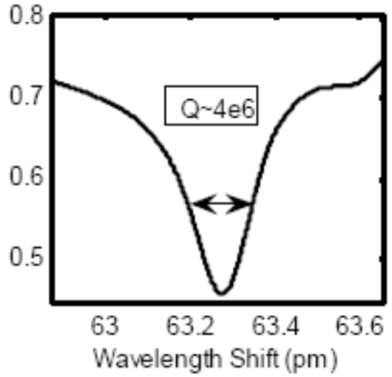


2 dB/cm
400nm

D. L. Kwong, A*STAR, 2008

Visible

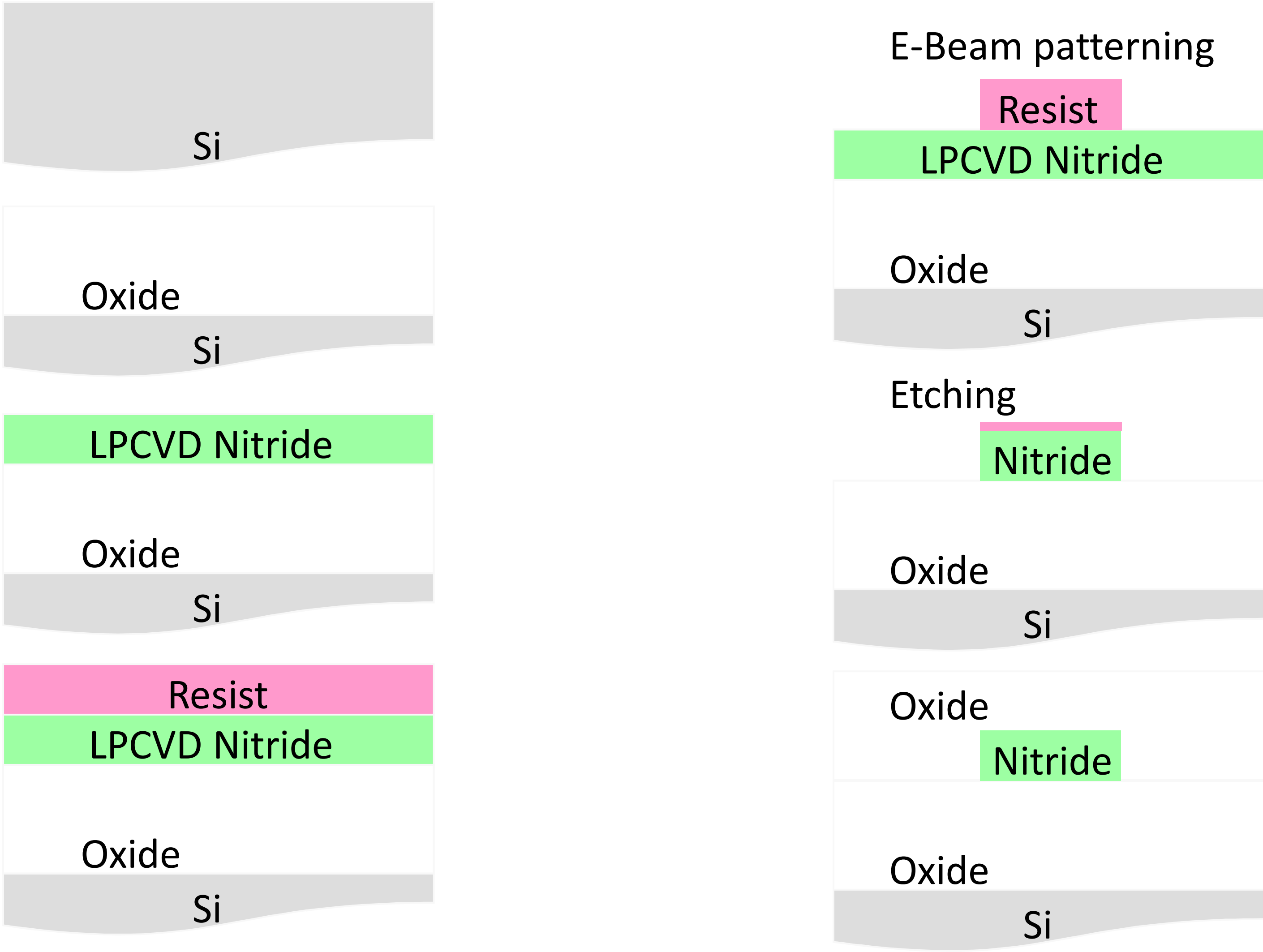
0.1dB/cm in the visible PECVD
P. Charette, U. of Sherbrooke, 2008



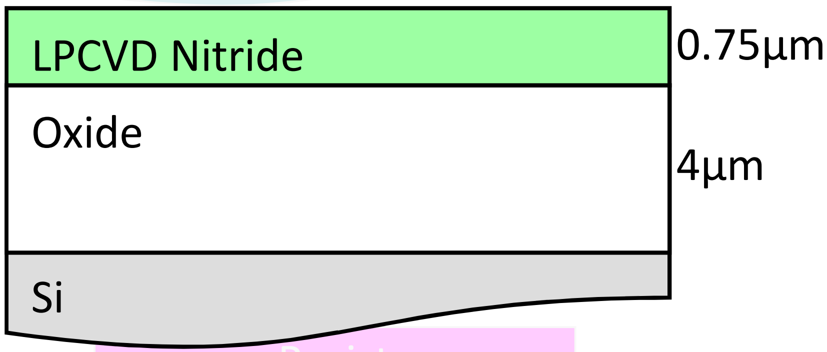
Q~4,000,000
200nm

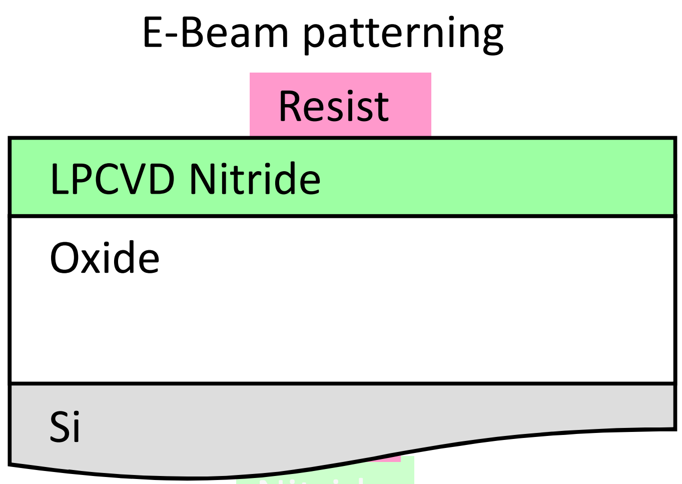
A. Adibi, GTech, 2008

Silicon Nitride process flow

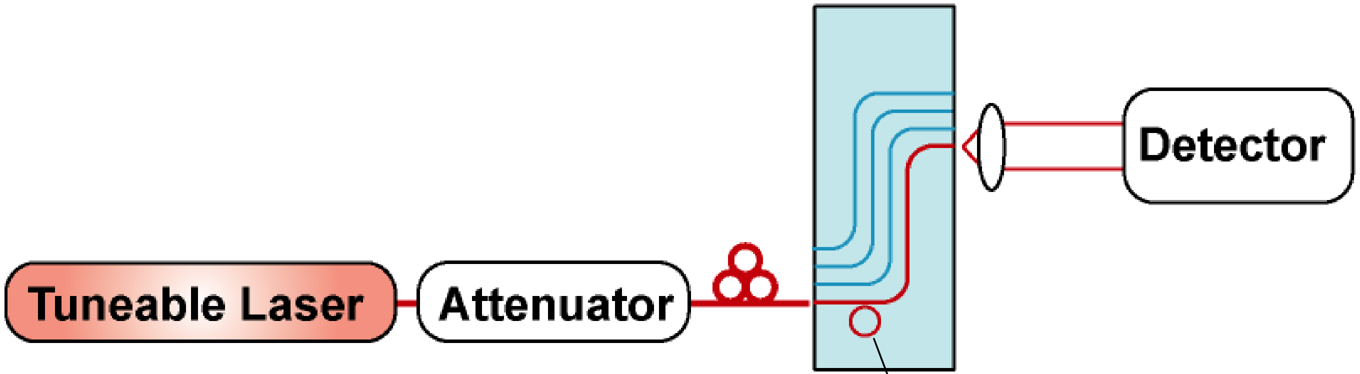


Silicon Nitride process flow

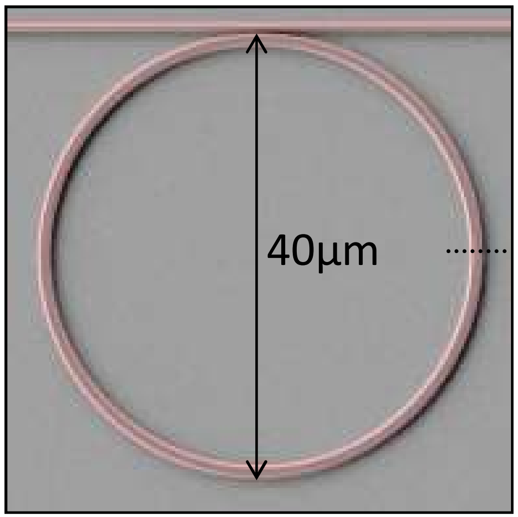




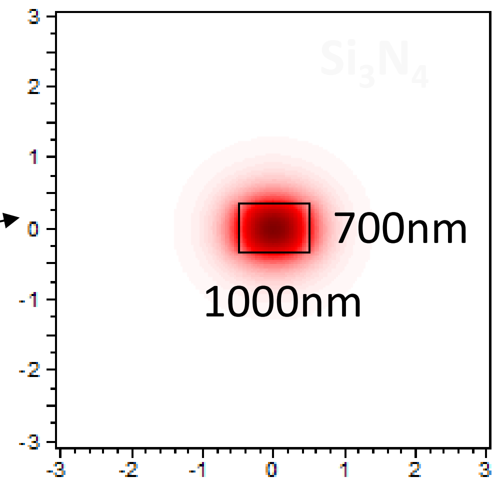
Experimental setup layout



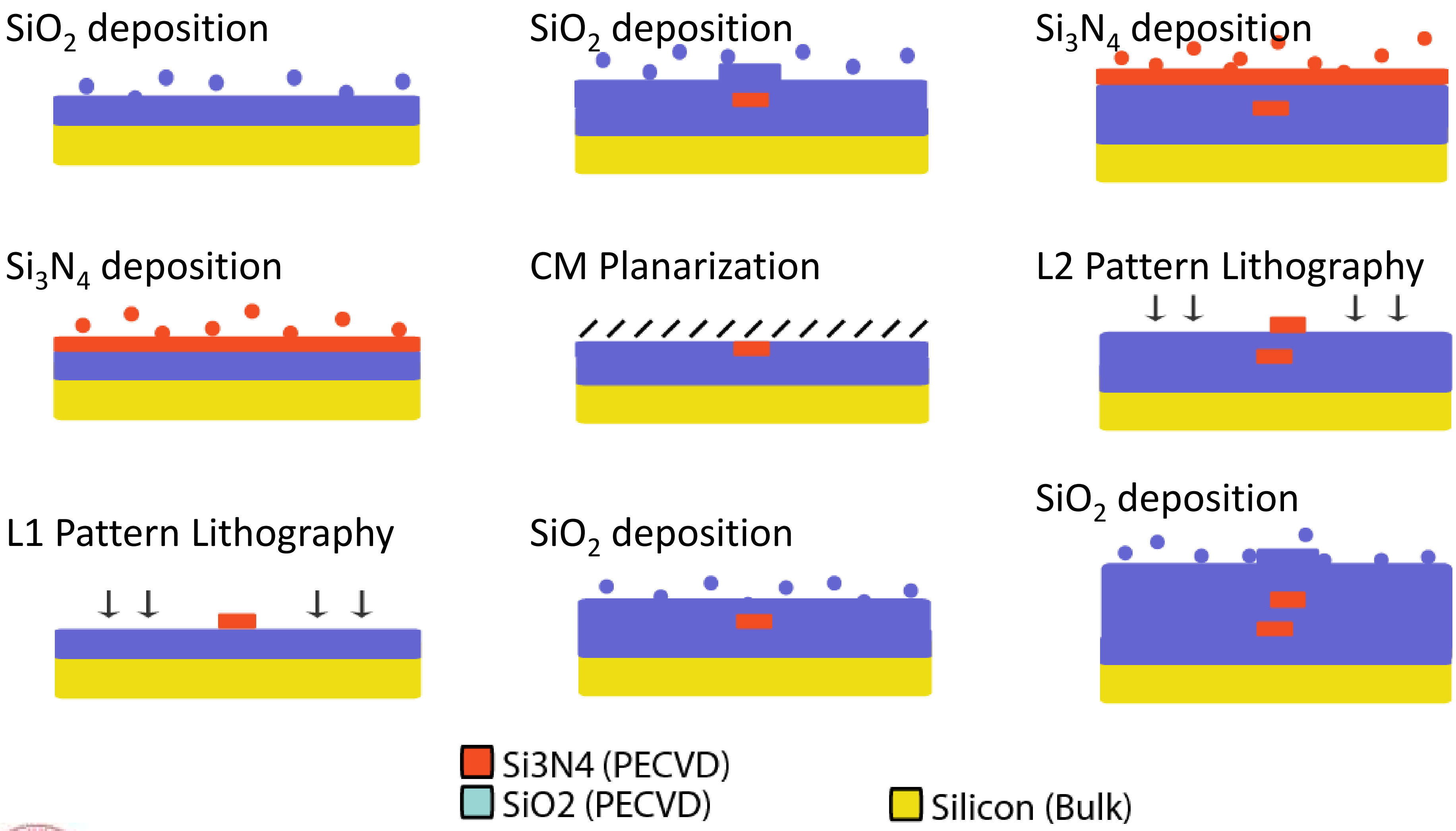
4dB total insertion loss (Fiber to Detector)
Qs up to 3,000,000
Waveguide losses ~0.1 dB/cm



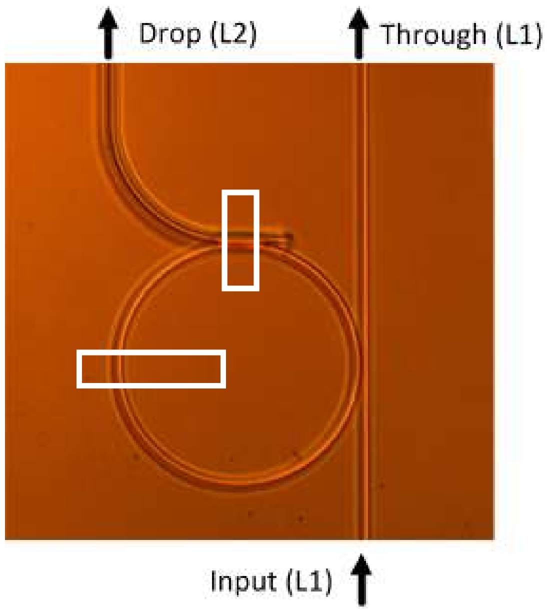
Waveguide cross section

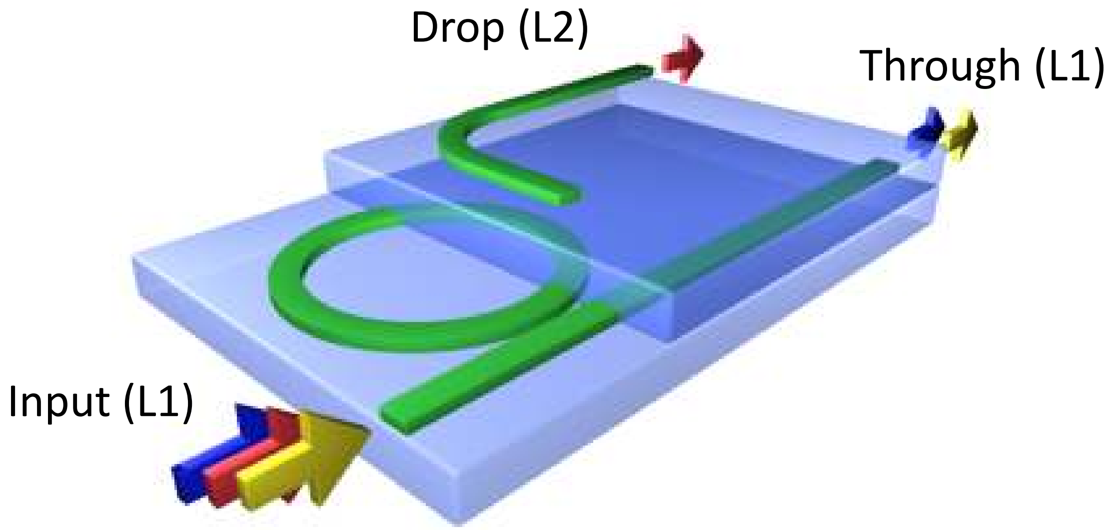


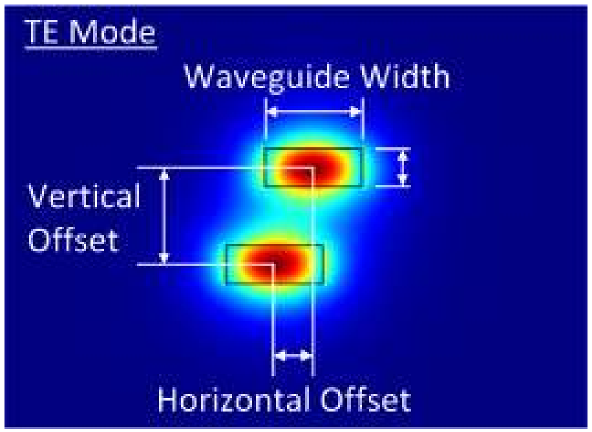
Backend integration

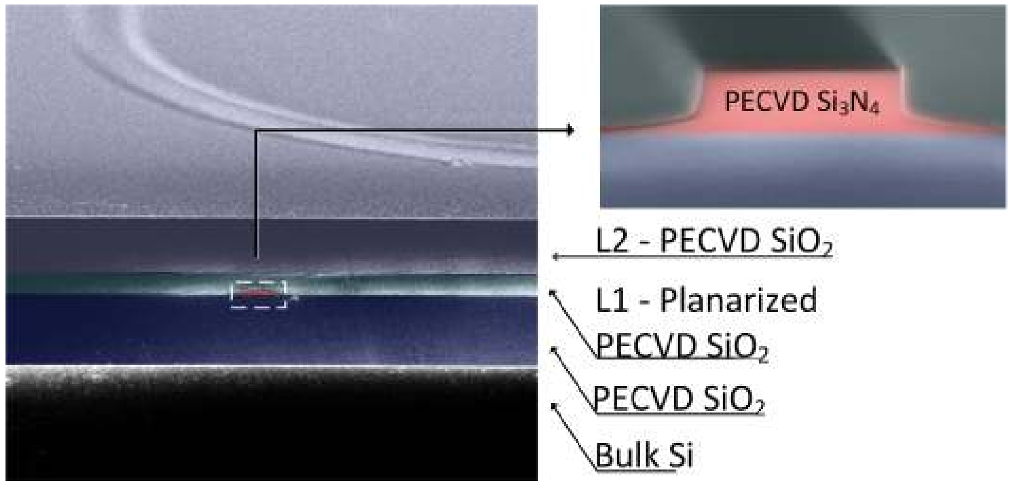


Vertically coupled rings









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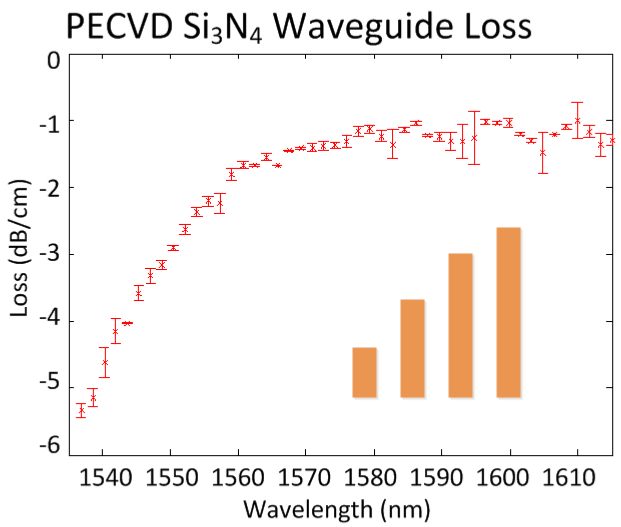
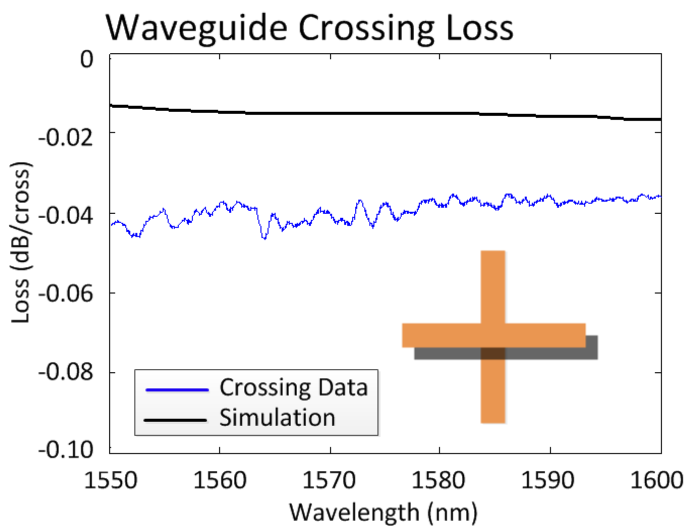
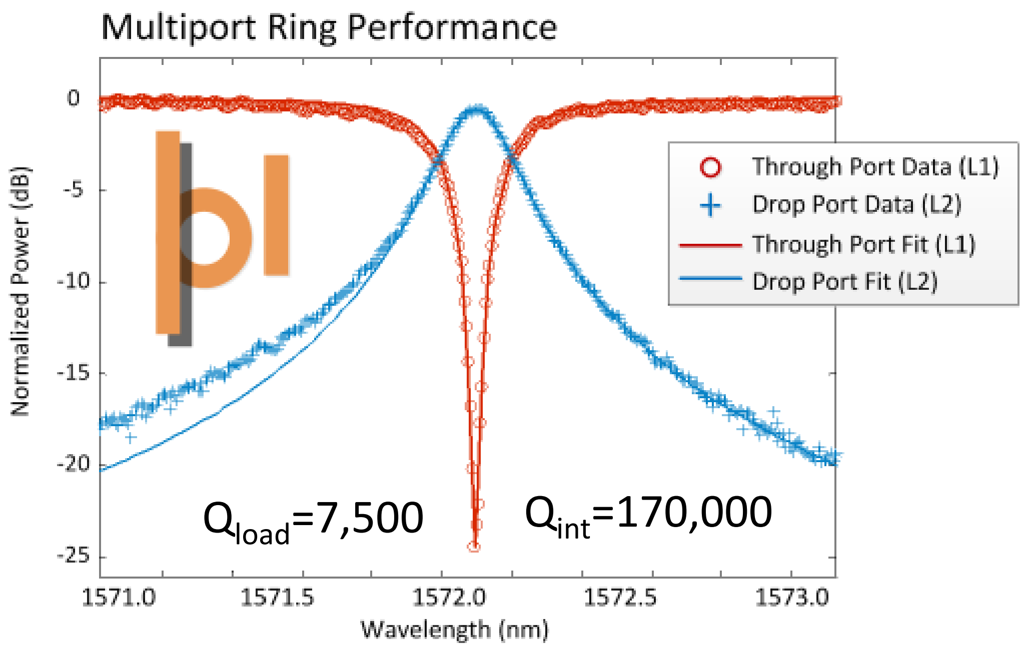
Low-temp 3D results





- WG loss < 1.5 dB /cm in L-Band
- Crossing loss 0.04±0.002 dB /cross
- 25 GHz / 24 dB extinction drop port



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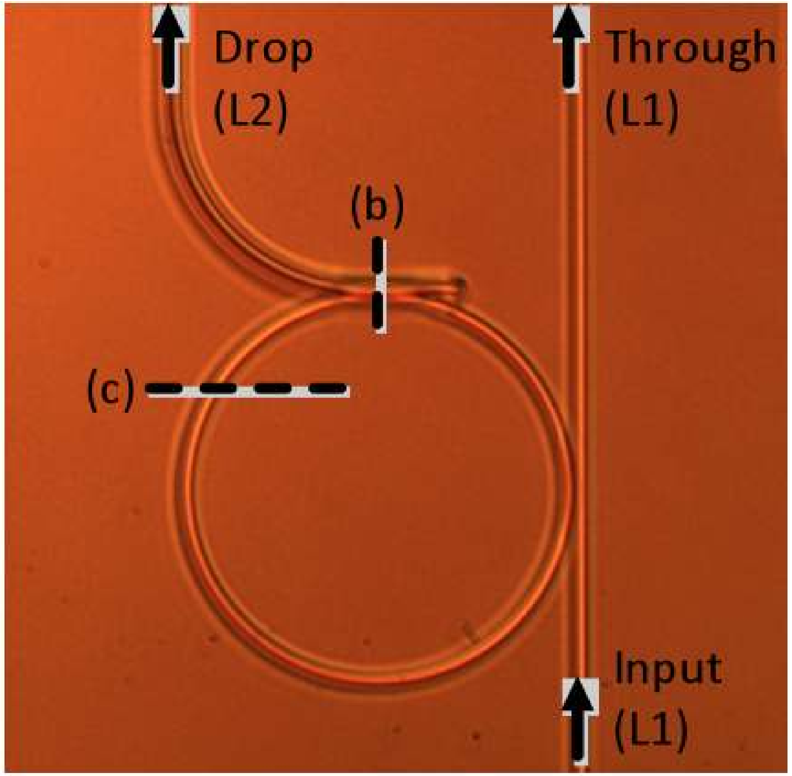
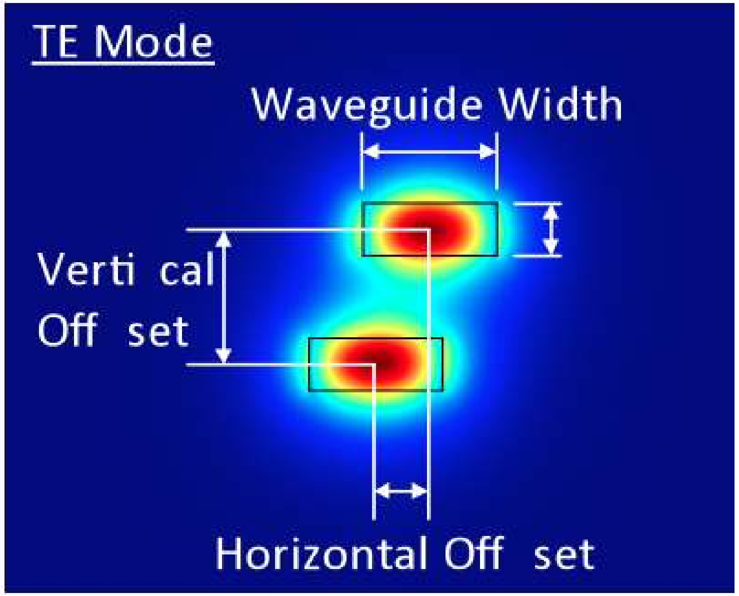
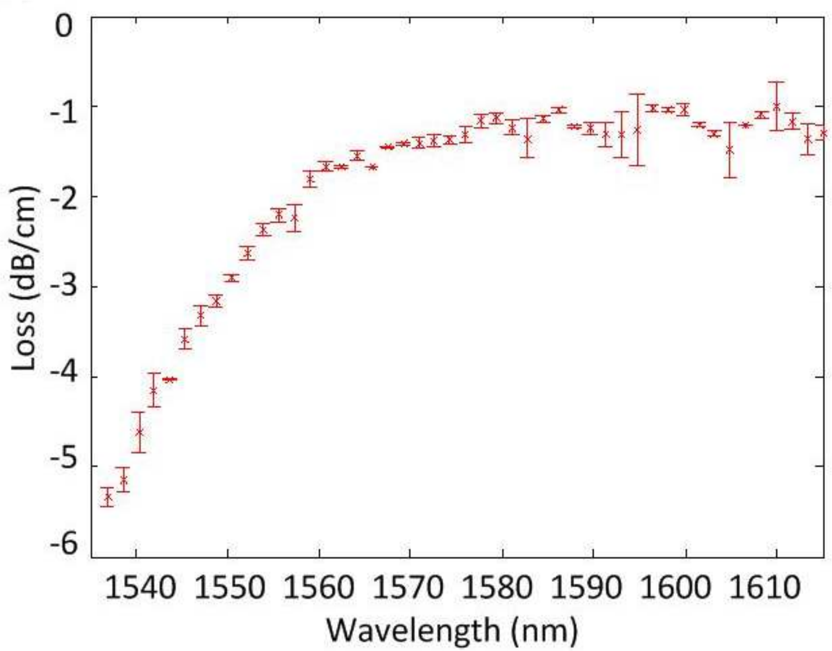
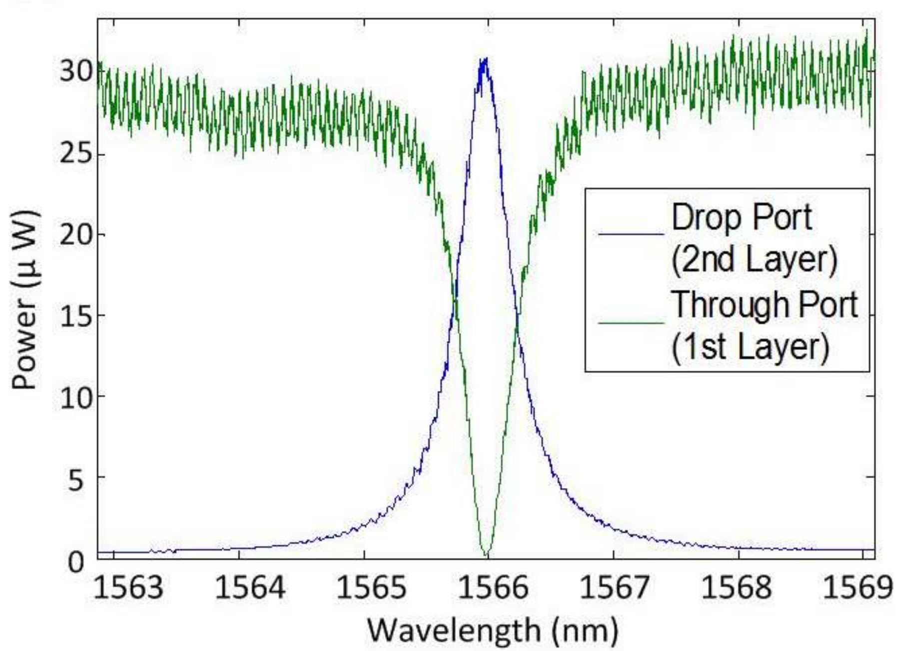

Drop
(L2)
Through
(L1)
(b)
(c)
Input
(L1)

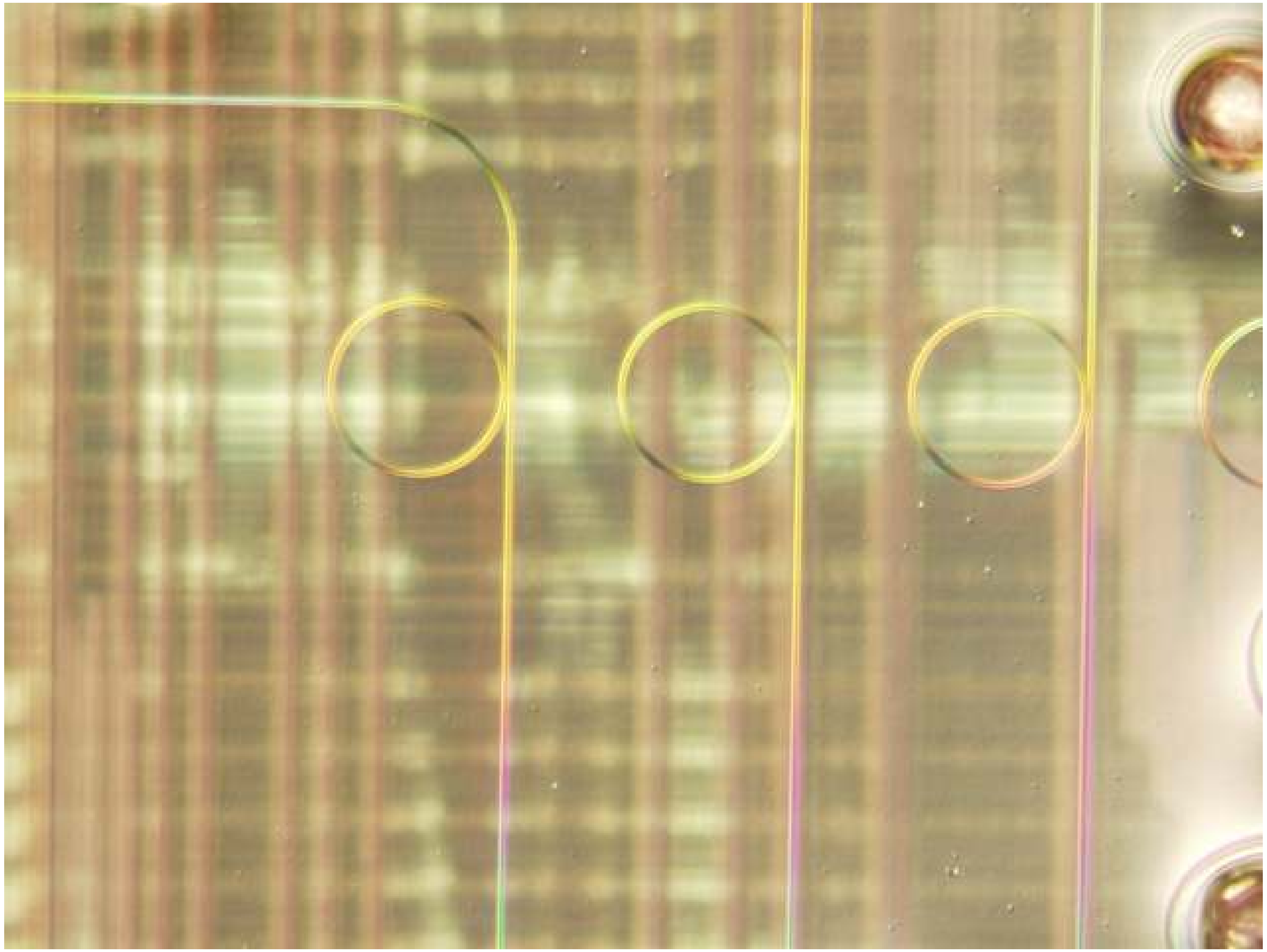

TE Mode
Waveguide Width
Verti cal
Off set
Horizontal Off set





Nicolás Sherwood-Droz, Michal Lipson, Multi-Layer Deposited CMOS Photonics for Microelectronics Backend Integration, CLEO 2011 (Submitted)

Integration of photonics on CMOS



Athermal Photonic Devices

Cornell University

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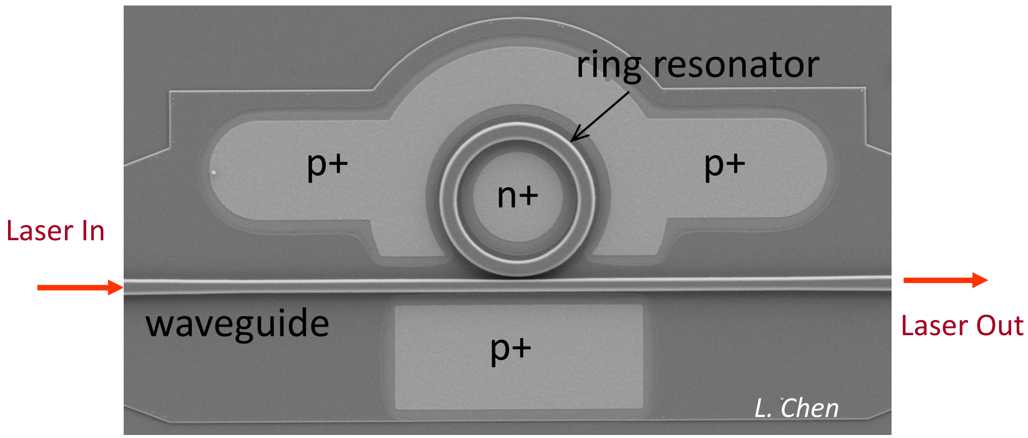
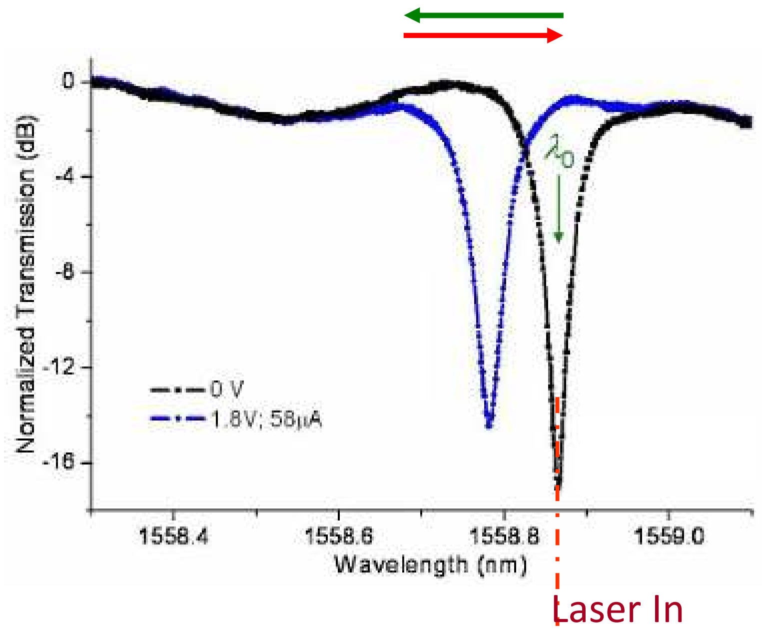
Si ring modulator

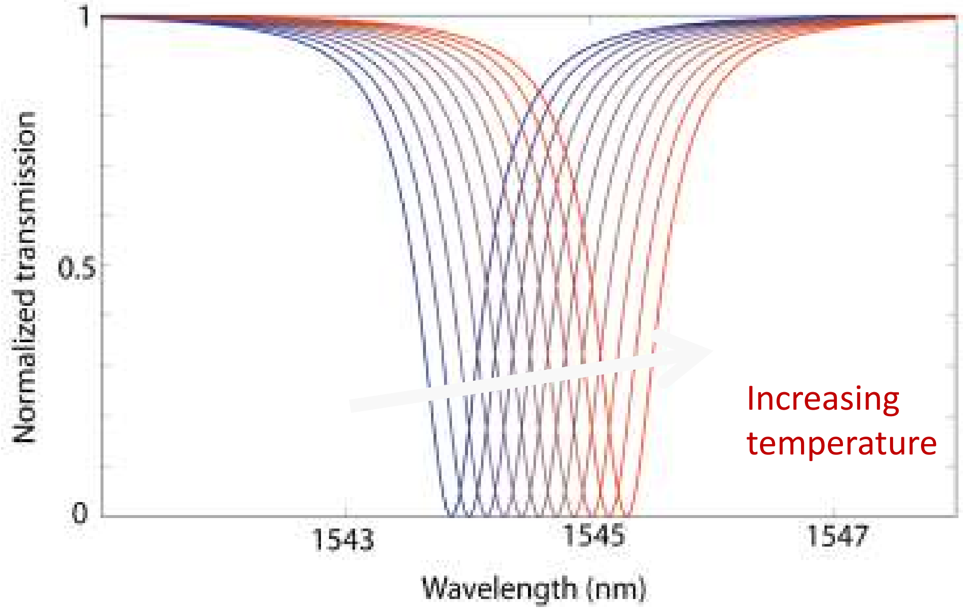




- Index changes are translated into large modulations in output power.
- The modulated light can be switched on and off at a high speed.

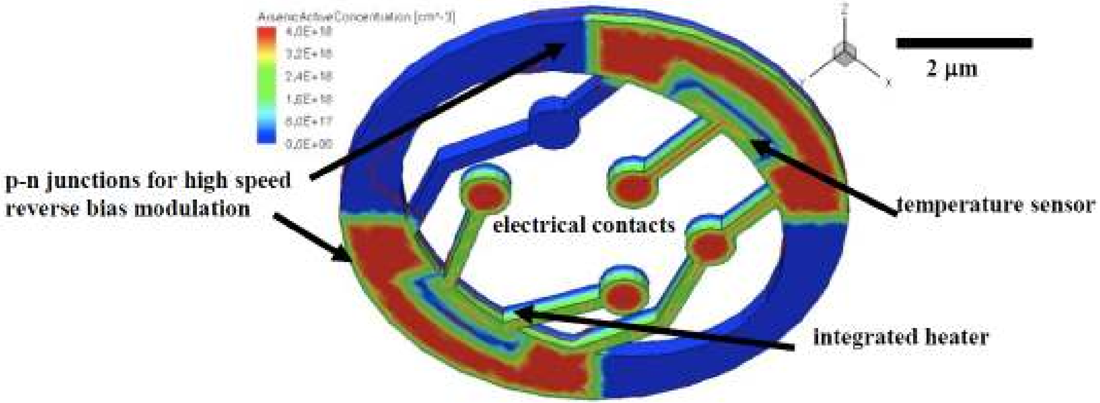
Cornell University

The Problem



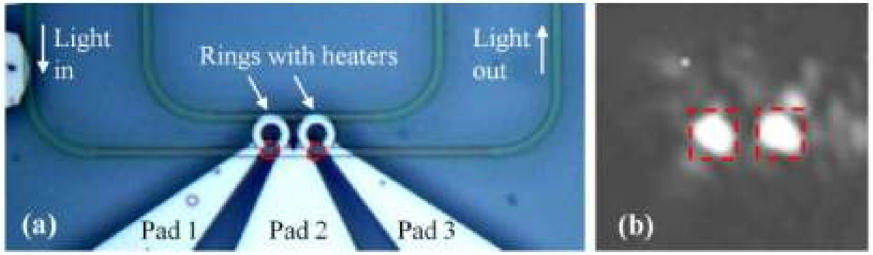
Decrease optical path length (n L) with temperature

Active compensation



Integrated feedback loop

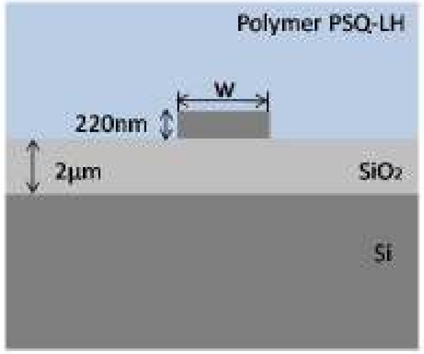
C.T. DeRose, M.R. Watts, CLEO 2010

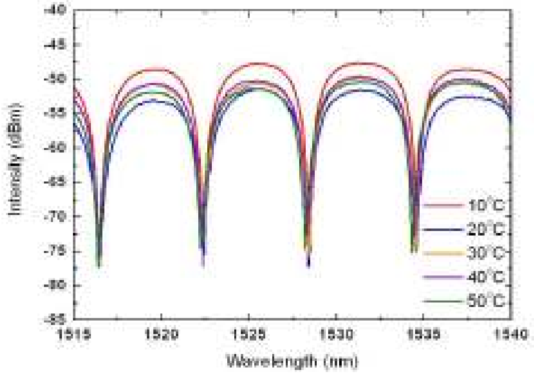


External feedback loop (image processing)

Q. Xu, Opt. Exp. 5143, Vol 19, 2011

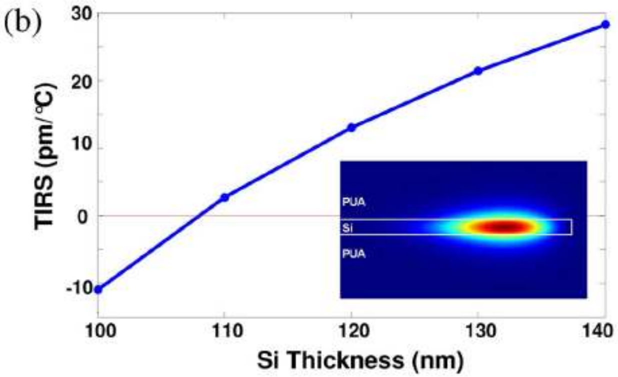
Passive compensation

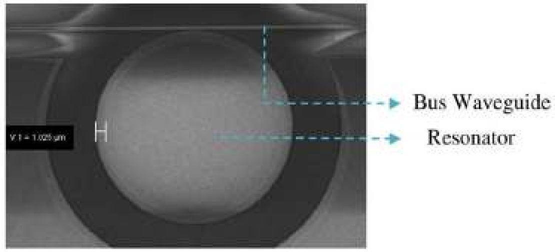




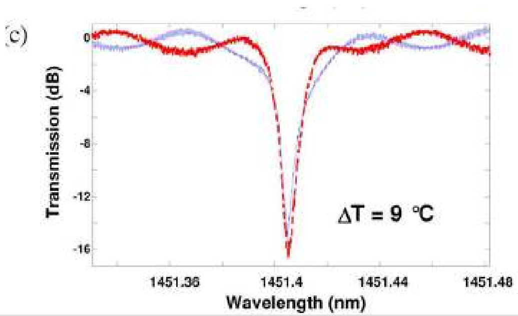
Polymer as top cladding

J. Teng, R. Baets et. al., Opt.Exp. 14627, Vol. 17, 2009



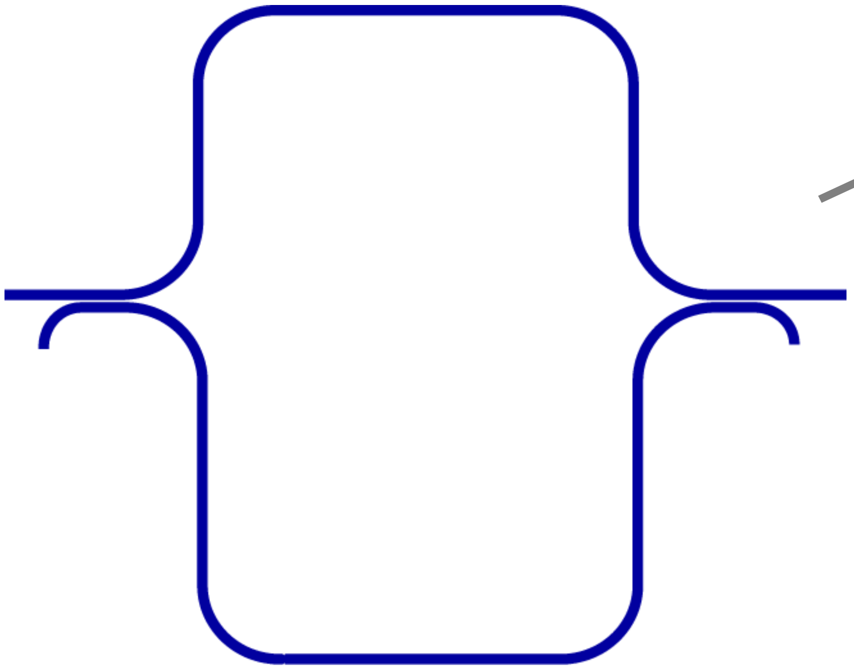


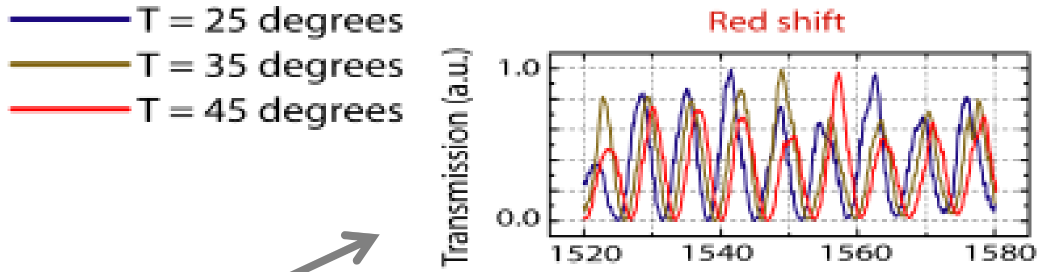
Polymer as top and bottom cladding



P. Alipour, A. Adibi et. al., Opt. Lett. Vol 35 No. 20, 2010

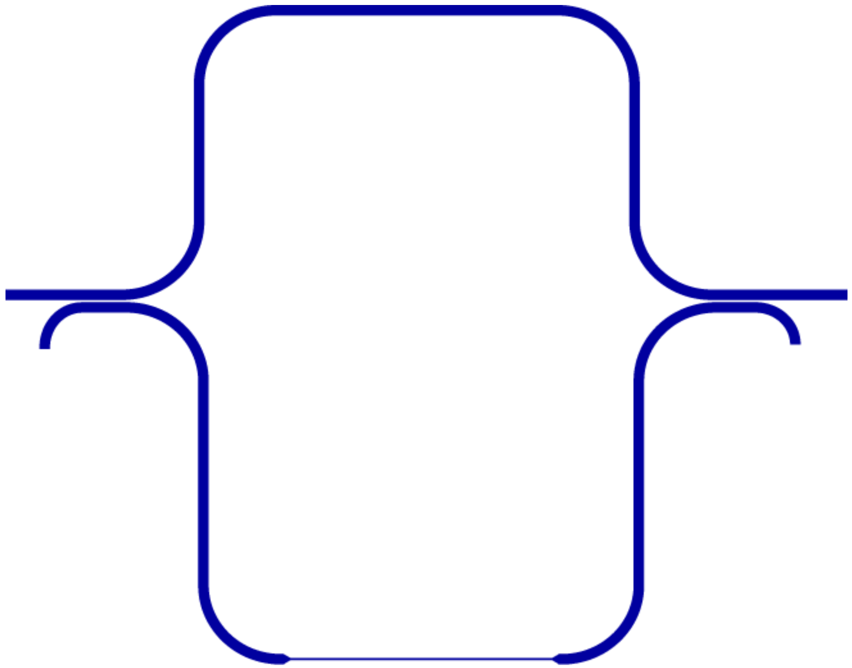
Getting blueshift





Guha, B., Gondarenko, A. and Lipson, M., ***Minimizing temperature sensitivity of silicon Mach-Zehnder interferometers****, Optics Express, Vol. 18, No. 3, Feb. 2010.*

Getting blueshift

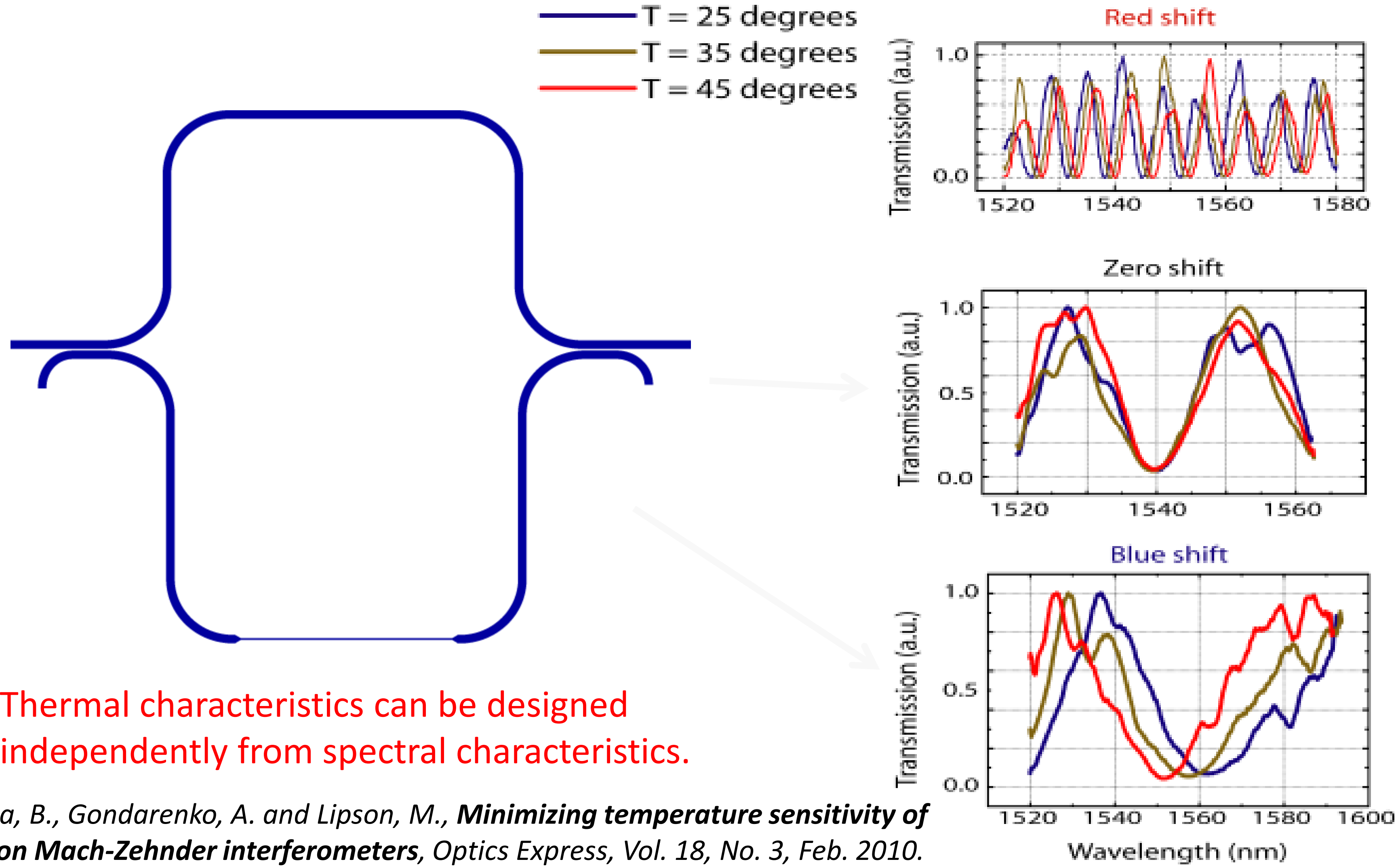


$$m\lambda = n_{eff}\Delta L + \Delta n_{eff} L$$

Thermal characteristics can be designed independently from spectral characteristics.

Guha, B., Gondarenko, A. and Lipson, M., ***Minimizing temperature sensitivity of silicon Mach-Zehnder interferometers****, Optics Express, Vol. 18, No. 3, Feb. 2010.*

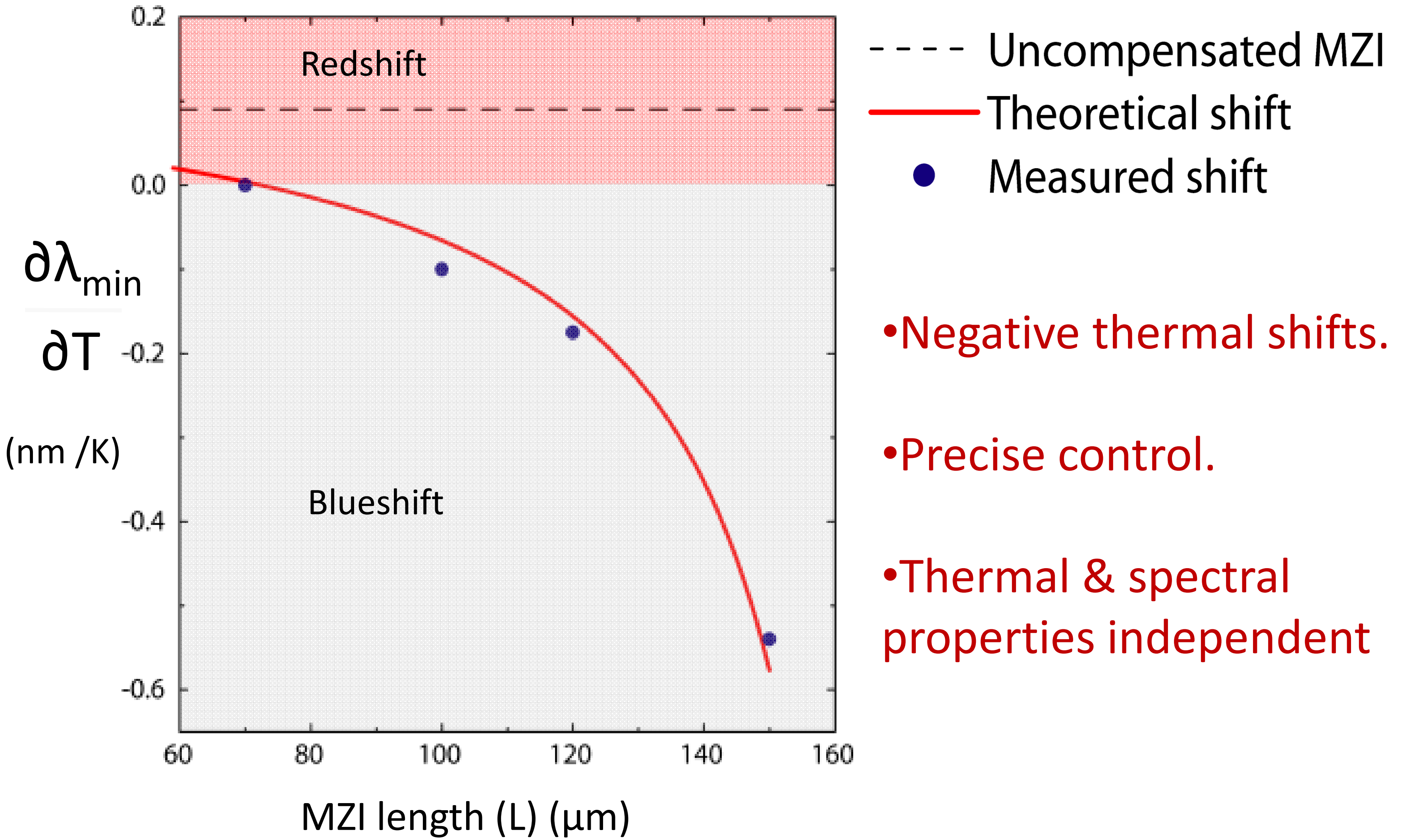
Getting blueshift in silicon-passive compensation



Thermal characteristics can be designed independently from spectral characteristics.

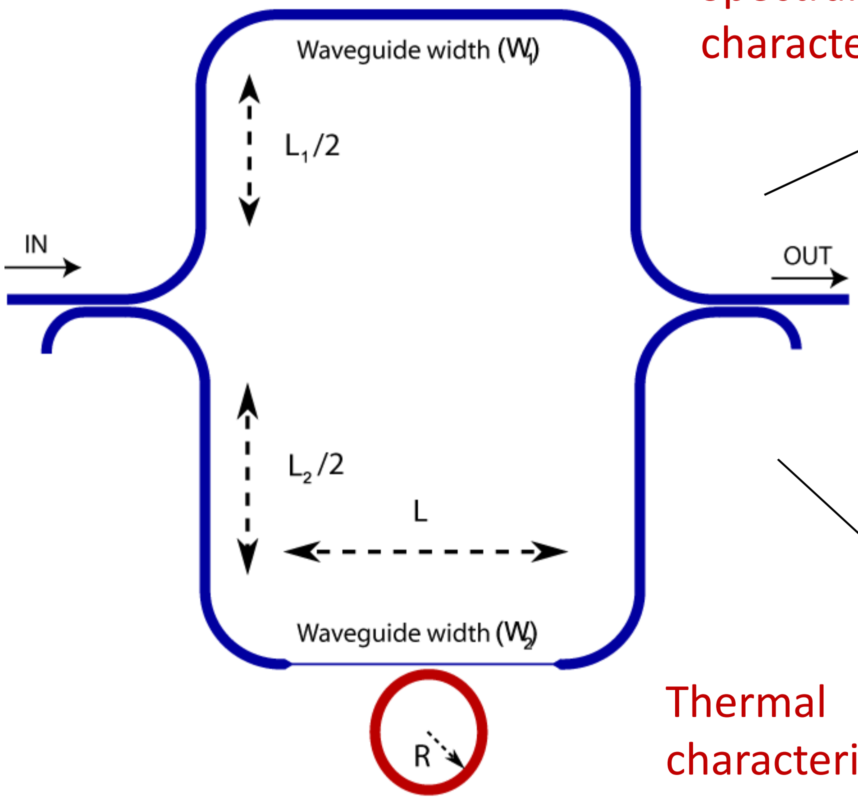
*Guha, B., Gondarenko, A. and Lipson, M., **Minimizing temperature sensitivity of silicon Mach-Zehnder interferometers**, Optics Express, Vol. 18, No. 3, Feb. 2010.*

Controlling thermal response

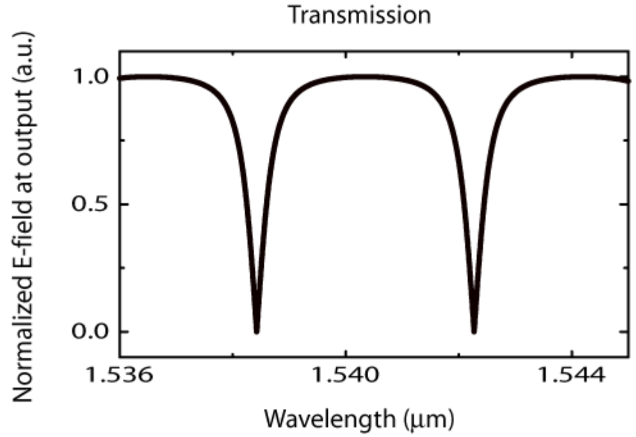


- Negative thermal shifts.
- Precise control.
- Thermal & spectral properties independent

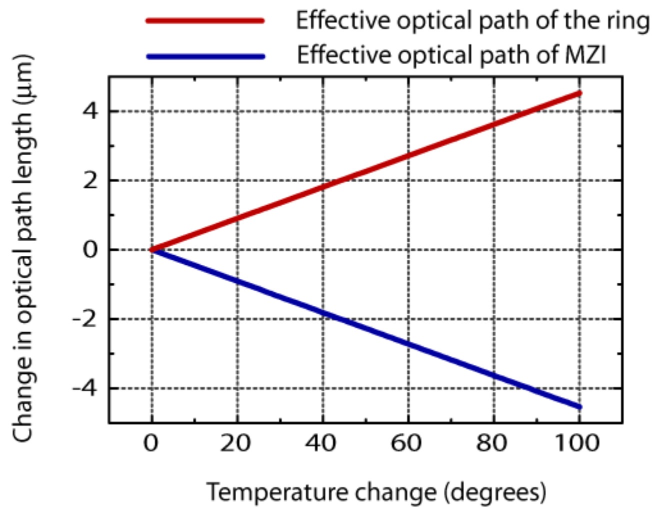
Athermal ring resonators



Spectral characteristics

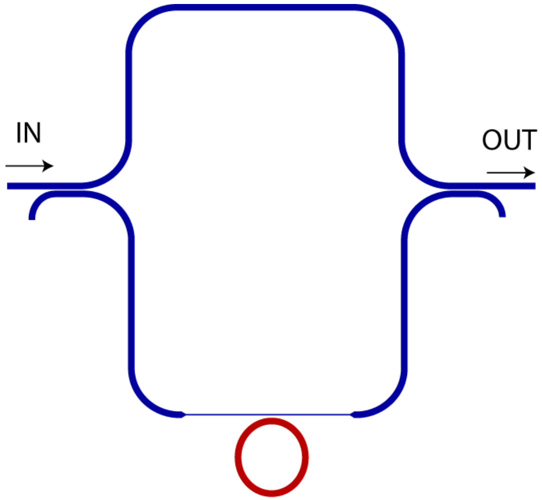


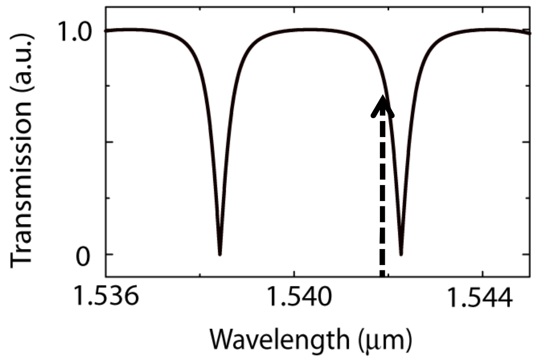
Thermal characteristics

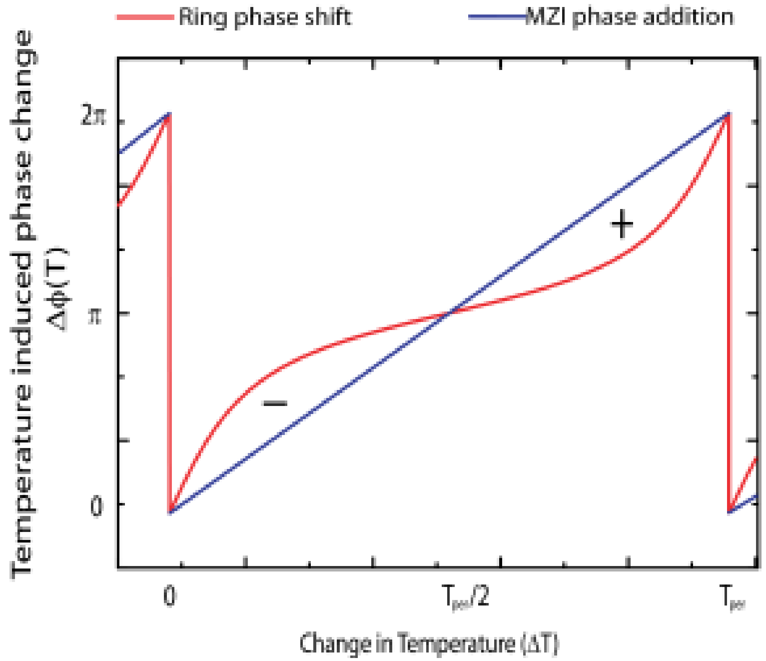


Ring resonator overcoupled to a balanced MZI

Working principle

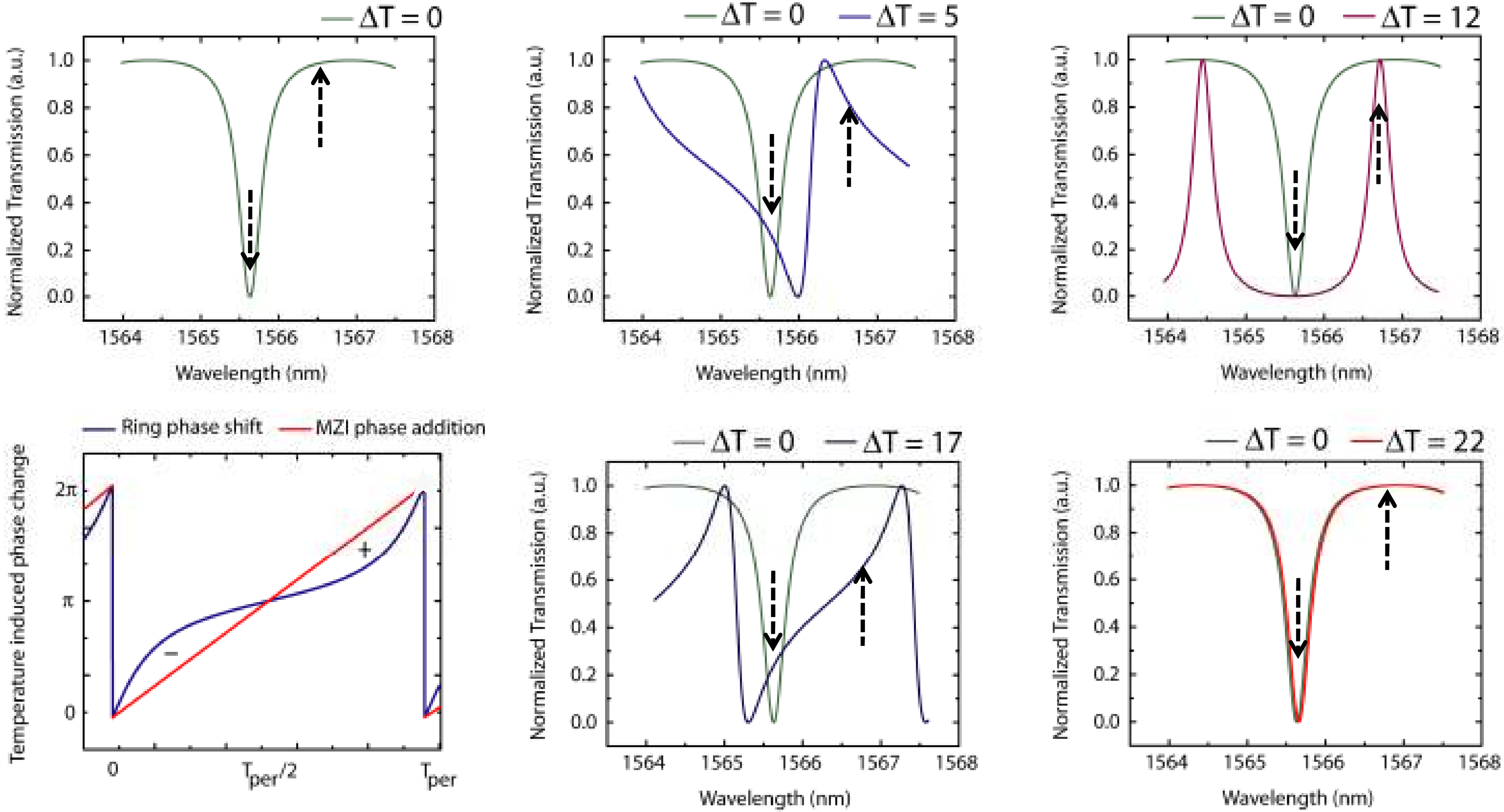






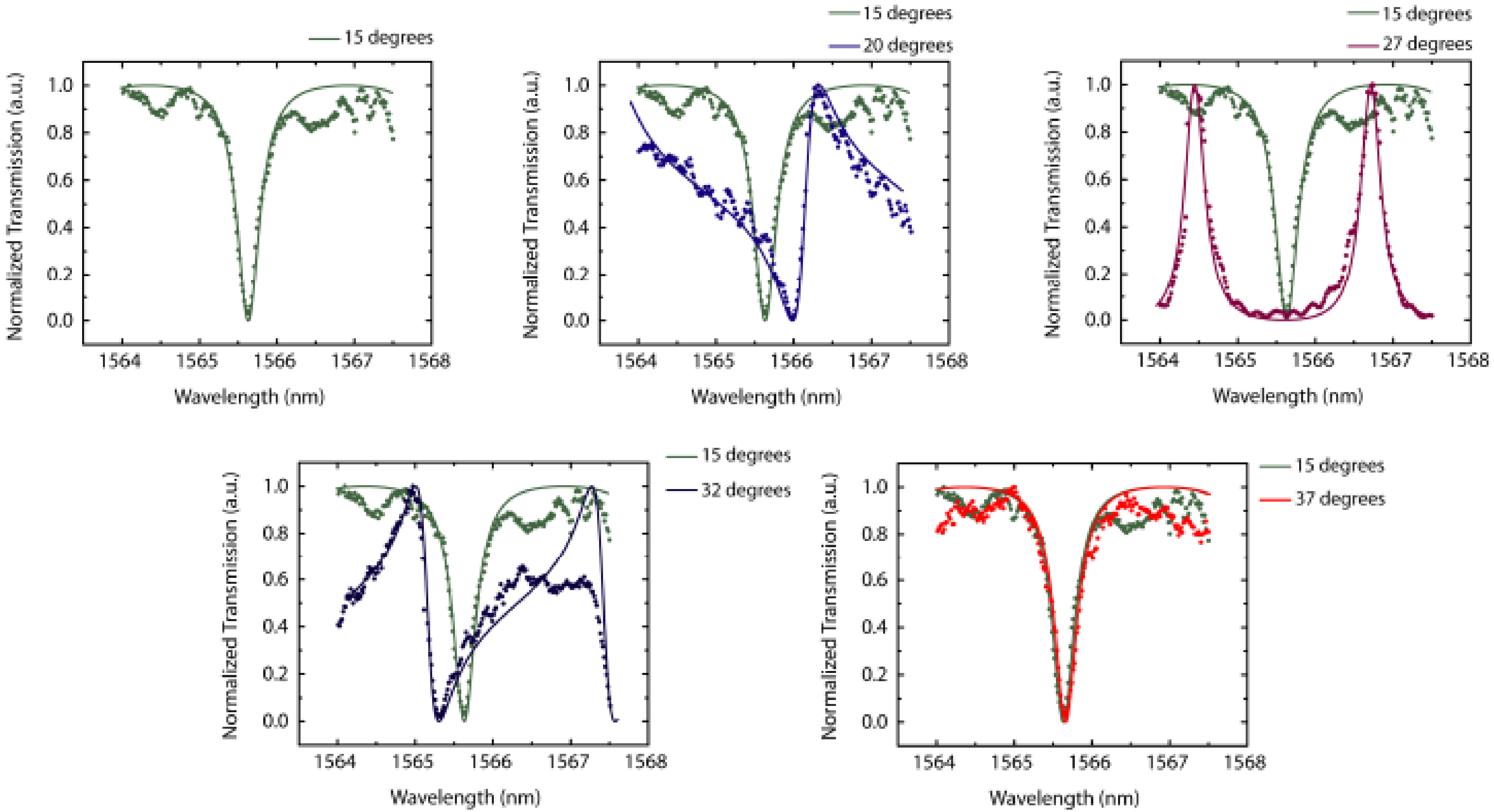
Matching linear and nonlinear phase changes

Self restoring resonances



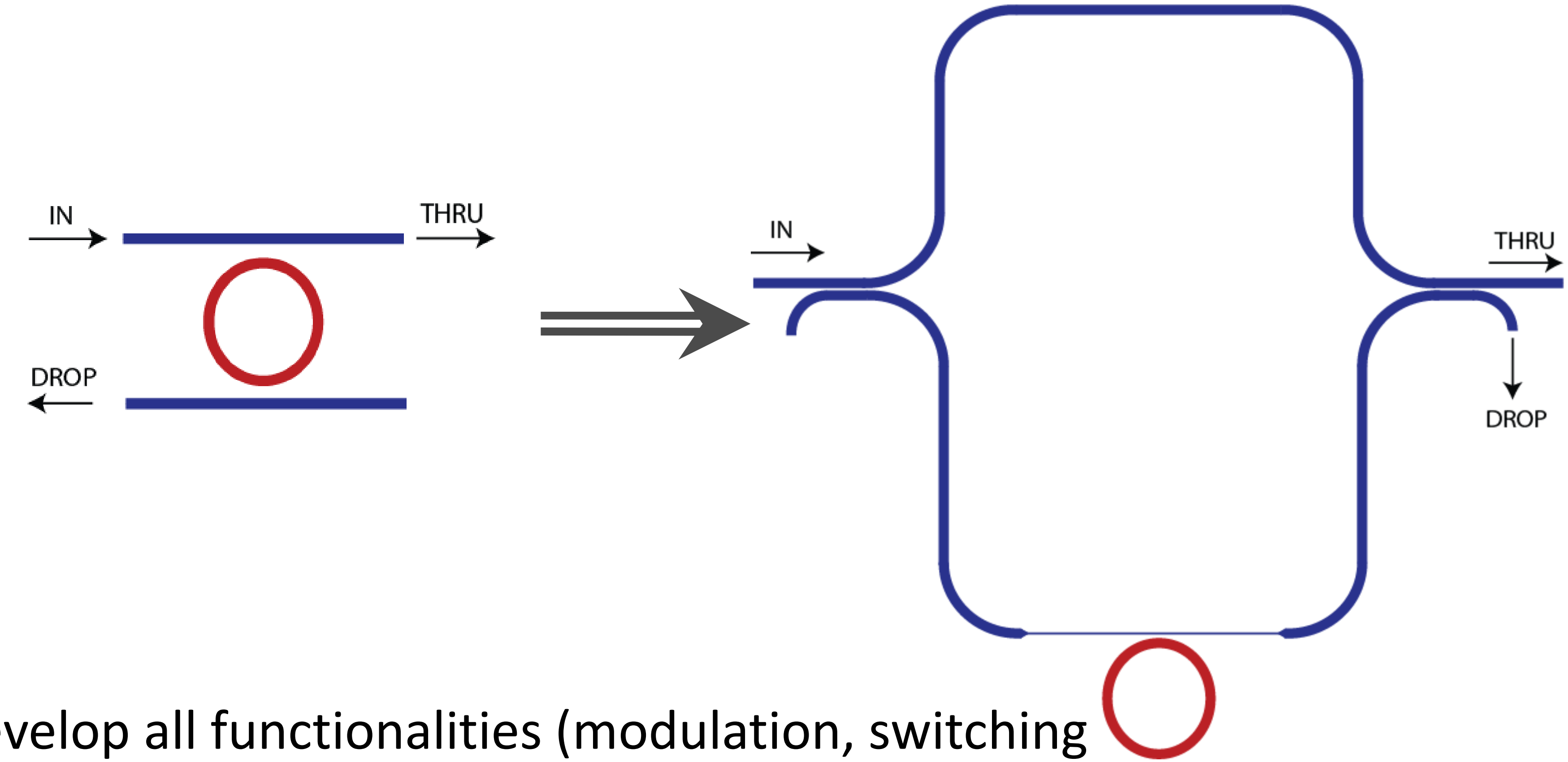
Guha, B., Kyotoku, B.B.C. and Lipson, M., ***CMOS-compatible athermal silicon microring resonators****, Optics Express, Vol. 18, No. 4, Feb. 2010.*

Measured spectra



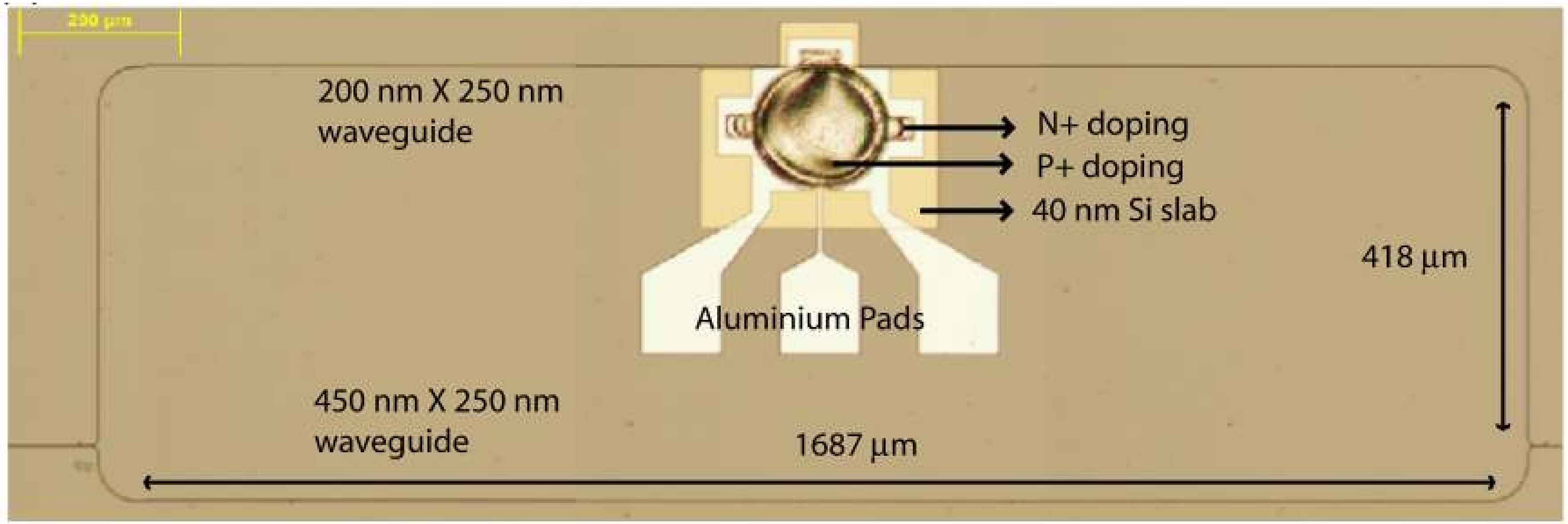
Guha, B., Kyotoku, B.B.C. and Lipson, M., ***CMOS-compatible athermal silicon microring resonators****, Optics Express, Vol. 18, No. 4, Feb. 2010.*

New building block



Develop all functionalities (modulation, switching etc.) within the framework of this new building block !!

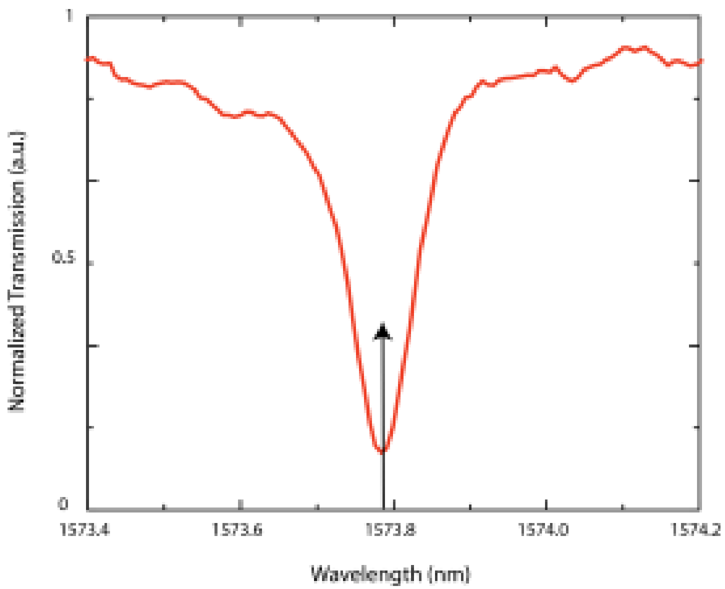
Athermal modulator



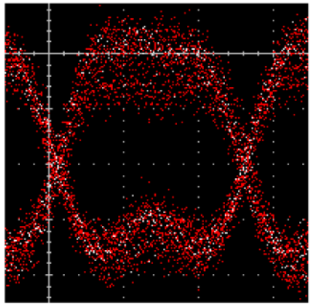
- Fix laser at resonance wavelength.
- Measure modulation characteristics as a function of temperature.

2 Gbps modulation

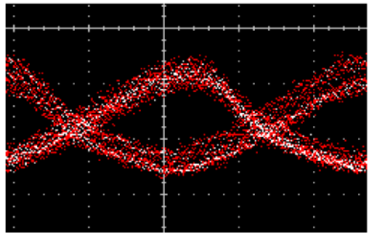
Set Laser at resonance



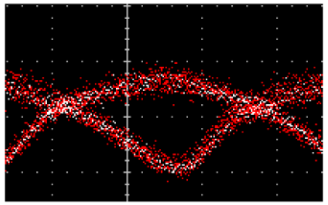
15 °C



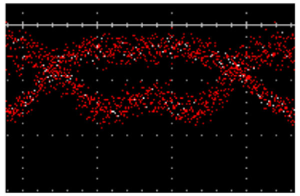
20 °C



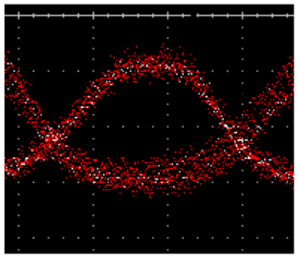
25 °C



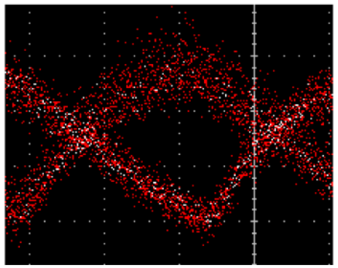
30 °C



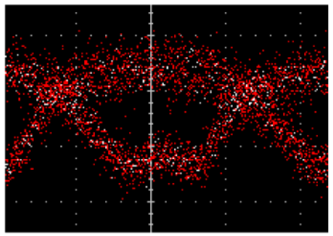
35 °C



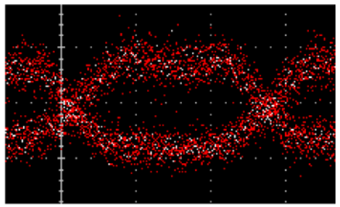
40 °C



45 °C



50 °C



Hands on

1. Calculate the approximate mode size of a taper designed to couple a waveguide with a fiber with effective index 1.505. The taper core index=3, cladding index=1.5. What is the effective angle of propagation in the taper?
2. Consider ~10^17/cm^3 carriers being injected in a 10Gb/sec ring resonator (when operated under 1V forward bias) with radius 30 micron and a cross of the modulator? what is the approximate power consumption of this modulator? How would you decrease this power? What would you then be trading off?