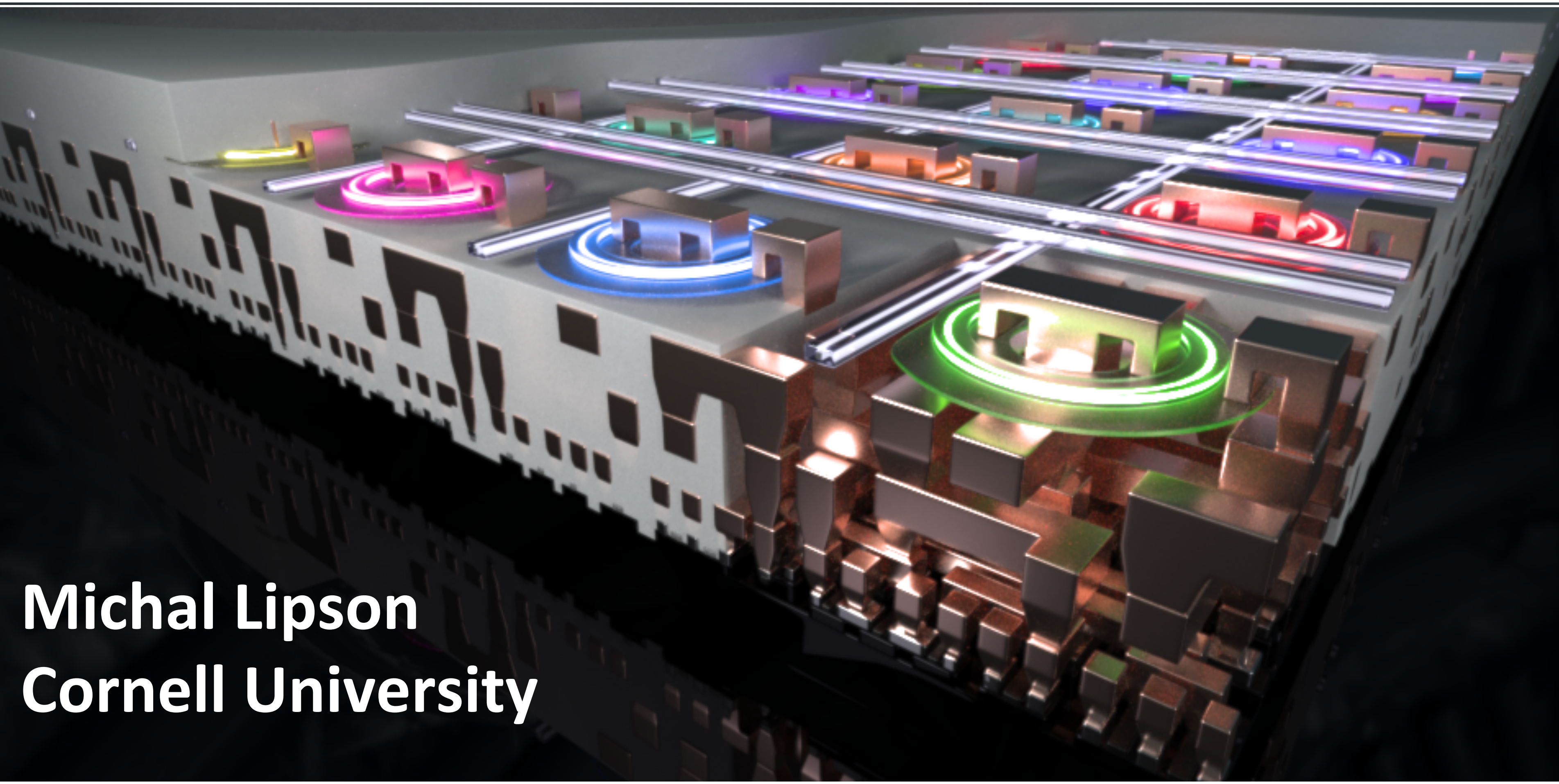
Silicon Photonics

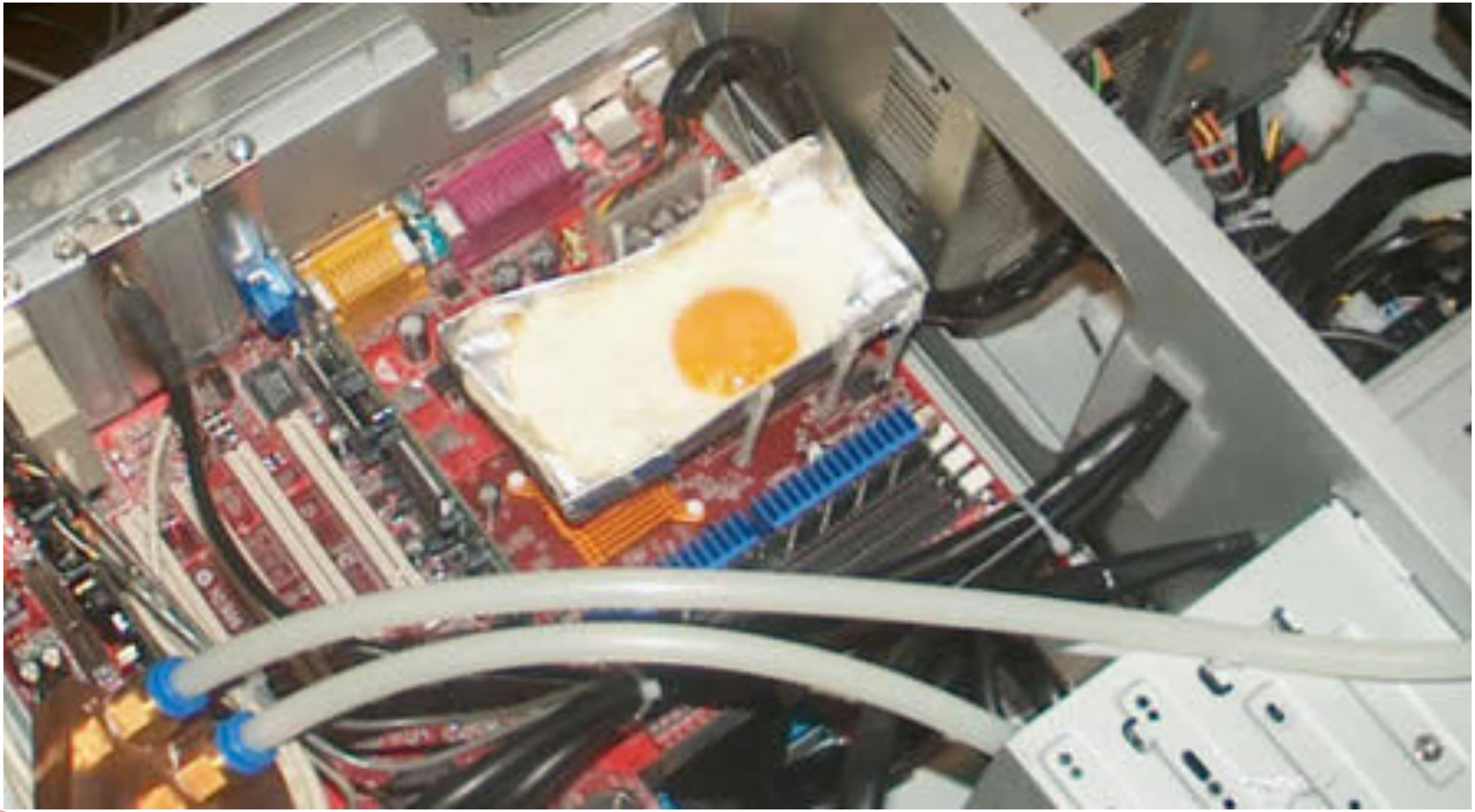


Michal Lipson
Cornell University

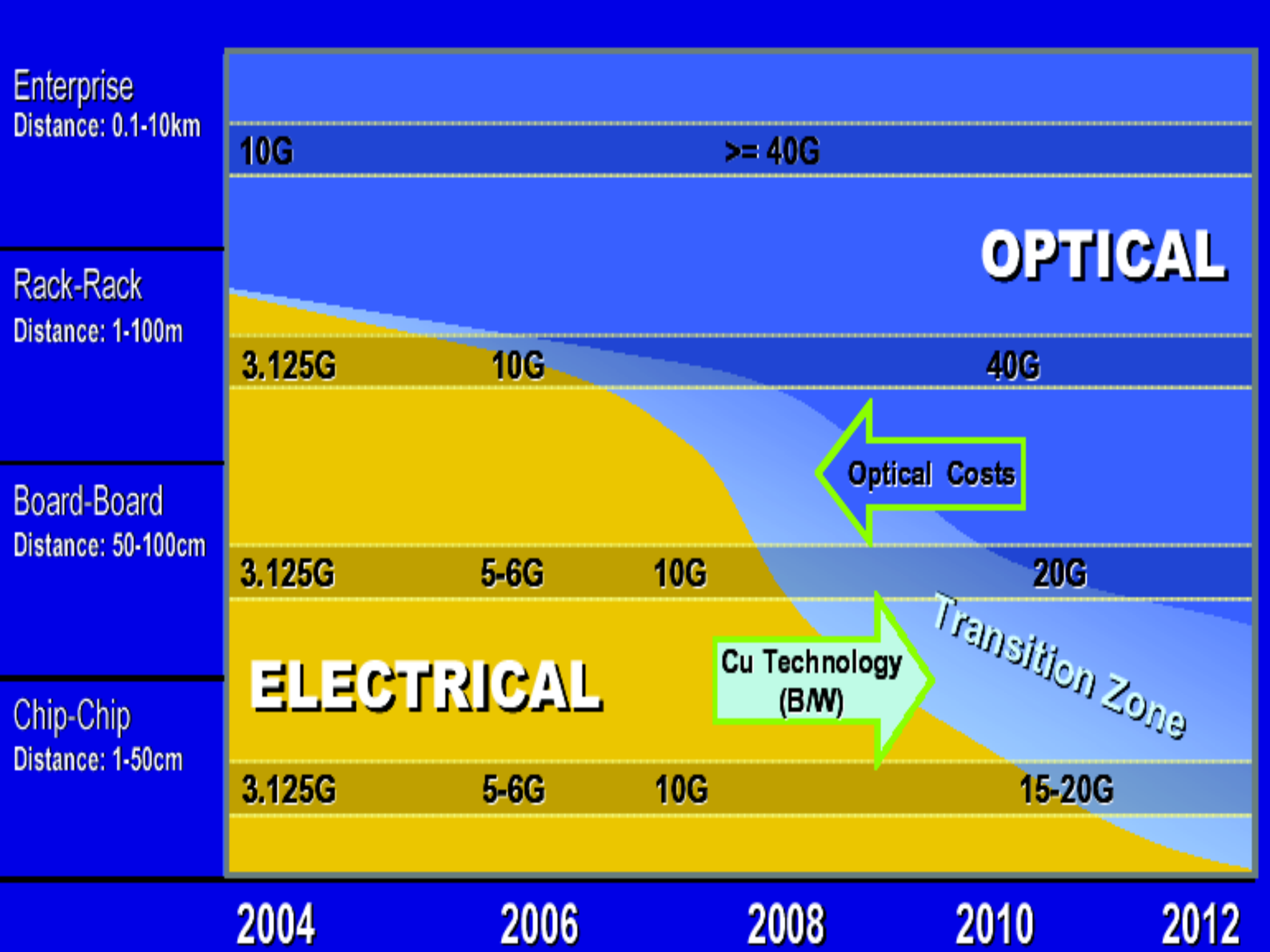
Picture by N. Sherwood

Cornell University

Photonics Could Alleviate Power Dissipation in Computers

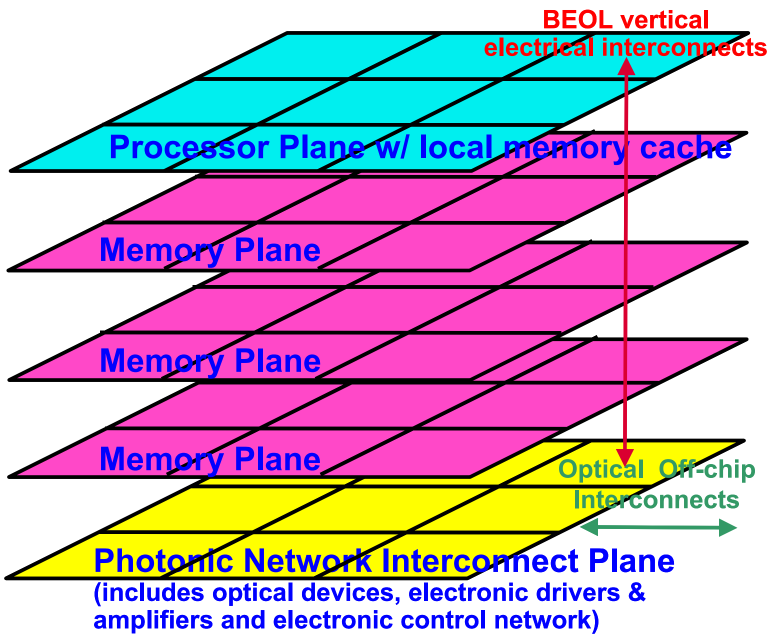


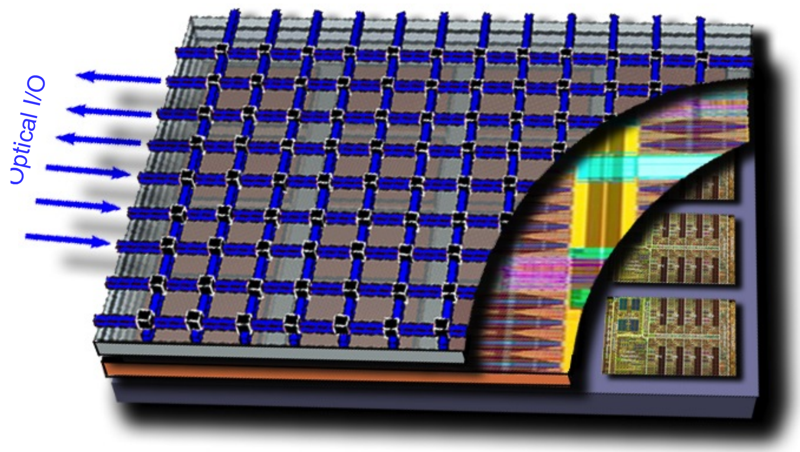
..and in Data Centers


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
ELECTRICAL
Cu Technology
(B/W)
3.125G
5-6G
10G
15-20G
2004
2006
2008
2010
2012

Silicon Photonics for Multi-Core Interconnect

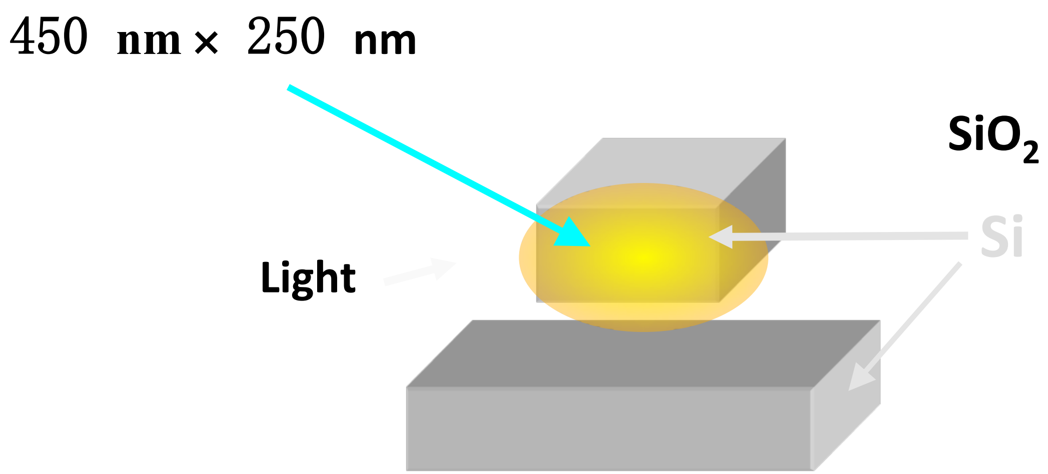
IBM





K. Bergman et al, Networks-on-Chip, pp. 53-64 (2007)

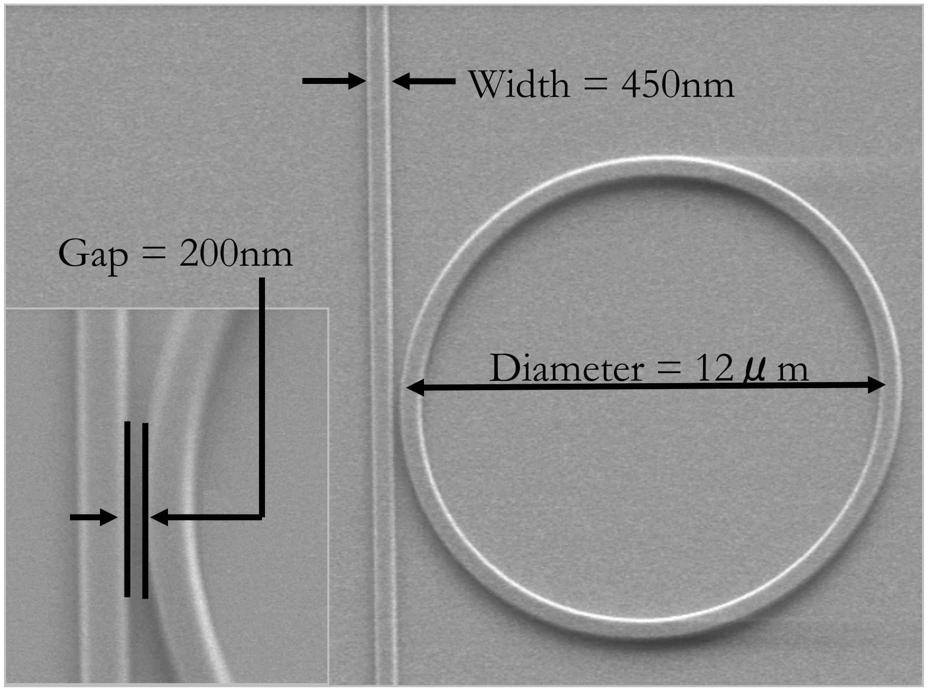
High Confinement Waveguides

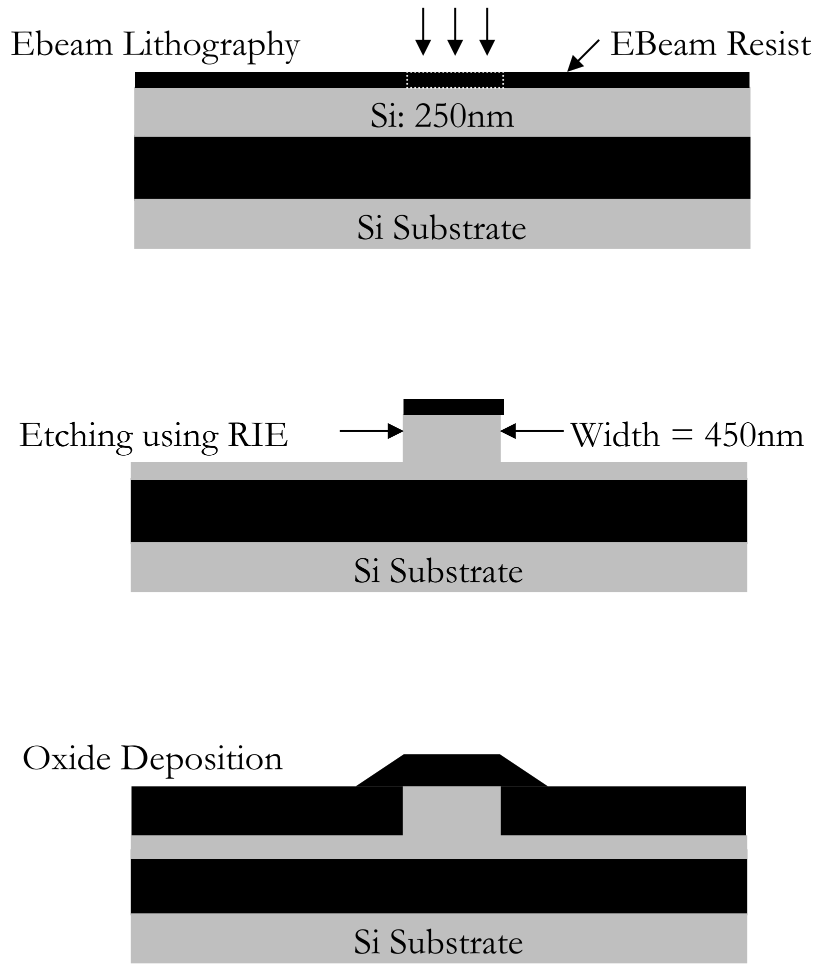


Intensity in the waveguides can be orders of magnitude higher than the intensity in the core of single mode optical fiber.

Fabrication

Scanning electron micrograph of a ring resonator

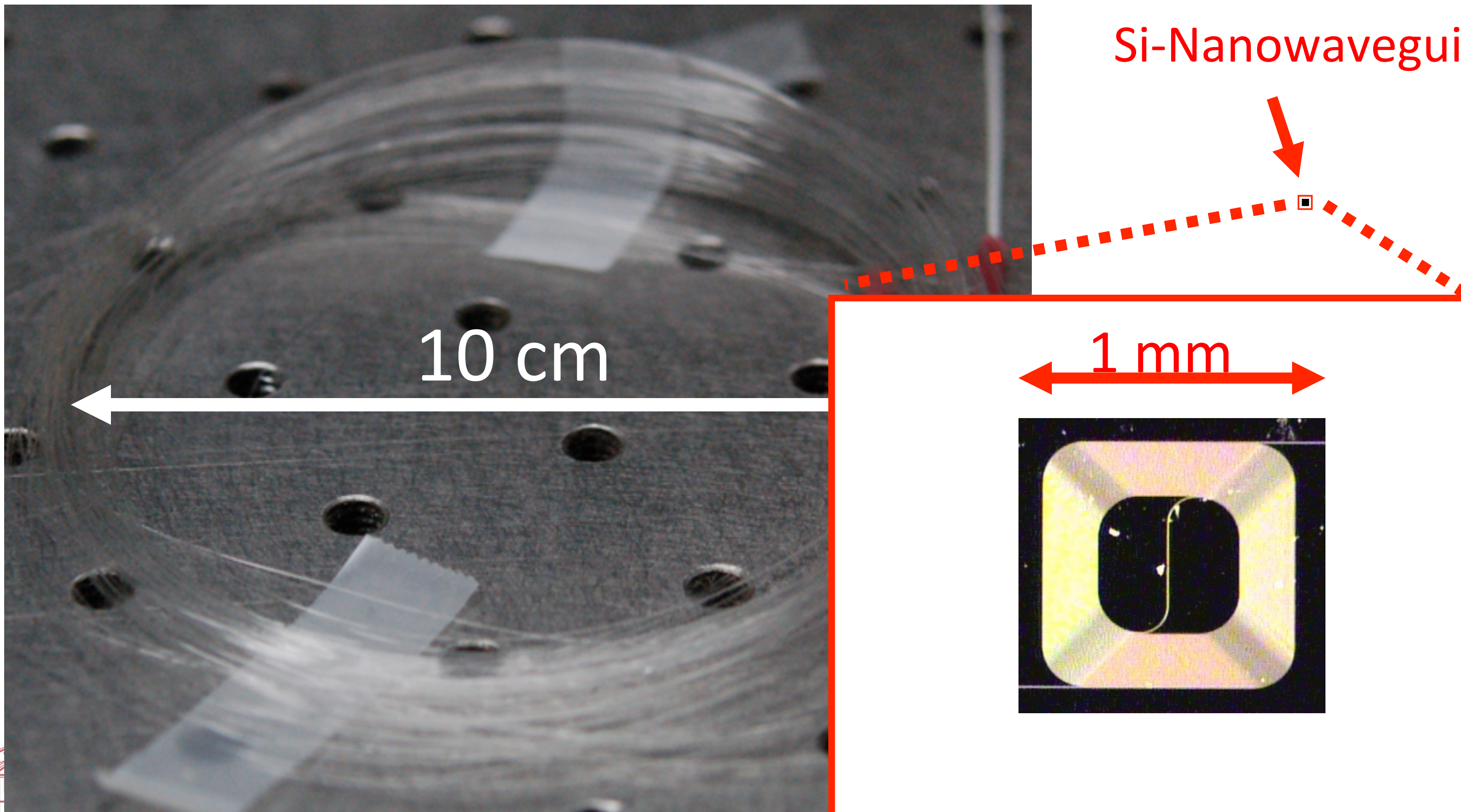




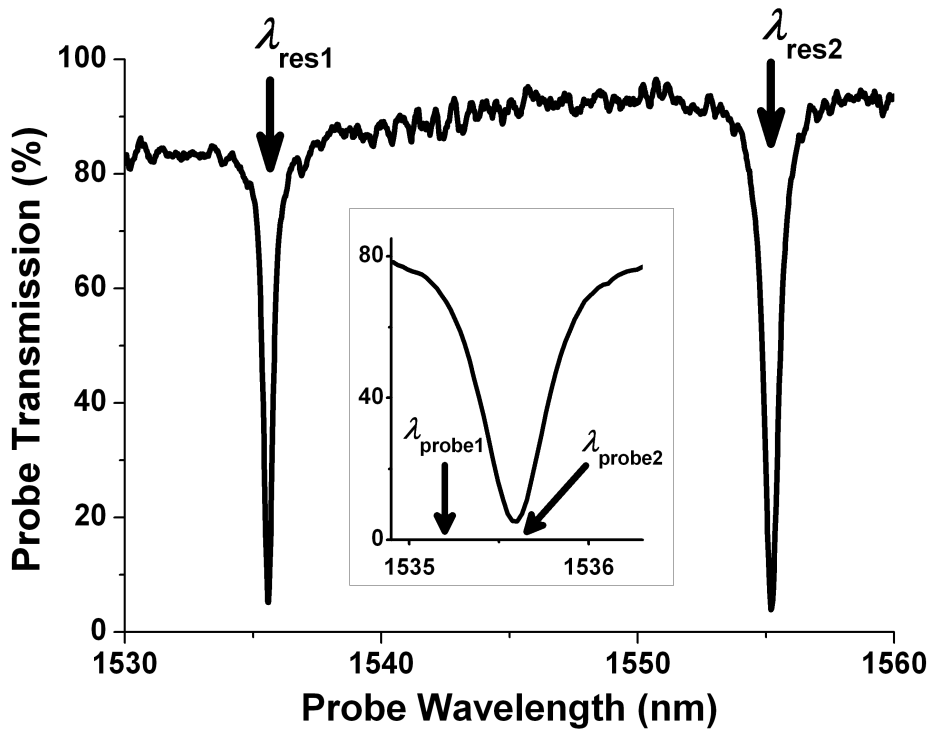
Physical Device Size

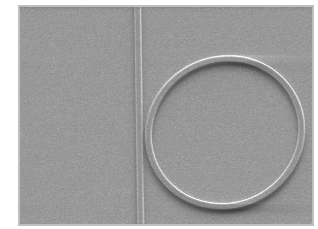
100-m highly nonlinear fiber

4-cm
Si-Nanowaveguide



Strong Light Confining Structures





,

Device is very sensitive to small perturbations in the Silicon

Cornell University

Prof. Michal Lipson

Ultra Low Loss Waveguides and Ring Resonators

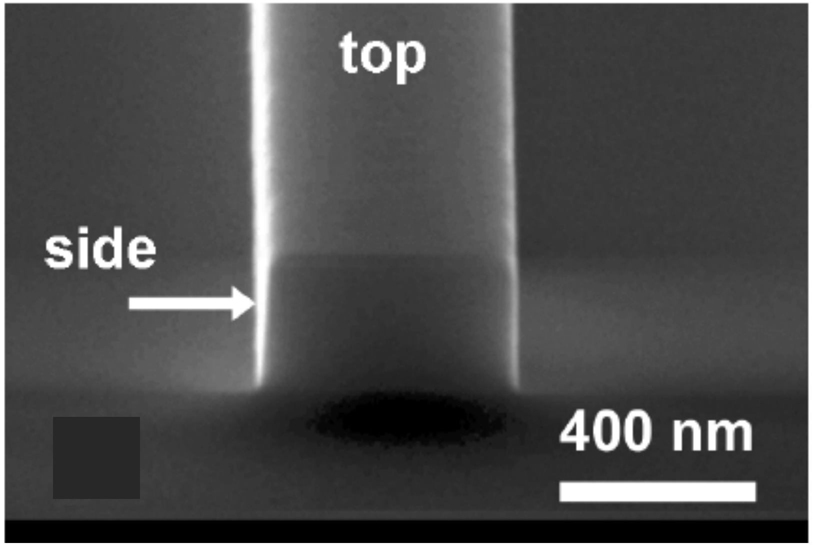
Losses

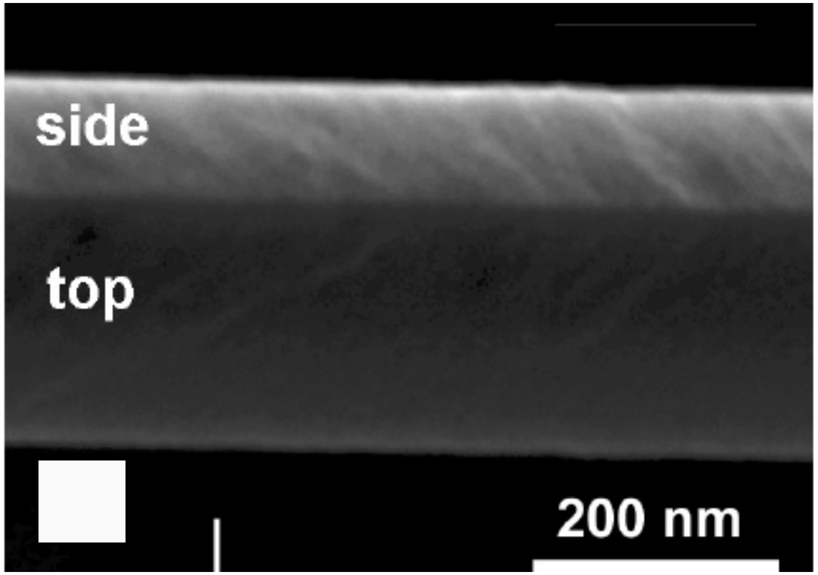
Dipole approximation:

Scattering~$\Delta n^4/\lambda^3$

Other Losses: Absorption, Interference based

Loss: Propagation and Bending





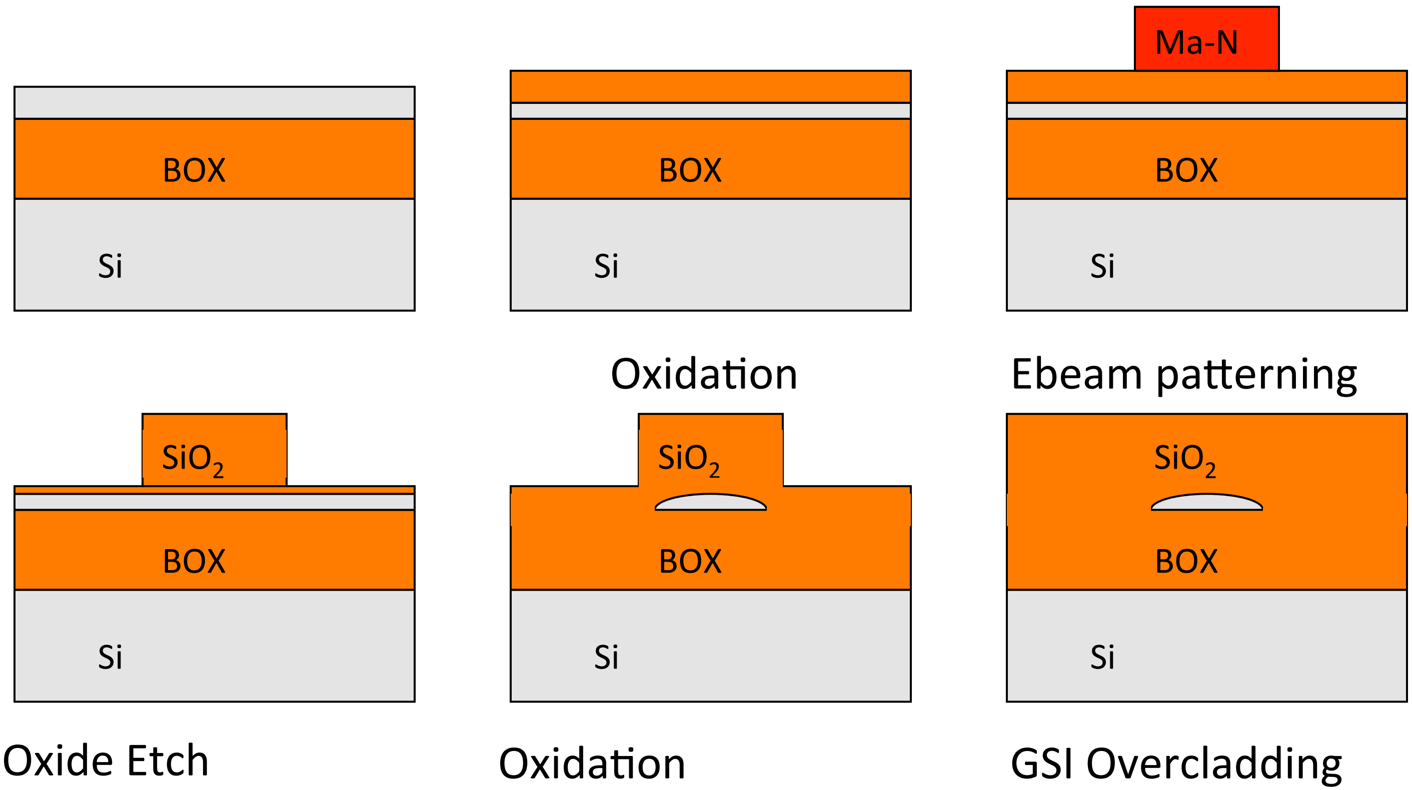
waveguide: 445 nm X 220 nm, wavelength 1500 nm, TE-like

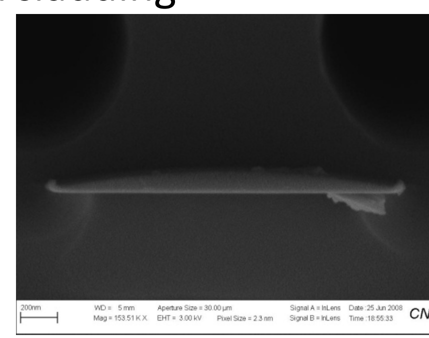
propagation loss: ~1-2dB/cm Vlasov (IBM)

Using oxidation methods: < 0.3 dB/cm!

Cardenas, Lipson, M. et al ,Optics Express, Vol. 17, 16 Mar 2009

Etchless Waveguides





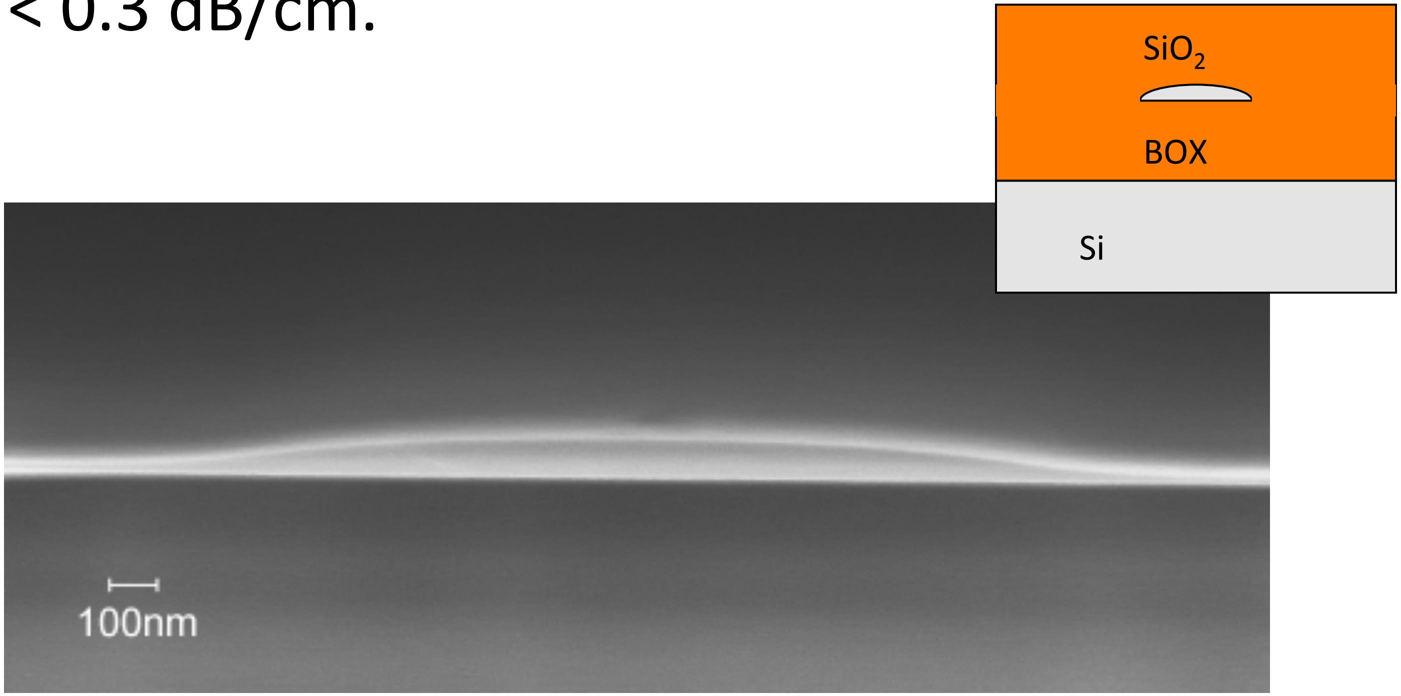
Cardenas, J., Poitras, C.B., Robinson, J.T., Preston, K., Chen, L. and Lipson, M., *Low loss etchless silicon photonic waveguides, Optics Express, Vol. 17, No. 6, 4752, 16 Mar. 2009.*

Cornell University

Etchless Waveguides

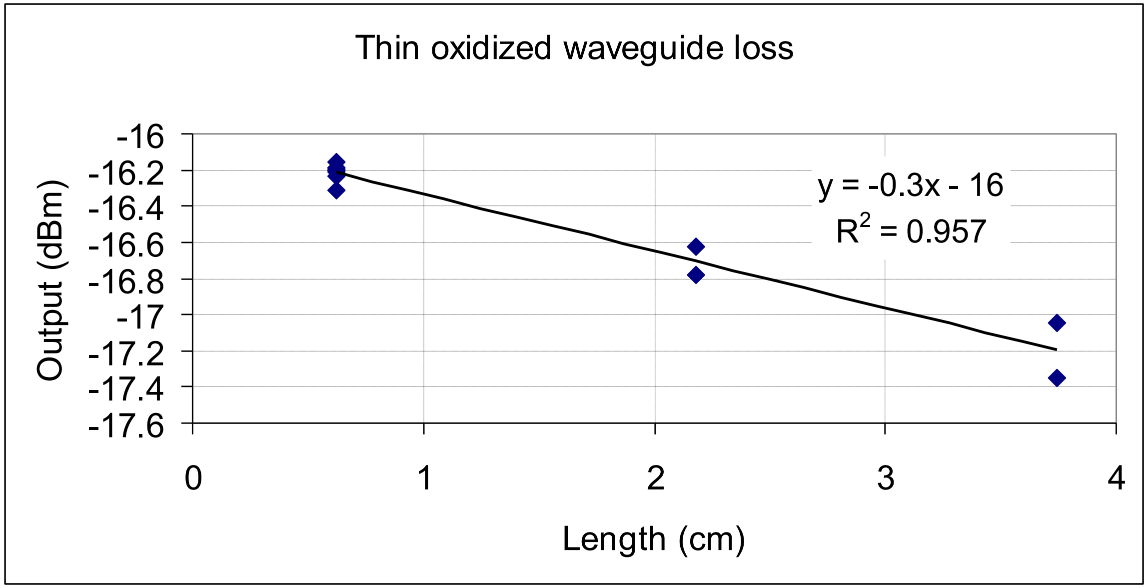
Waveguides dimensions: 315-nm high by 1-μm wide.

Losses < 0.3 dB/cm.

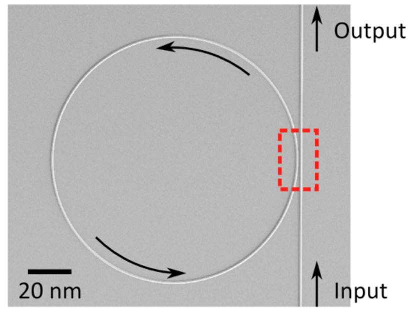


Results

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

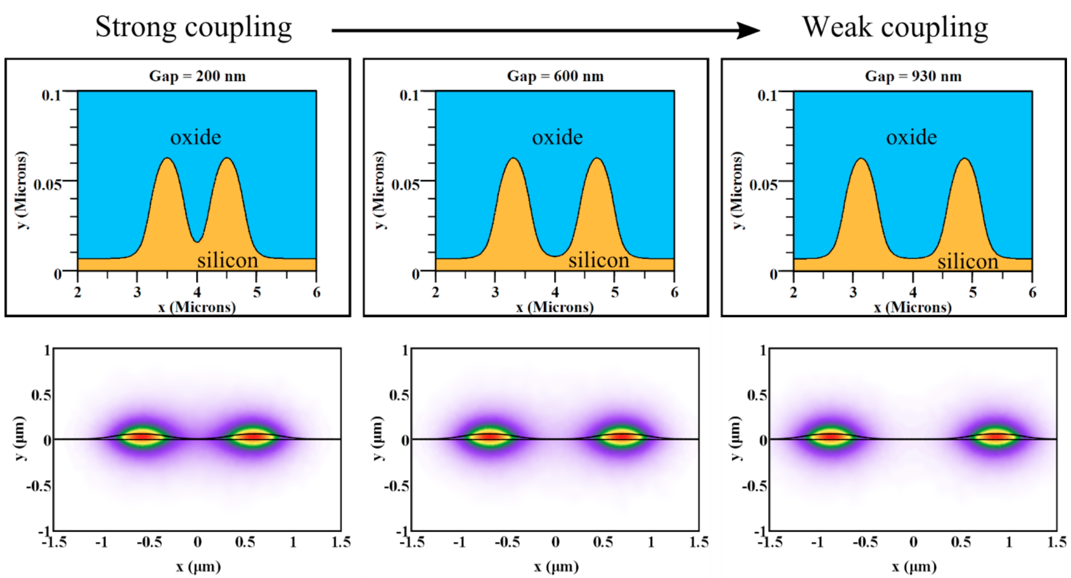


Etchless Cavities

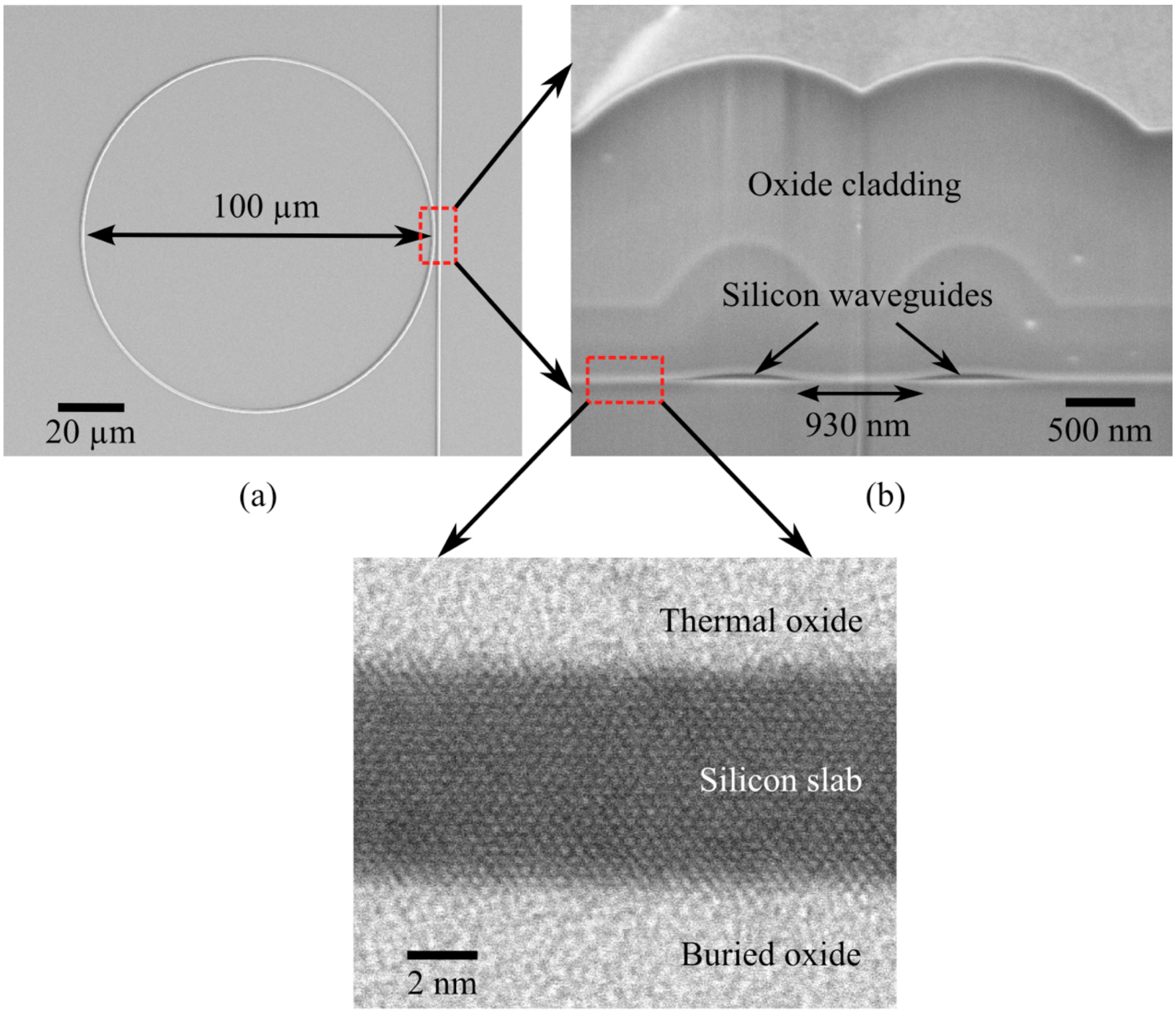


(a)

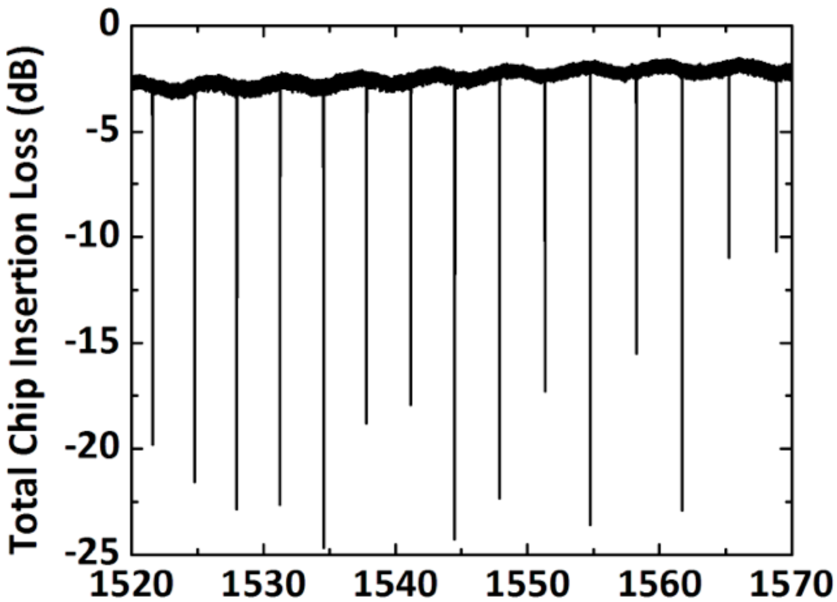
Lian-Wee Luo, Gustavo S. Wiederhecker, Jaime Cardenas,and Michal Lipson, High quality factor etchless silicon photonic ring resonators, Optics Express, 2011 (submitted)

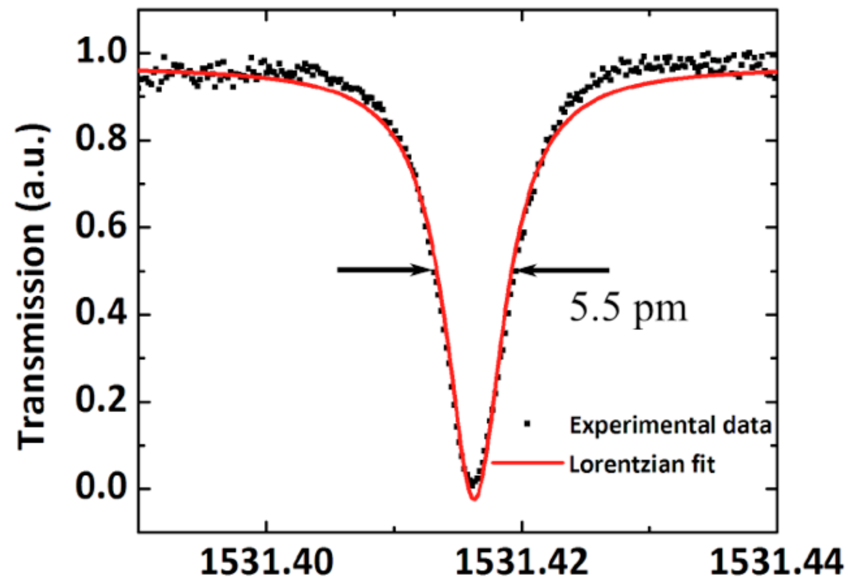


(b)


100 μm
20 μm
Oxide cladding
Silicon waveguides
930 nm
500 nm
Thermal oxide
Silicon slab
Buried oxide
2 nm

(a) (b) (c)





Q~1M

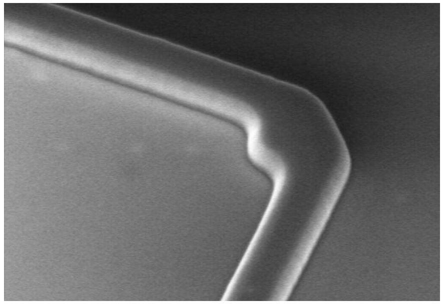
Lian-Wee Luo, Gustavo S. Wiederhecker, Jaime Cardenas,and Michal Lipson, High quality factor etchless silicon photonic ring resonators, Optics Express, 2011

Electro-Optics Modulation

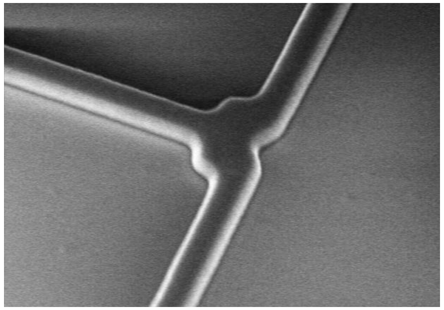
The Microelectronics Platform for Optics On Chip

Passive Devices

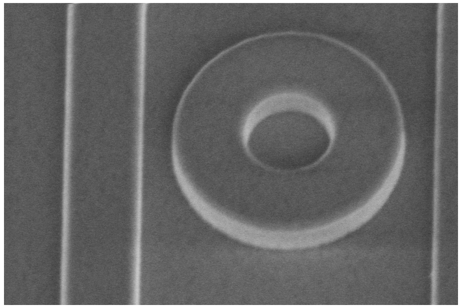
Bends



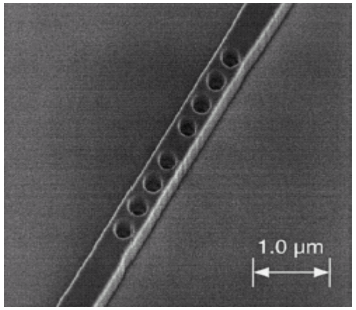
Splitters



Filters



Cavities



Massachusetts Institute of Technology , 2000

Cornell
Nanophotonics Group 2003

J. S. Foresi et al.
Nature 390, 143 (1997)

Need for active devices!
Modulators, Amplifiers

Switching Light on Silicon Using Free-Carriers

Mechanism: Plasma Dispersion Effect (linear process)

Refractive index change by free carrier injection

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8\times 10^{-22}\cdot \Delta N + 8.5\times 10^{-18}\cdot (\Delta P)^{0.8}]$$

Challenge:

Weak index dependence on free carrier concentration

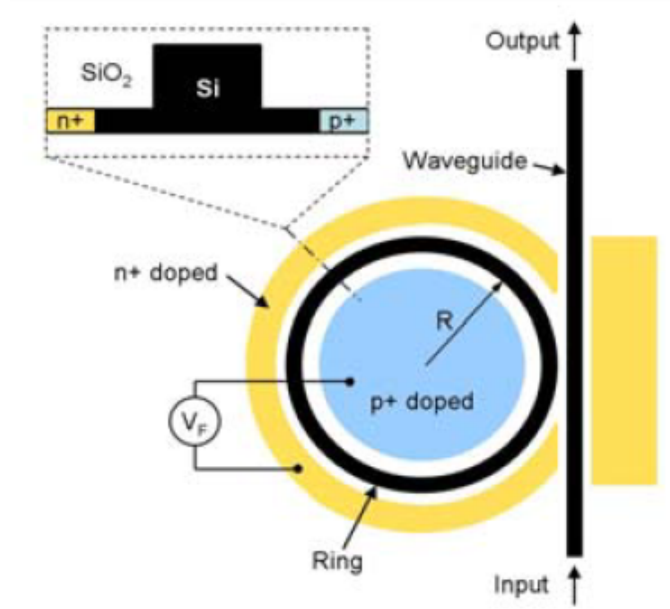
R.A. Soref, et al , *IEEE Journal of Quantum Electronics*, vol. 23, (1987)

Forward PIN

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

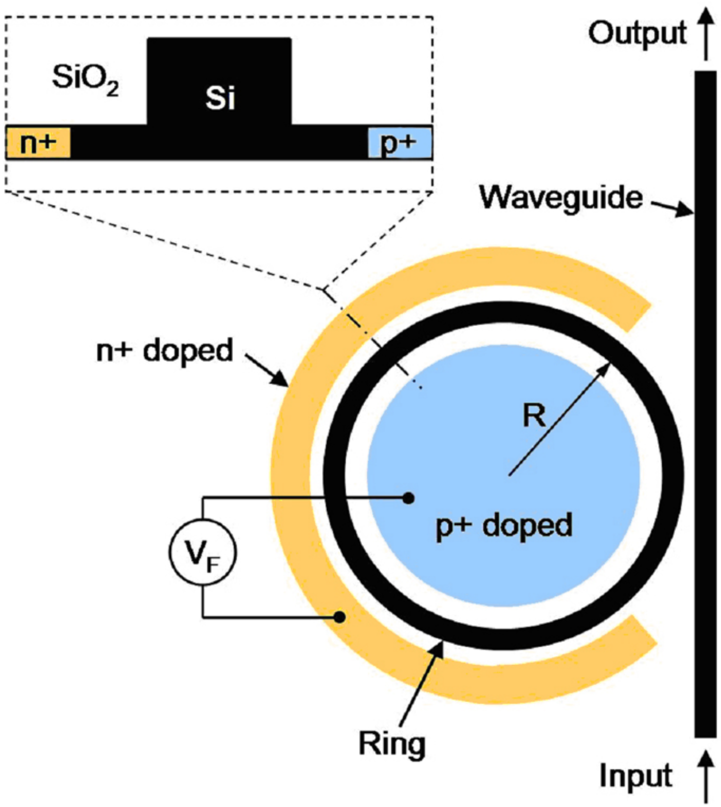
Can achieve very high index change per applied voltage due to exponential I-V characteristic of a diode.

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)

Ring Resonator Based Electro-optic Modulator On Silicon-On-Insulator- Microns In Size

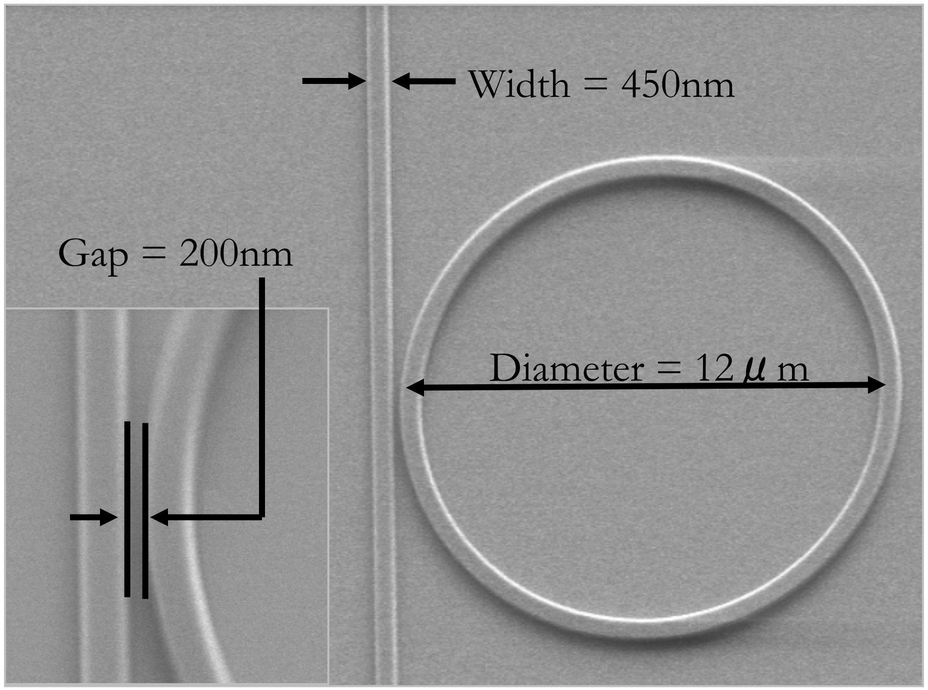


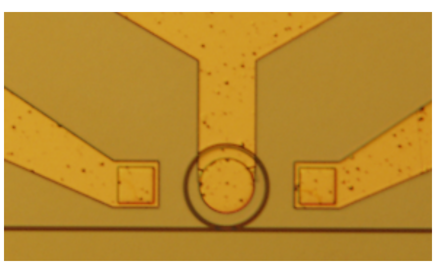
Liu, A. et al. Nature 427, 615 (2004)

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

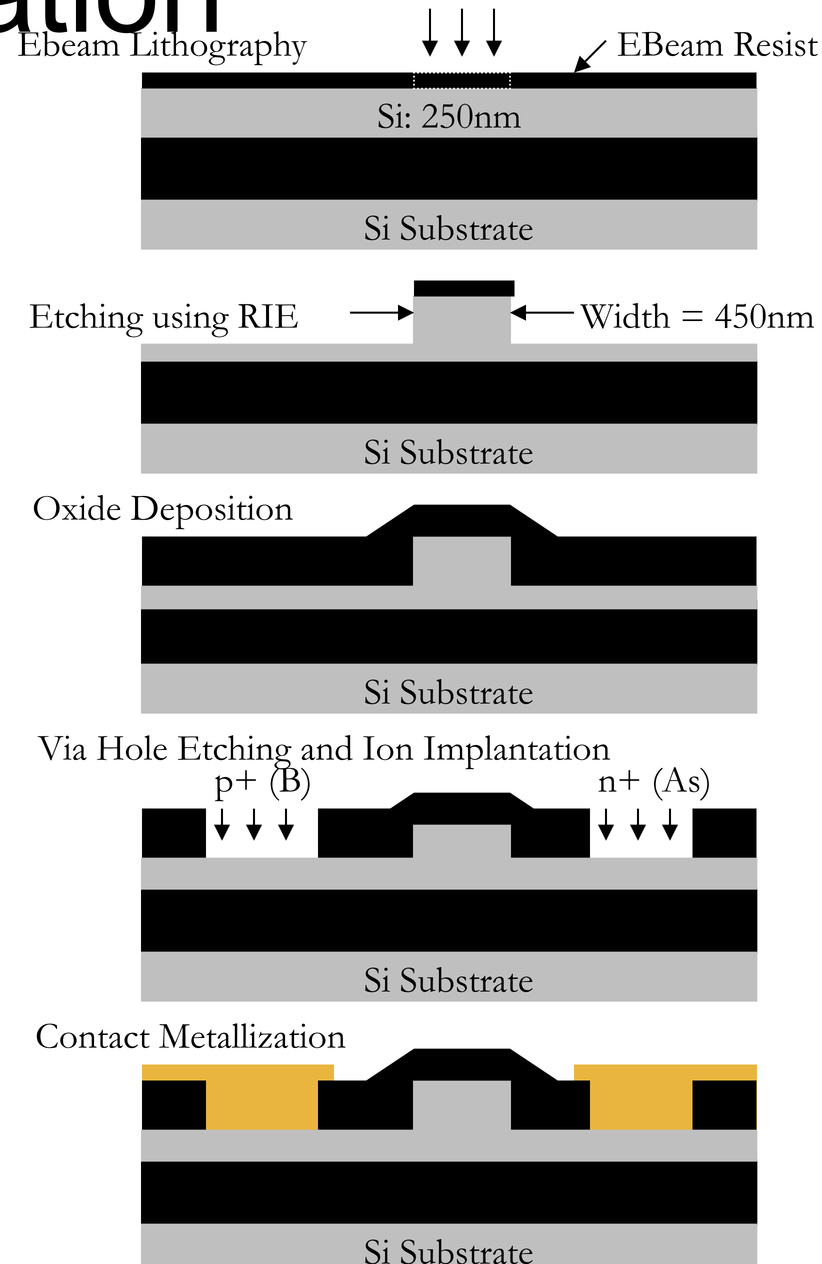
Fabrication

Scanning electron micrograph of a ring resonator

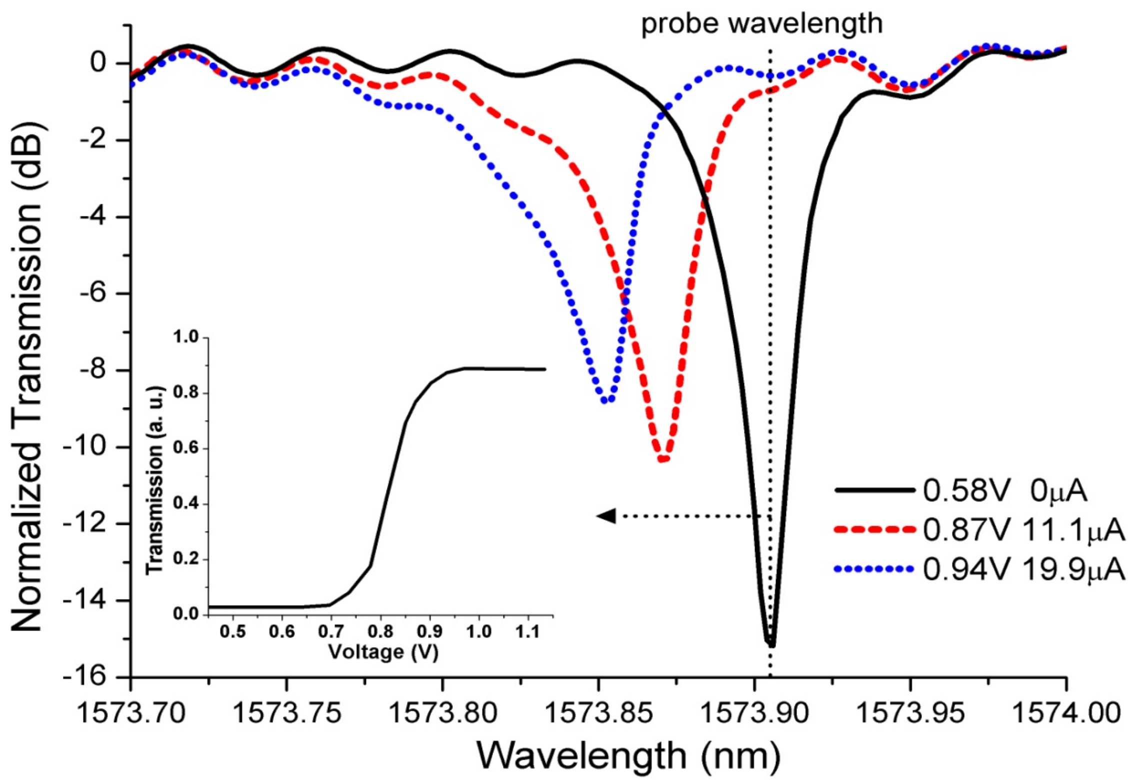




Microscope image of fabricated optical modulator with electrical contacts

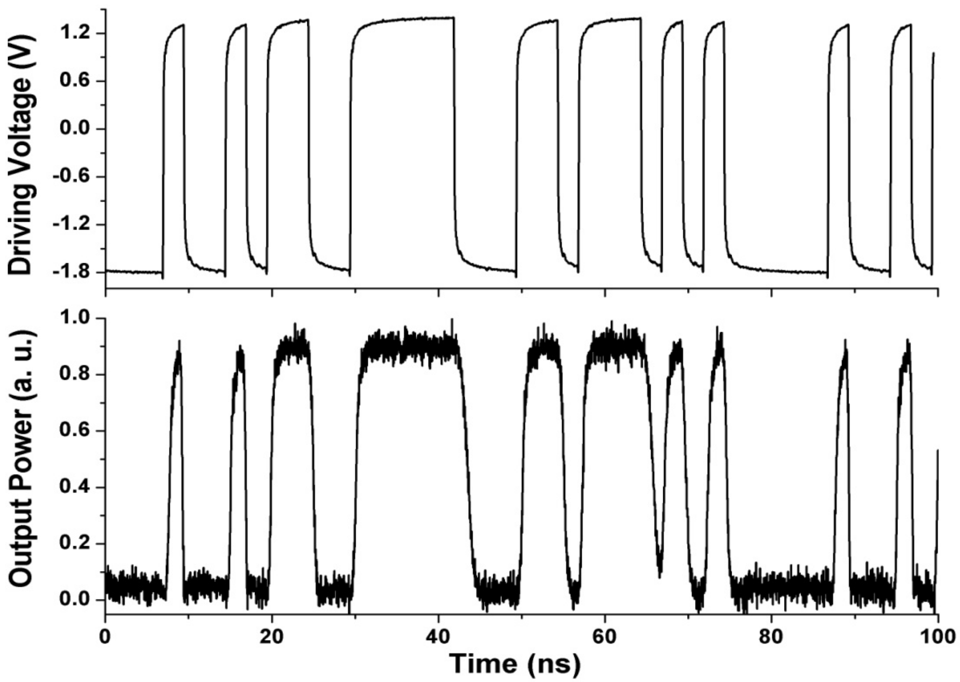


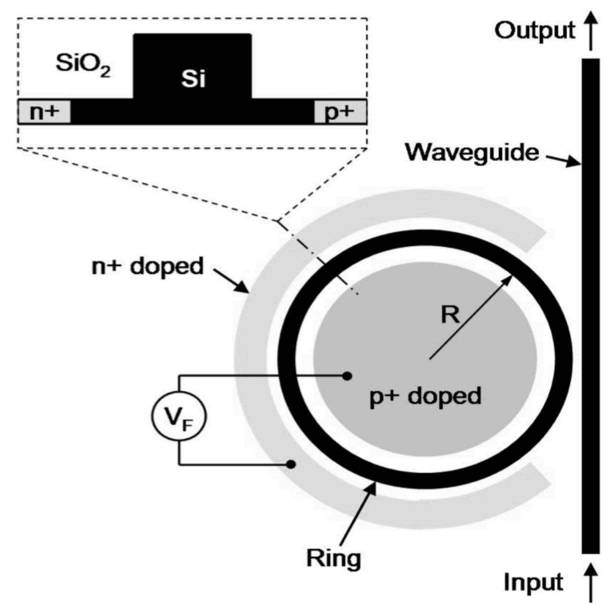
Modulation Results (DC)



Dynamic Response

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

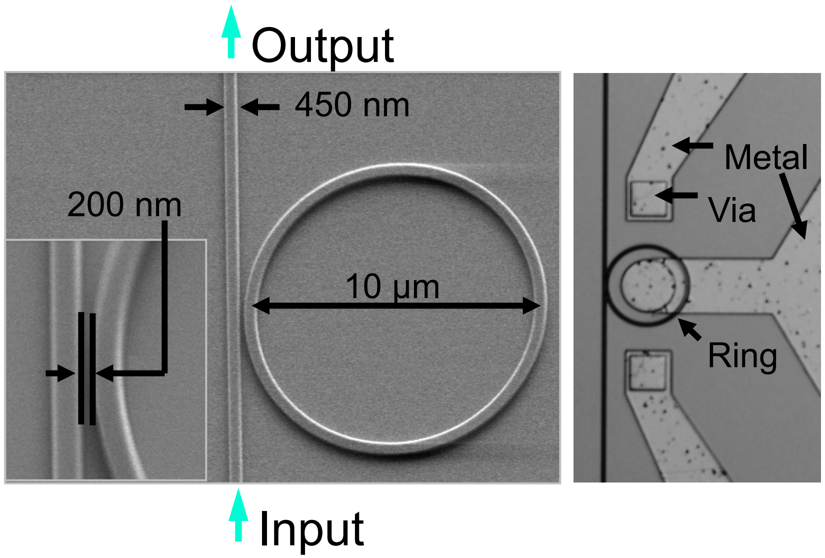




Lifetime under junction: 0.2nsec

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

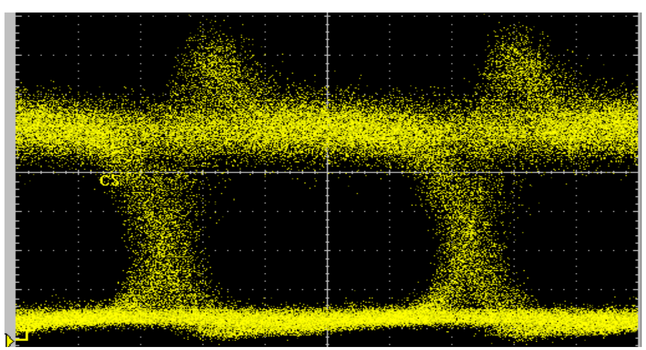
Microring Modulator : Experiments

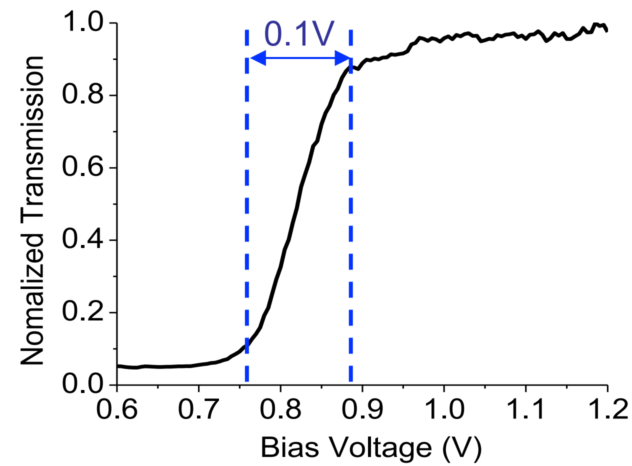


Gate-like transfer function.

Gb/s modulation with over-drive.

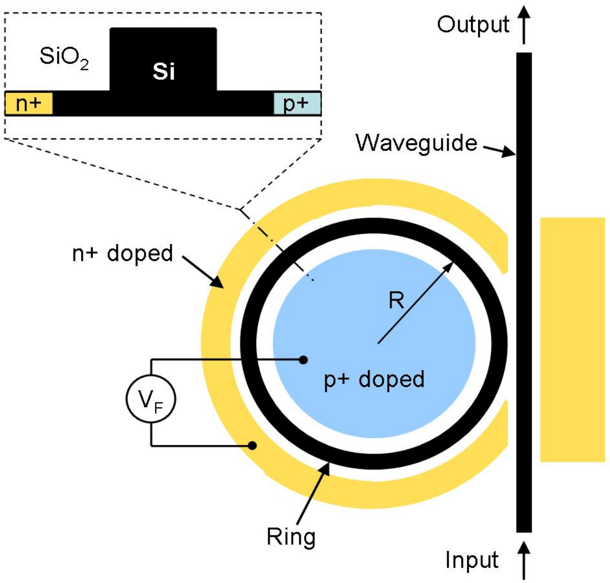
4 Gbit/s NRZ

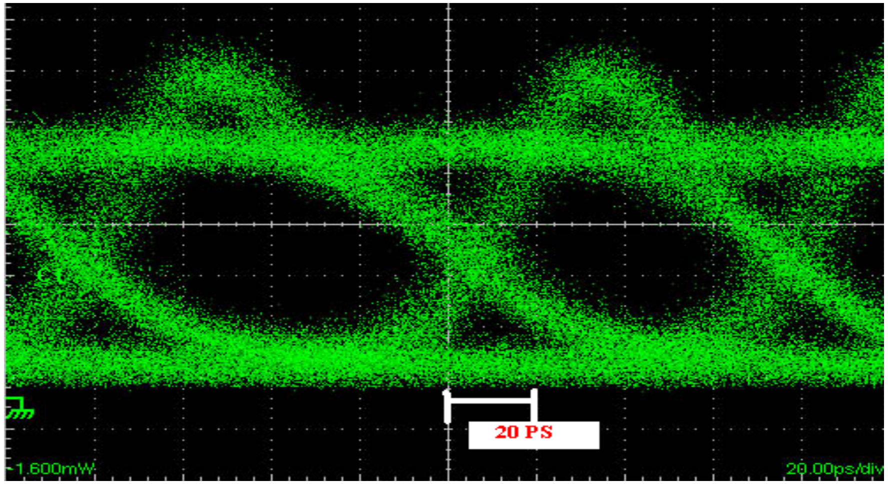


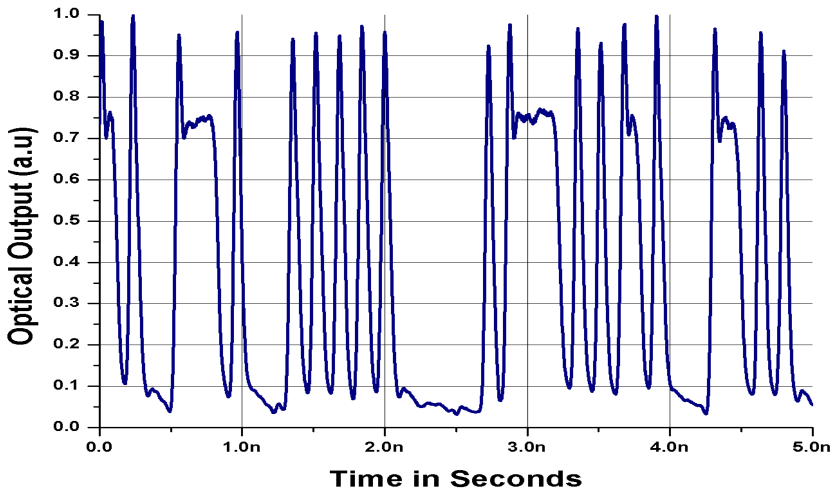


Q. Xu, B. Schmidt, S. Pradhan, & M. Lipson, *Nature* 435, 325 (2005)

Micrometer Scale Silicon Electrooptic Modulator At 20 Gbps







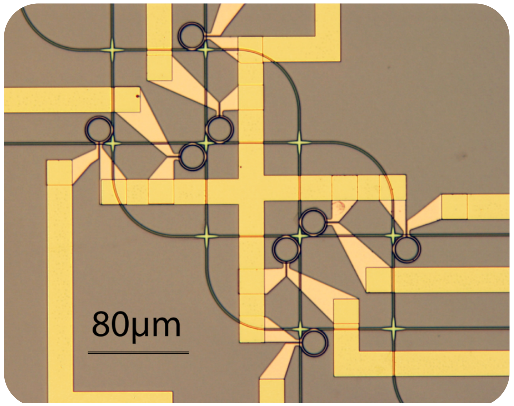
PRBS 2^{10}-1

>9dB modulation depth!

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

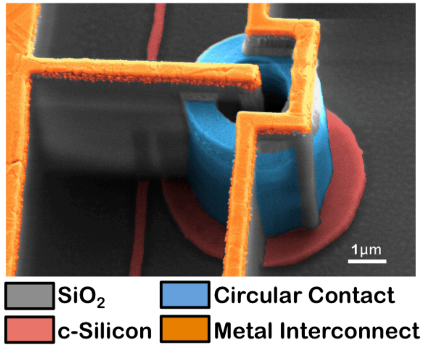
Ultrafast Devices and Networks based on Silicon Modulators

Optical 4x4 Hitless Silicon Router for Optical Networks-on-chip



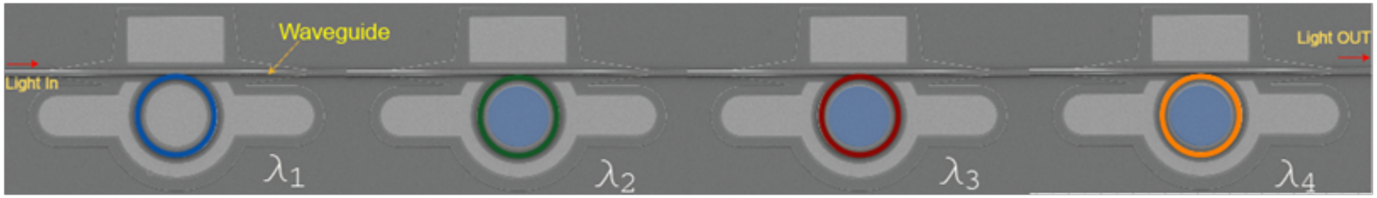
N. Sherwood-Droz, K. Bergman, and M. Lipson, Opt. Express,. 16, pp. 15915, 2008.

Ultrafast low Power Modulators



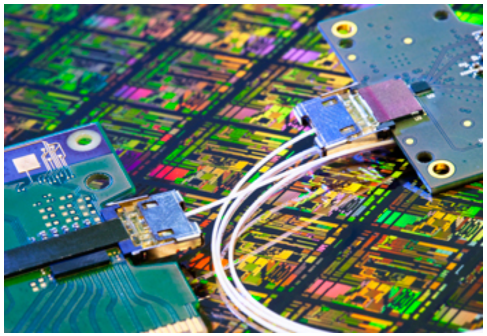
25GHz w M. Watt et al, http://arxiv.org/abs/1312.2683

40-Gb/s DPSK Data Transmission Through a Silicon Microring Switch

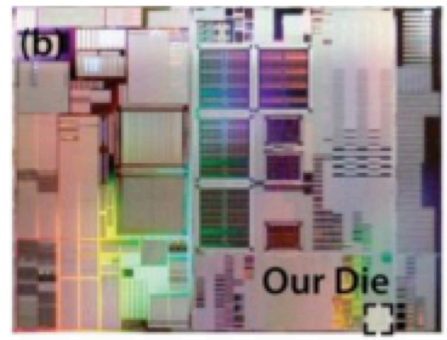


Xu, L.., Lipson, M. and Bergman, K., IEEE Phot. Tech. Lett., 24, 2012.

Silicon Photonics in Industry

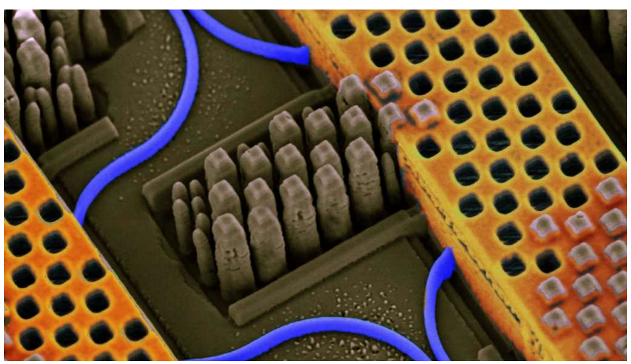


Intel



Texas Instruments

F. Kärtner, H. Smith, V. Stojanović, R. Ram et al, Opt. Express 19, 2335 (2011)



IBM

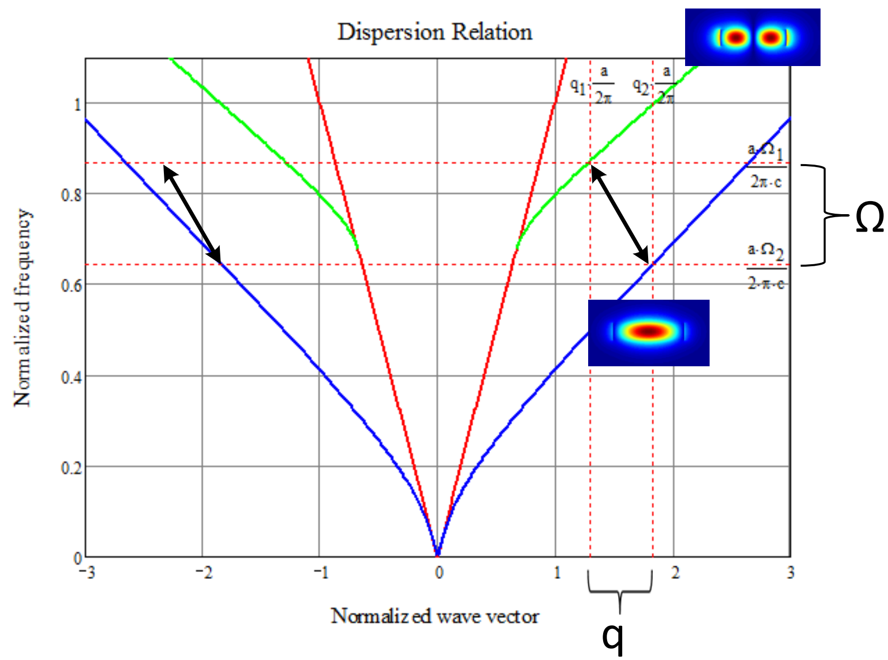
Mellanox, Infinera, Luxtera..

Breaking the reciprocity of Light

Indirect Photonic Transition for Optical Isolation

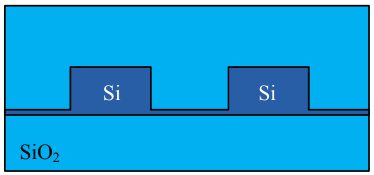
w/ S. Fan (Stanford)

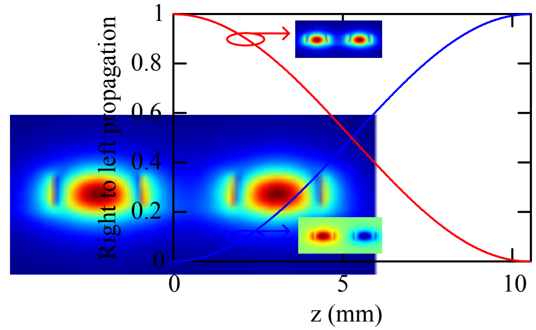
$$\varepsilon'(x,z,t) = \delta(x)\cos(\Omega t - (-q)z)$$

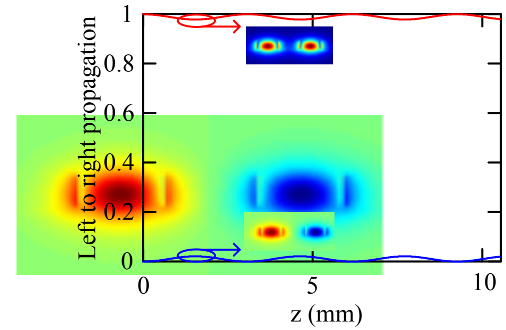


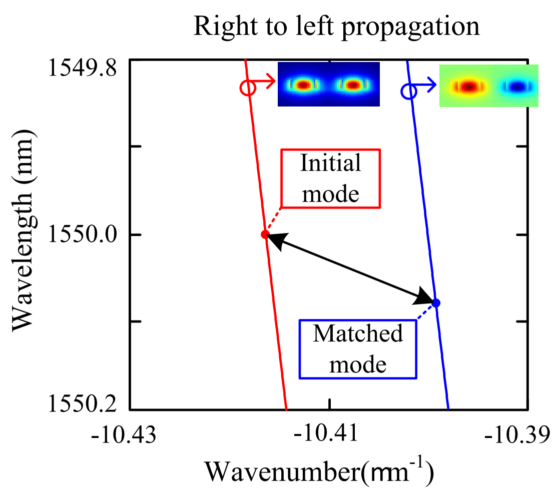
Fan, S., et al., Nat. Photon., **3** (2009)

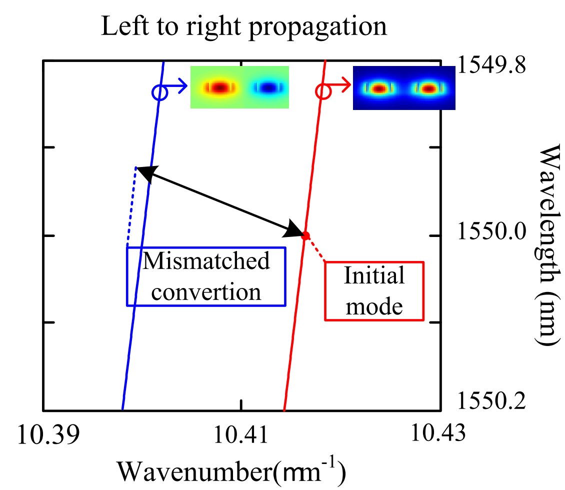
Principle of Operation and Simulation







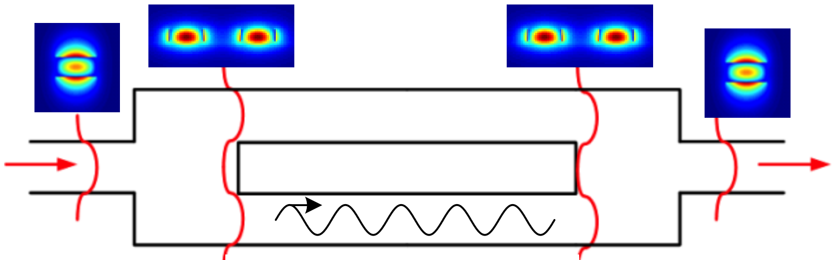




Modulation: f_{mod}=10 GHz **Wavelength required: λ_{mod} =450µm**

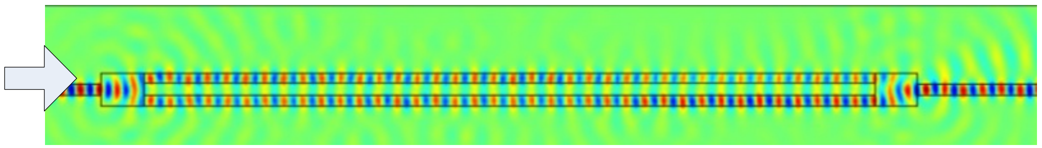
Principle of Operation and Simulation

- Left to right propagation:

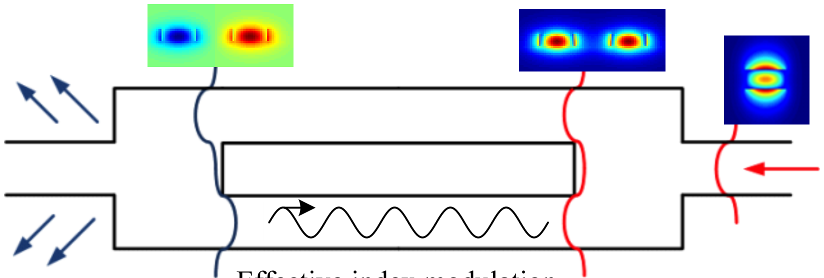


- Simulation:

Left to right: mode is kept

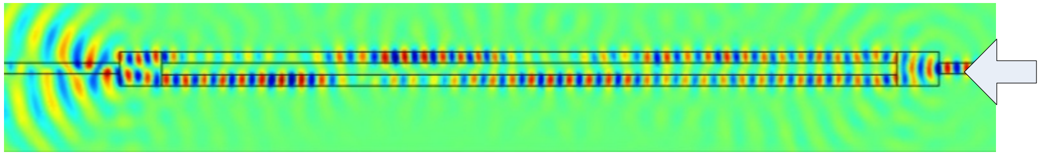


- Right to left propagation:



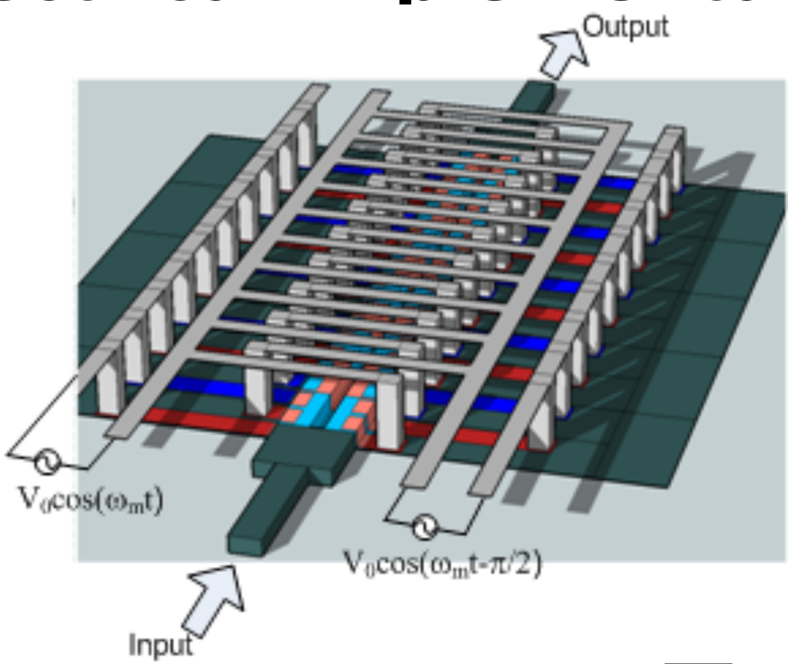
- Simulation:

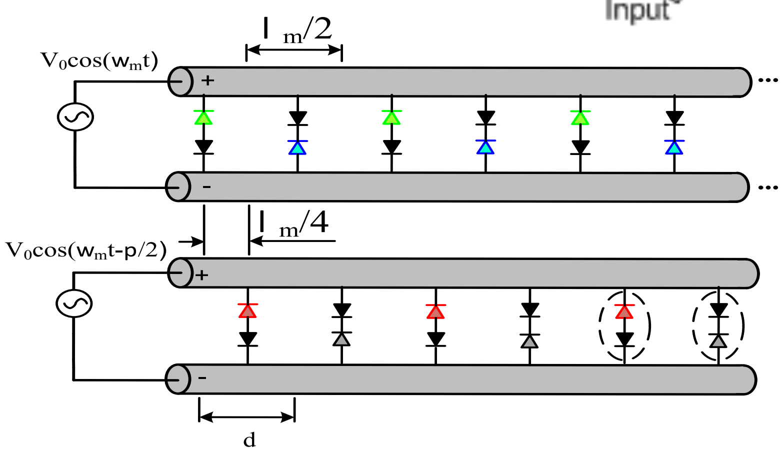
Right to left: mode is converted and scatterd

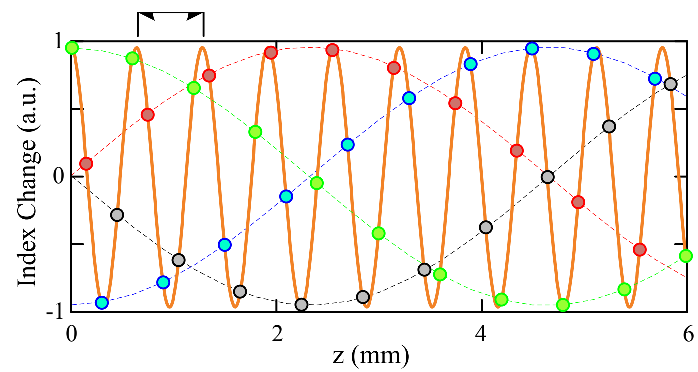


Lira, H.,Lipson M. et al., Phys. Rev. Lett., Vol. 109, No. 3, 033901, 16 July 2012.

Electrical Implementation



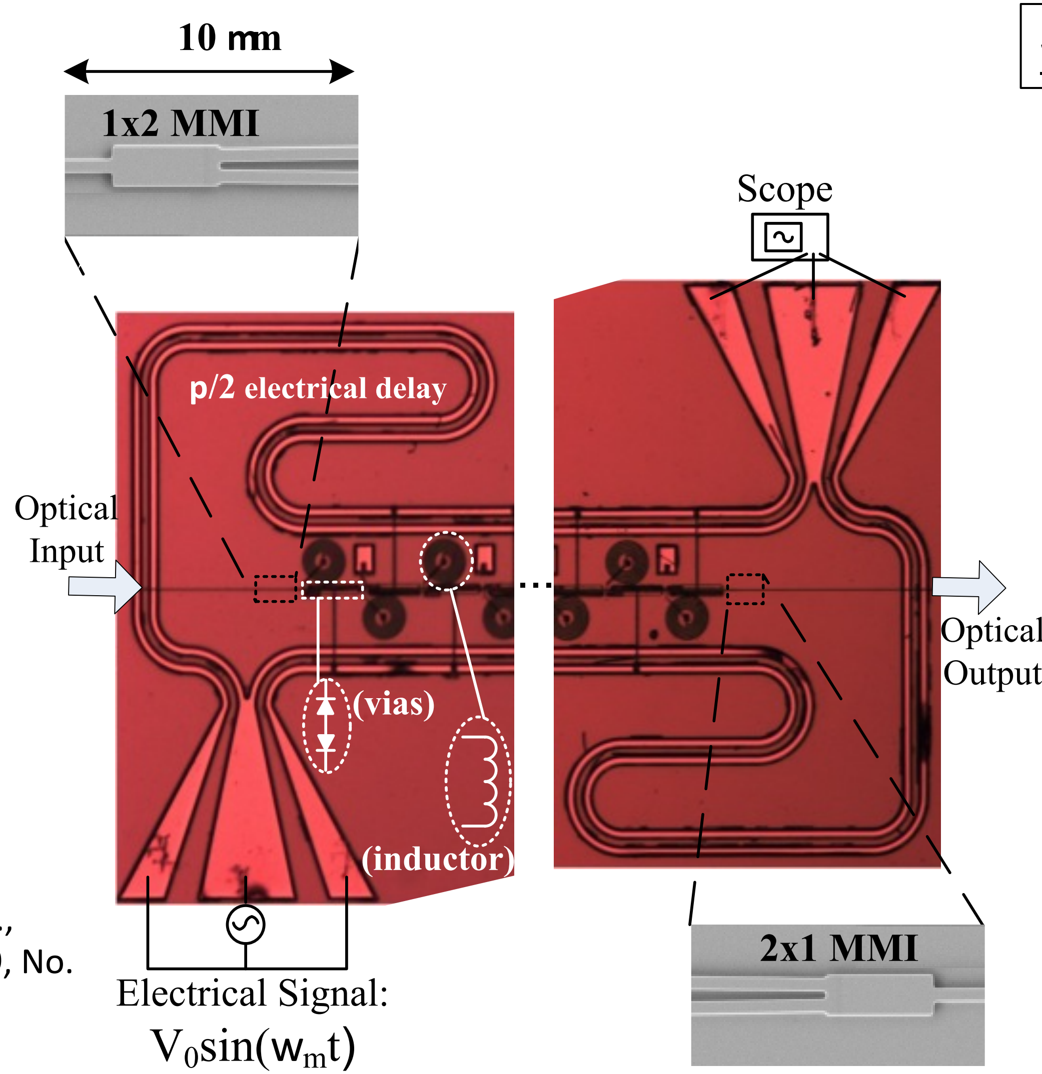




Lira, H., Lipson M. et al., Phys. Rev. Lett., Vol. 109, No. 3, 033901, 16 July 2012.

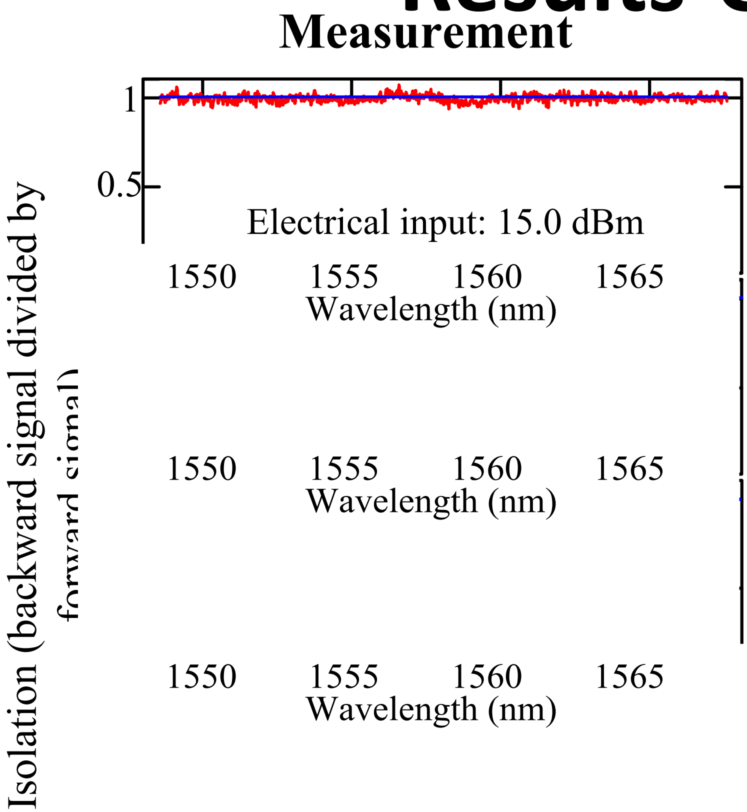
Isolator

w/ S. Fan (Stanford)

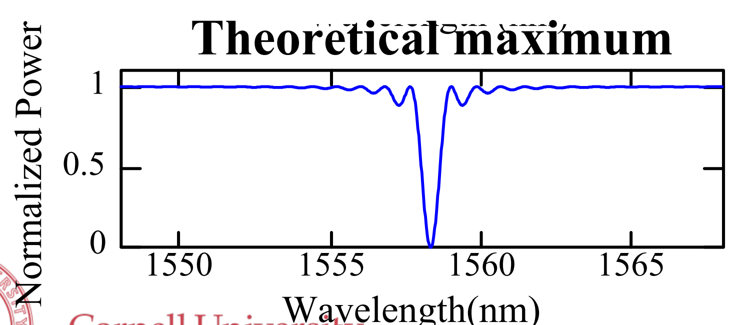


Lira, H., , Lipson M. et al., Phys. Rev. Lett., Vol. 109, No. 3, 033901, 16 July 2012.

Results-Optical Isolation



3 dB isolation achieved with 25 dBm of electrical power

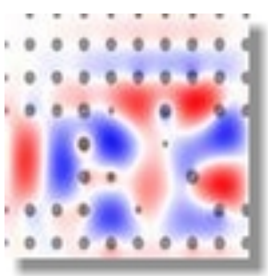


Lira, H, Lipson M. ., et al., Phys. Rev. Lett., Vol. 109, No. 3, 033901, 16 July 2012.

Multimode Photonics

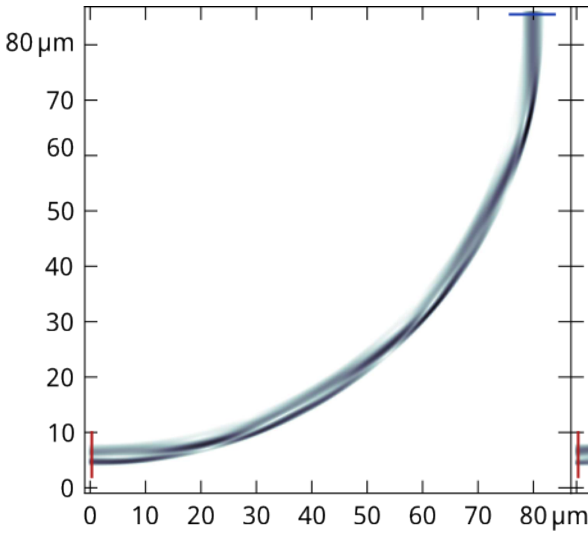
Multimode Photonics

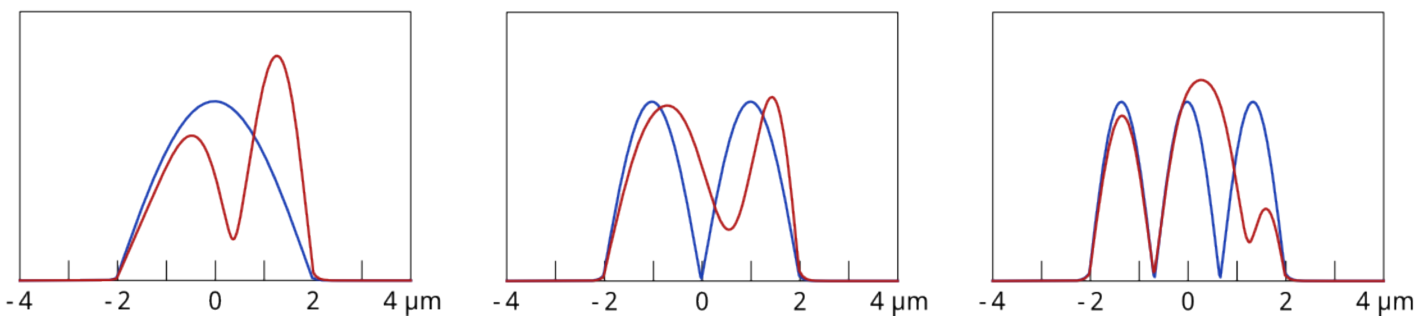
J. M. Kahn and K.-P. Ho, "Mode-Division Multiplexing Systems: Propagation Effects, Performance and Complexity", to be presented at Optical Fiber Commun. Conf., Anaheim, CA, March 17-21, 2013 (*Invited Tutorial*).



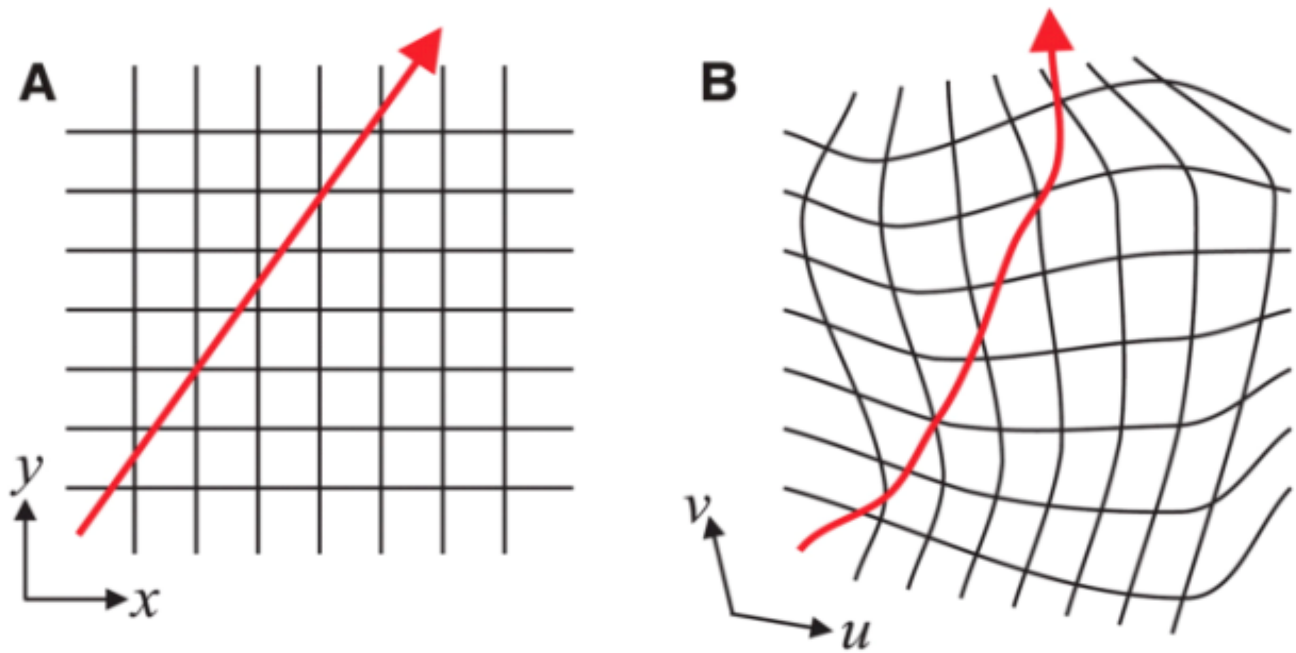
Victor Liu, David A. B. Miller, and Shanhui F, Ultra-compact photonic crystal waveguide spatial mode converter and its connection to the optical diode effect, Optics Express, Vol. 20, Issue 27, pp. 28388-28397 (2012)

Inter-Mode Coupling



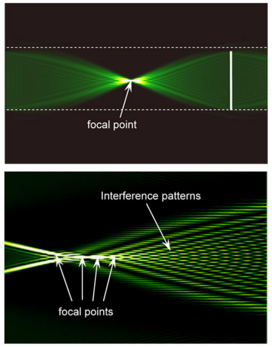


Transformation optics

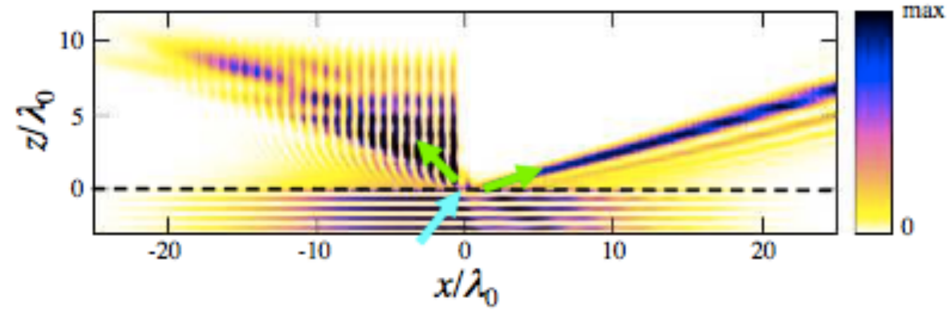


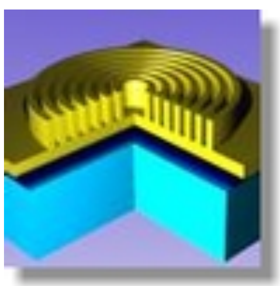
J.B. Pendry, D. Schurig, and D. R. Smith, Science 312, (2006)
U. Leonhardt, Science 312 (2006)

Transformation Optics



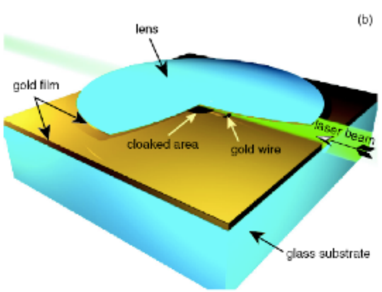
Y. Yang, L. K. Chin, J. M. Tsai, D. P. Tsai, N. I. Zheludev, and A. Q. Li, Transformation optofluidics for large-angle light bending and tuning, Lab Chip 12, 3785 (2012)



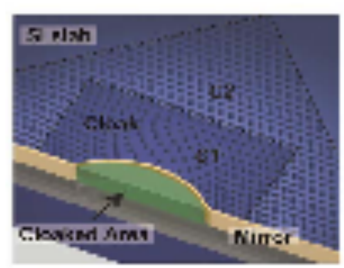


M. J. Grajower, G. Lerman, I. Goykhmann, B. Desiatov, A. Yanai, D. R. Smith, and U. Levy, "plasmonic graded-index planar lens based on subwavelength features in the effective index regime," in CLEO: QELS 2012, paper QM1C.3.

G. Castaldi, V. Galdi, A. Alu, and N. Engheta, “Transformation-based Cloak/Anti-Cloak Interactions: A Review,” a chapter in “Transformation Electromagnetics and Metamaterials: Fundamental Principles and Applications,” edited by D. H. Werner and D.-H. Kwon, Springer, submitted on June 24, 2012.

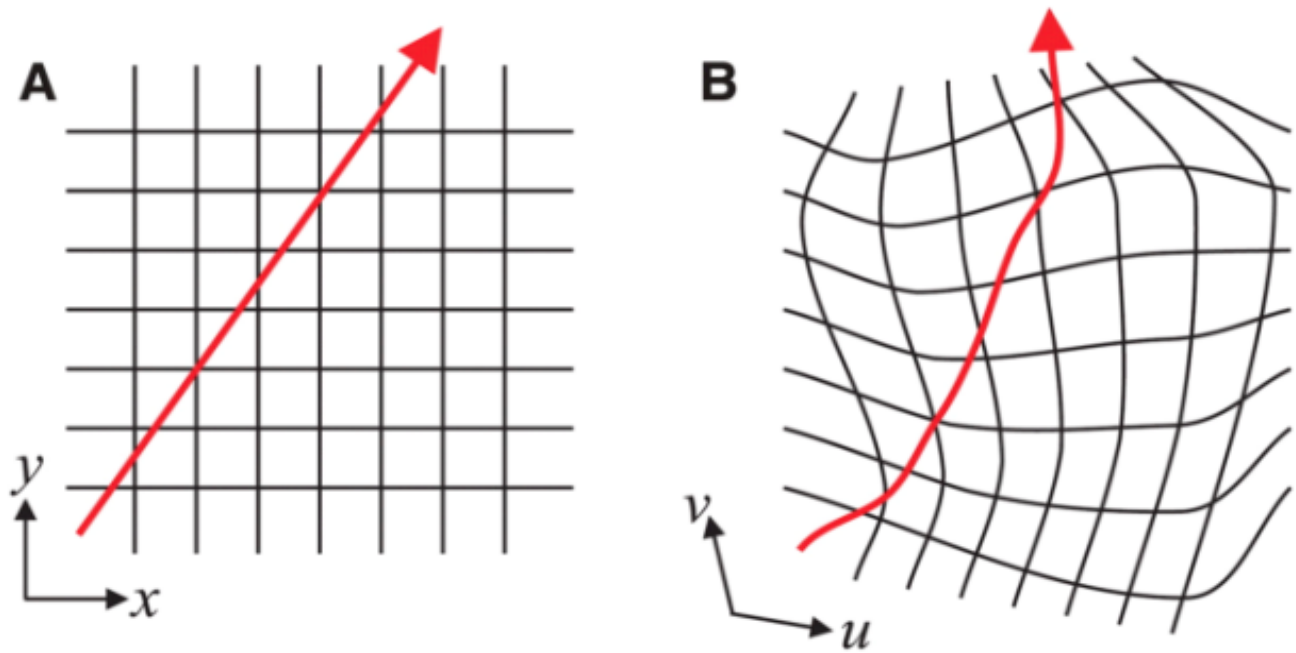


Vladimir M. Shalaev and John Pendry, Transformation optics, Journal of Optics 13 (2) (2011).



Yongmin Liu and Xiang Zhang, "Recent advances in transformation optics", Nanoscale, 4 (17), 5277 - 5292.

Transformation optics



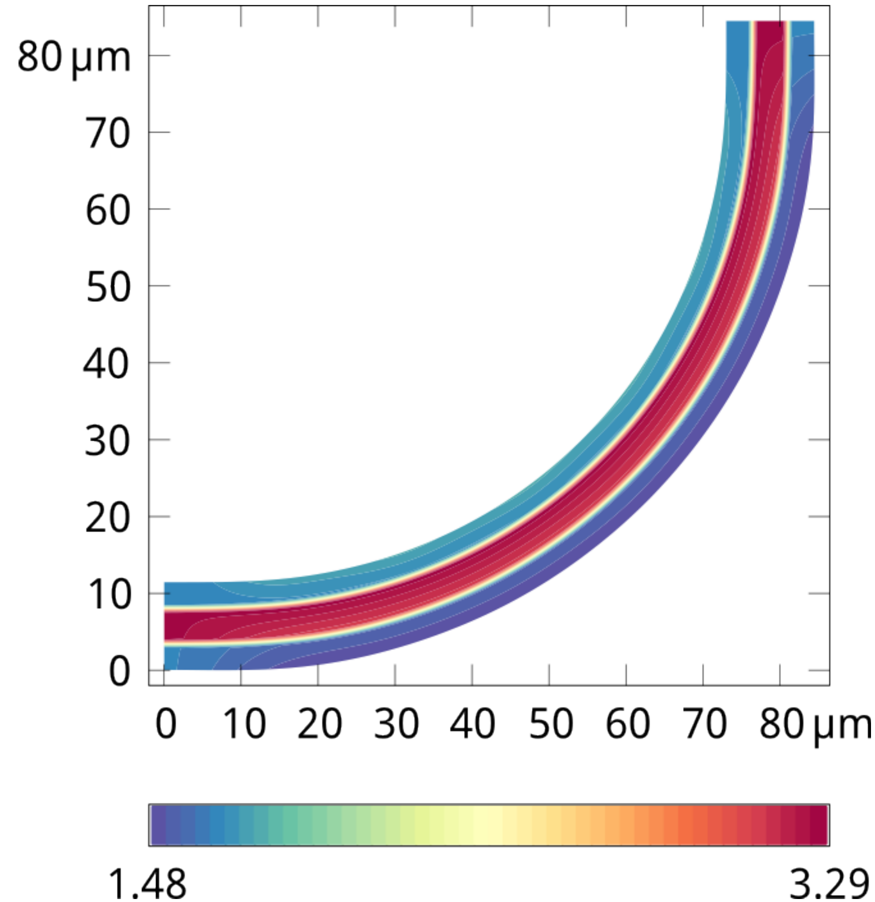
J.B. Pendry, D. Schurig, and D. R. Smith, Science 312, (2006)
U. Leonhardt, Science 312 (2006)

TO Design

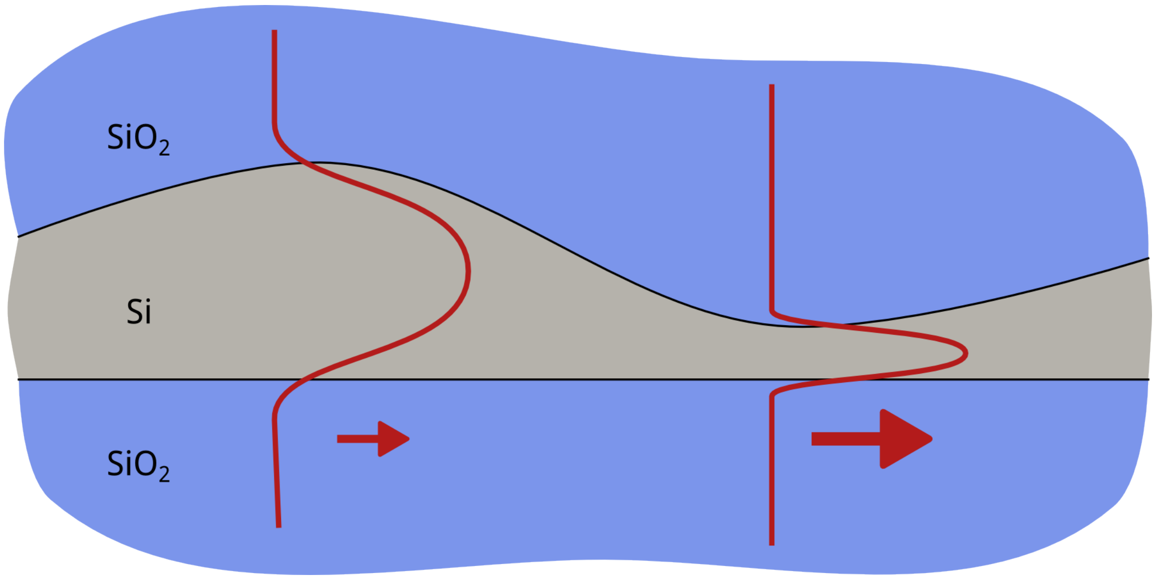
Isotropic materials

Constrained index range

Mode matching at end facets

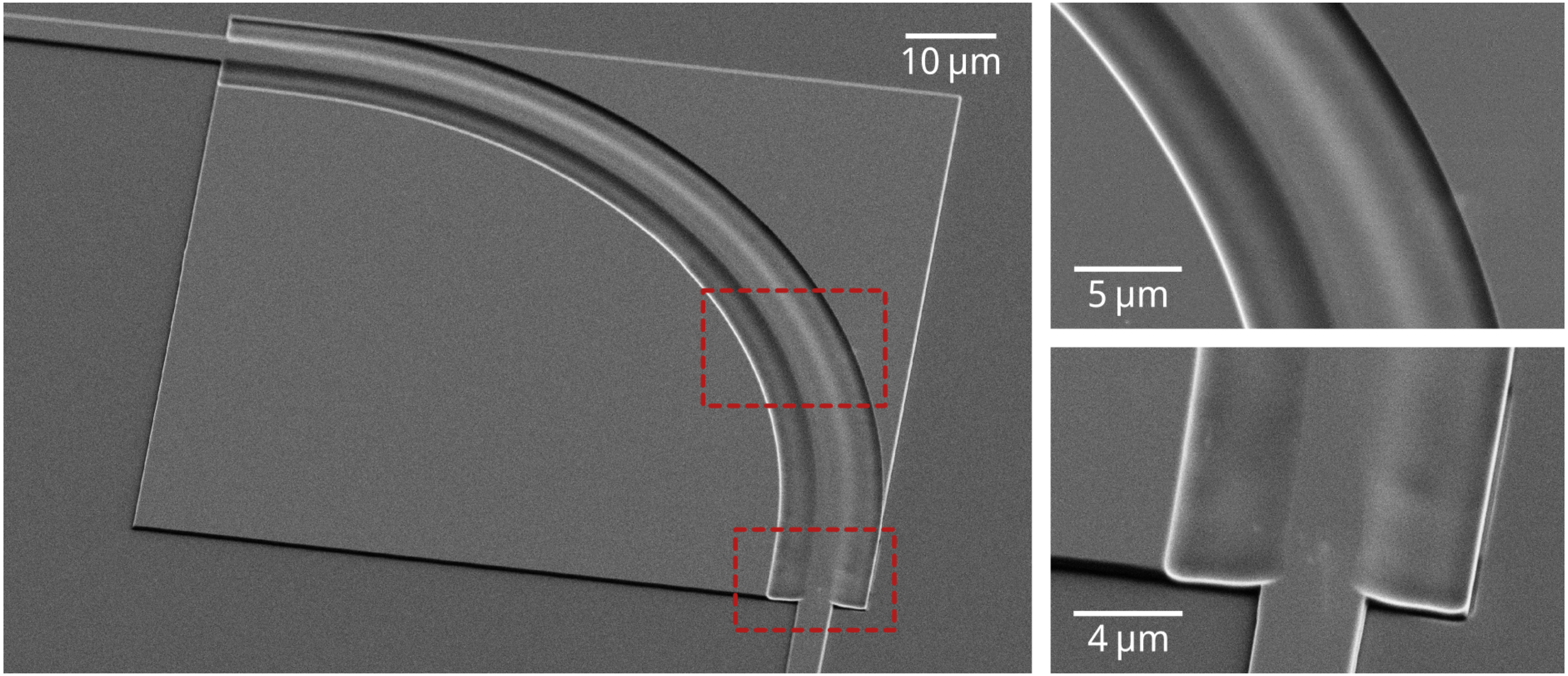


Low Loss Platform



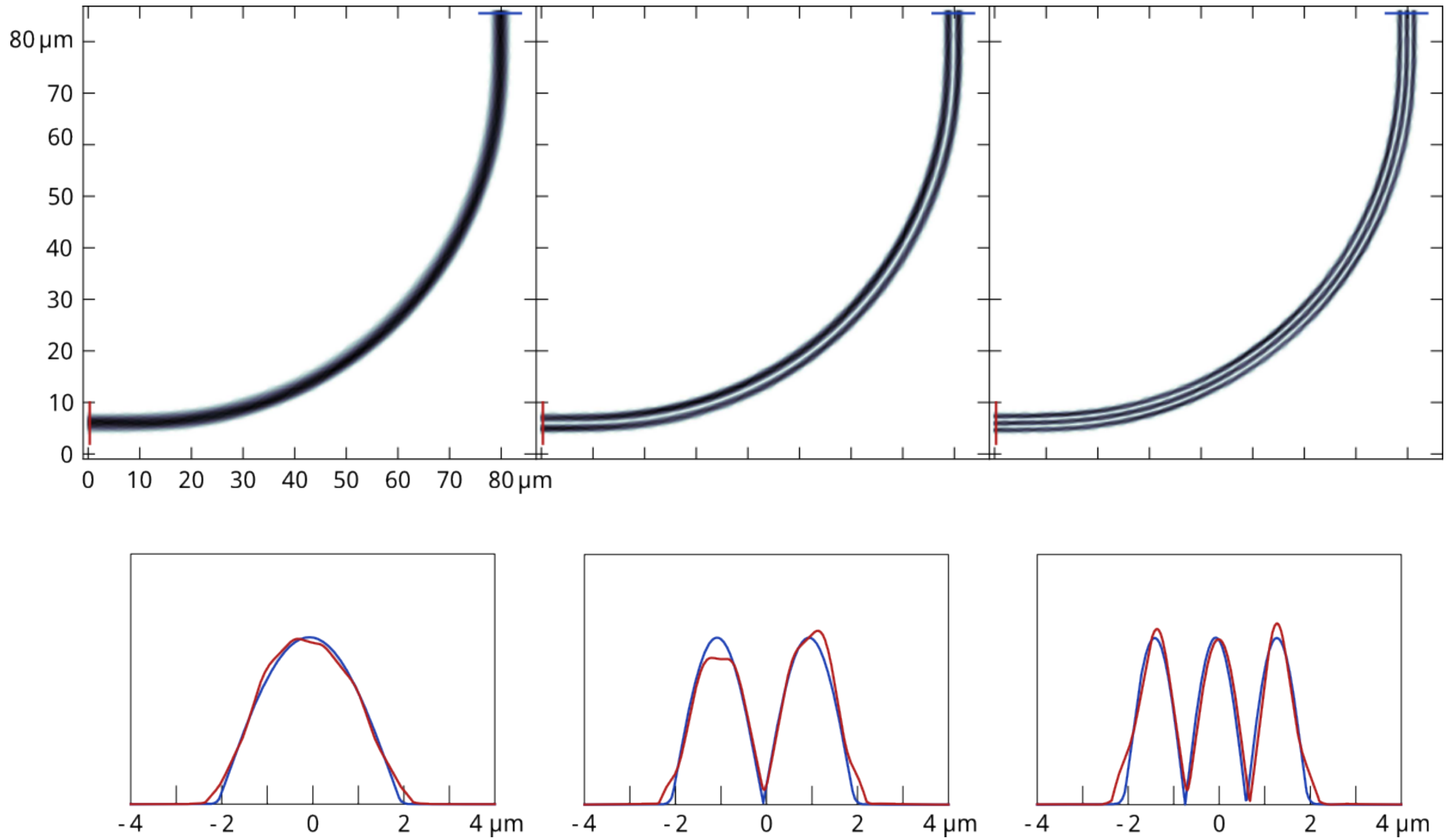
Grayscale patterning: well controlled **scattering**

Grayscale Fabrication

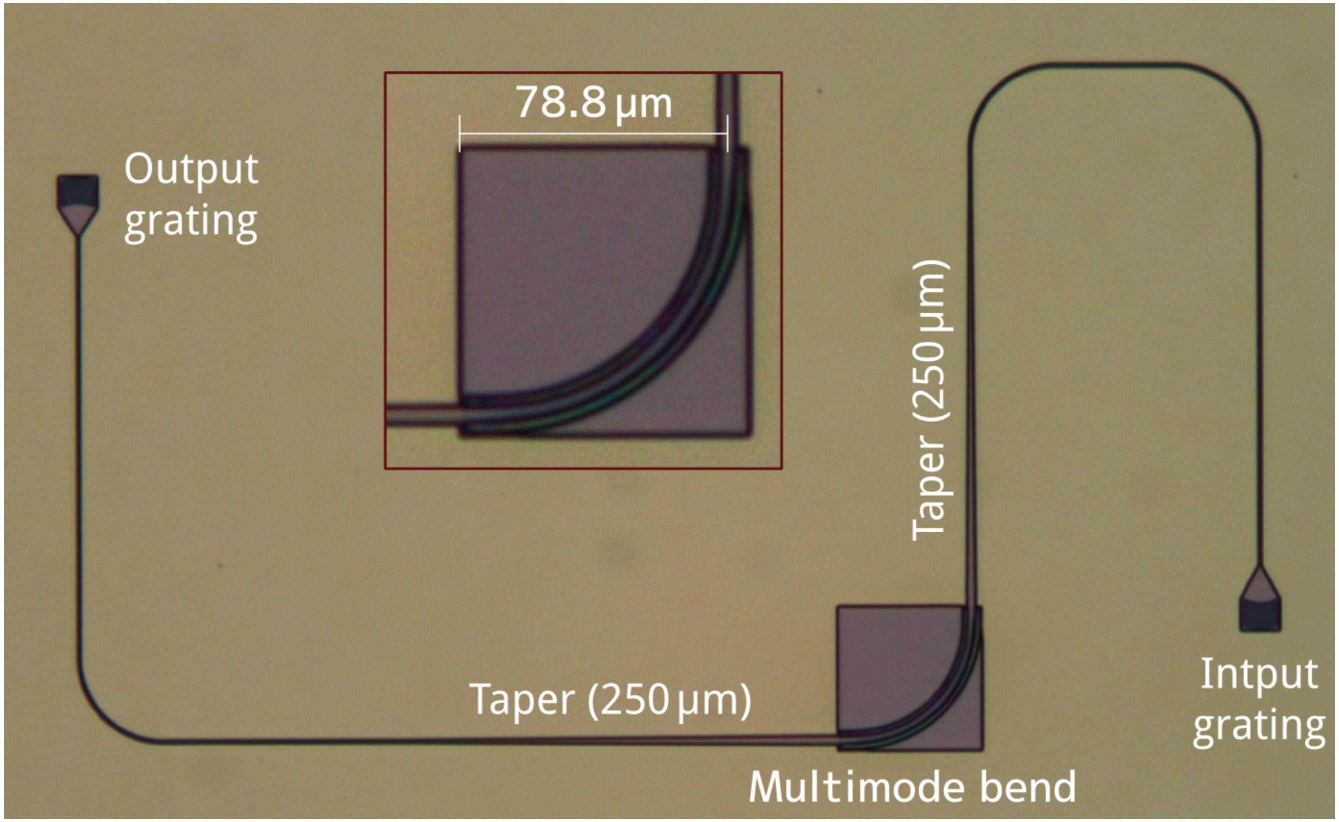


Gabrielli, L., Liu, D., Johnson, S.G. and Lipson, M., Nat. Comm., Vol. 3, Art. 1217,Nov. 2012

Mode Preservation

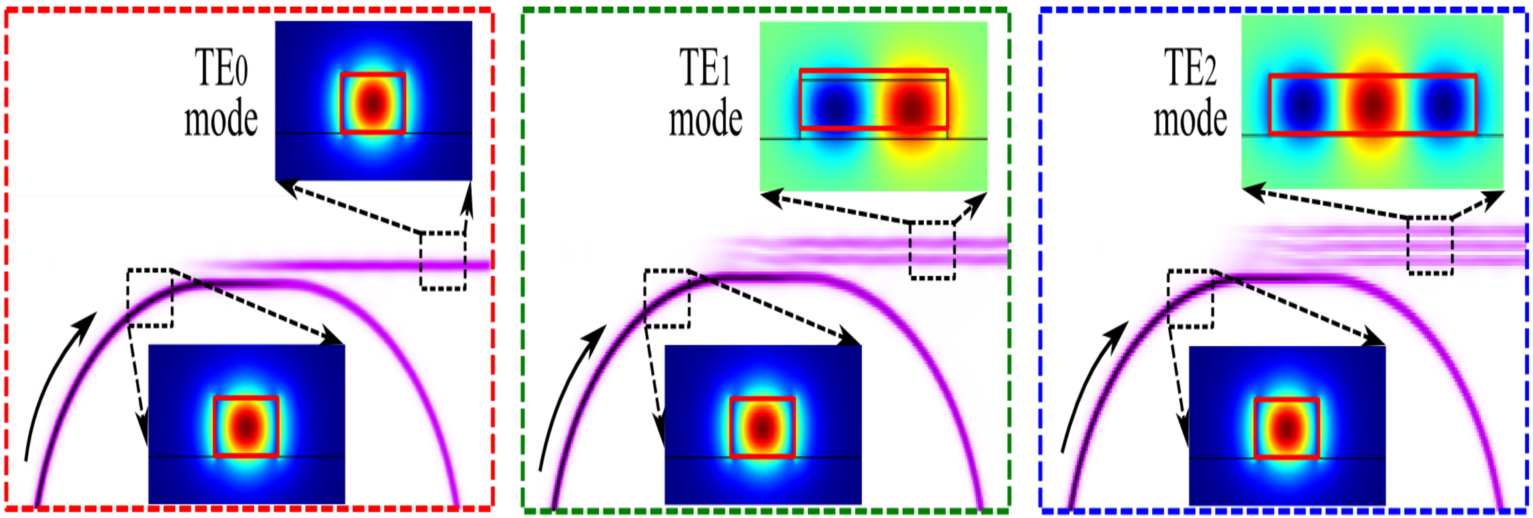


>14dB reduction in loss



Gabrielli, L., Liu, D., Johnson, S.G. and Lipson, M., Nat. Comm., Vol. 3, Art. 1217,Nov. 2012

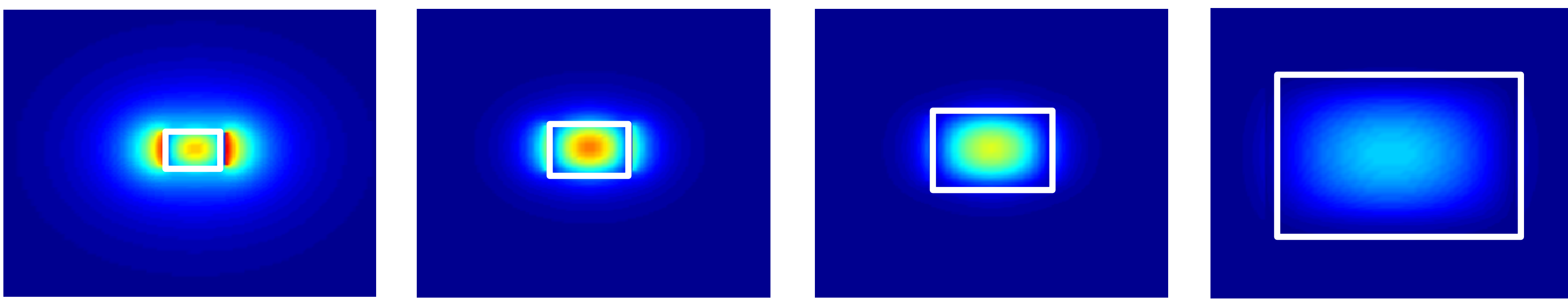
Multimode Multiplexing



Silicon Photonics for Nonlinearities

High index contrast of waveguide

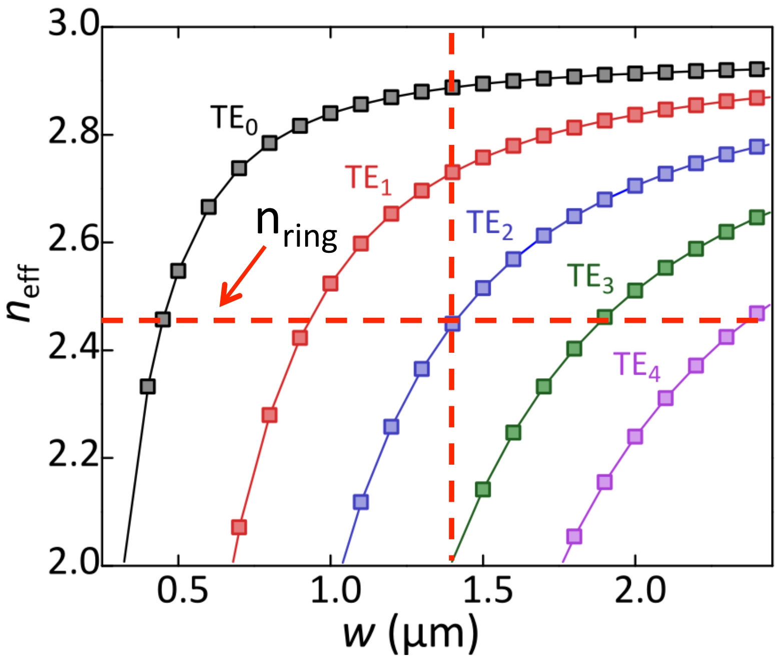
- Careful control of light confinement
- Ability to engineer waveguide dispersion

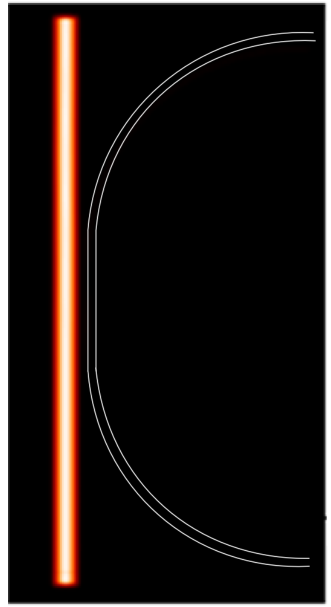


core area = 0.06 μm² | core area = 0.12 μm² | core area = 0.26 μm² | core area = 1.00 μm²

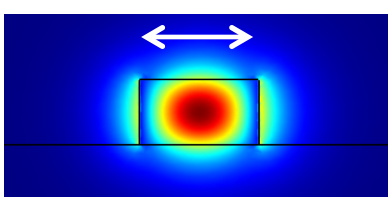
Multimode Multiplexing

L. Luo



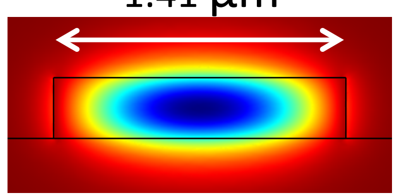


450 nm



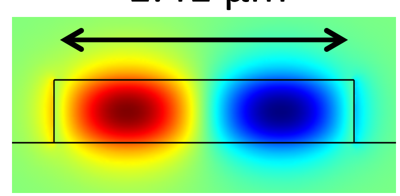
n = 2.46

1.41 µm



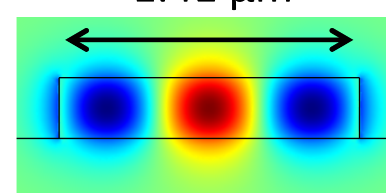
n = 2.89

1.41 µm



n = 2.72

1.41 µm



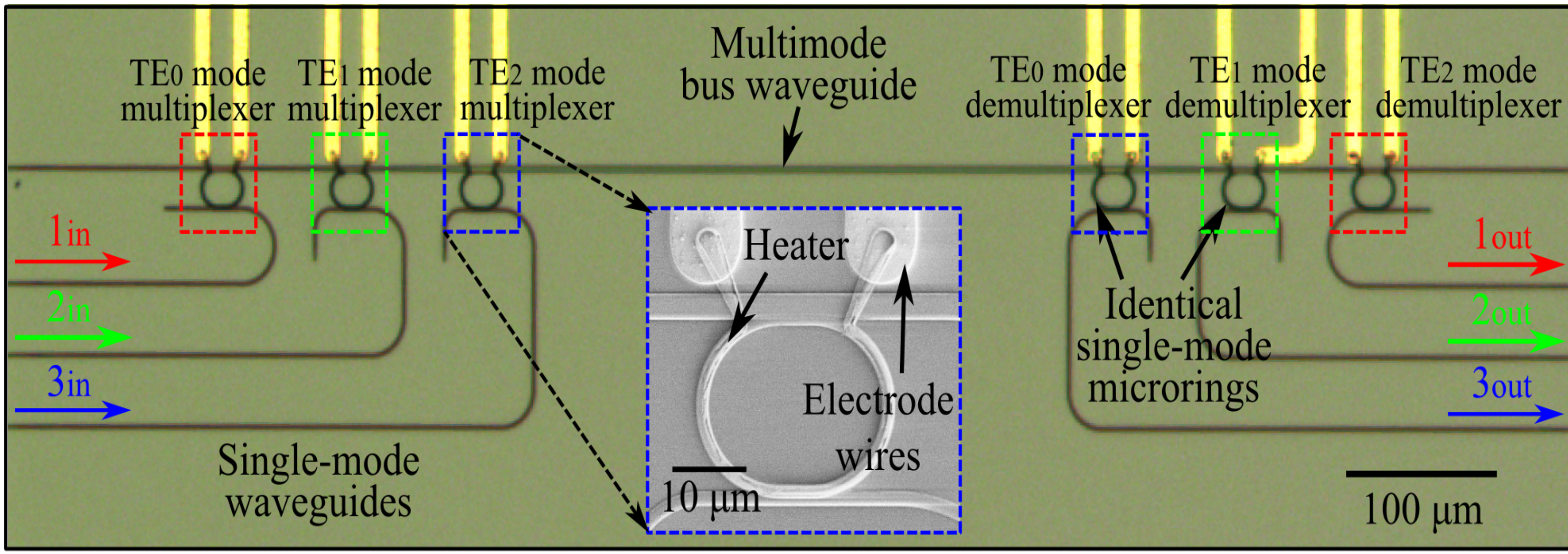
n = 2.46

Luo, L.-W., Lipson, M., et al., WDM-compatible mode-division multiplexing on a silicon chip, **Nat. Comm.**, 5, p. 3069, 15 Jan. 2014

Cornell University

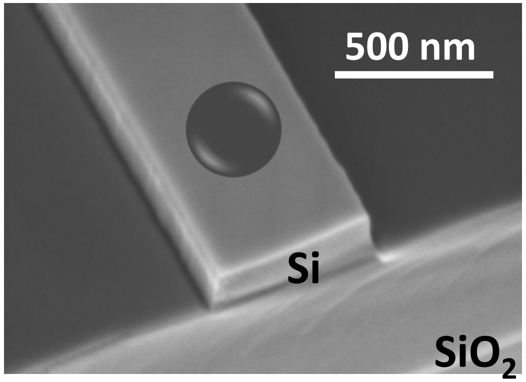
Prof. Michal Lipson

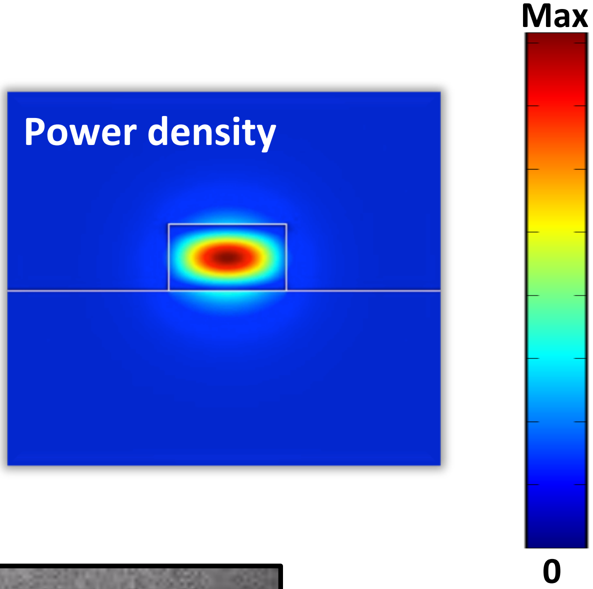
Multimode Multiplexing-Fabrication

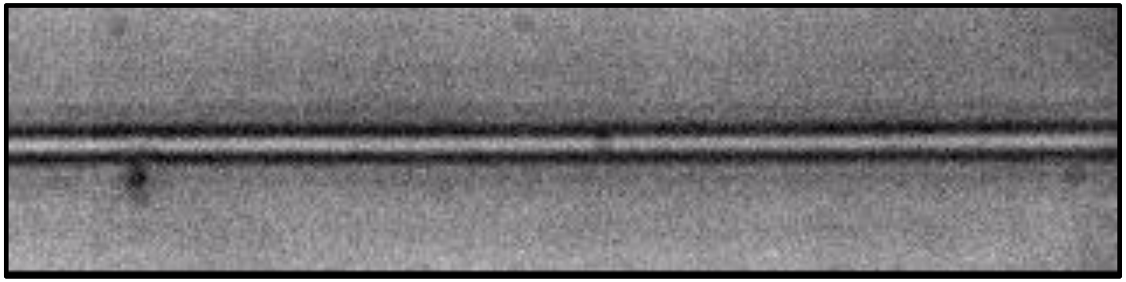


Optofluidics

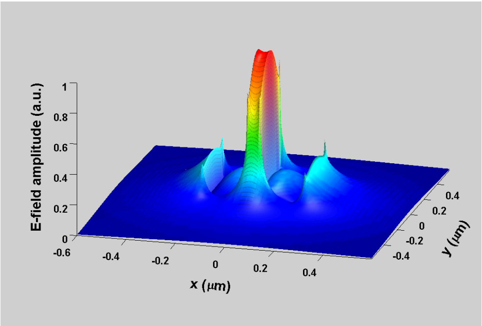
High Confinement Micro/Nano Photonics



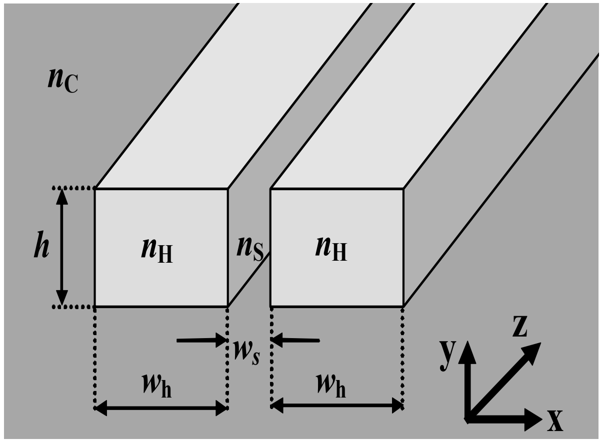


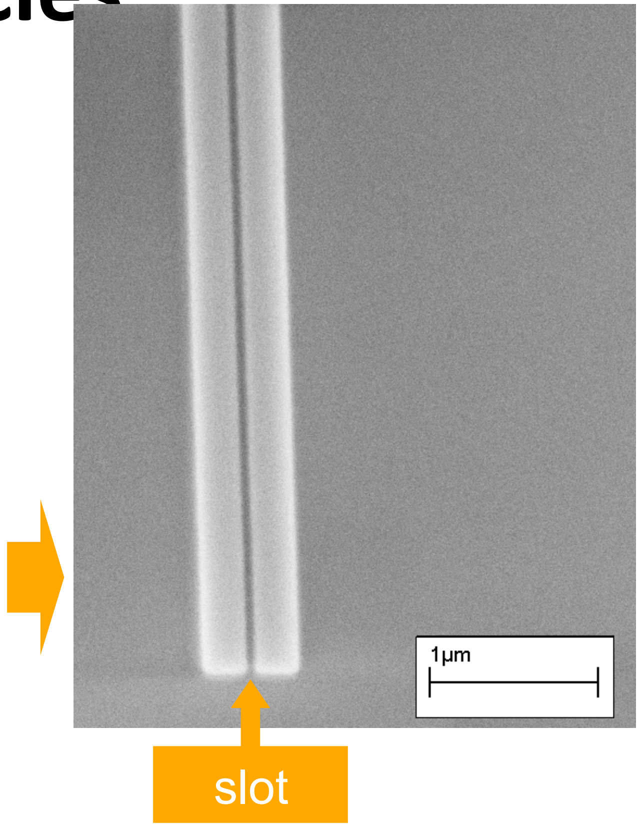


Demonstration of Optical Trapping on chip of Ultra Small Particles



Robinson, J.T., Chen, L. and Lipson, M., Optics Express,, 13 March 2008.

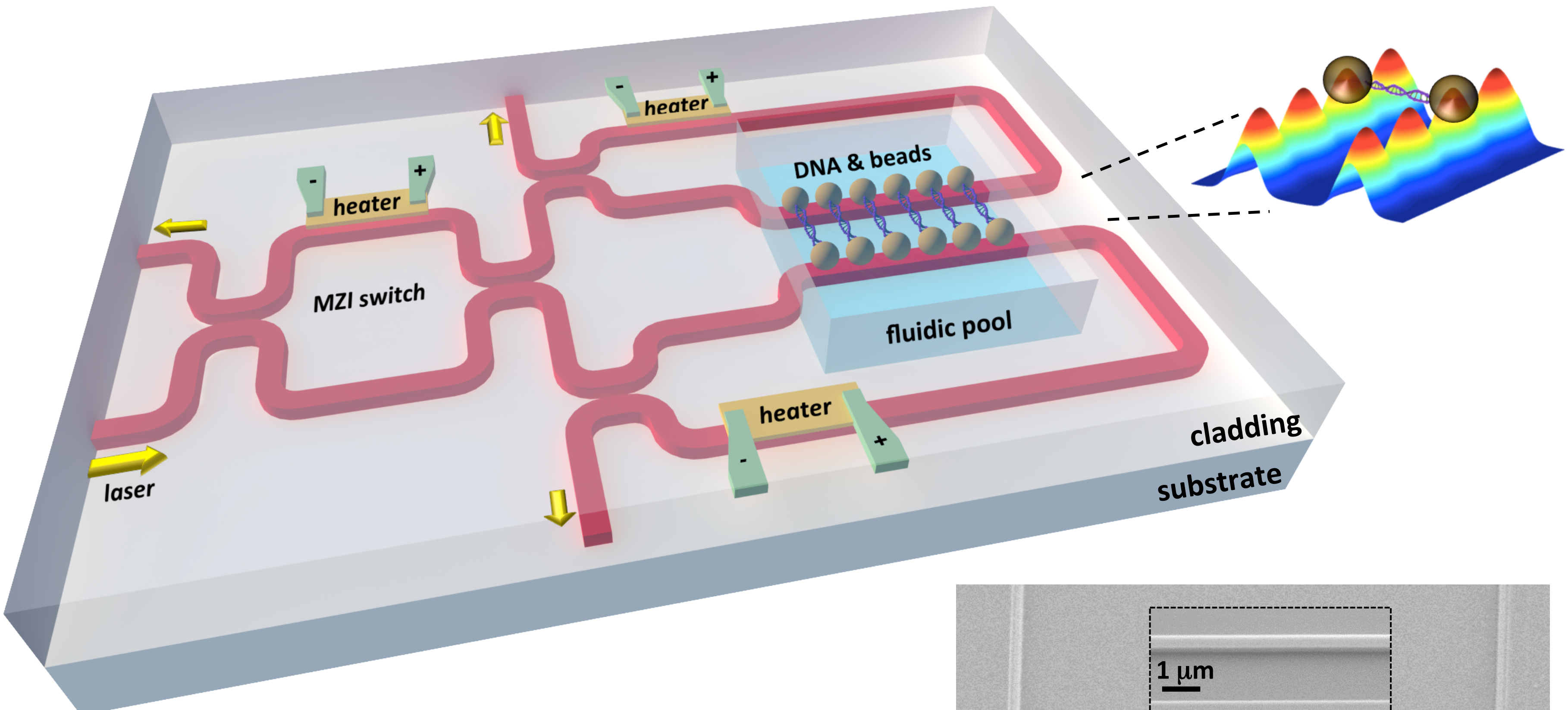


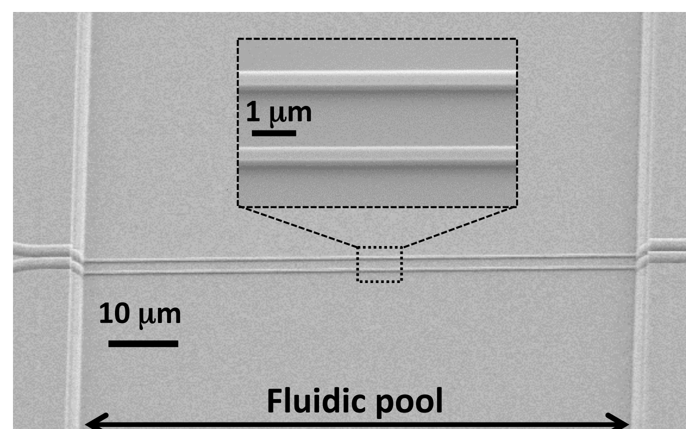


Trapping 75nm DNA using Slots: Yang, A.H.J., Moore, S.D., Schmidt, B.S., Klug, M., Lipson, M. and Erickson, D., Nature, Vol. 457, 71-75, 01 Jan. 2009.

Applications include sorting, sensing: L. C. Kimerling, G. M. Whitesides, and A. Agarwal. et al , Nano Lett. 14, 231 (2014).

Electro-optofluidic Platform





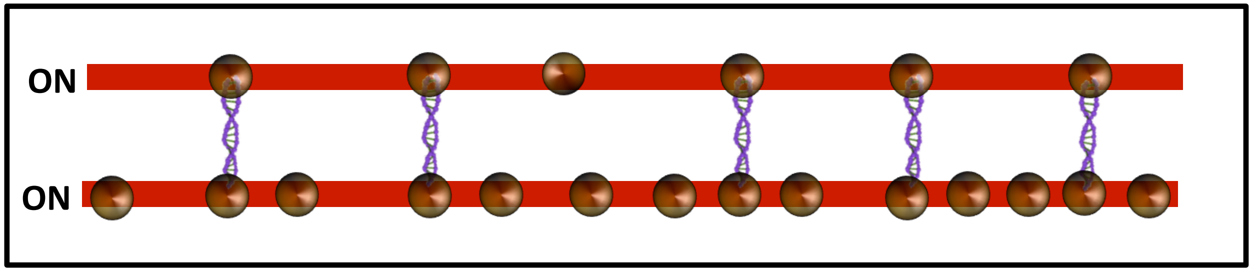
M. Soltani, M. Lipson, M. Wang, Nature Nanotechnology (in press)

Cornell University

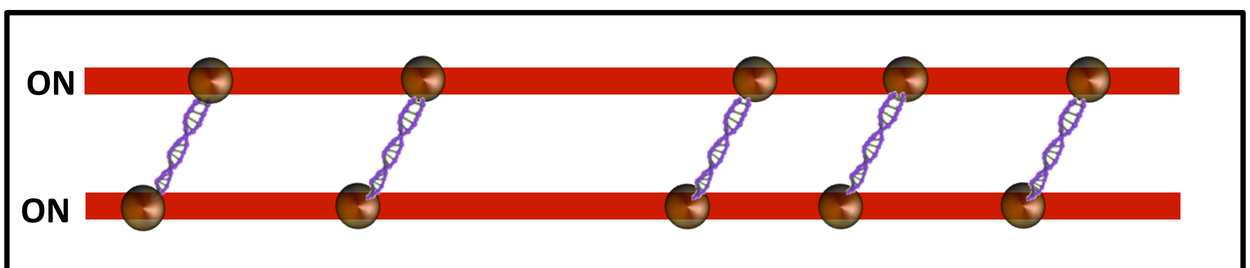
Prof. Michal Lipson

DNA Arrays Sorting and Manipulation

Initial



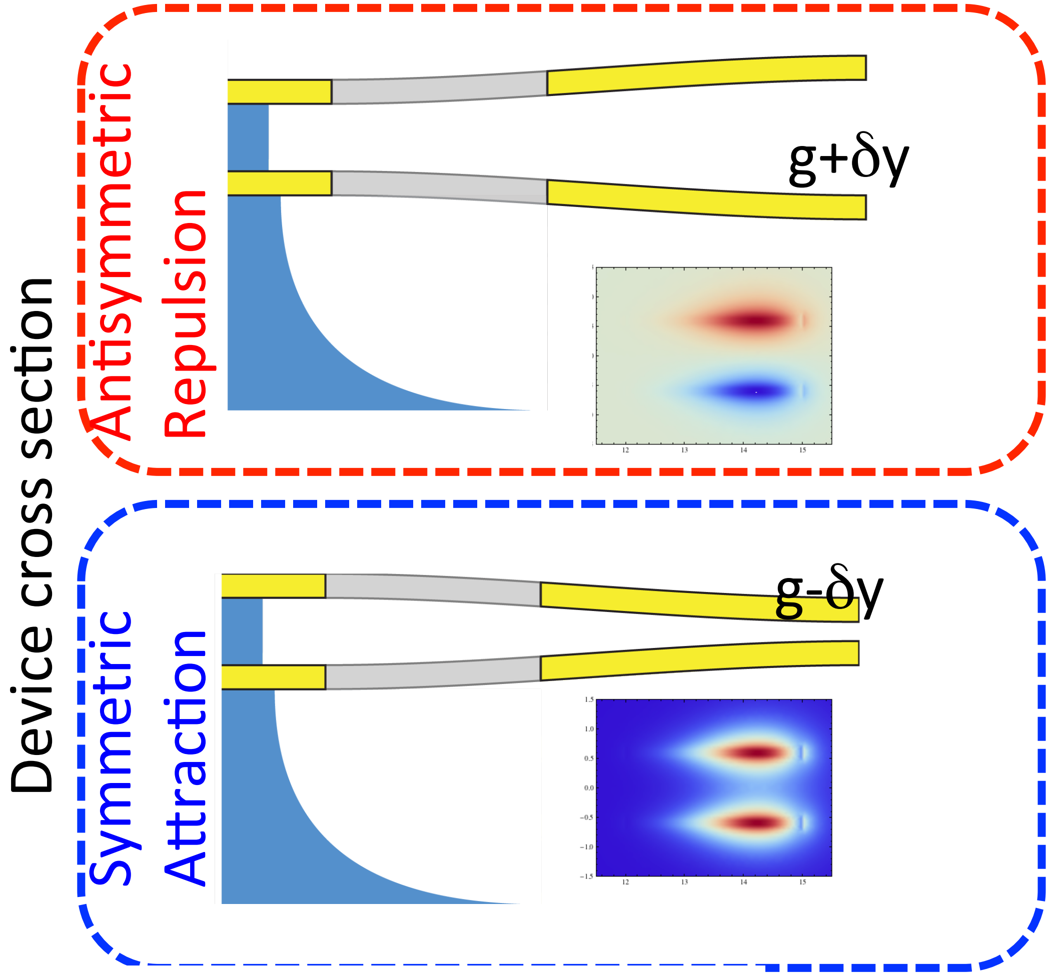
Final



w/ Michelle Wang, Cornell

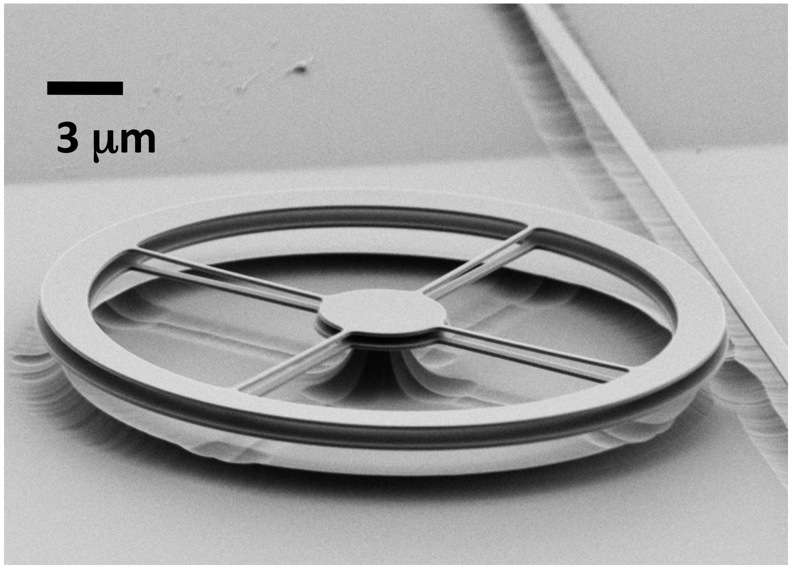
Optomechanics

Demonstration Optical Forces for Reconfigurable Objects

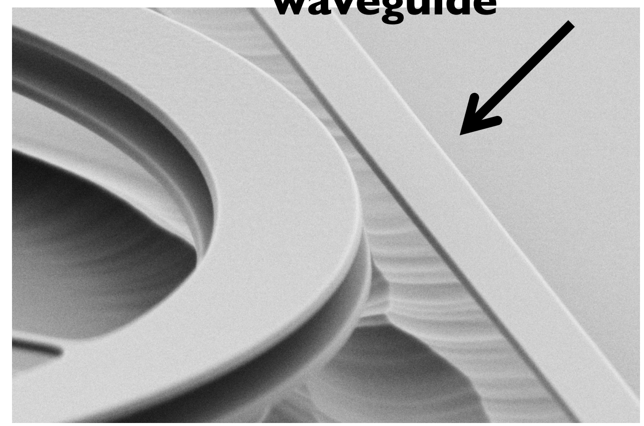


Wiederhecker, G.S., Chen, L., Gondarenko, A. and Lipson, M., Nature, p. 08584, (2009).

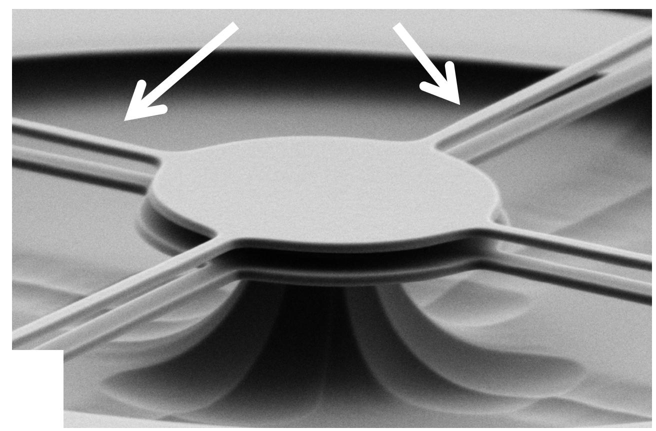
Demonstration Optical Forces for Reconfigurable Objects



Integrated coupling waveguide



300 x 200 nm spokes

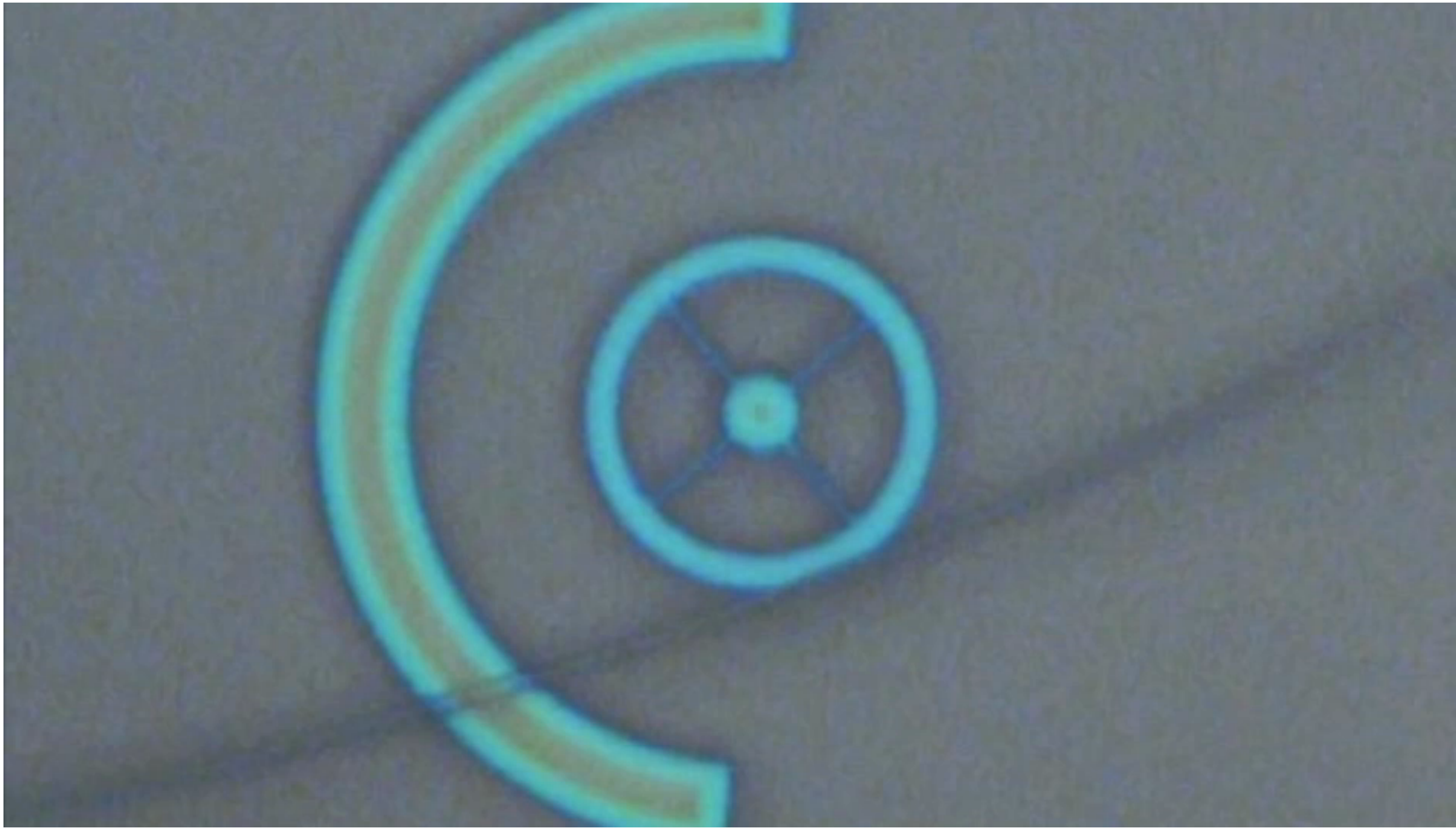


Opt. Q ≈ 10^5
Gap = 600 nm
$d\omega/dy$=5 GHz/nm

Mech. Q ≈ 10
m_{eff}=120 pg
k= 1.2 N/m

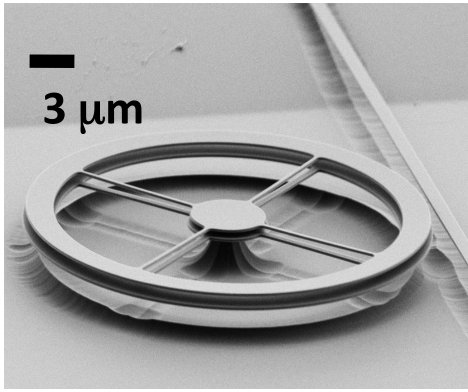
Wiederhecker, G.S., Chen, L., Gondarenko, A. and Lipson, M., Nature, 08584, 15 Nov. 2009.

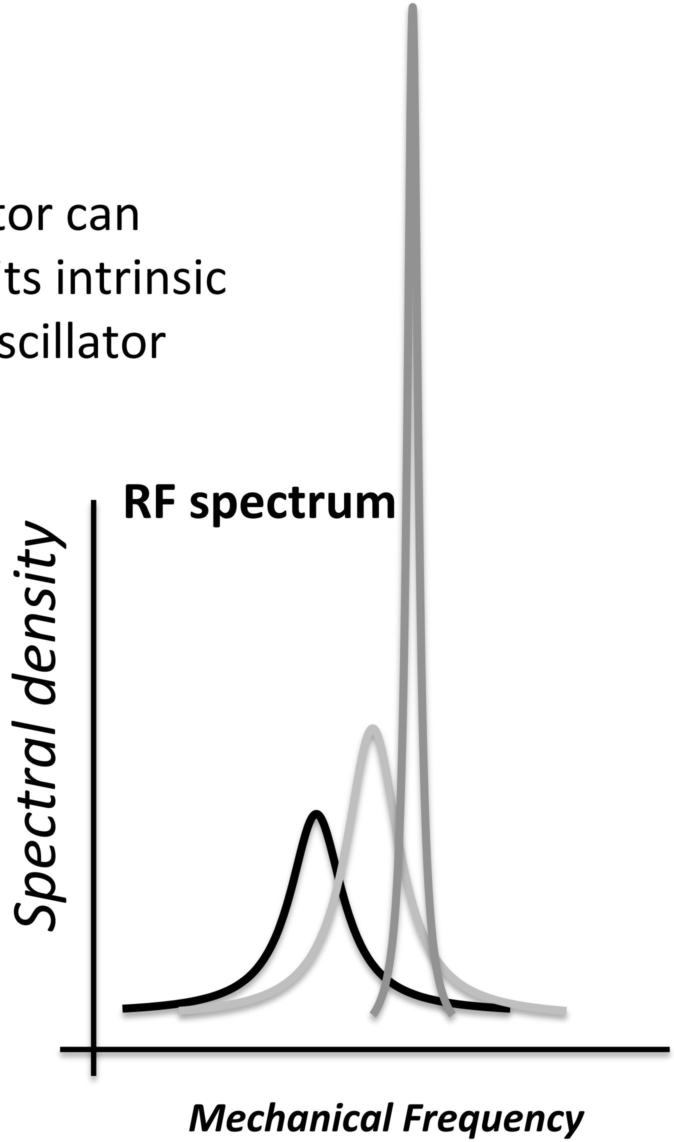
Demonstration Optical forces for Reconfigurable Objects

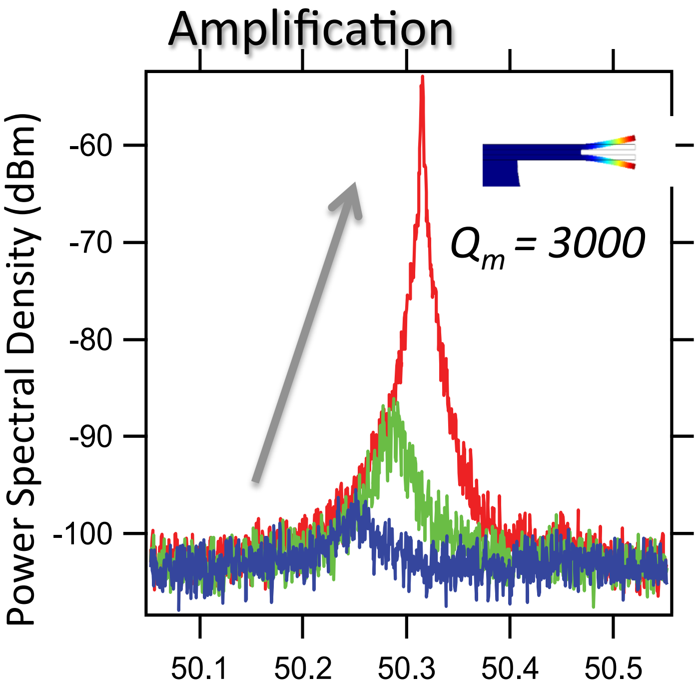


Parametric Amplification

- The oscillator can overcome its intrinsic damping-oscillator







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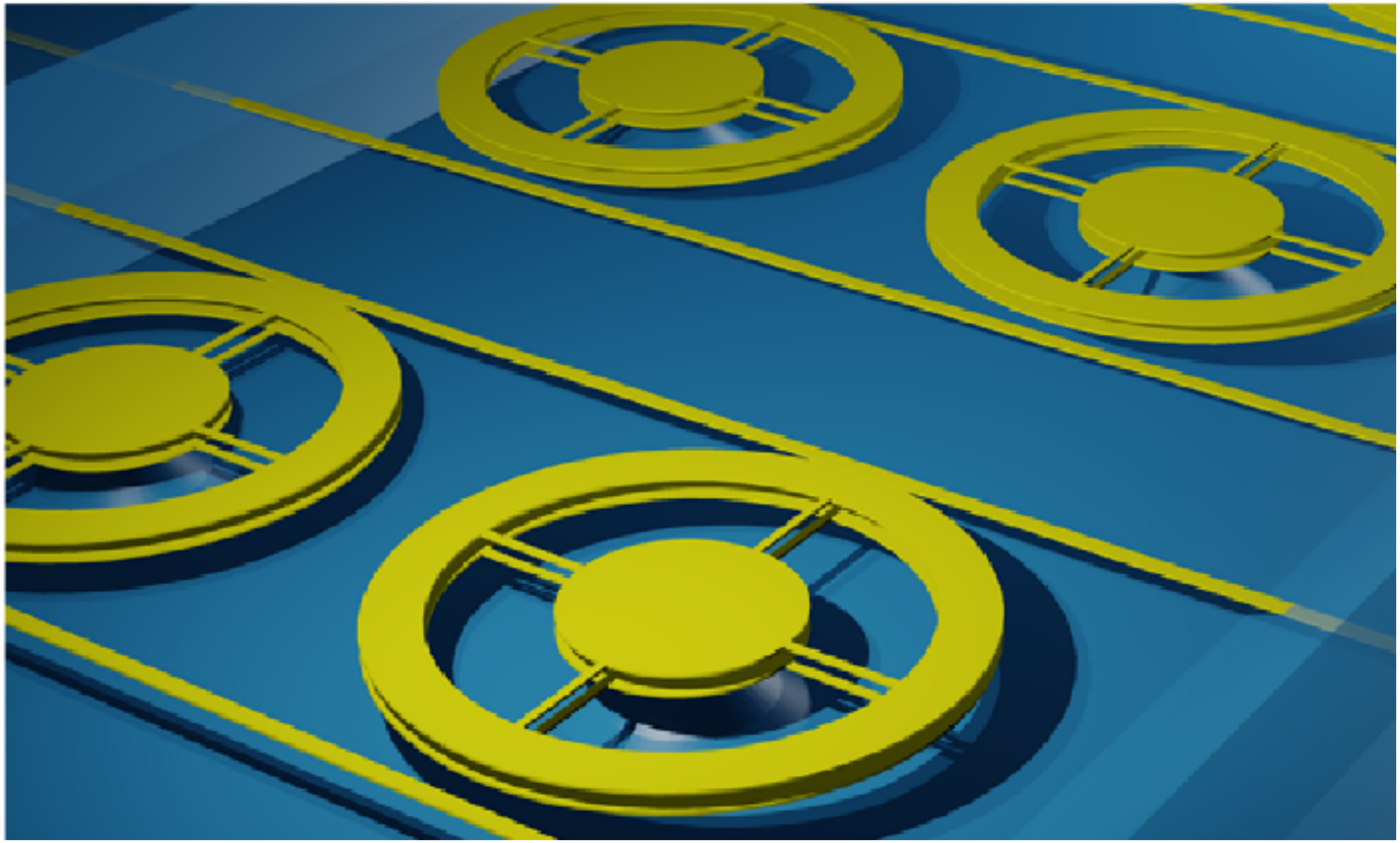
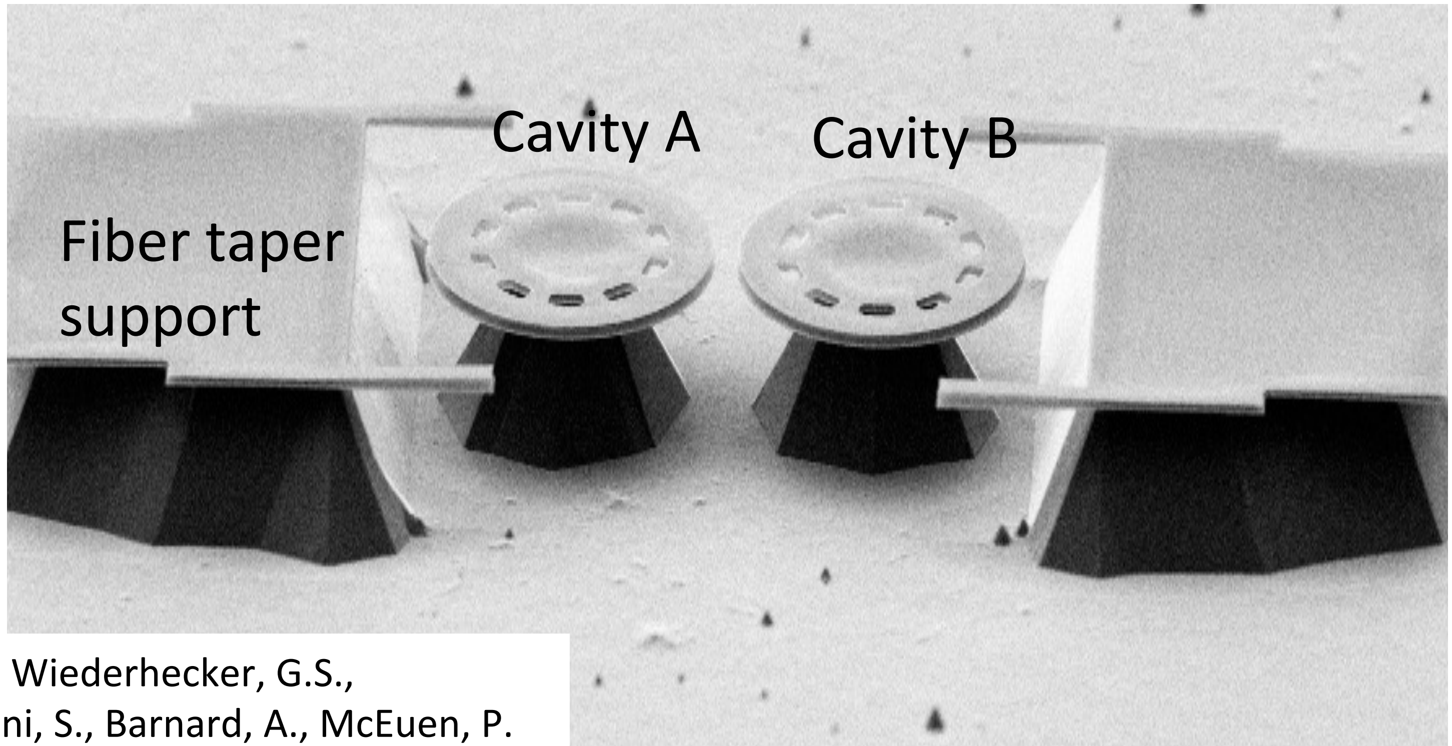


Vision: Light Coupling Mechanical Oscillators

Cornell University

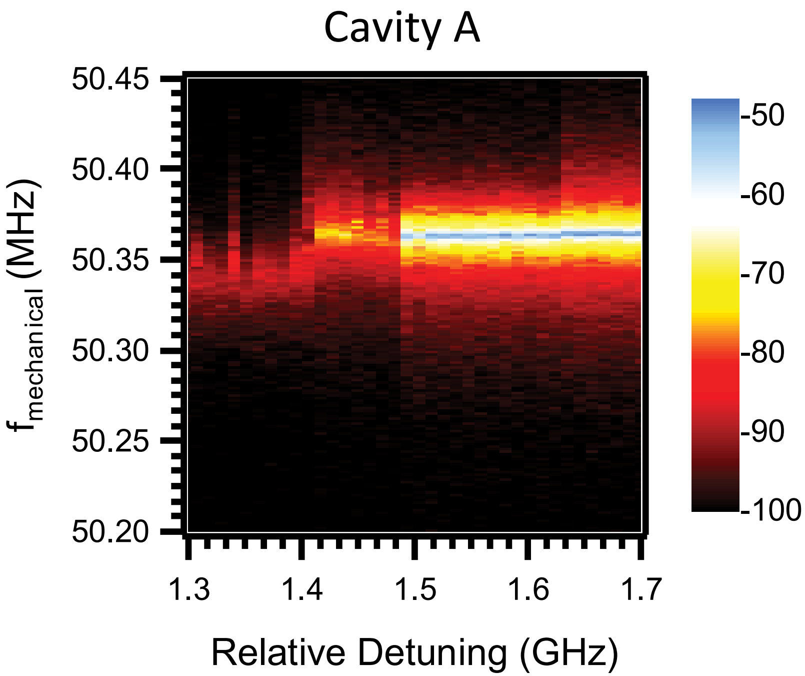
Prof. Michal Lipson

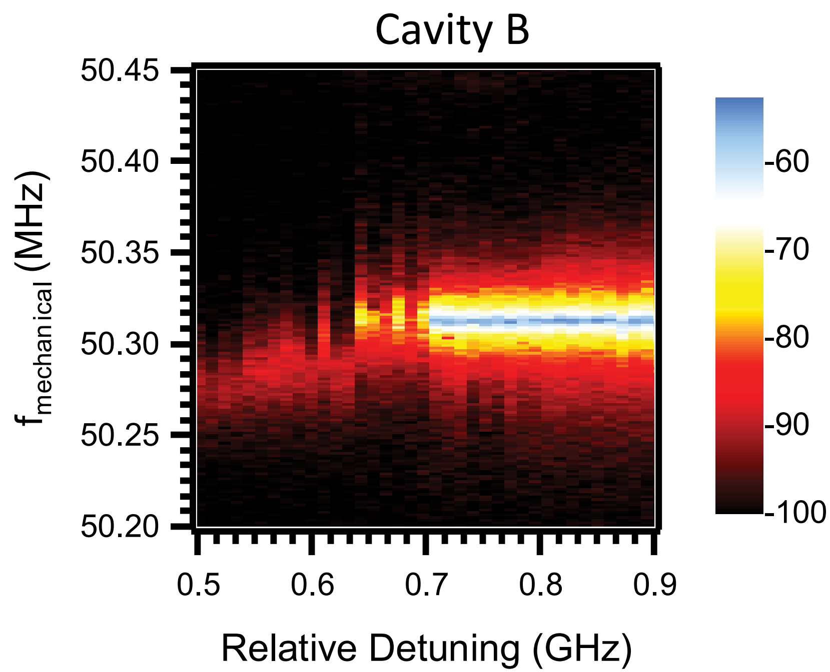
Demonstration of Synchronized Optomechanical Resonators



Zhang, M., Wiederhecker, G.S., Manipatruni, S., Barnard, A., McEuen, P. and Lipson, M., Phys. Rev. Lett., Vol. 109, 233906, 07 Dec. 2012

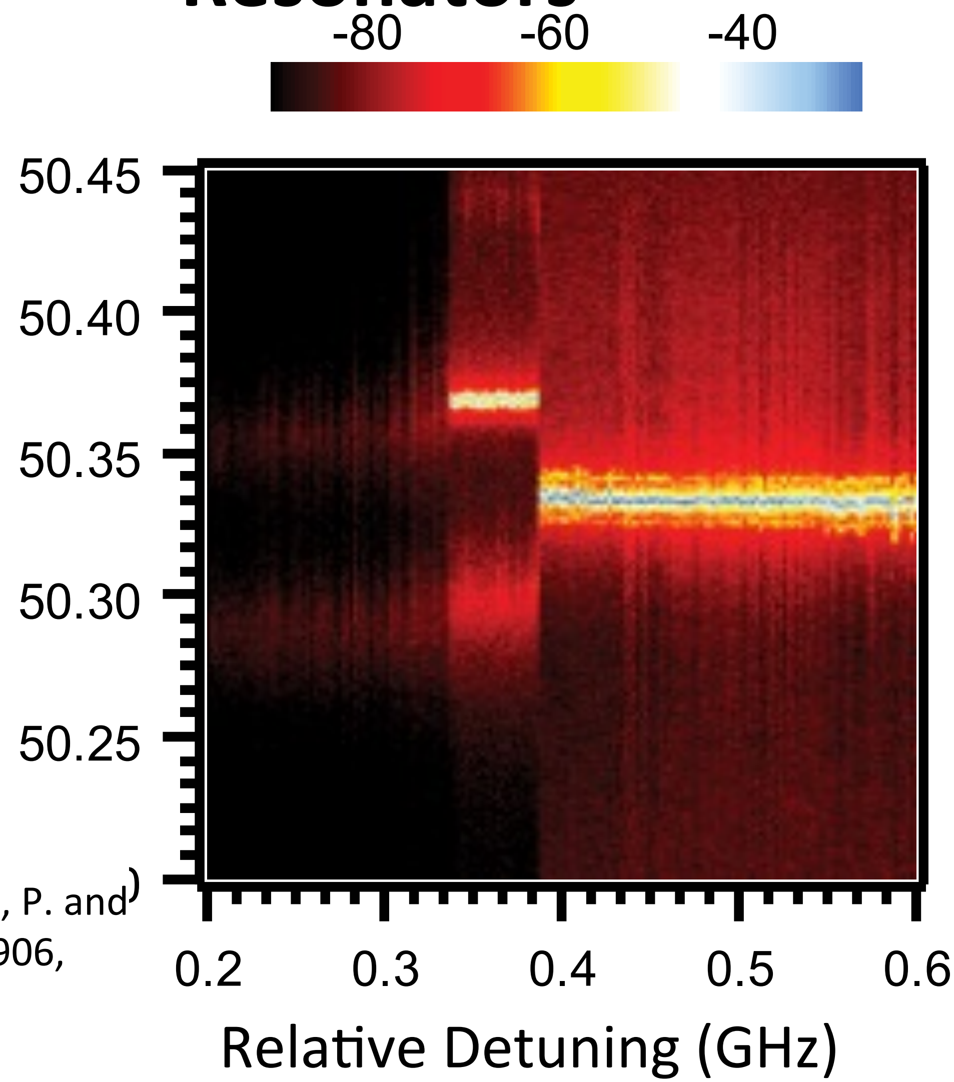
Single Cavity Result (decoupled)





Zhang, M., Wiederhecker, G.S., Manipatruni, S., Barnard, A., McEuen, P. and Lipson, M., Phys. Rev. Lett., Vol. 109, 233906, 07 Dec. 2012

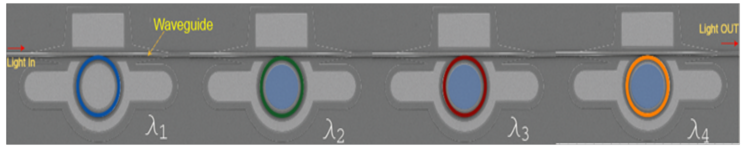
Demonstration of Synchronized Optomechanical Resonators

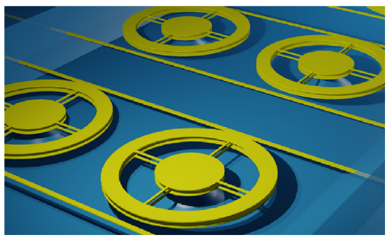


Zhang, M., Wiederhecker, G.S., Manipatruni, S., Barnard, A., McEuen, P. and Lipson, M., Phys. Rev. Lett., 109, 233906, 2012

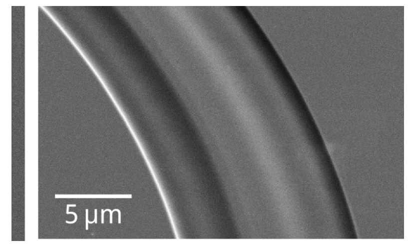
Summary

Ultra high frequency modulators

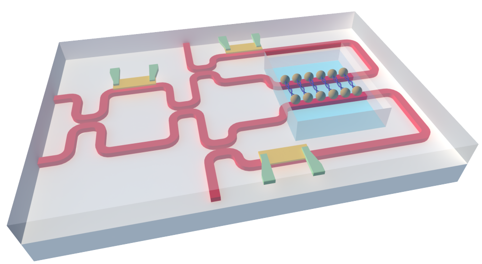




Synchronization between mechanical structures using light



Platform for Multimode communication on-chip



Optofluidics for control of individual molecules

Prof. Alexander Gaeta
Prof. Michelle Wang
Prof. Paul Mcuen
Dr. Carl Poitras
Lawrence Tzuang
Dr. Hugo Lira
Dr. Qianfan Xu
Dr. Kyle Preston
Dr. Nicholas Sherwood
Dr. Vilson Almedia
Dr. Lucas Gabrielli
Prof. Steven Johnson
Prof. Keren Bergman
Dr. Jaime Cardenas
Dr. Lian-Wee Luo
Dr. Noam Ophir
Christine Chen
Mian Zhang
Dr. G. Wederhecker
Dr. Mohammad Soltani

Cornell University

Prof. Michal Lipson