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Innovative R&D by NTT

Integrated Nanophotonics Technology Toward fJ/bit Optical Communication in a Chip

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MPSoC'14, Margaux, France

Outline

Introduction

Limitation of E-Interconnect

Photonic network into a chip

Integrated Nanophotonics

Photonic crystal

Conclusion

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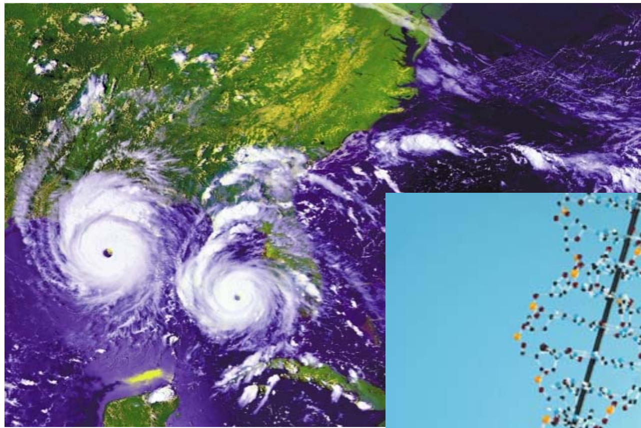
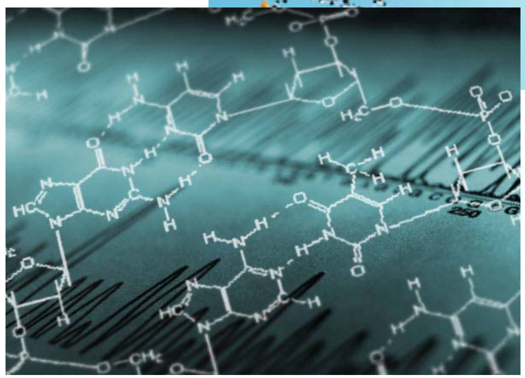
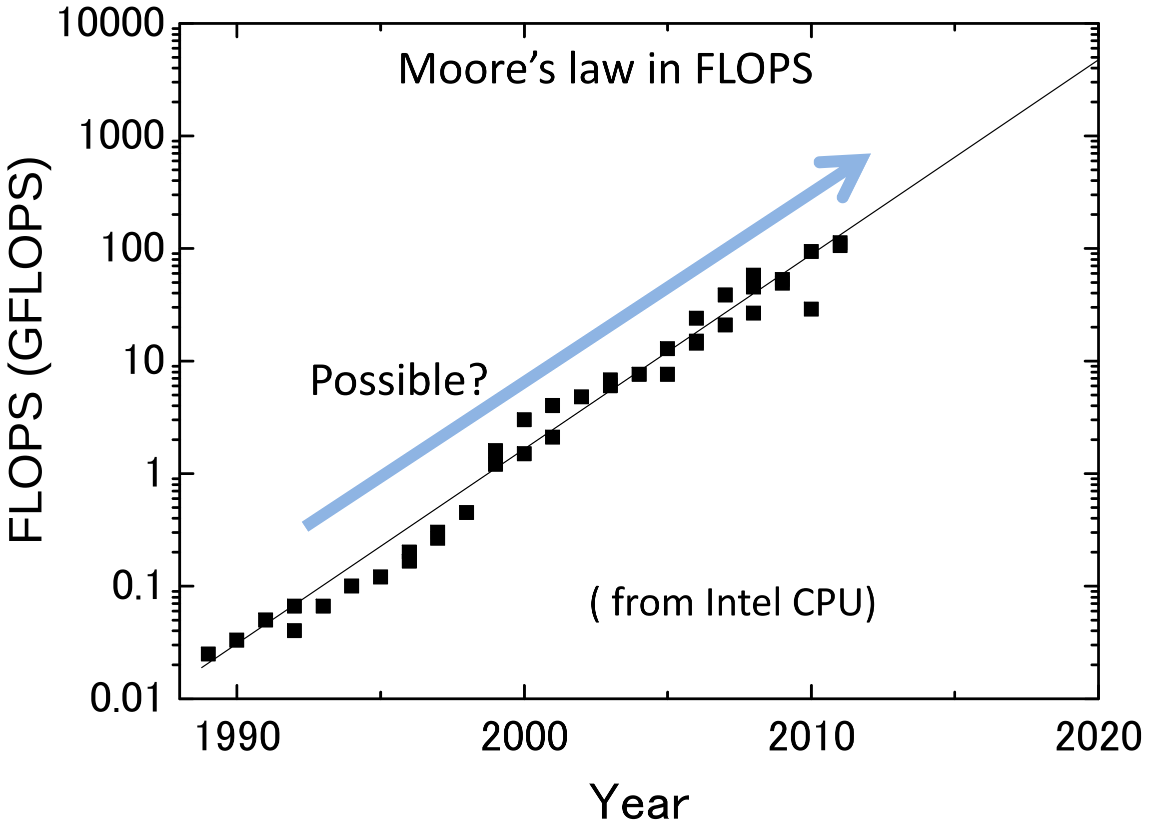
Era of Many-core Systems

- Need for explosive computational power
  - Scientific applications
    - Weather prediction, earthquake forecast
    - Bioinformatics, molecular dynamics, computational chemistry
  - Consumer electronics
    - Graphics, animation, games



Era of Many-core Systems



How to keep up with demands on computational power:

Increase number of cores (parallelism)

Interconnection of the cores!

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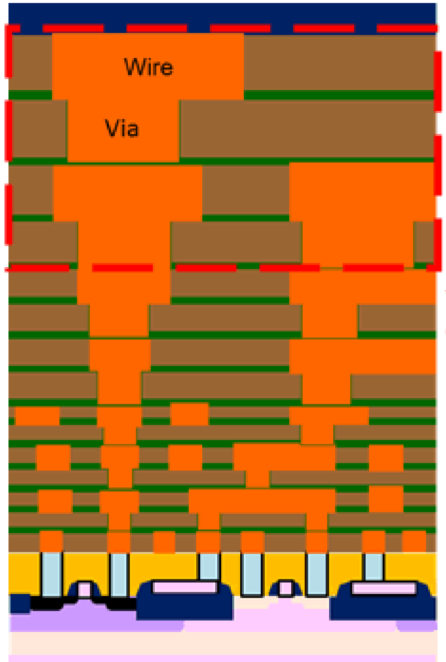
Recent Trend in Chips

Spaghetti-wiring on chip

http://www.itrs.net/Links/2007ITRS/2007_Chapters/2007_Interconnect.pdf

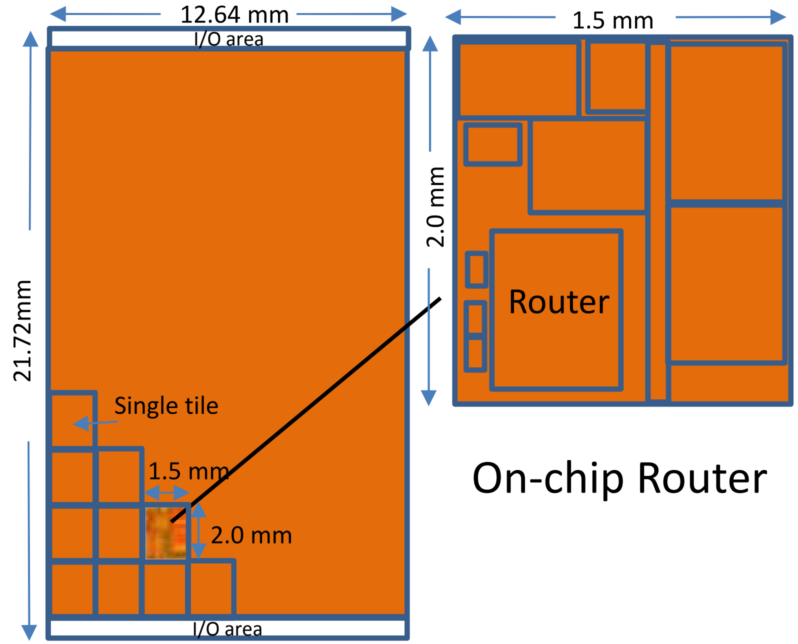


Electric wiring consumes half of CPU power

Limitation of Metal Wire-line

80-Core NoC CMOS (2007)

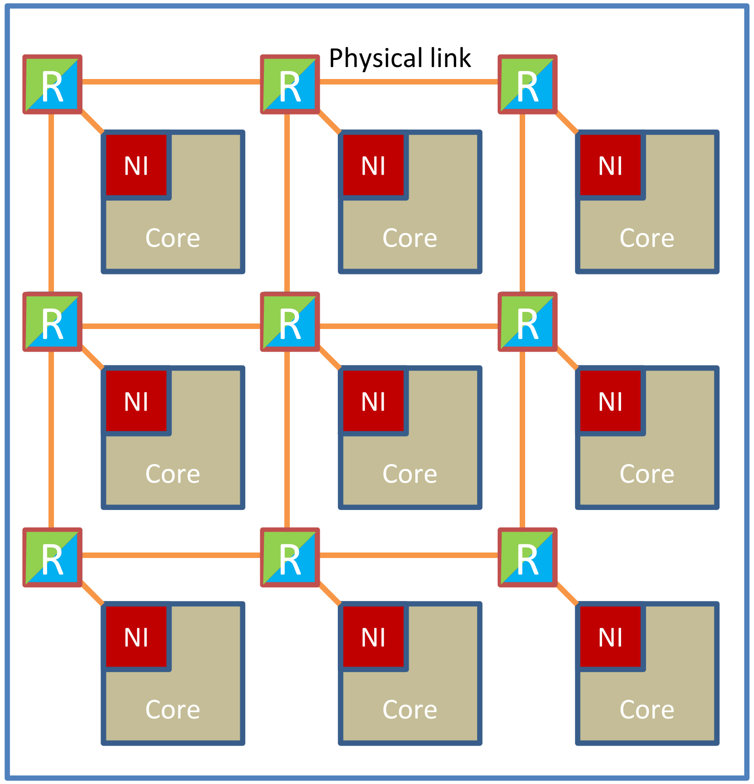
ISSCC 2007 / SESSION 5 / MICROPROCESSORS / 5.2



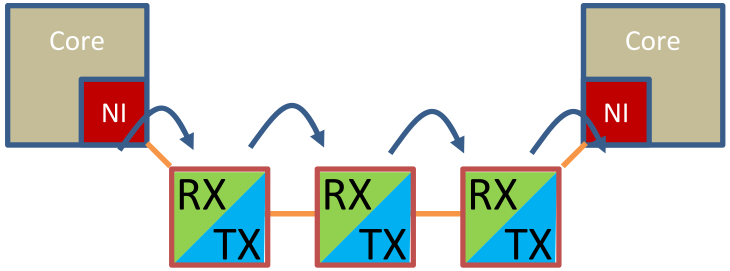
Router consumes 28% of CPU power

Limitations of Traditional NoC

Limitations of Traditional NoC



R: Router
NI: Network interface
TX : Transmitter
RX : Receiver



Multihop wireline communication
- receive, buffer and retransmit every bit at every switch

High latency and energy dissipation

Limitation of Metal Wire-line

1) Limited BW per volume (RC delay)

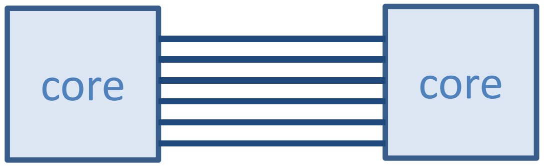
Signal attenuation

$$\tau \approx RC = \rho C_L \frac{L^2}{A} \qquad C = \varepsilon \frac{S}{d} = \varepsilon \frac{wL}{d} \approx C_L L \qquad R = \rho \frac{L}{A}$$

~1.8 as x (L^2/A) C_L= ~1 pF/cm =10^{-10} (F/m)   ρ=1.7 x 10^{-8} (Ωm)

$$B_{eye} \approx \frac{1}{10} \times \frac{1}{2\pi\tau_{RC}} = 10^{16}\left(\frac{A}{L^2}\right)$$

If L_{core}= 0.1 mm and w= 2μm, N_{wire}=25



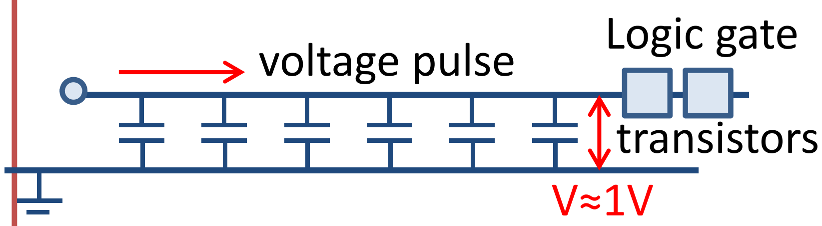
L_{IC} = 10 mm B_{eye} = 25 x 4 x 10^8 = 10 Gbps

L_{IC} = 1 mm B_{eye} = 25 x 4 x 10^{10} = 1 Tbps

L_{IC} = 0.1 mm B_{eye} = 25 x 4 x 10^{12} = 100 Tbps

Energy dissipation in information processing

) Energy cost for charging conductive wires



U_p > E= CV^2

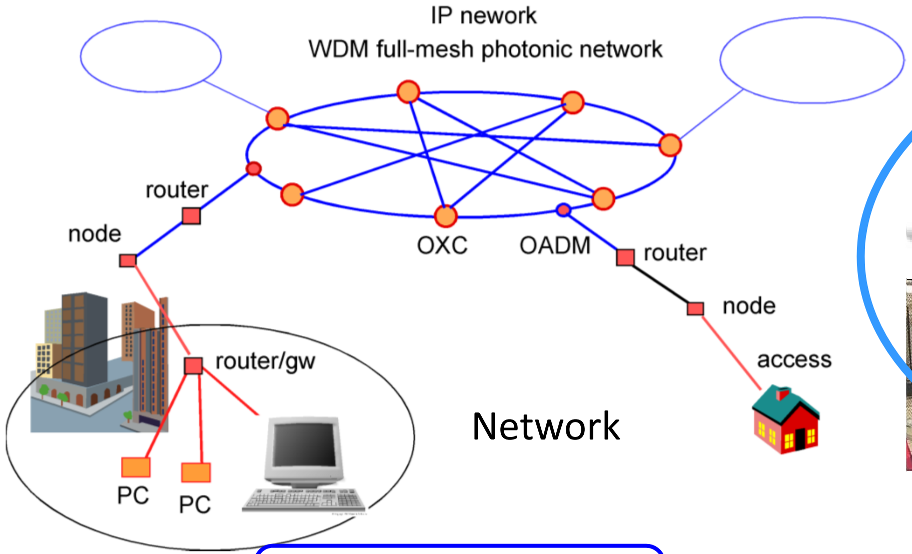
L_{wire} = 1 mm   E= 100 fJ/bit

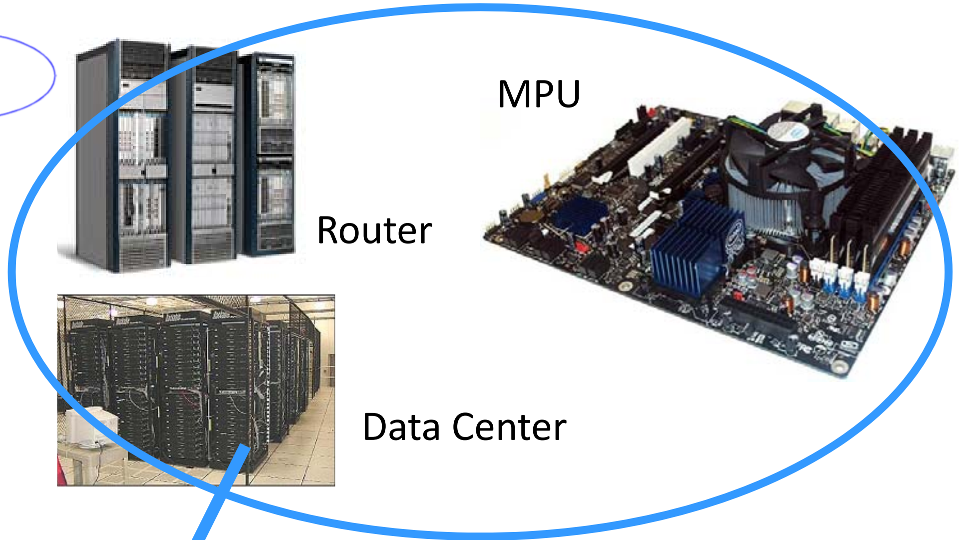
Note: Although this is nothing but conventional EM energy of light pulse, it needs to be irreversibly dissipated for meaningful processing.

Limitation of E-Interconnect

Point 1

The most power is lost during the electric communication.
Electronics is not good at high bit/s communication.





photonics ⟷ **electronics**

Long-haul *WAN* *LAN* *Inter-rack/board* *Chip*

Can we introduce photonic networking?

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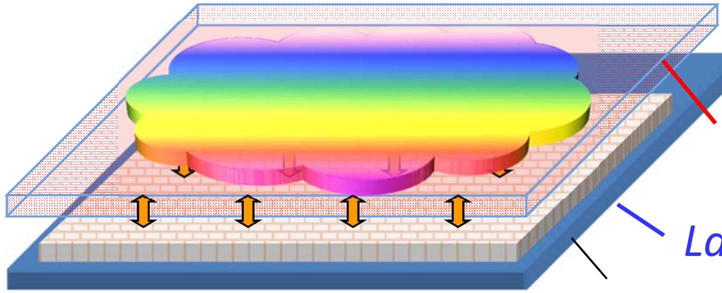
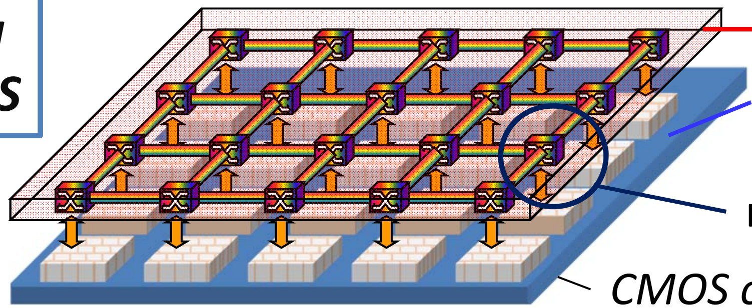
More sophisticated photonic network

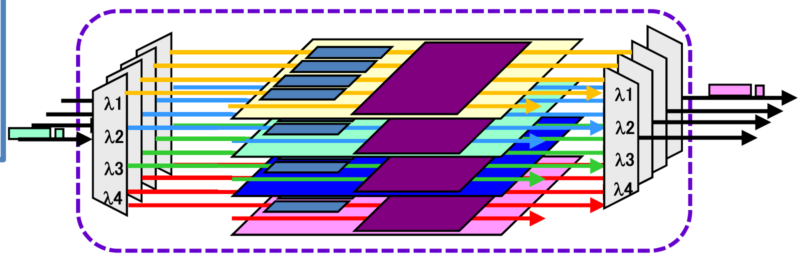
Large-scale MPU unified with photonic network



Photonic routing network on CMOS



One-chip photonic router



Why photonics?

1) Larger BW is possible for a long wire

Signal attenuation

BW does not scale with wire length.

BW can be enhanced by WDM.

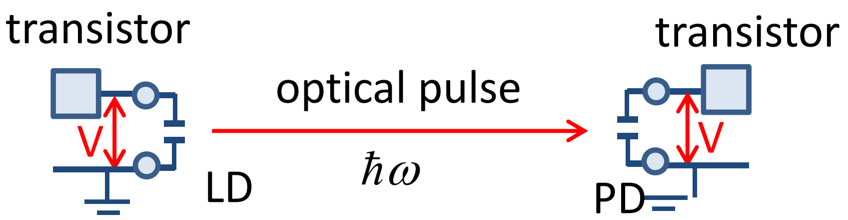
Non-WDM: O-I > E-I when L> 2 mm @10 GHz

100λ-WDM: O-I > E-I when L> 20 μm @10 GHz

prefix	value
micro	10^{-6}
nano	10^{-9}
pico	10^{-12}
femto	10^{-15}
atto	10^{-18}
zepto	10^{-21}

2) No energy cost for transfer (no charging energy)

Logic energy



$U_p = \hbar\omega \approx 0.1$ aJ

A photon can generate ≈1 volt (via photo-electric effect), which is NOT bound by the light intensity (= number of photons).

Energy of propagating photons (U_p) needs to be dissipated, but U is bound only at $\hbar\omega$.

Energy cost for Data transmission

Limitation		
Detector limit (PIN)	Least number of photons 10^4	1 fJ
(APD)	10^3	100 aJ
(+ optical amp.)	10^2	10 aJ
Poissonian limit (perfect detector)	21 @ BER=10^{-9}	3 aJ
Single photon limit	Energy of single photon $E_{photon} = \hbar\omega$	130 zJ
Ultimate limit	Entropy of 1 bit $E_{min} = \ln 2\, kT$	3 zJ

femt = 10^{-15}

atto = 10^{-18}

zepto = 10^{-21}

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Electronics vs. Photonics

Point 2

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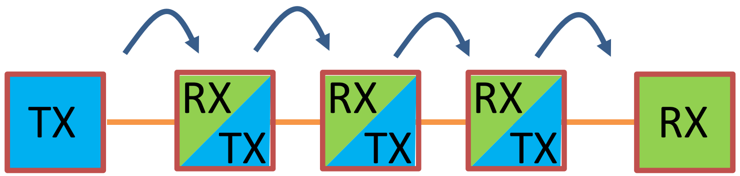
Photonic data transmission energy is extremely small.
Photonics is good at broadband communication.

ELECTRONICS



- Every single bit is buffered received and retransmitted at every switch
  (Limitation of Traditional NoC)
- Power dissipation is BW & Length dependent
  (Limitation of Metal wire-line)

PHOTONICS

- Data streams once.
  No retransmit.
- Nearly free power dissipation
  Broad band.

TX : Transmitter
RX : Receiver

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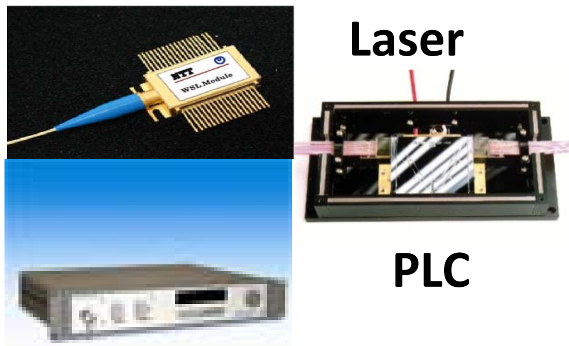
Evolution of Photonics

Electronics

tube → transistor → IC → LSI → Multi-core Many-core

Photonics



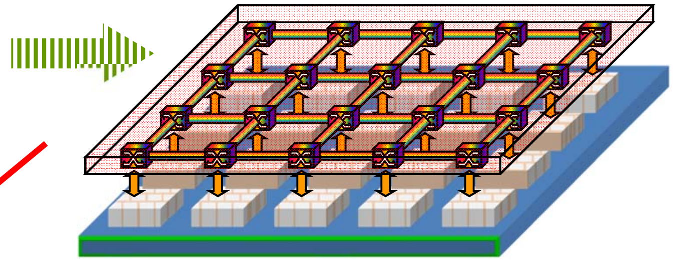
Laser

PLC

Fiber amp.

? → ~~Photonic ICs~~

Photonic network layer



CMOS layer

Large-scale photonics fused with CMOS

No mature photonic integration tech.

Major Problems in Photonic Integration

1. **Assembly cost**

   Established.

2. **Fabrication cost**

   Being explored by Si photonics.

3. **Low energy cost for data transmission**

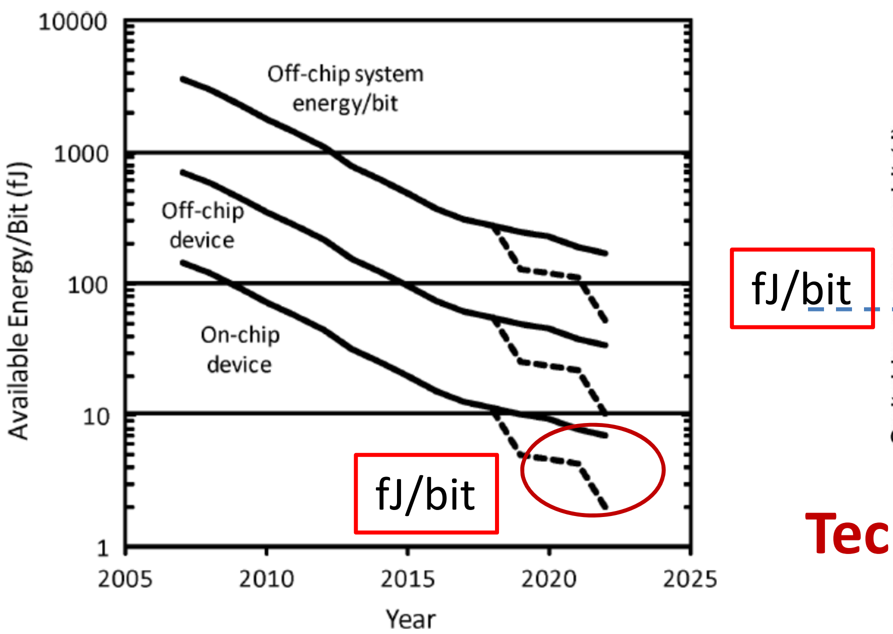
   Becoming a significant issue....,
   but how much should we reduce?

4. **Larger scale & higher density**

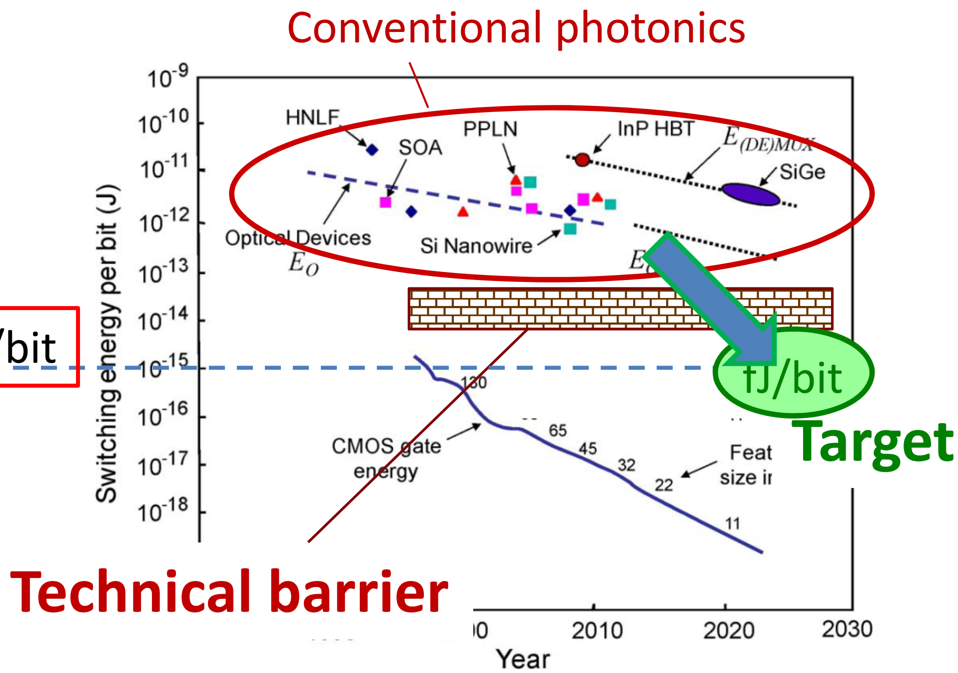
   Do we really need large-scale photonics?

Energy Cost for Information Processing

Required energy cost



Miller, *Proc. IEEE* (2009).



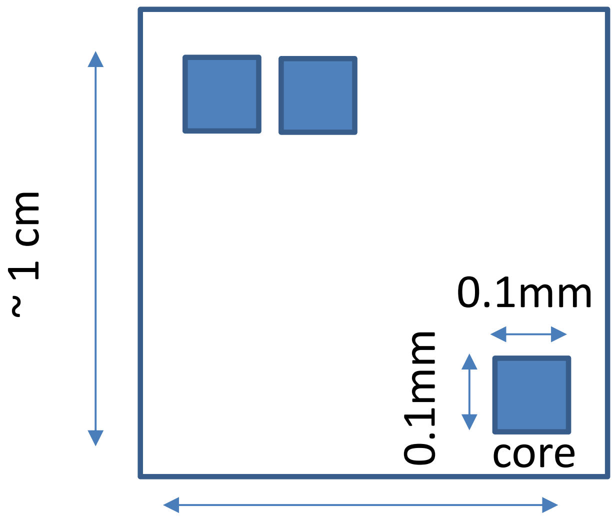
Tucker, *IEEE* Photonics Journal (2011).

Small transmission energy, but high processing energy

Large-scale Integration

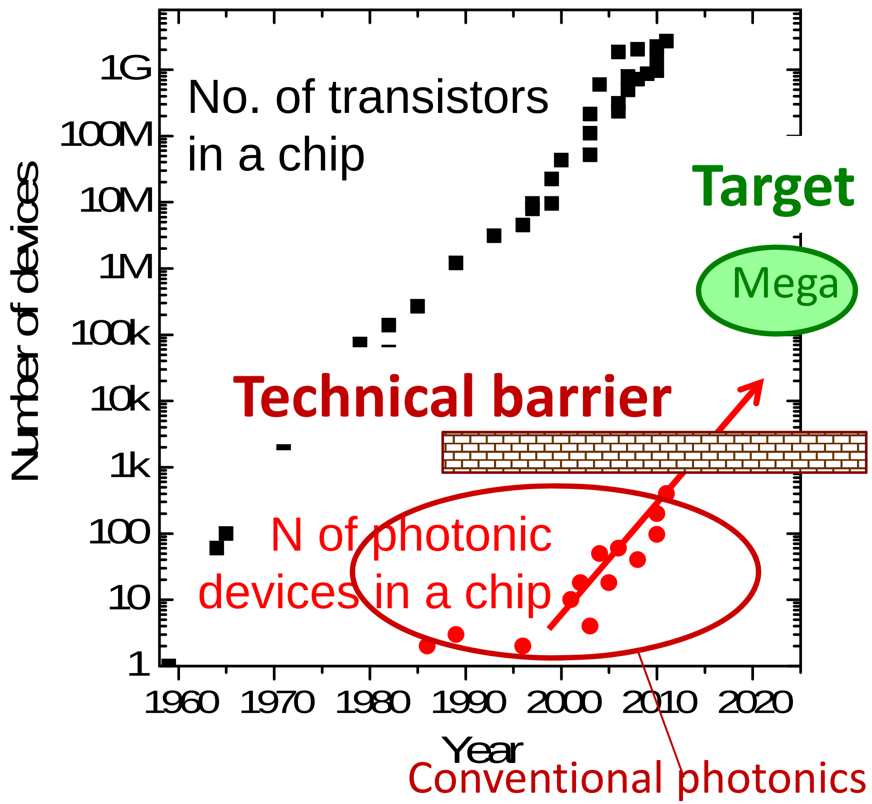
Required footprint

Device no. = 10 [/core/ch] = 10^7
Device size = 10 [μm^2]



100 channel WDM networks in 100 x 100 cores

Moore's law



Large footprint limits integration scale

M. Notomi et al.
Optics Communications 314 (2014)

What technology should we use?

Point 3

We will need integratable nanophotonic devices with ***ultralow power consumption***

Energy cost: ≈ fJ/bit

Footprint: ≈10 μm^2

Available technologies

Silica PLC

InP-based PIC

Si photonics

Photonic crystal

Plasmonics

Nanophotonics

Issues to be met

1. **Footprint: μm^2**
2. **Energy consumption: fJ/bit**
3. **Loss: 2dB/cm**
4. **Integratability: Yes**
5. **NoC management: Maybe**
6. **Cost: Maybe**

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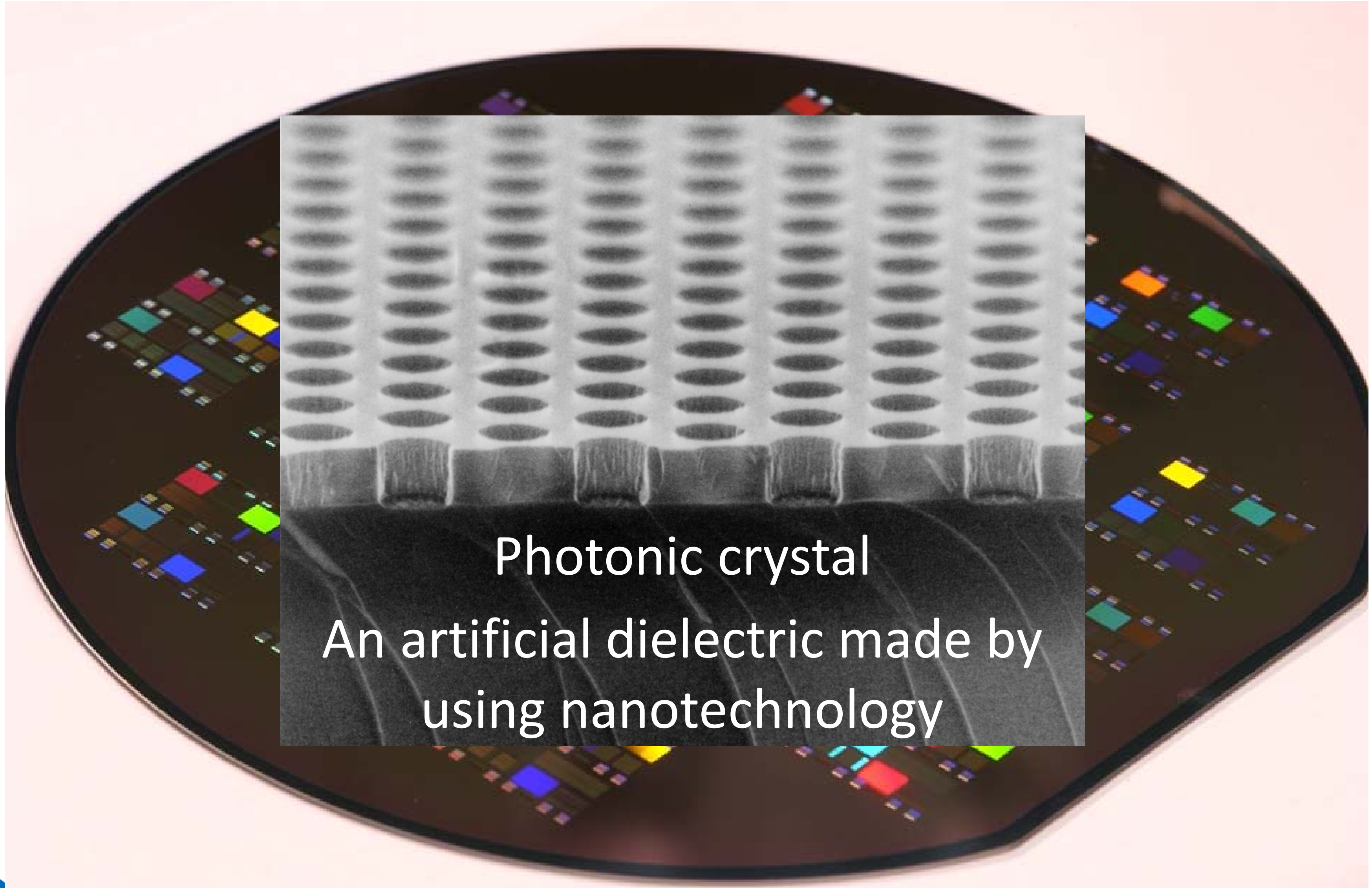
- **Photonic crystal**
- Conclusion

Photonic Crystal



What is photonic crystal?

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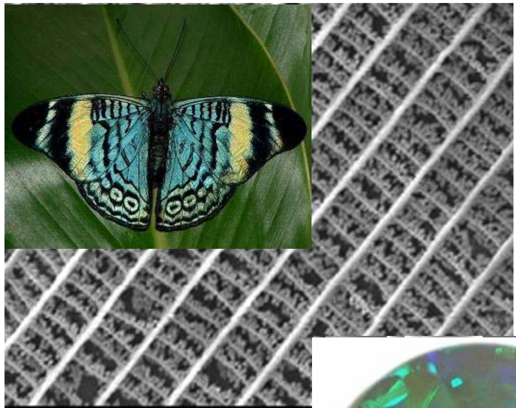
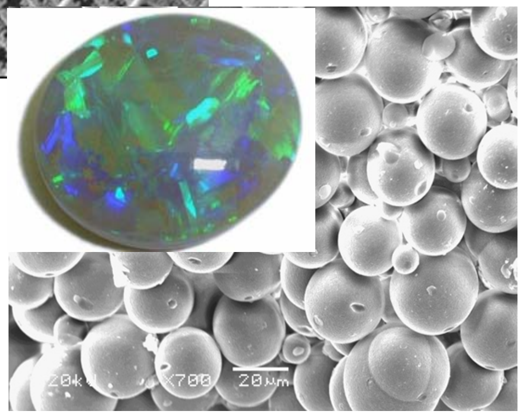
Natural Photonic Crystal

Butterfly

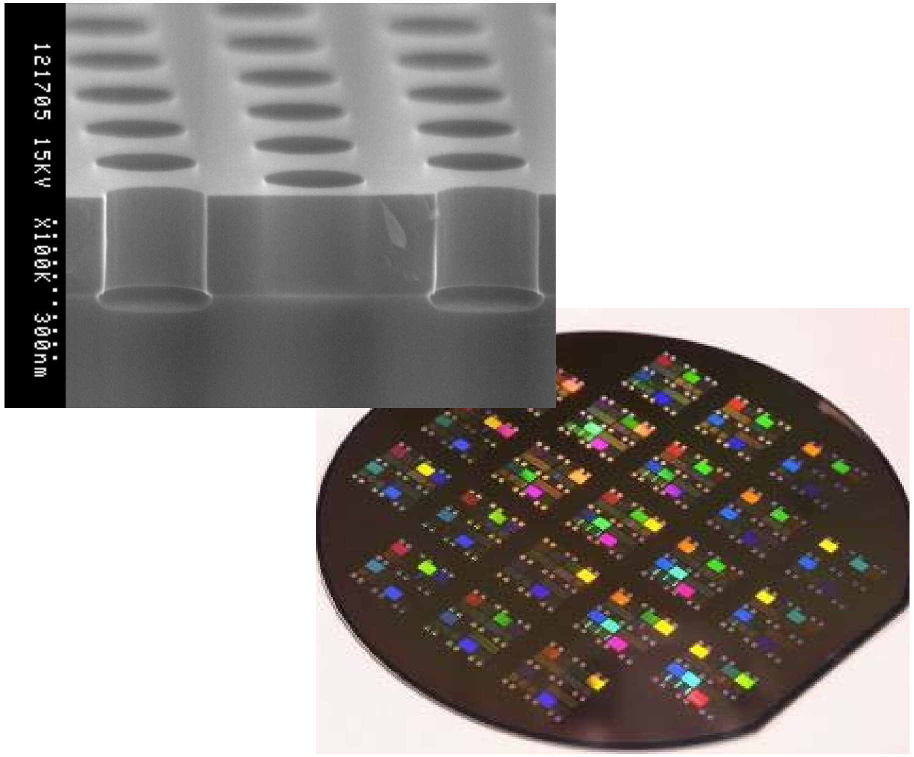


Opal

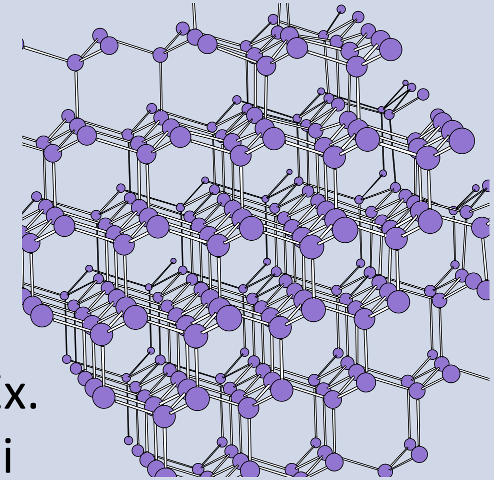
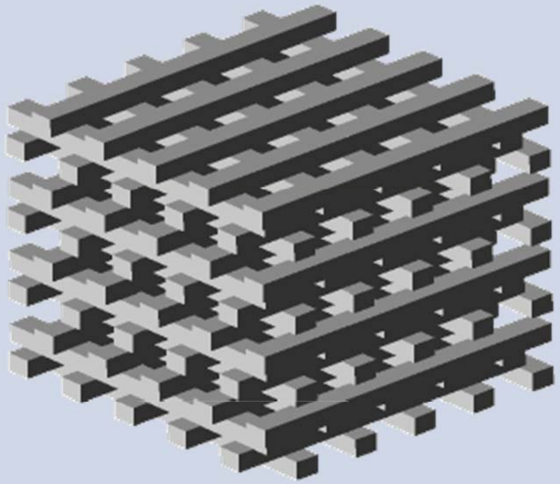


Artificial Photonic Crystal

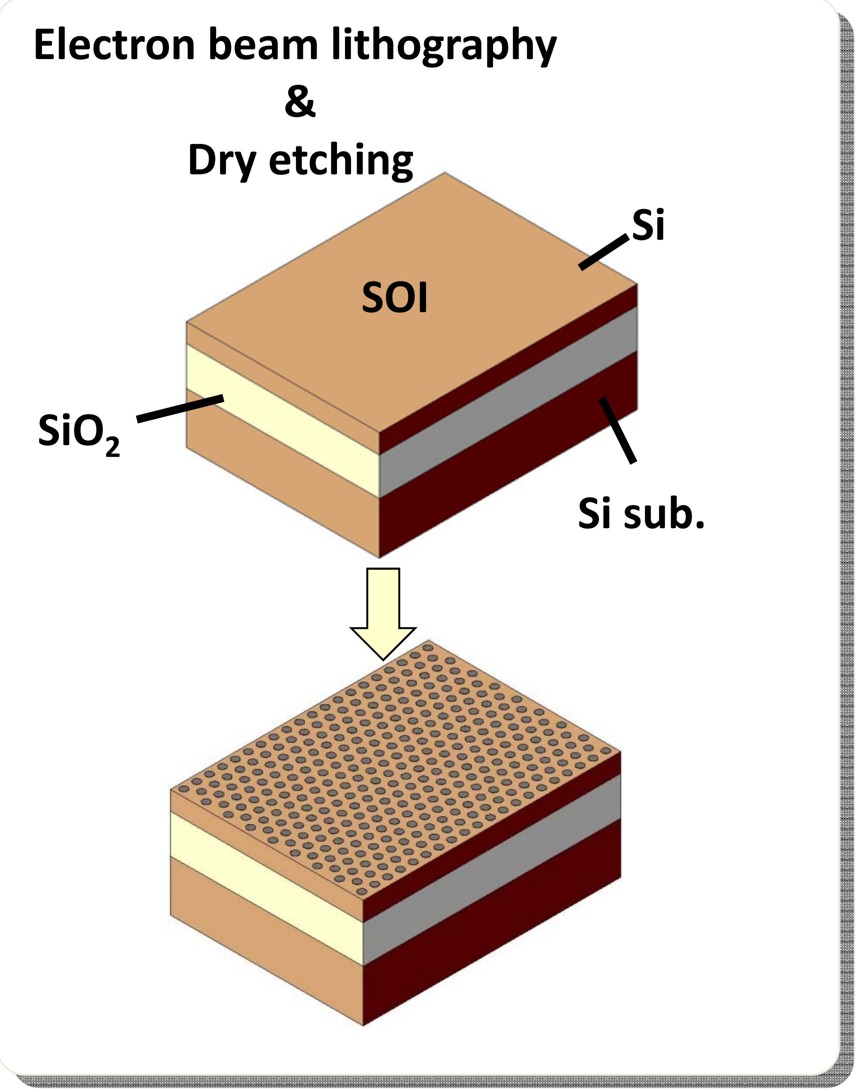
Photonic crystal on Si wafer

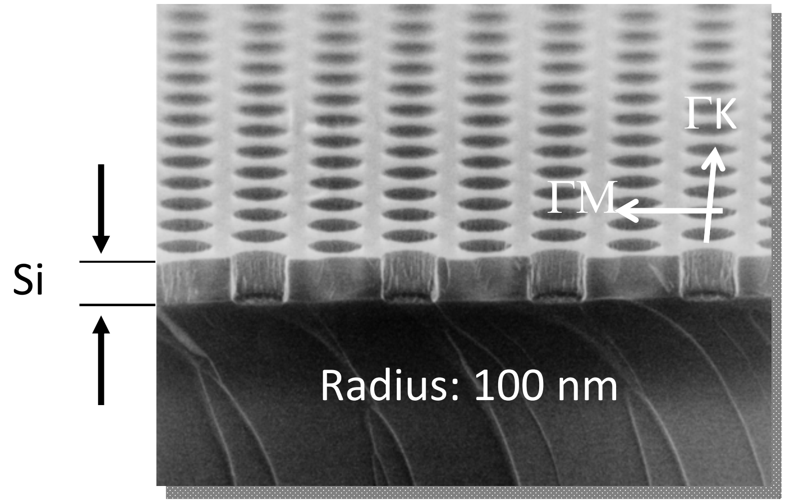


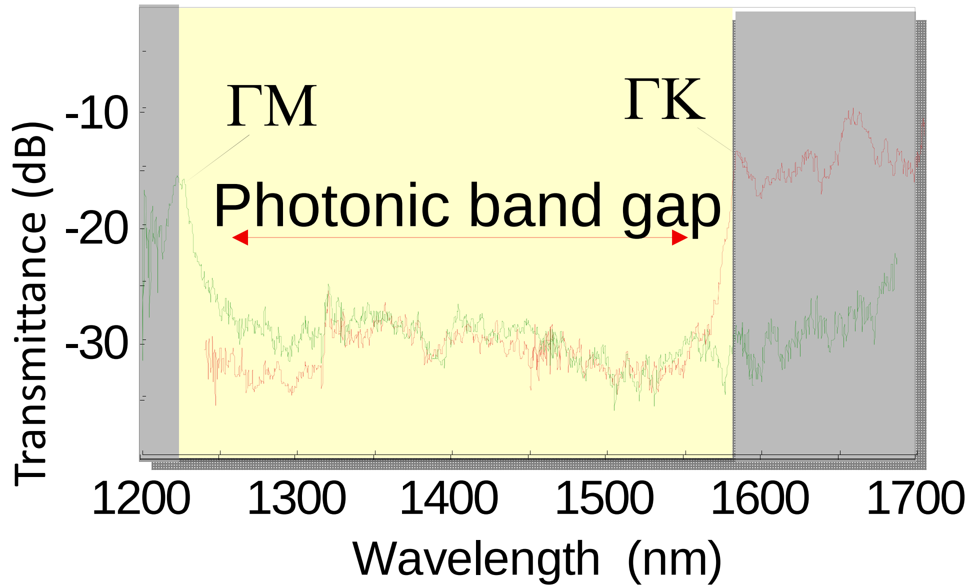
Analogy between Electronic and Photonic Crystal

Electronic crystal	Photonic crystal
 Ex. Si	
Period ~ 0.1nm = electronic wavelength	Period ~ 100 nm = optical wavelength
Various electrical properties ● Conductor ● Semi conductor ● Insulator	New optical properties ● Optical insulator ● Slow light ● Negative refraction

2D Photonic Crystal

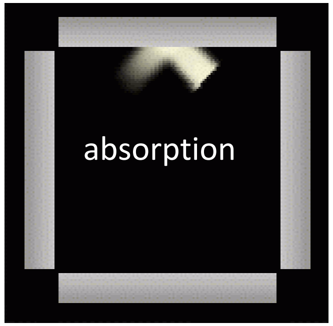






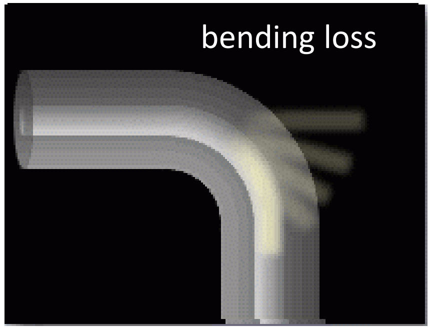
Why photonic crystal?

Metal mirror



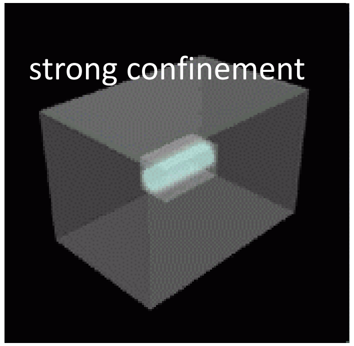
Optical absorption

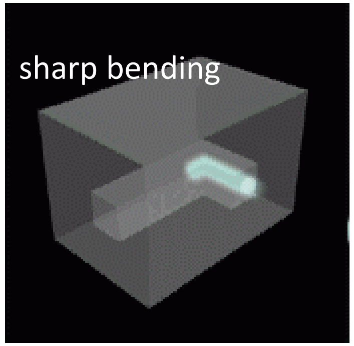
Fiber



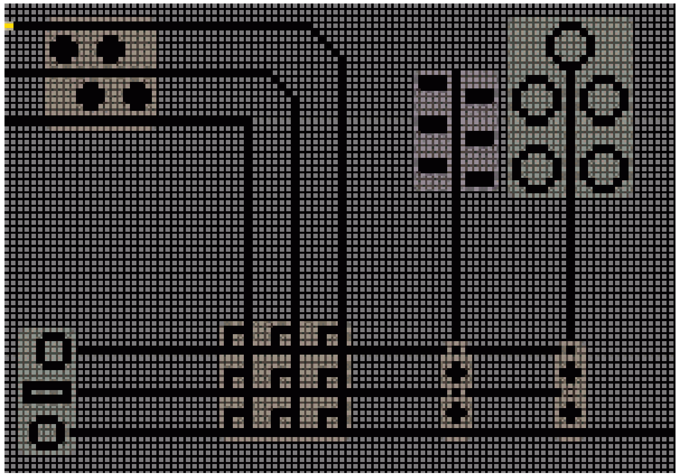
Leakage at bending

Photonic crystal



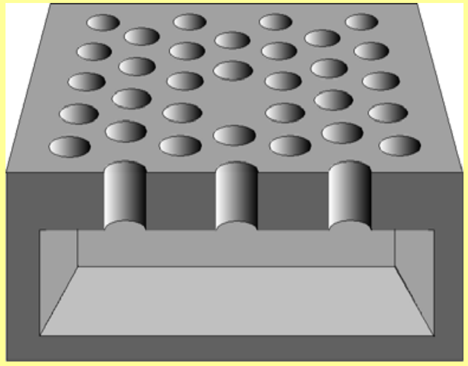


Light is completely confined



Large-scale
photonic integration

What can photonic crystals do?

Toroid cavity	Micro-disk	Micro-post	**Photonic Crystal**
			
V = >100$(\lambda/n)^3$ Q = 10^8	$V = 6(\lambda/n)^3$ Q = $\mathbf{10^3 - 10^6}$	$V = 5(\lambda/n)^3$ Q = $\mathbf{10^3}$	$\mathbf{V = 0.5\text{-}1.5\ (\lambda/n)^3}$ $\mathbf{Q = 10^5\text{-}10^6}$

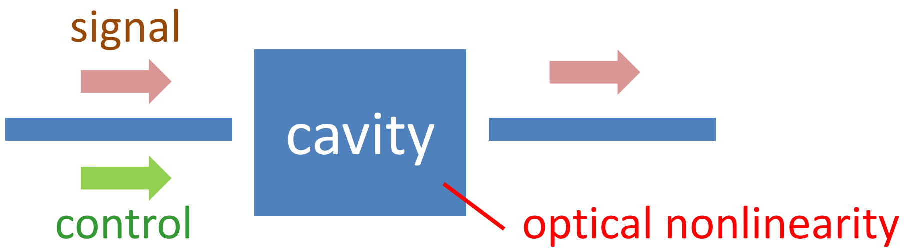
(λ/n): light wavelength in cavity

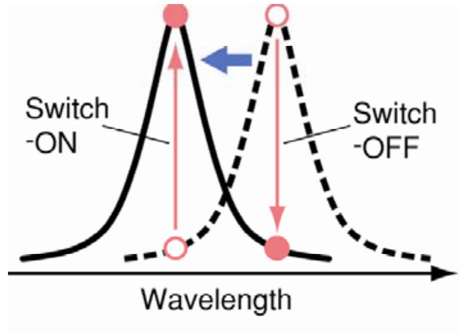
Ultrasmall high-Q cavity

Small footprint (~ μm²)
Strong light-matter interaction

→ **fJ/bit & Mbit photonics**

Q/V Scaling in Photonic Devices





Light intensity per unit input power
Interaction time per unit volume
Photonic DOS per unit volume

~Q/V

Switching energy

$$U_{sw} = \frac{\varepsilon_0 \varepsilon n}{2n_2} \frac{V_{cav}}{Q}$$

Power consumption of optical memory

$$P_{bias} = \frac{\varepsilon_0 \varepsilon n \omega}{2n_2} \frac{V_{cav}}{Q^2}$$

Threshold current of laser

$$I_{th} \approx \frac{e}{\tau_c} \left(\frac{\omega V}{g' Q} + N_0 V_c \right)$$

Driving current of modulator

$$I_{\mathrm{mod}} \approx \frac{en}{\sigma \tau_c} \frac{V}{Q}$$

See Notomi et al. IET Circuits, Devices & Systems (2011)

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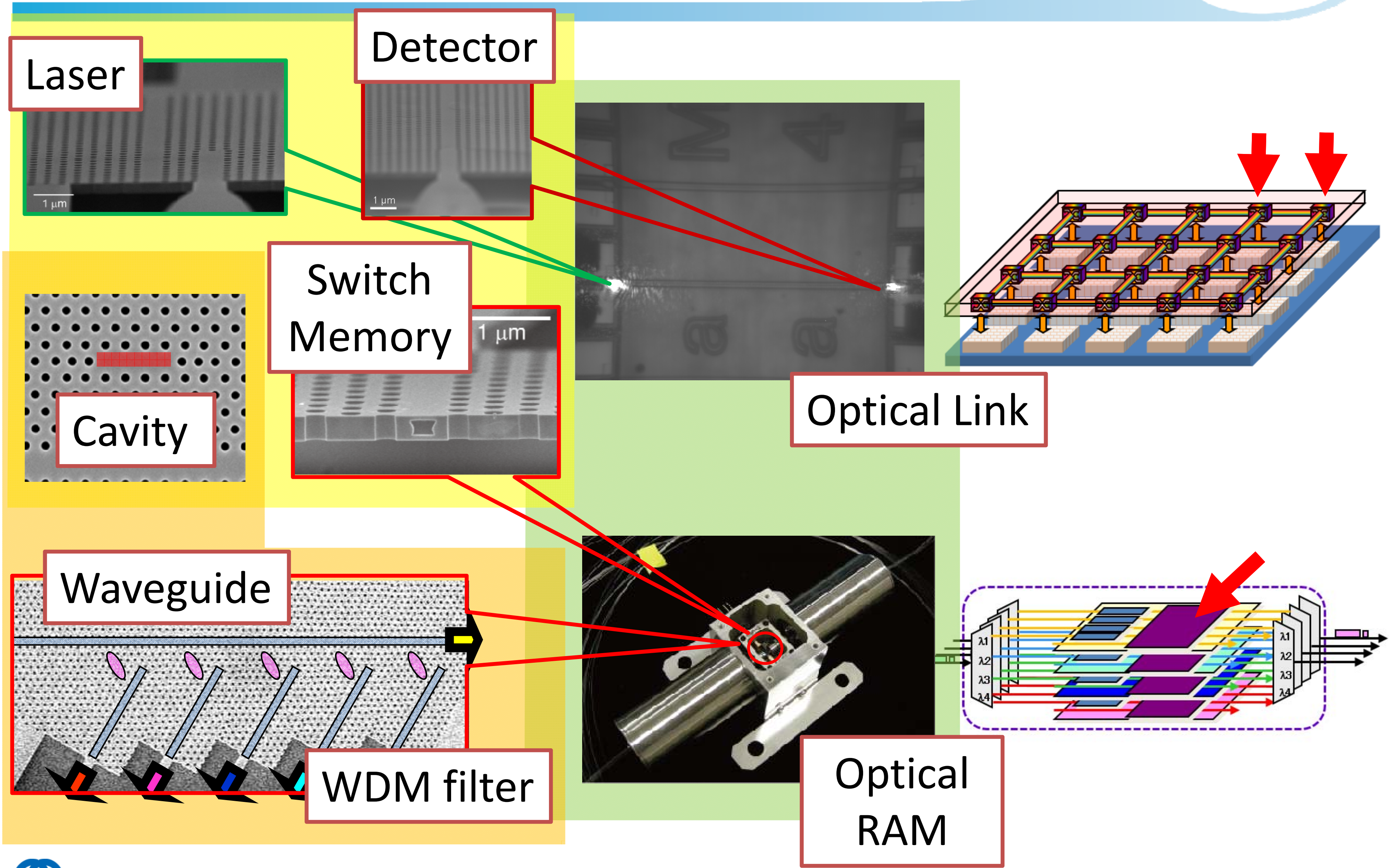
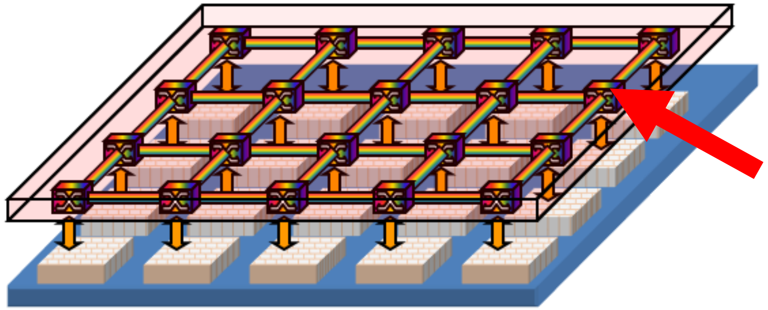
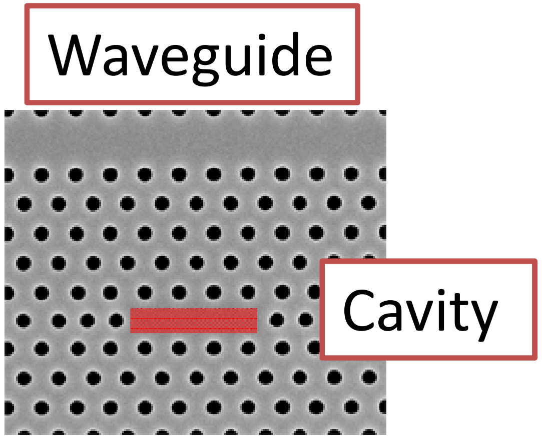
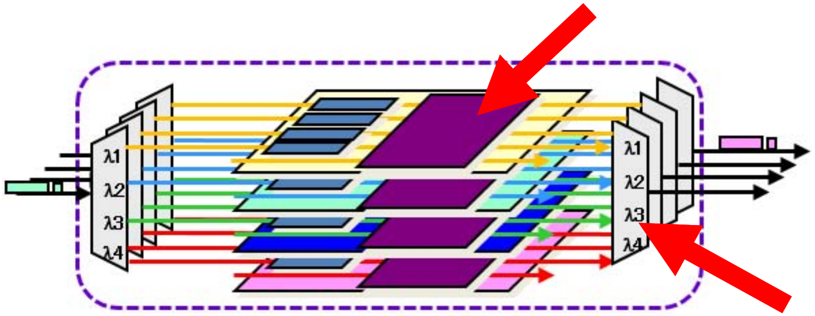
Elementary Building Blocks

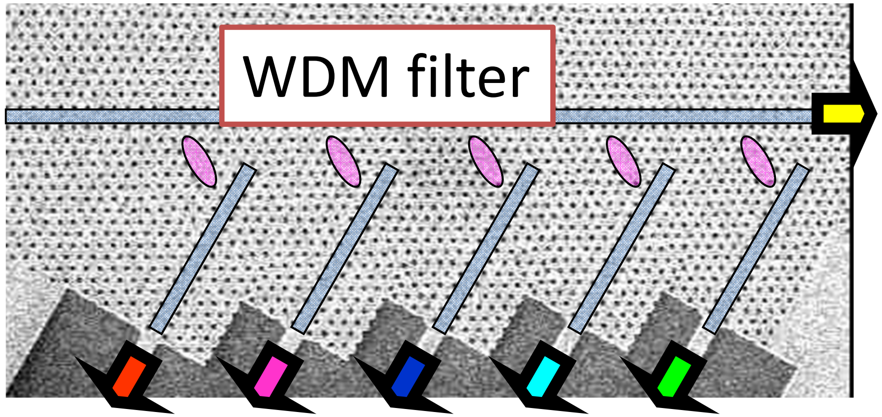


Passive devices

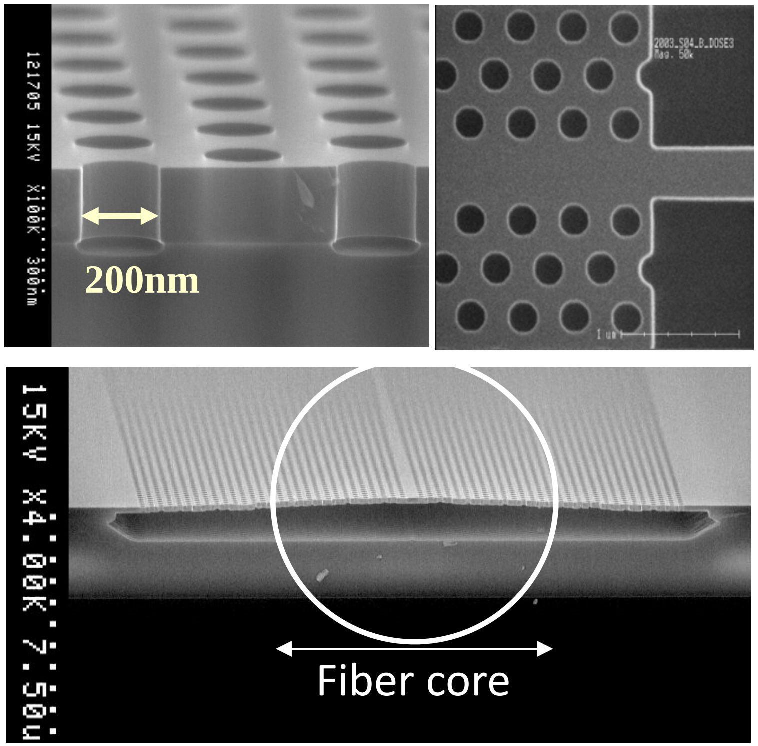




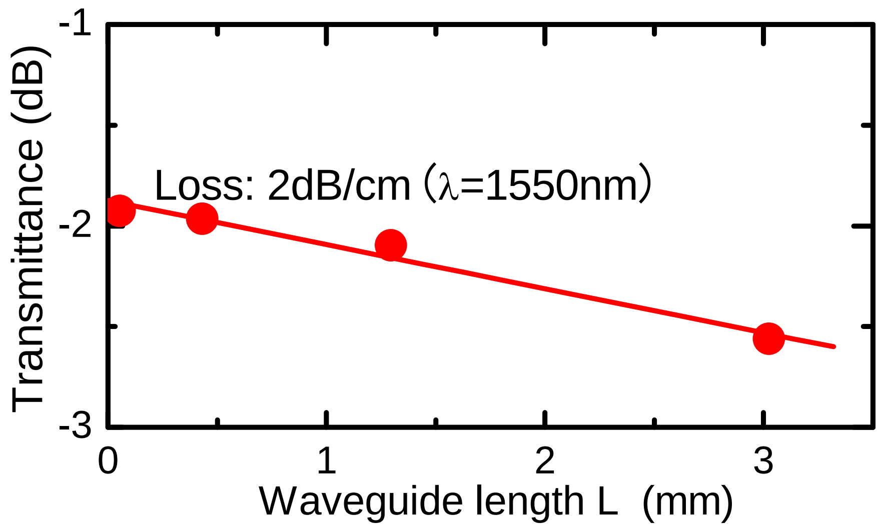




Low-loss Optical Waveguides



Disorder of sidewall：<2 nm (RMS)

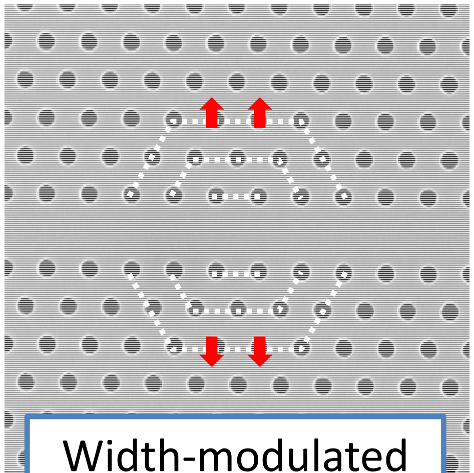


2dB/cm is record loss data as a photonic crystal slab waveguide.

Ultrahigh-Q Nanocavity

Tanabe et al. Nature Photonics (2007)

1 μm

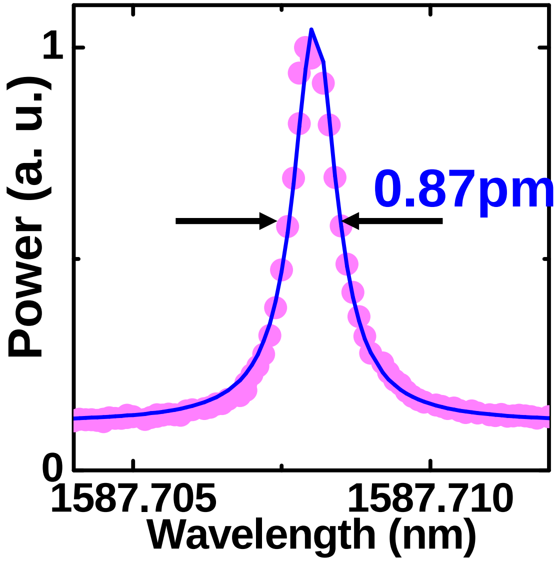


Width-modulated line defect cavity

V: 1.5 $(\lambda/n)^3$

Spectral measurement

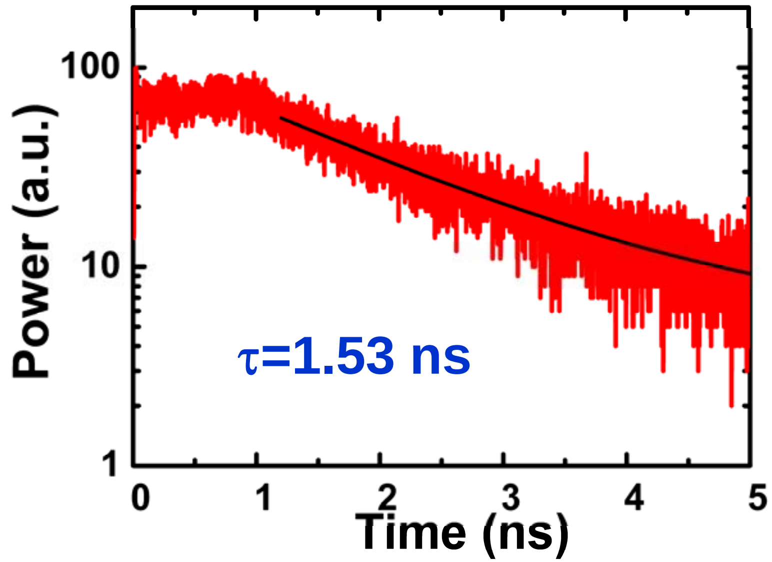
Q = 1.8x10^6



(accuracy <0.06 pm)

Time-domain measurement

Q = 1.8x10^6



$Q_{unloaded}$~2 x 10^6

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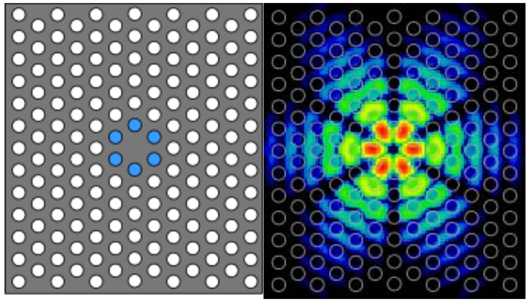
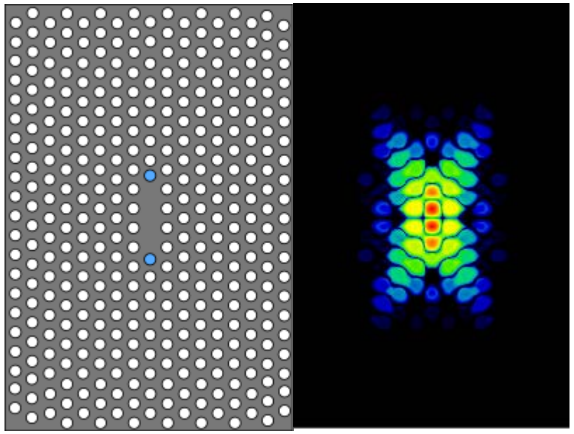
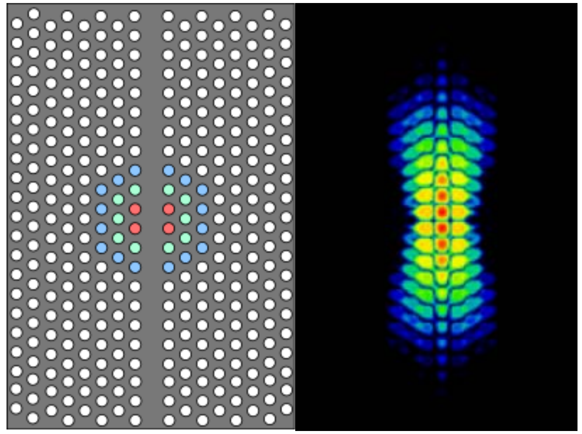
Ultrasmall High-Q Cavities



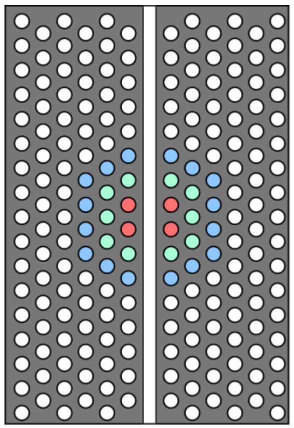
$Q = 2 \times 10^6$, $V = 1.1 (\lambda/n)^3$

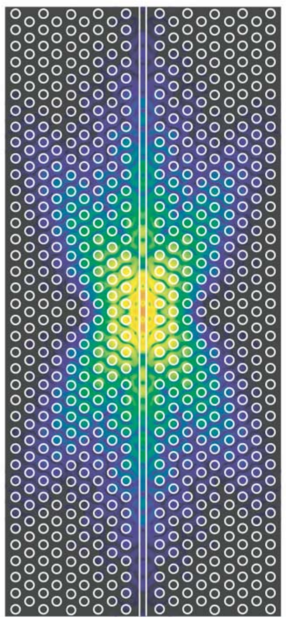


$Q = 2 \times 10^5$, $V = 0.7 (\lambda/n)^3$

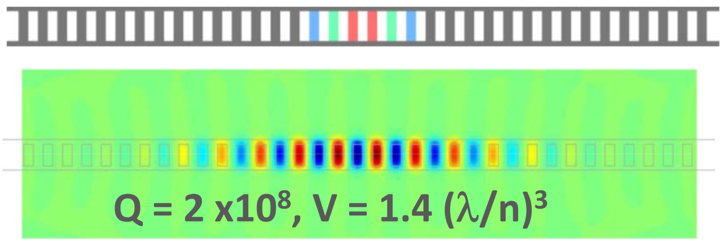


$Q = 2 \times 10^8$, $V = 1.6 (\lambda/n)^3$

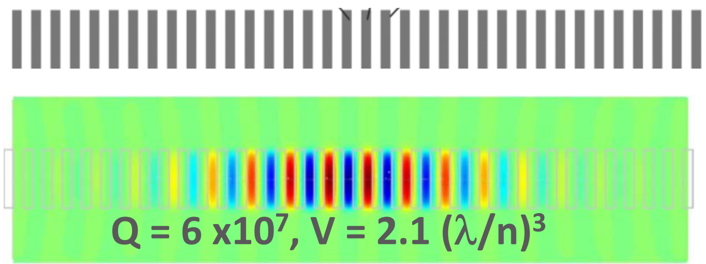




$Q = 6 \times 10^6$,
$V = 0.02 (\lambda/n)^3$

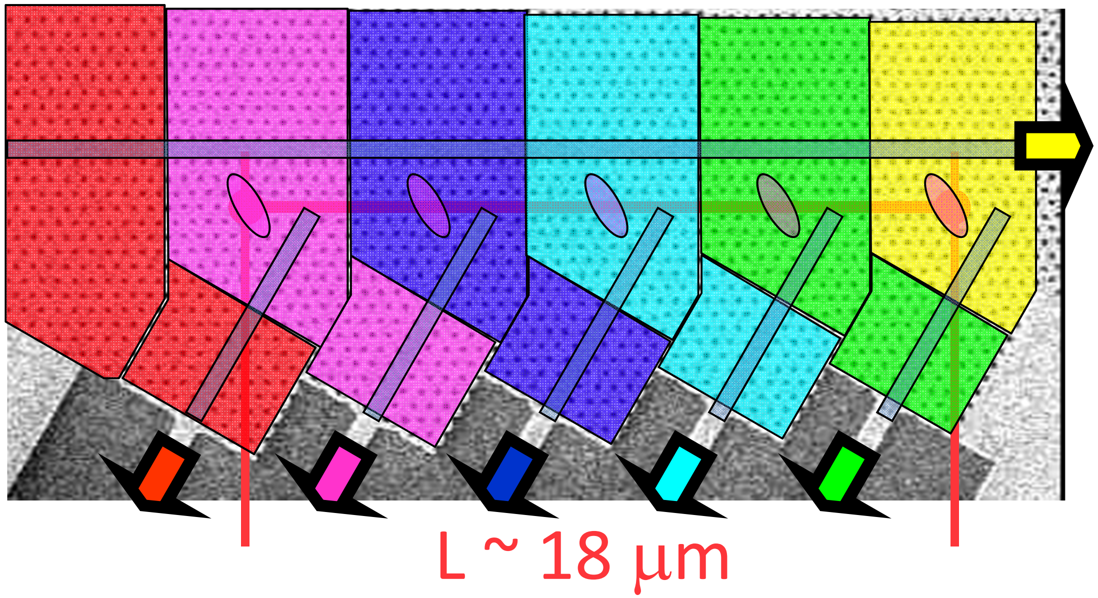


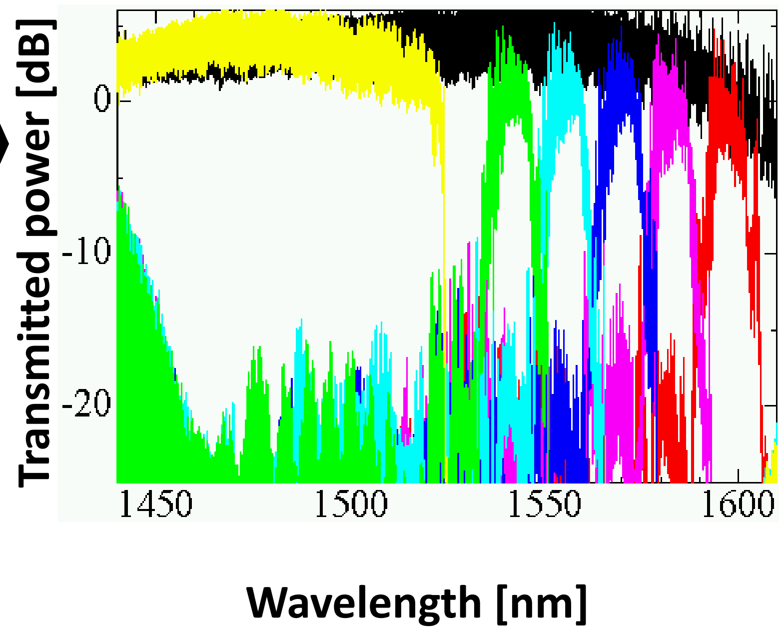
$Q = 2 \times 10^8$, $V = 1.4 (\lambda/n)^3$



$Q = 6 \times 10^7$, $V = 2.1 (\lambda/n)^3$

Compact Multichannel Drop Filter

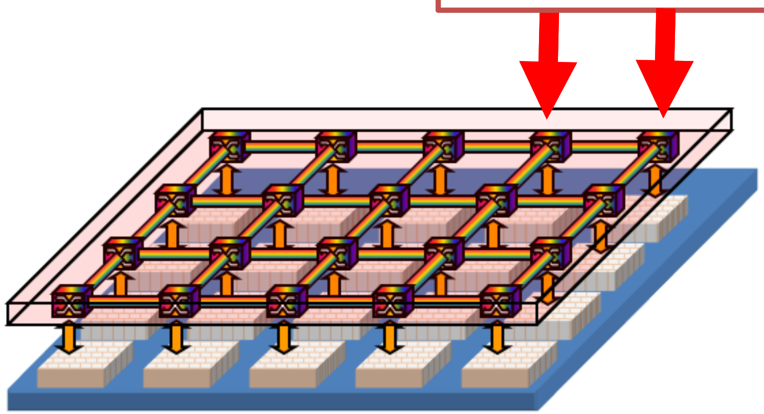


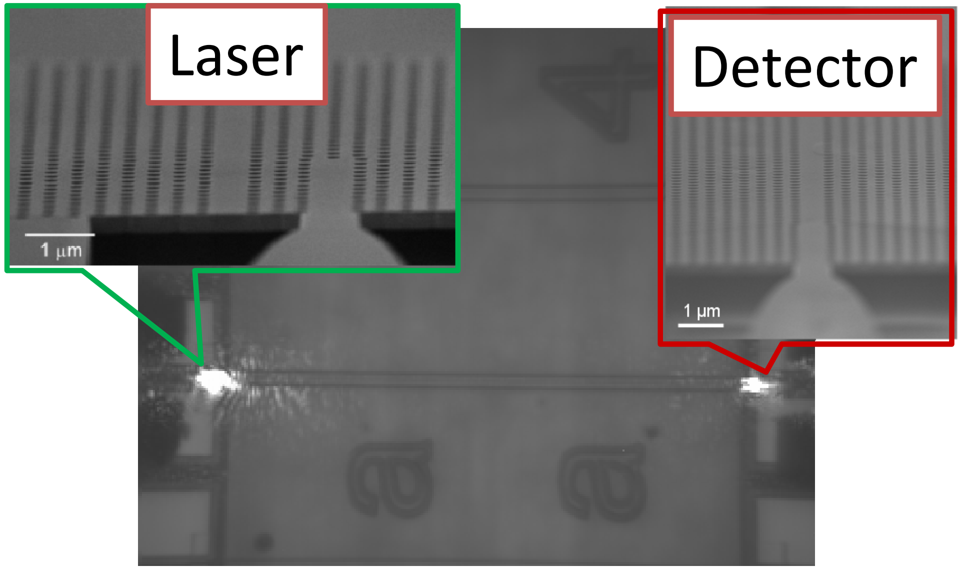


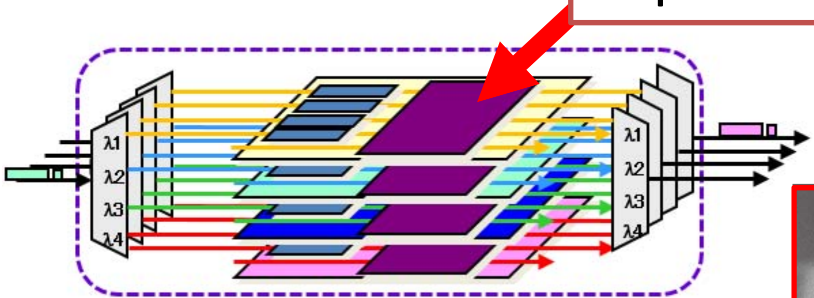
Demonstration of compact WDM filter on a chip

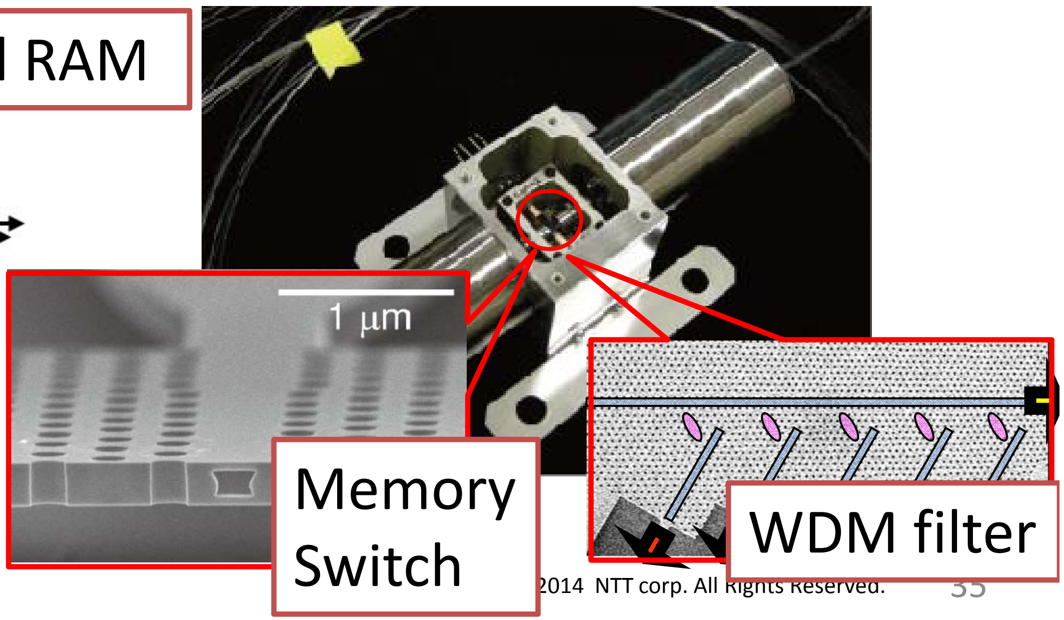
Shinya et al. Opt. Express (2006)

Photonic Integrations

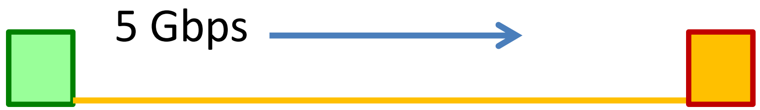




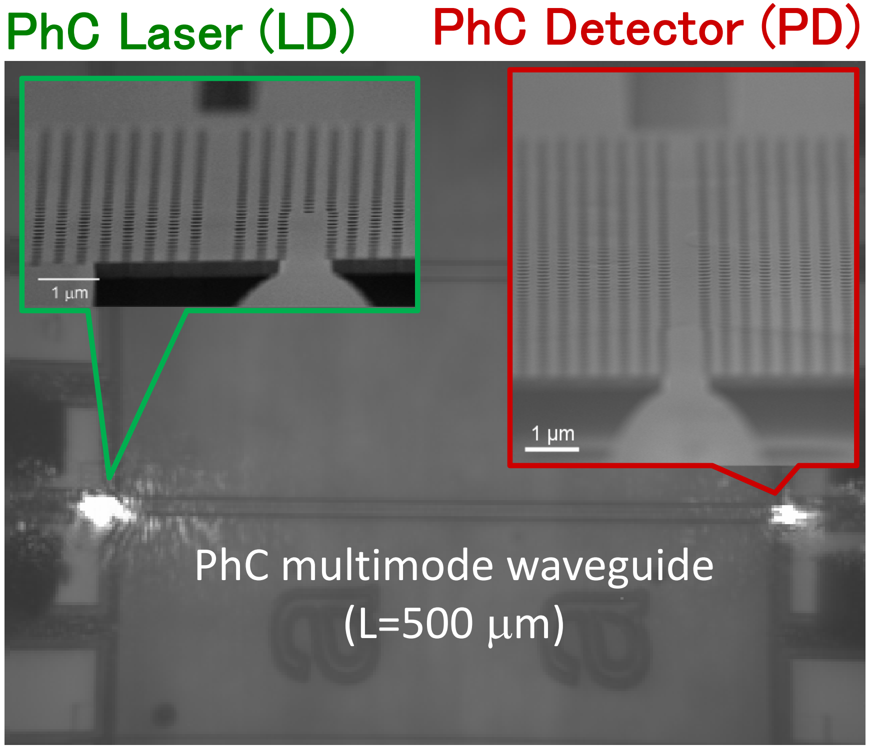


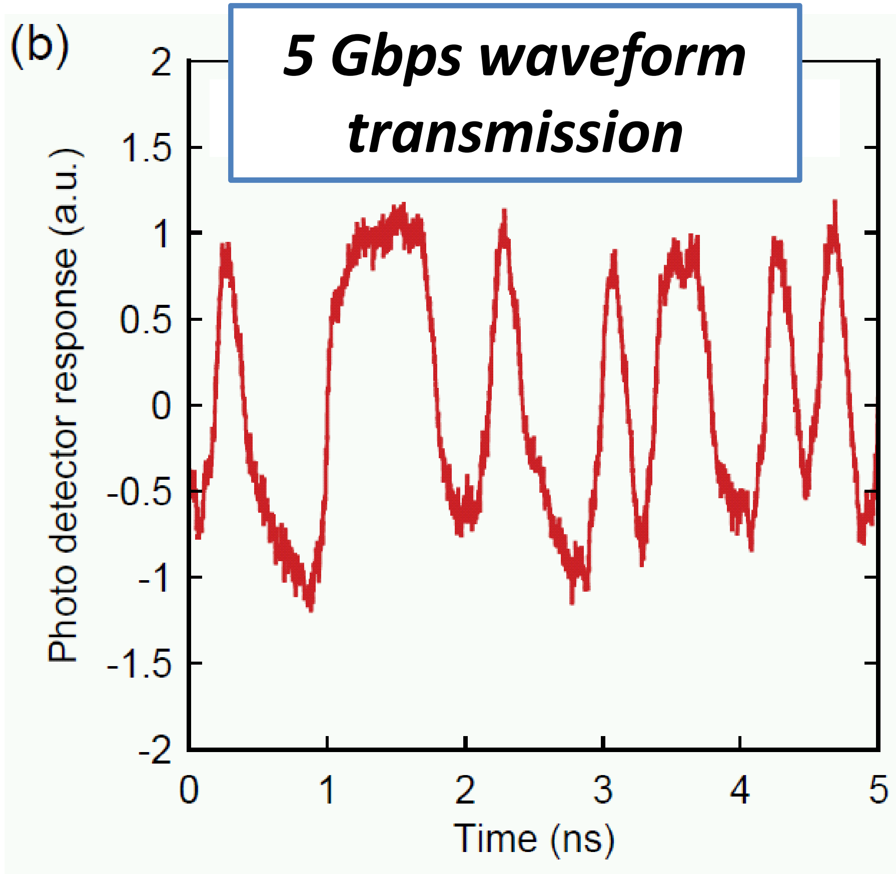


Monolithically Integrated Link



Takeda et al. OFC (2013)



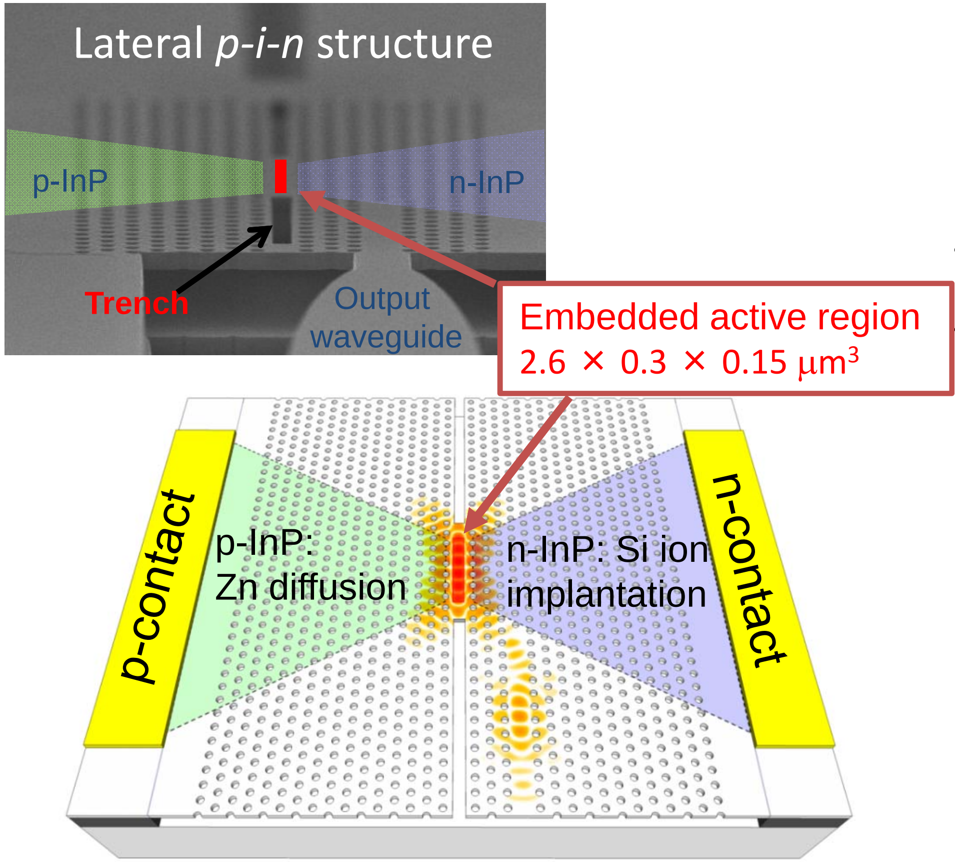


LD: V_b=1.7 V, I_b=51 µA, V_{pp}=0.5 V
PD: V_b=-1 V
Without 50-Ω termination

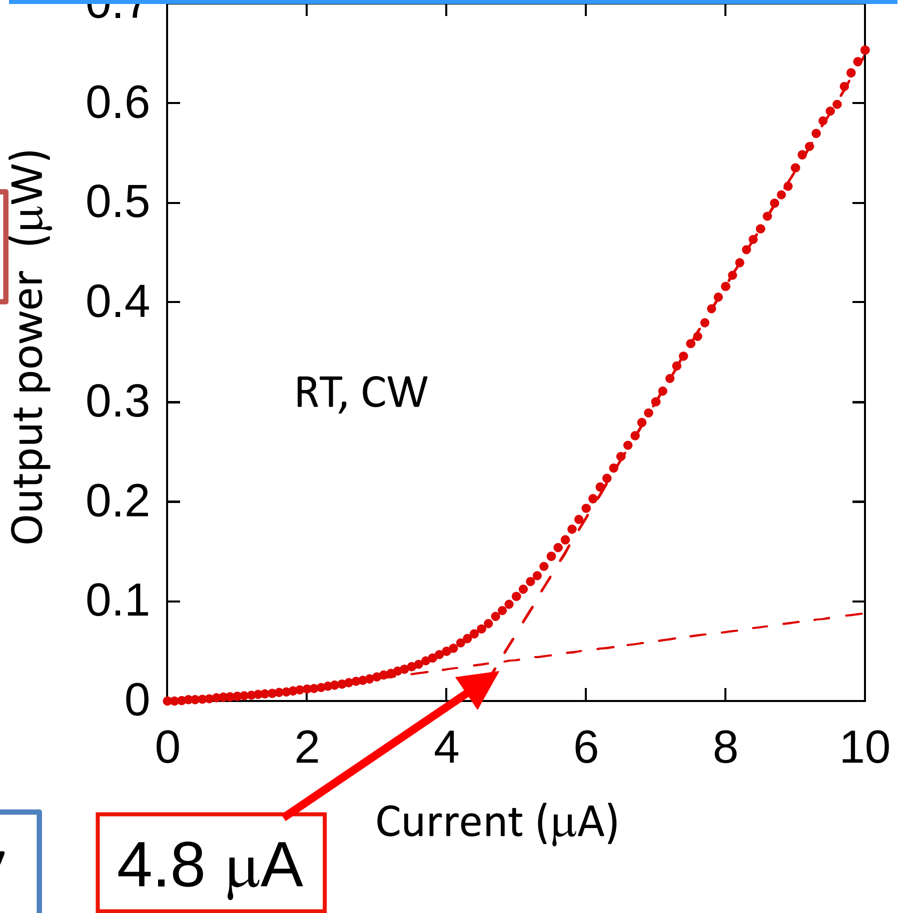
Energy cost (LD): 17.3 fJ/bit

NTT

Ultralow-threshold Laser

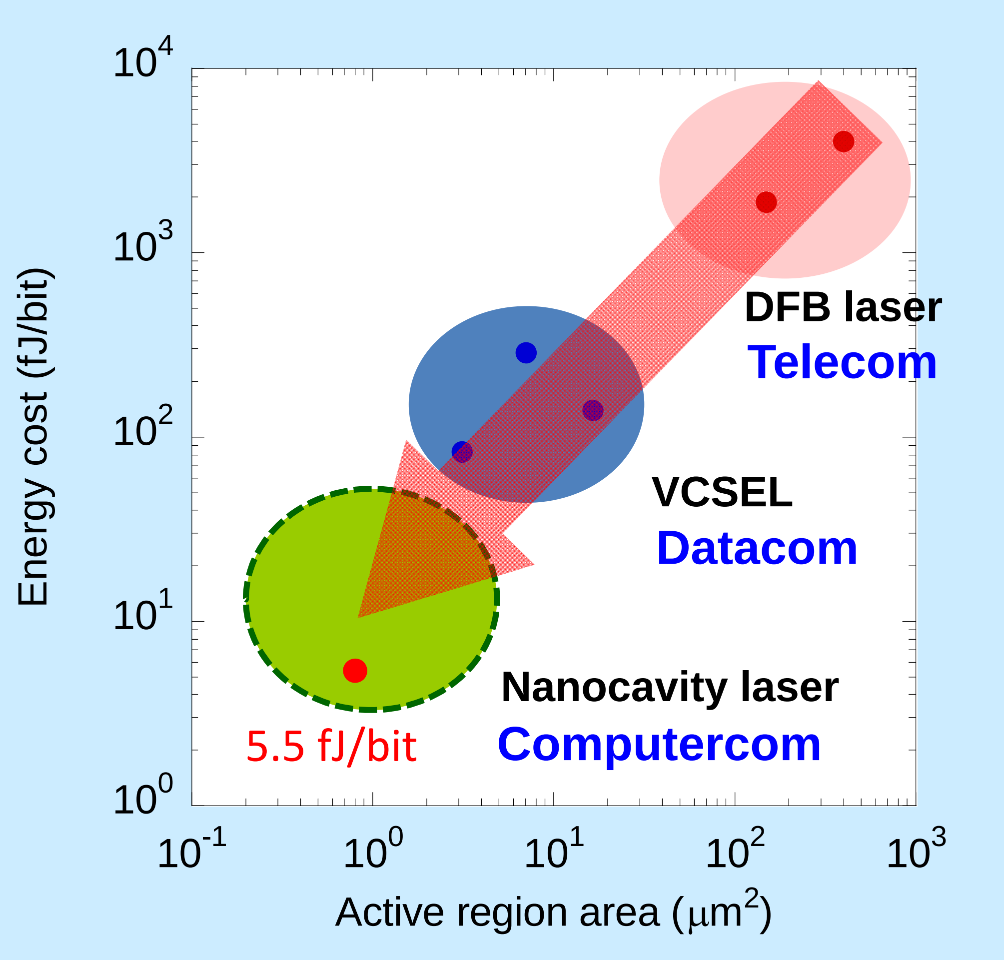


Takeda et al. Nature Photon. 7, 569 (2013)



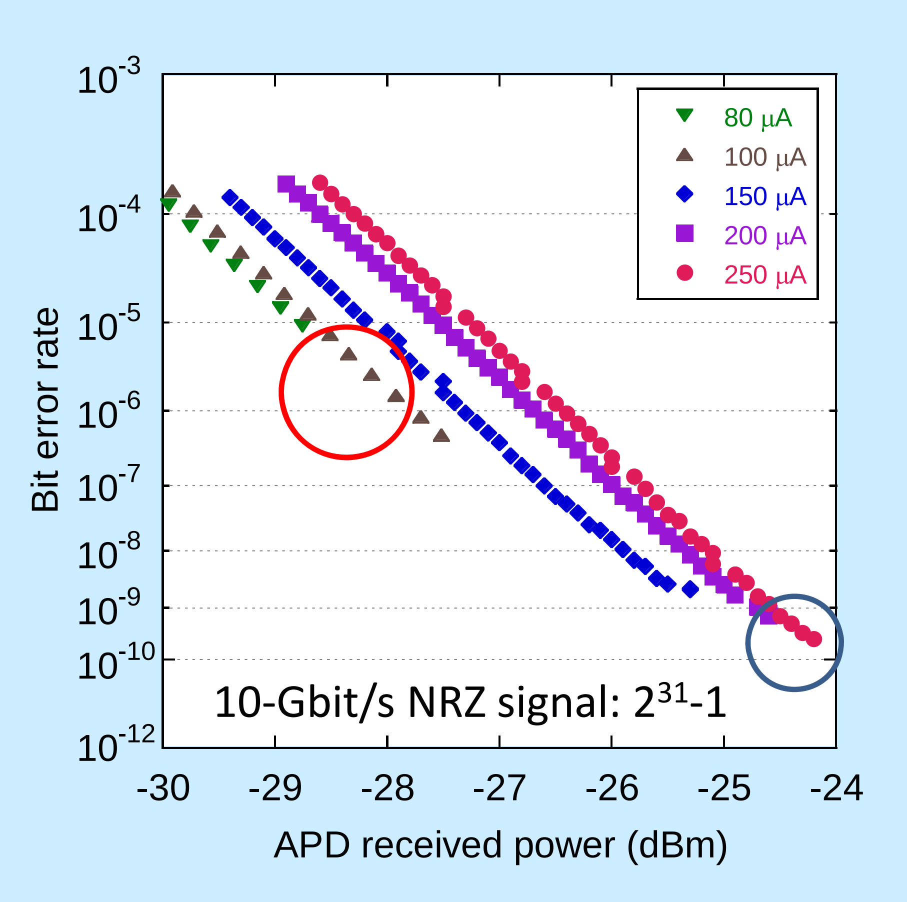
World's lowest threshold for any type of laser diode

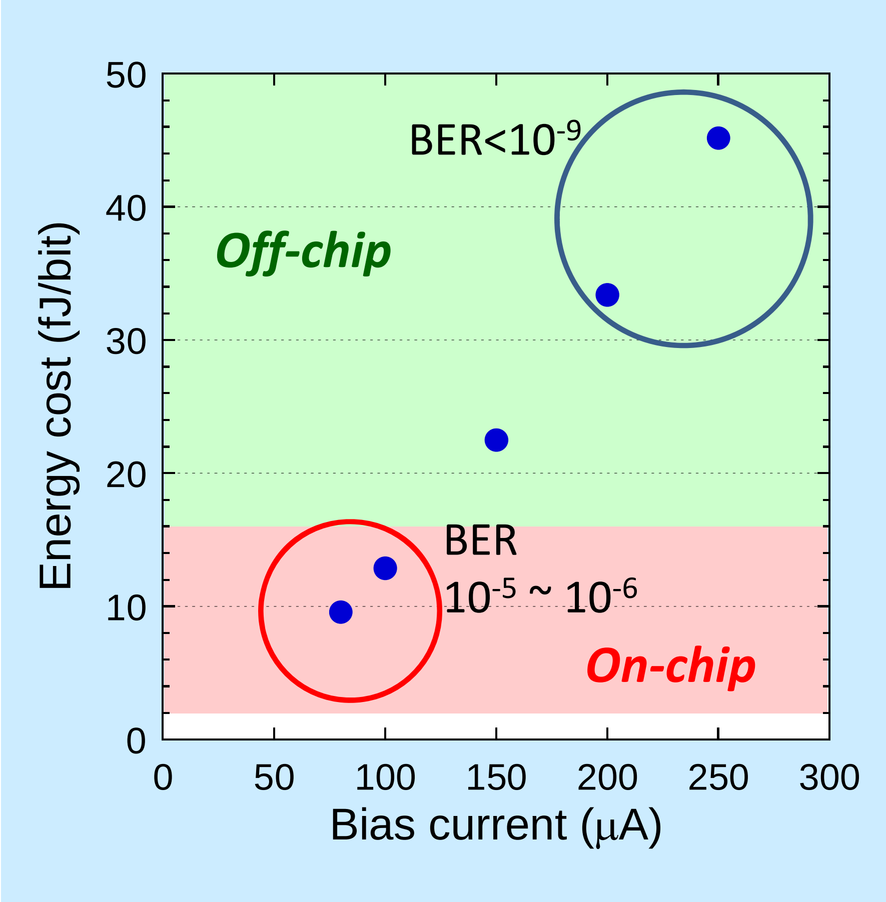
Energy Cost vs. Active Volume



Bit Error Rate Measurement

w/o 50-Ω termination & optical amplifier

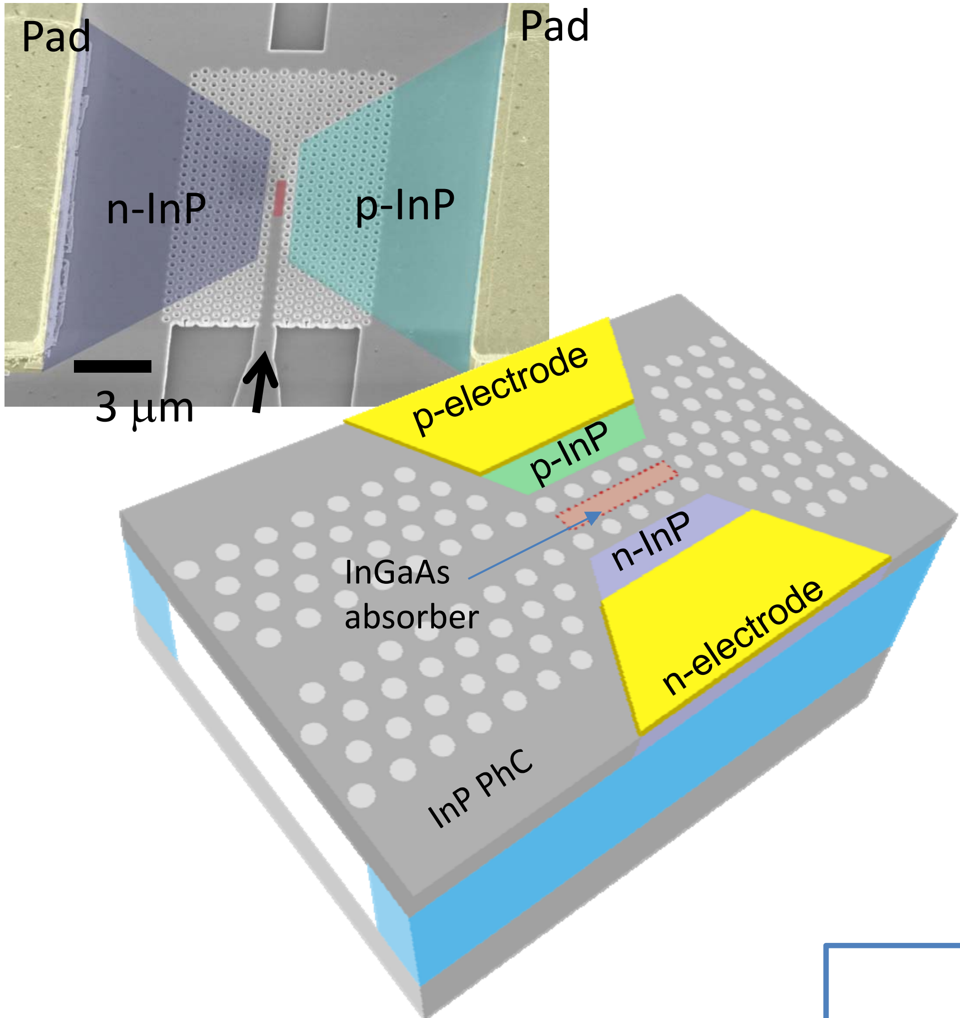




- ✓ ***BER < 10^{-9}*** @ 200&250 μA
- ✓ Limited by coupling loss

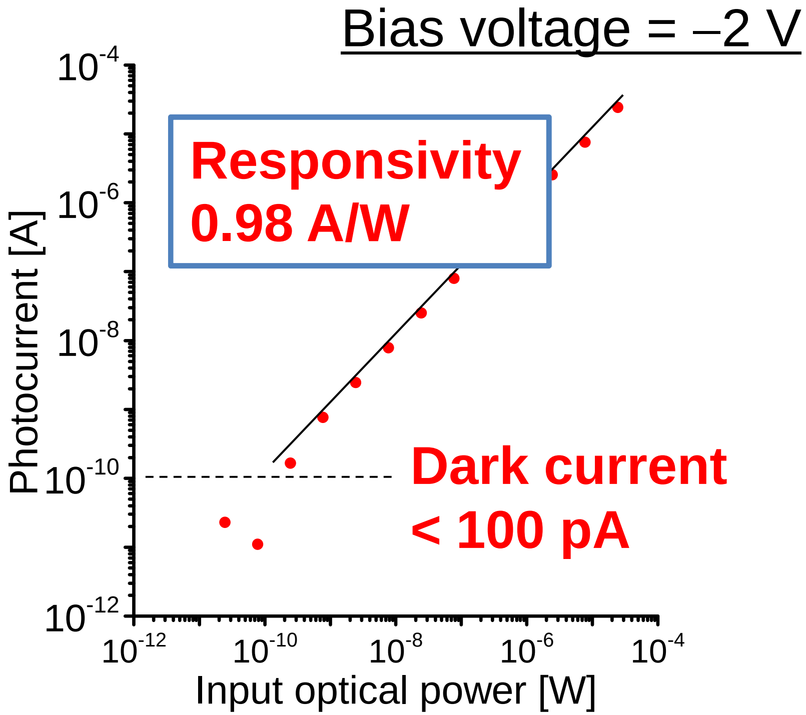
- ✓ ***Energy cost < 50 fJ/bit***

High-responsivity Detector



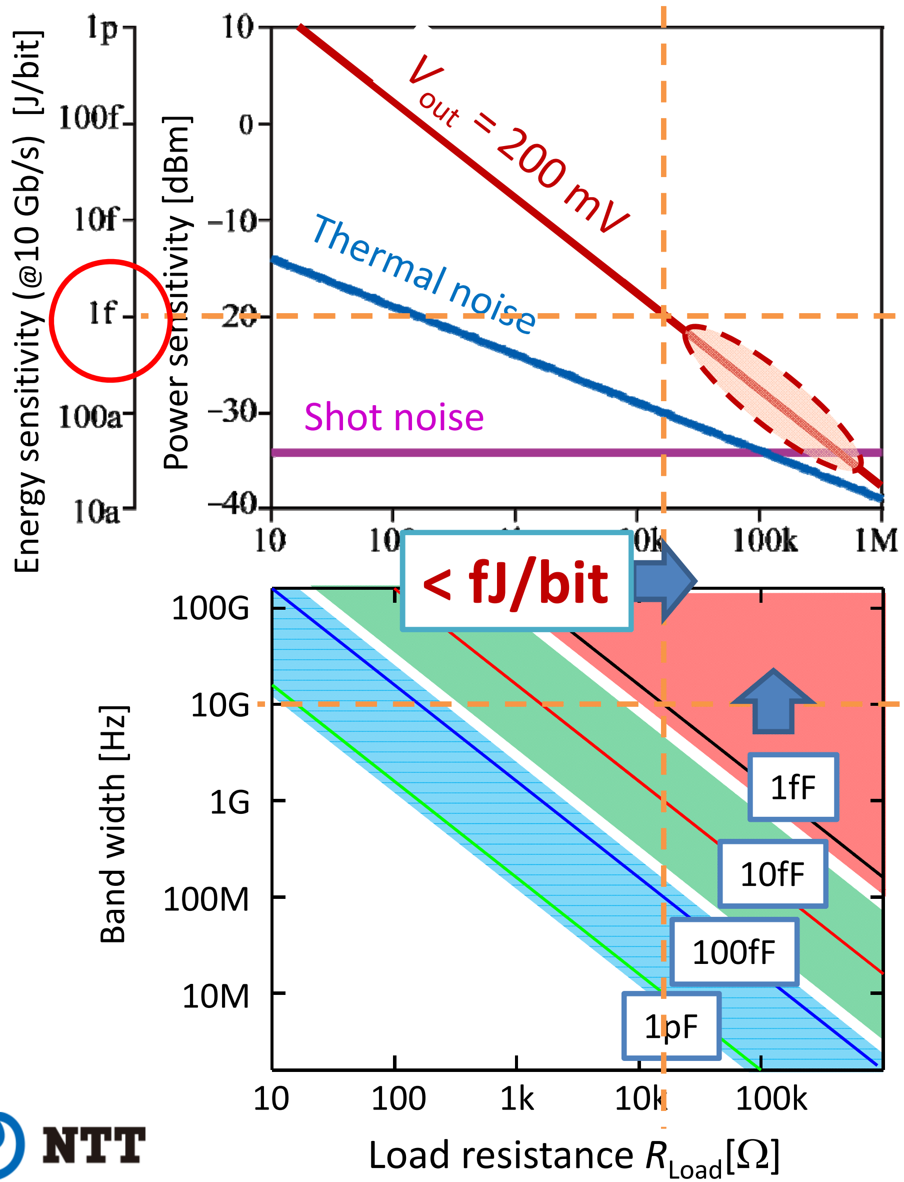
C_{theory} = 0.3~0.5 fF

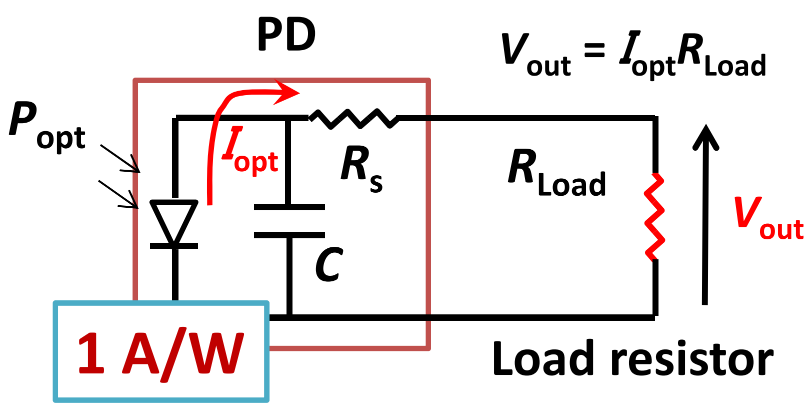
Nozaki et al., CLEO (2014)



Best candidate for receiver-less photodetector

Requirement for Receiver-less PD





> 10 Gb/s

Our target (1 fF or less)

Recent Ge PDs (~10 fF)

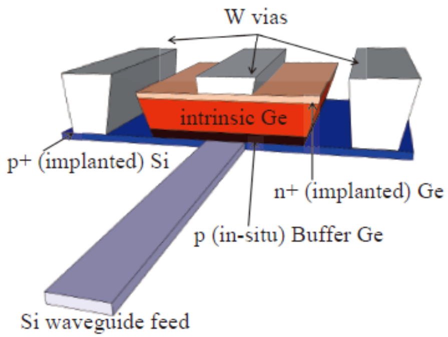
Conventional PDs (~pF)

NTT

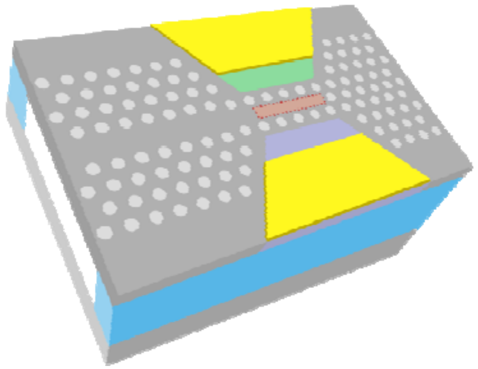
Comparison of Ultra-small PDs

Ge waveguide

C.T. DeRose, *Opt.Exp* **19**, 24897, (2011)

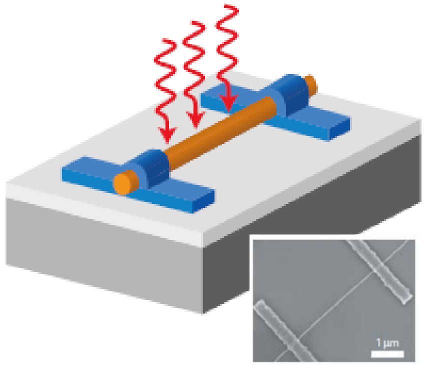


Our device (InGaAs-BH PhC)



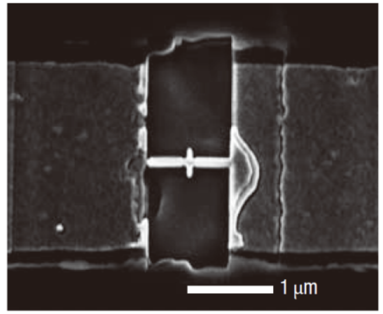
Nanowire

L. Cao, *Nat.Mat.* **8**, 643, (2009)



Plasmon antenna

L. Tang, *Nat.Photon.* **2**, 226, (2008)



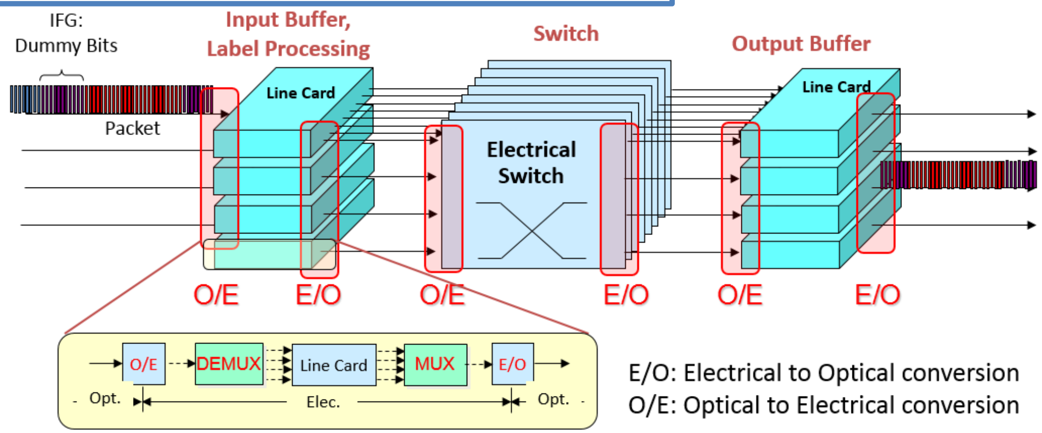
	Ge waveguide	Our device (InGaAs-BH PhC)	Nanowire	Plasmon antenna
Absorber volume	**3.1 μm^3**	**0.11 μm^3**	**0.05 μm^3**	**0.0007 μm^3**
Responsivity	**0.8 A/W**	**1 A/W**	**0.01 A/W**	**0.0001 A/W**
Bandwidth	**45 GHz**	**28.5 GHz**	**untested**	

Best candidate for small junction capacitance, efficient, and fast PD
→ capability of receiver-less configuration

NTT

All-optical Optical RAM
Toward One-chip Photonic Router

Electric router

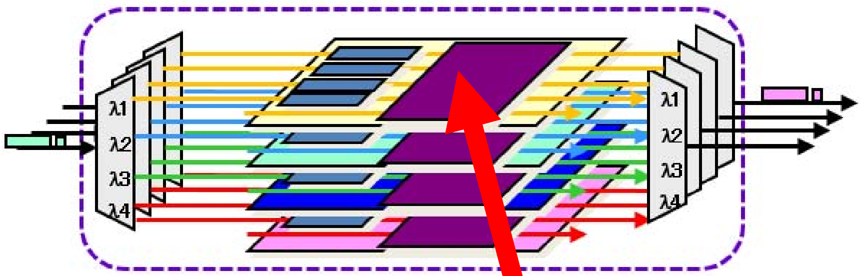


Multiple MUX/DEMUXes increase power

E/O: Electrical to Optical conversion
O/E: Optical to Electrical conversion

Large Energy is consumed at
- E-O/O-E conversion
- Electrical MUX/DEMUX
- Electrical switching

One-chip photonic router



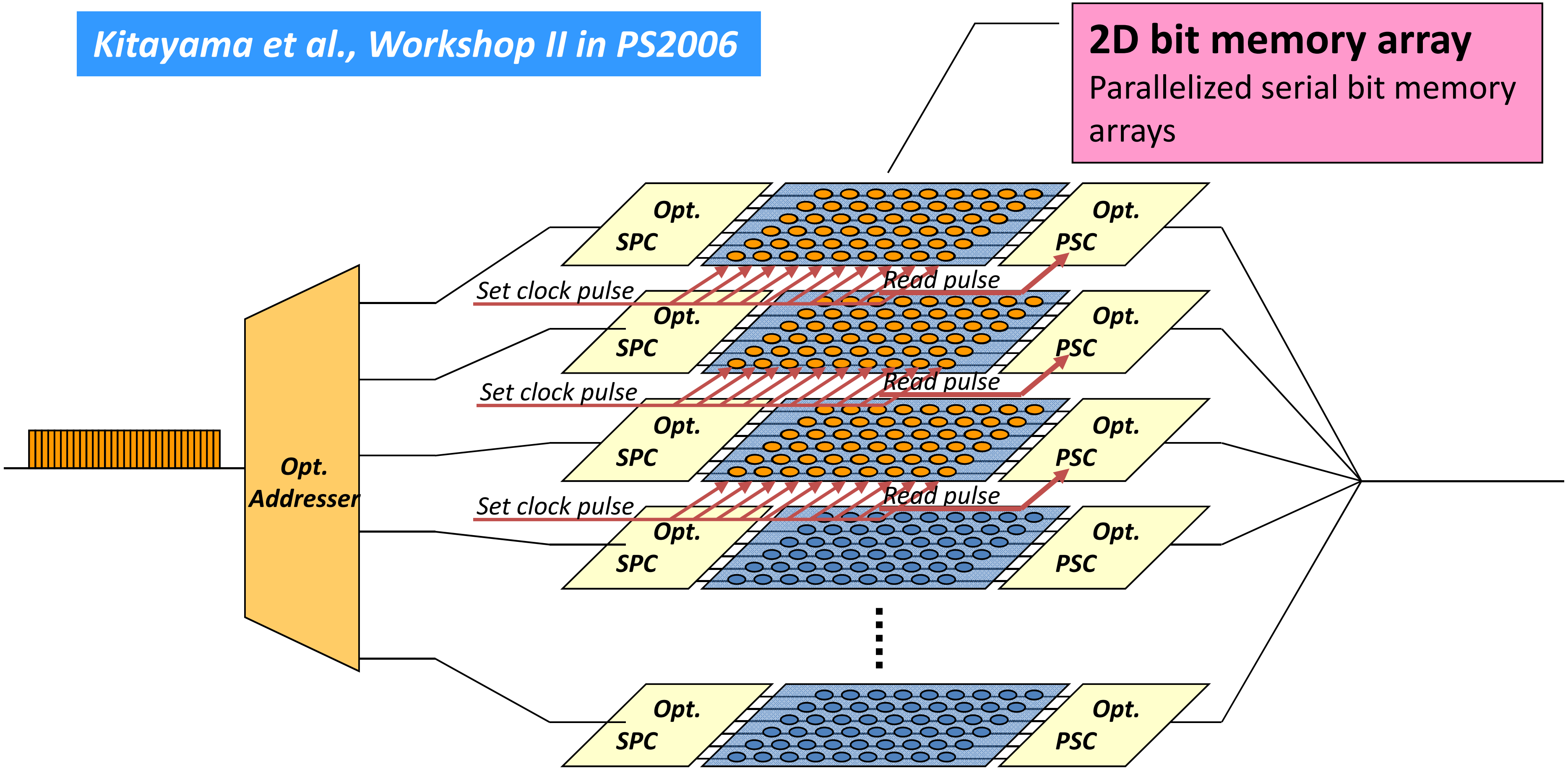
Optical RAM

No need of E-O/O-E conversion
Effective in DMUX/MUX/switching
Less energy cost for signal transmission
Use of WDM to expand the bandwidth

NTT

All-optical RAM System

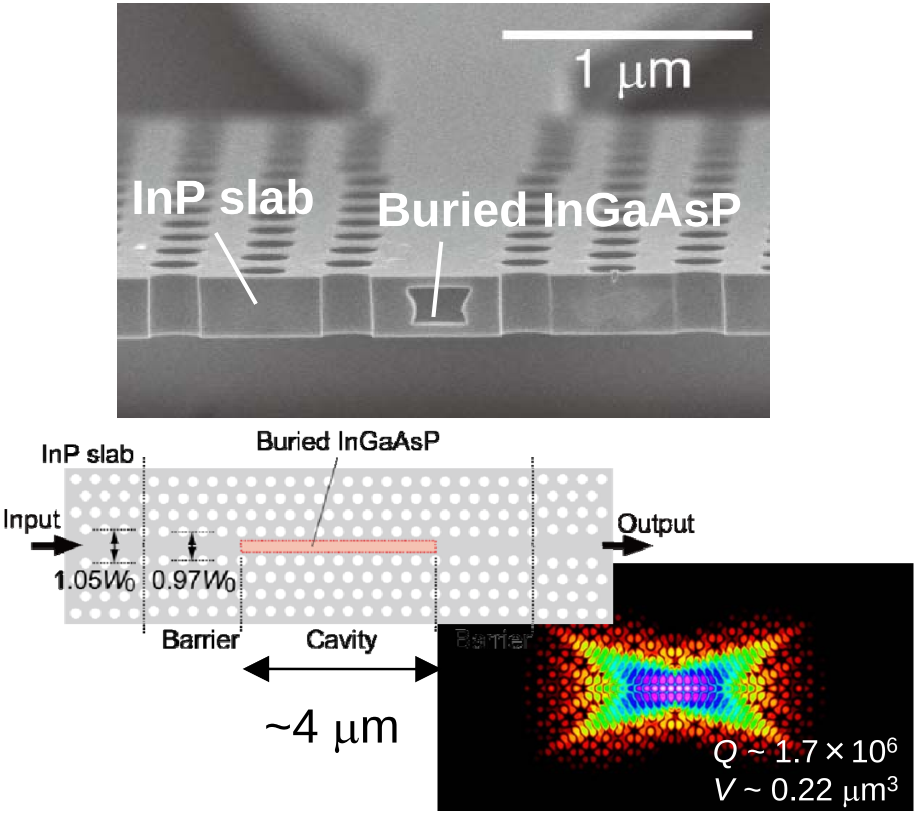
Kitayama et al., Workshop II in PS2006



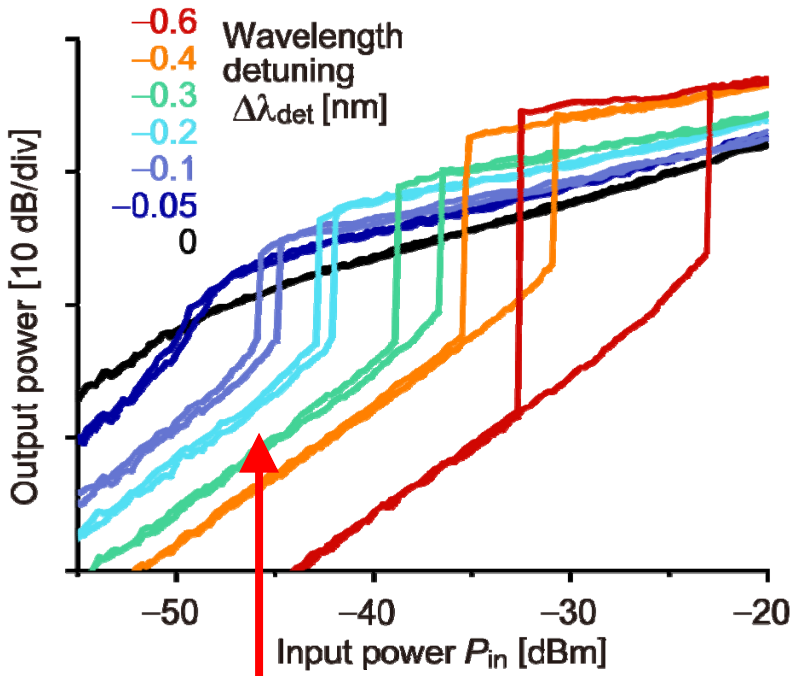
This work is supported by NICT

NTT

Ultralow-power All-optical Bit Memory



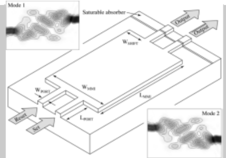
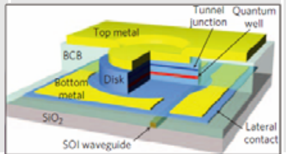
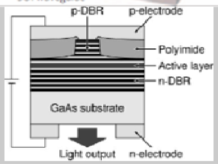
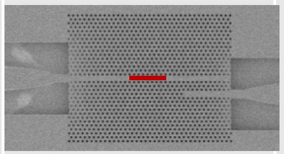
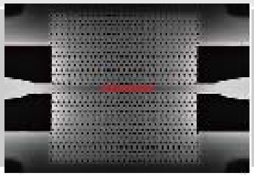
Nozaki et al. Nature Photon. 6 248 (2012)



World's lowest operation power

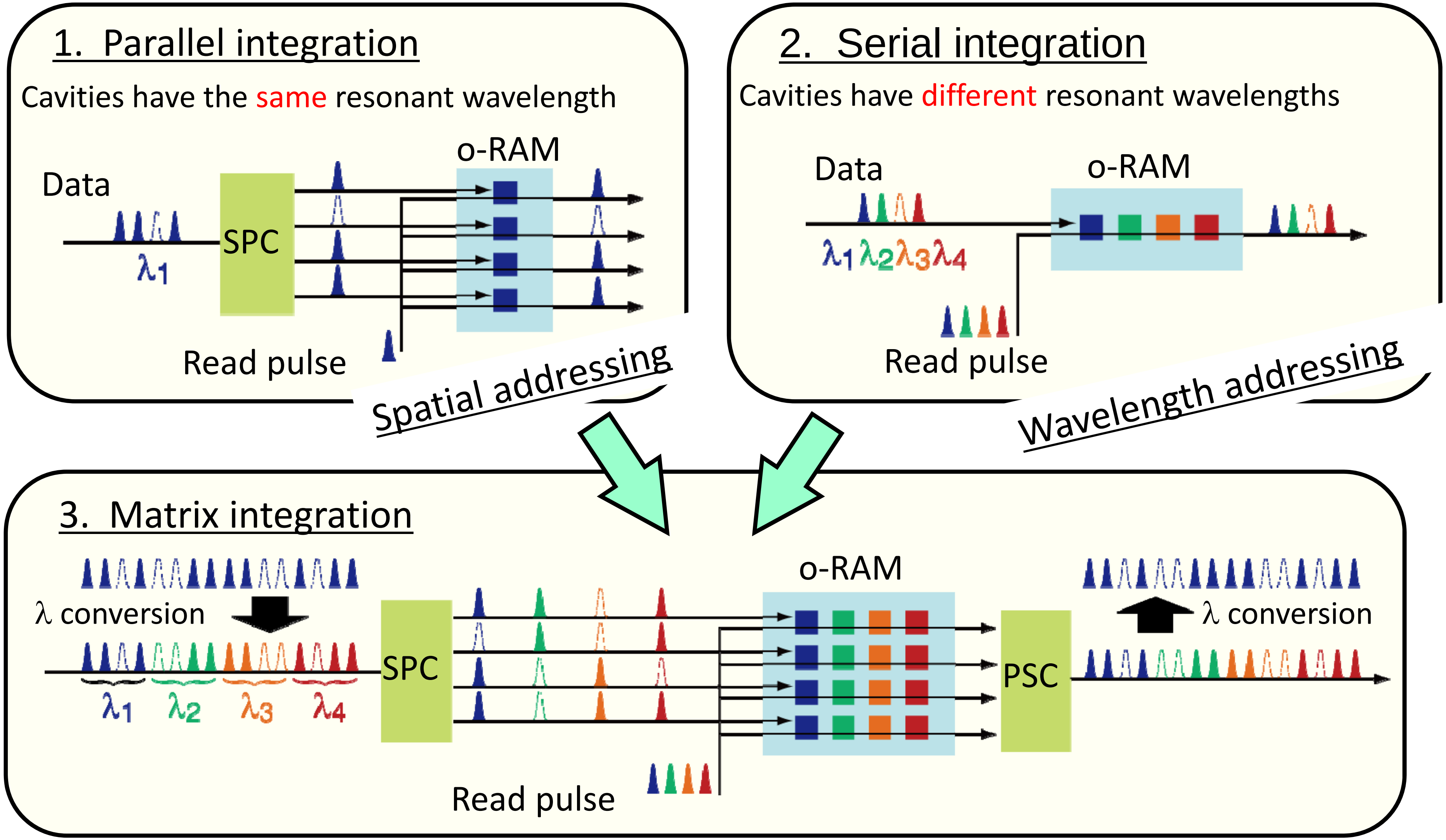
U= 25 nW

All-optical Memories: Comparison

		Area (μm^2)		Power (mW)	P x Area ($mW\ \mu m^2$)
Laser	**MMI-BLD** Takenaka, *PTL* **17**, 968, (2005)		7000	~ 100 (160 mA)	~10^6
Laser	**Ring laser** Liu, *Nature photon.* **4**, 182, (2010)		45	~6 (3.5 mA)	~10^2
Laser	**VCSEL** Mori, *APL* **88**, 101102 (2006)		20	~ 1 (7 mA)	~10^1
Laser / PhC cavity	**PhC nanolaser** Chen, *Opt. Exp.* **19**, 3387 (2011)		~10	0.025	~10^{-1}
PhC cavity	**PhC nanocavity w/ nonlinearity**		~10	**0.00003** ***This work***	**~10^{-4}**

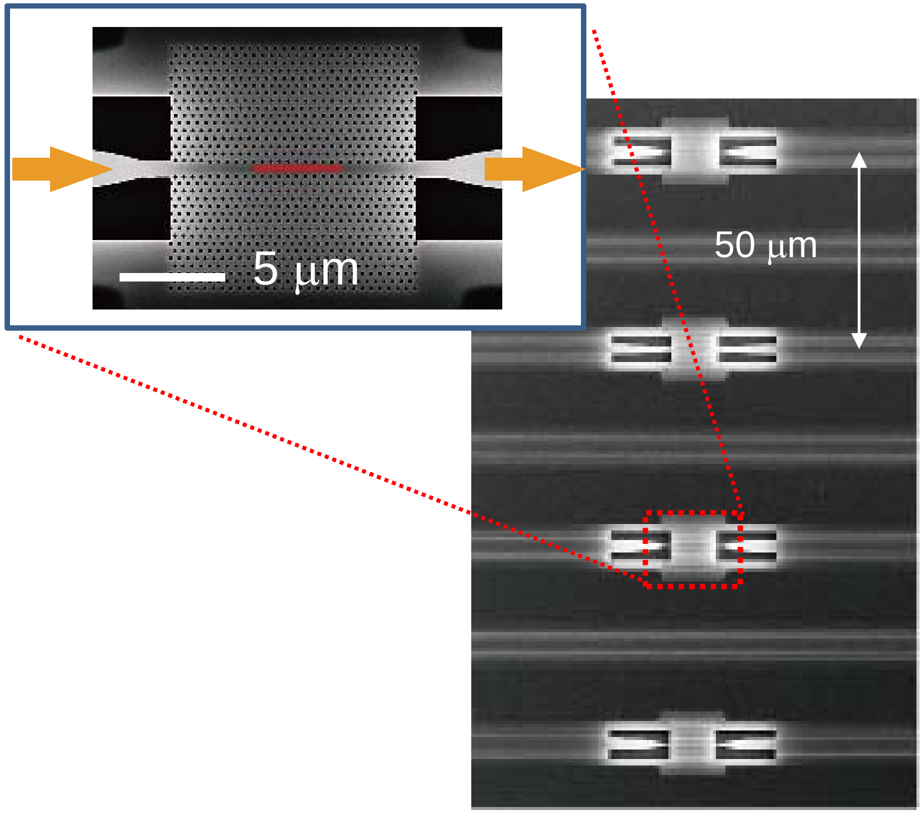
1-Mbit memory   Power: 30 mW   Size: Order of mm.

Integration Schemes for o-RAMs

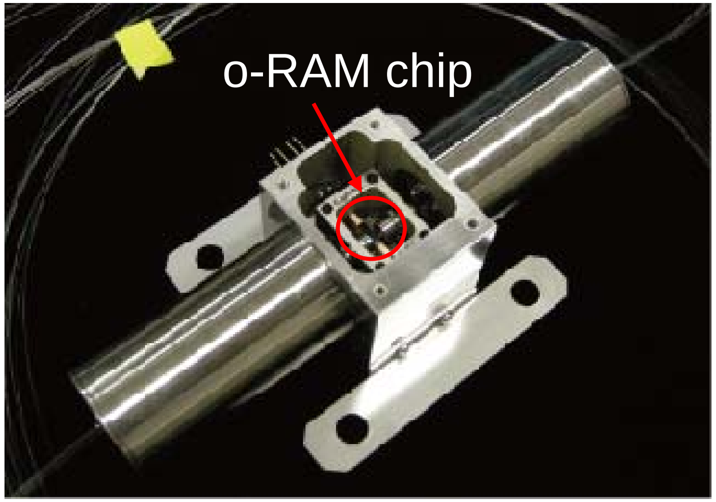


SPC: Serial-to-parallel converter
PSC: Parallel-to-serial converter

4-bit Memory Parallel Integration for o-RAM



Nozaki et al. Nature Photon. 6 248 (2012)

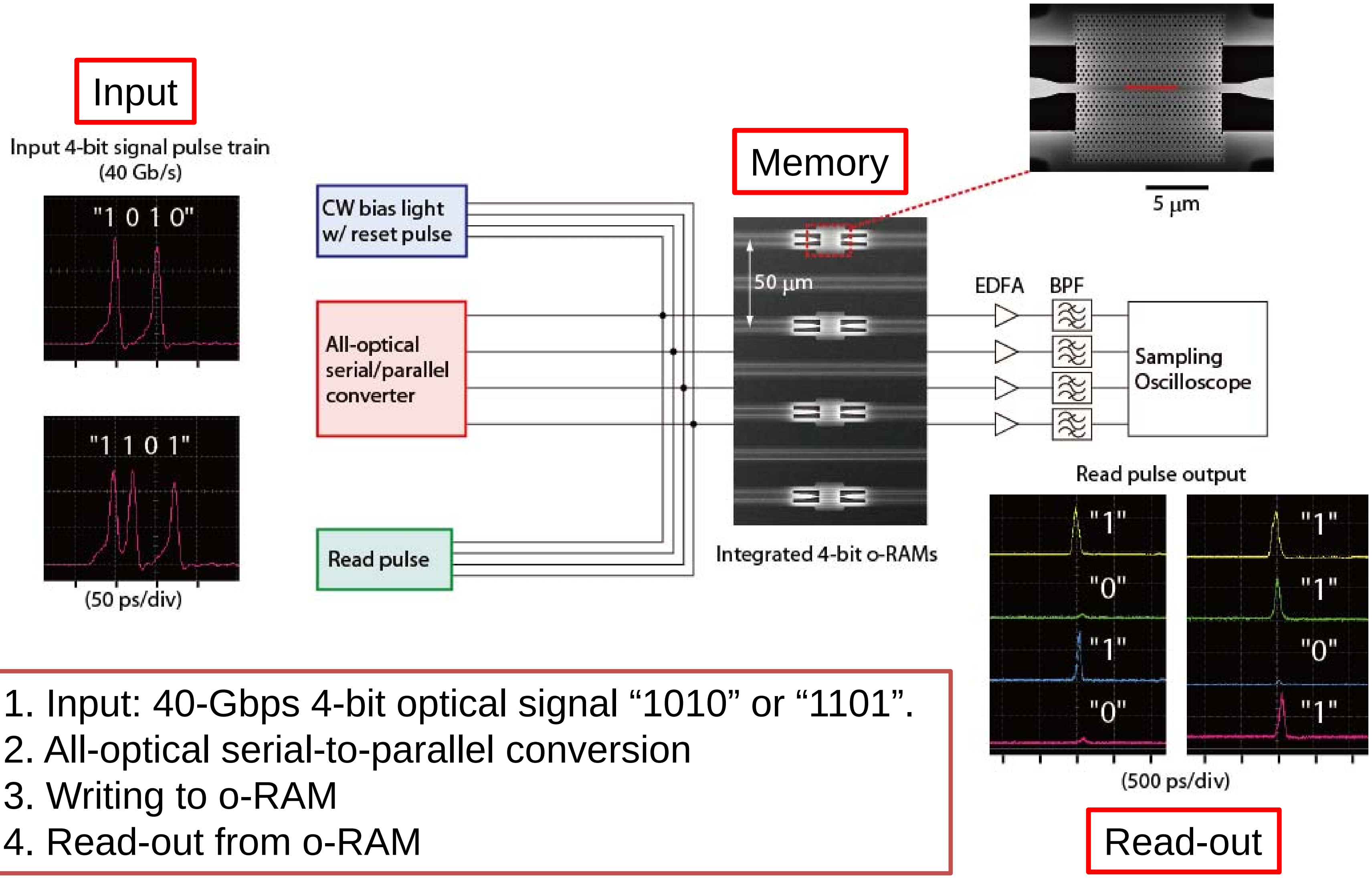


Fiber module equipped with o-RAM chip used for experiment

First demonstration of integrated o-RAM

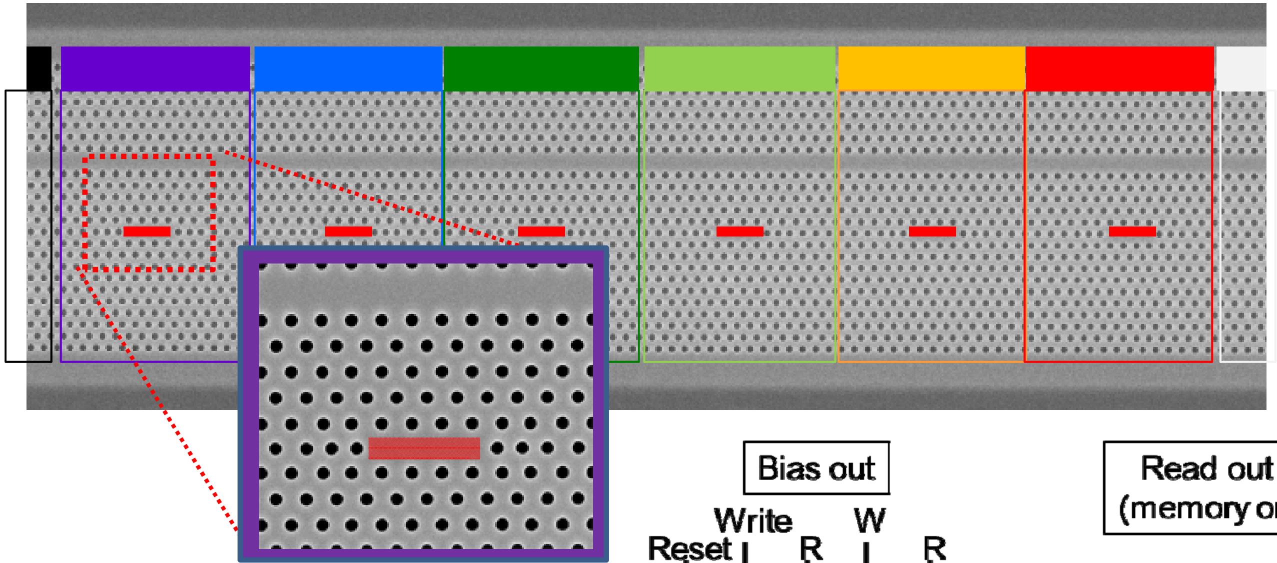
Sharing the same operation wavelength

40-Gbps Random Access Operation

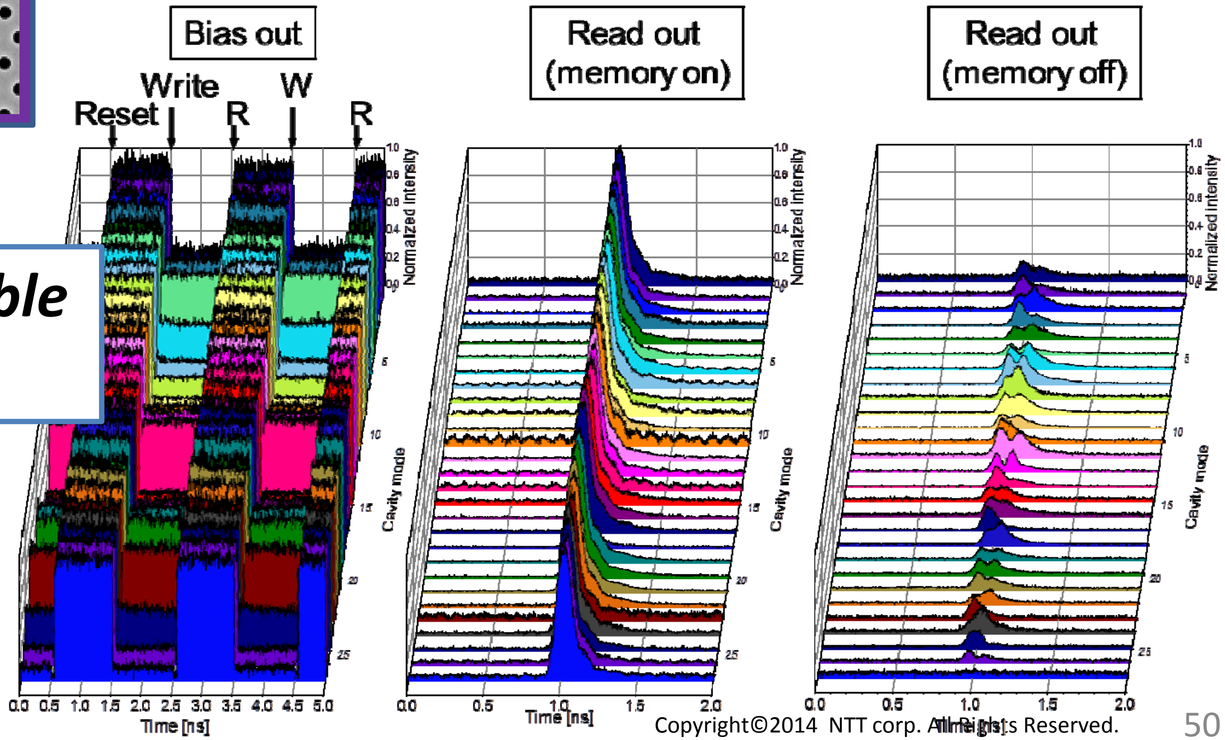


1. Input: 40-Gbps 4-bit optical signal “1010” or “1101”.
2. All-optical serial-to-parallel conversion
3. Writing to o-RAM
4. Read-out from o-RAM

32-bit Memory Serial Integration for o-RAM



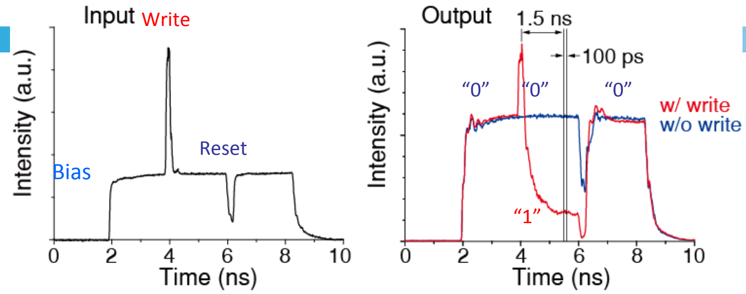
Kuramochi et al.
Nature Photon. 8 , 474 (2014)

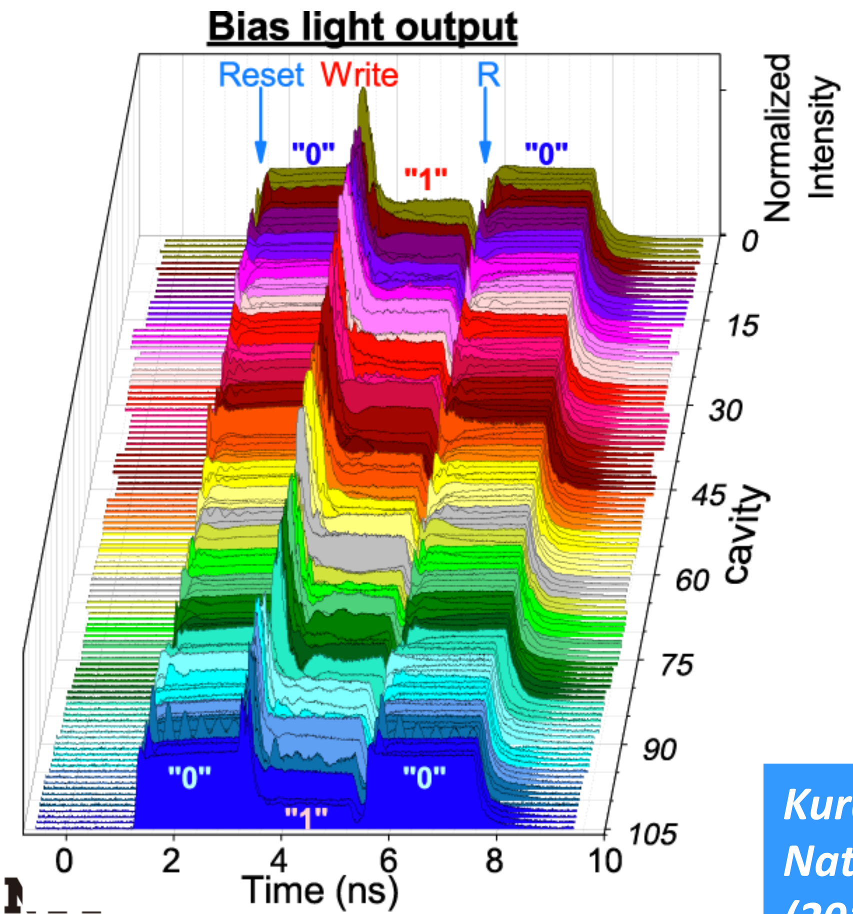


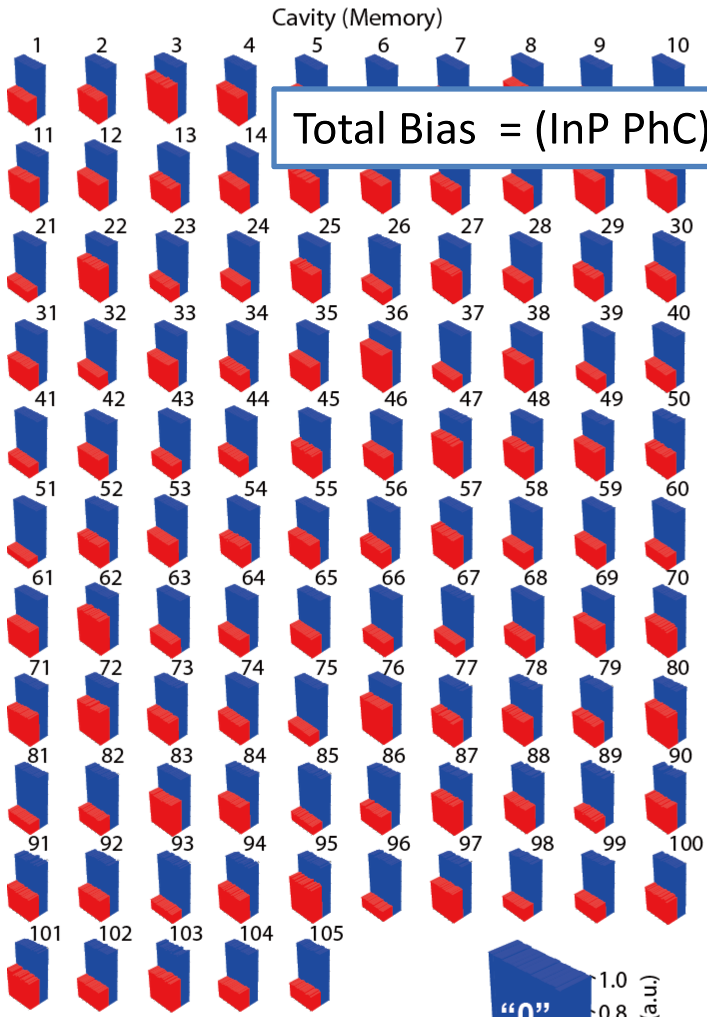
Wavelength-addressable Memories

Total Bias = 137 μW
Write/Read = 100-200 fJ

105-bit Integrated Memories





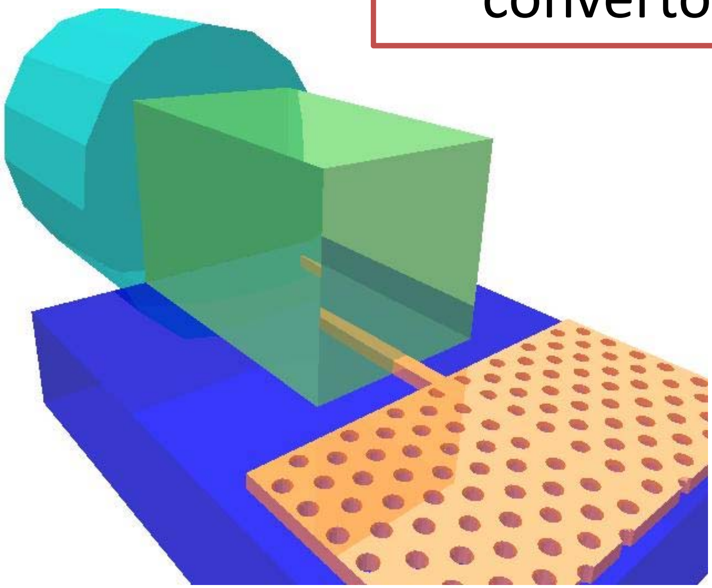


Total Bias = (InP PhC)x10^2

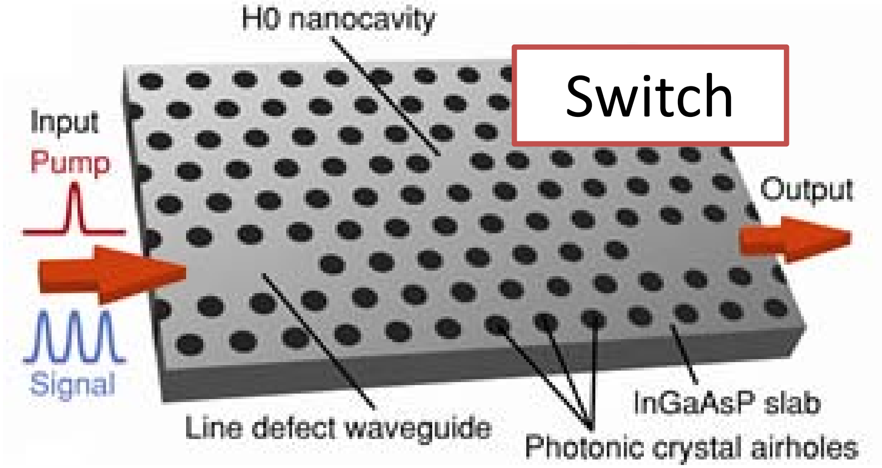
Kuramochi et al. Nature Photon. 8 , 474 (2014)

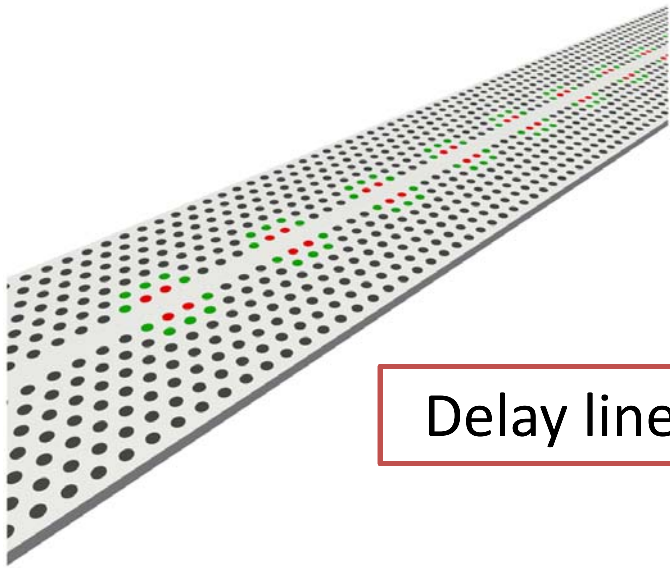
Other devices

Spot size convertor



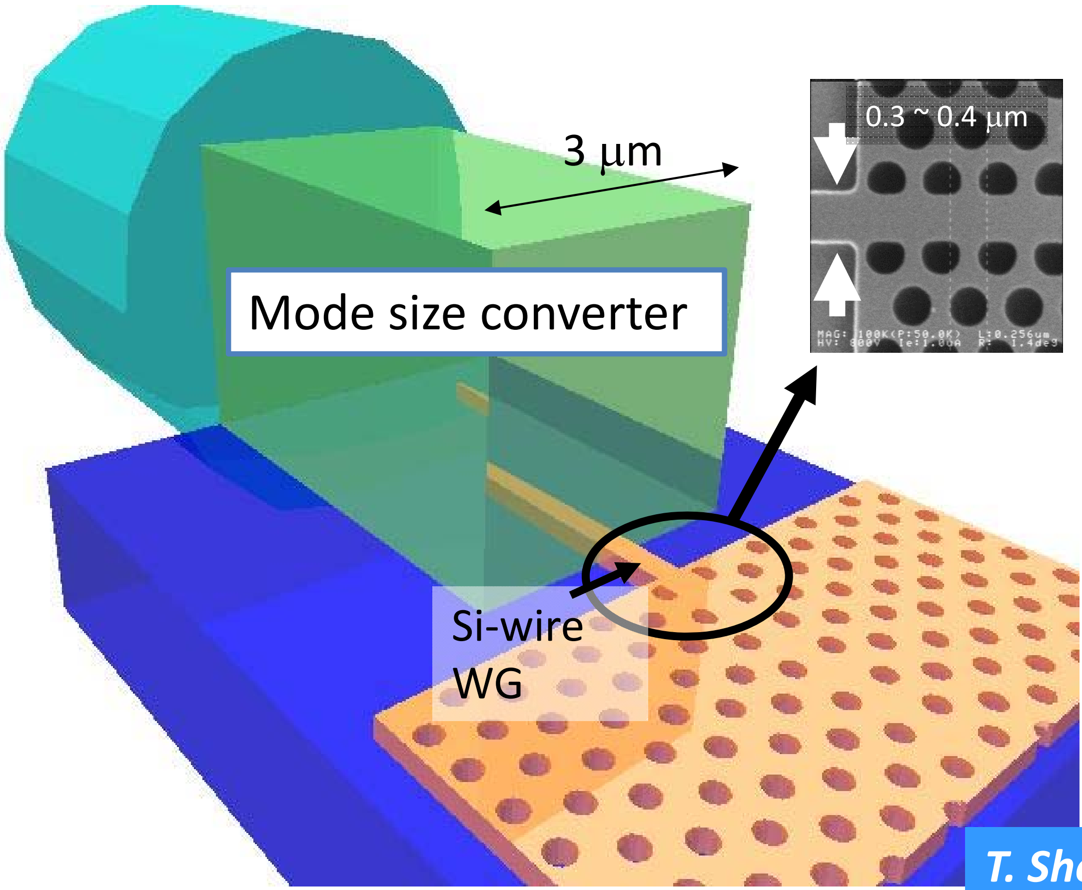
Switch





Delay line

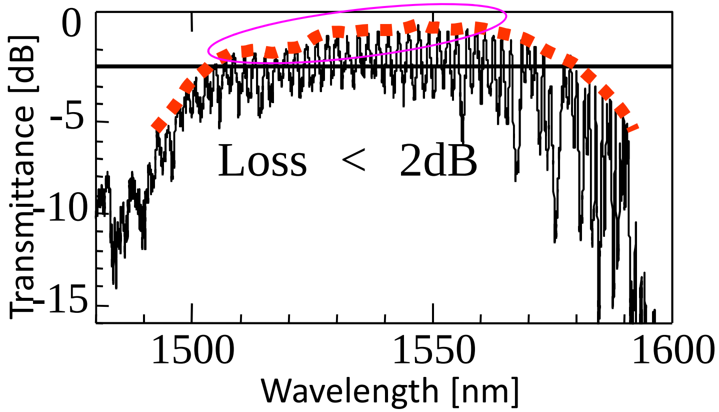
Adiabatic Mode Connector for Fiber Coupling

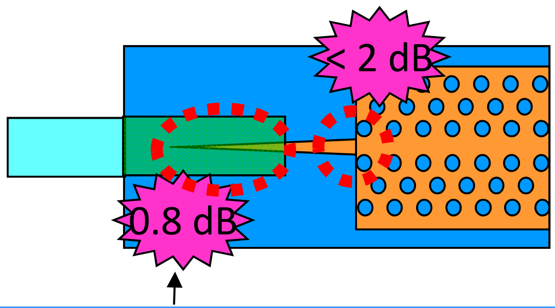


Adiabatic Mode Connector

Shinya et al. Proc. SPIE 5000, 104, (2003)

Connection between PBG-WG and Si-wire WG



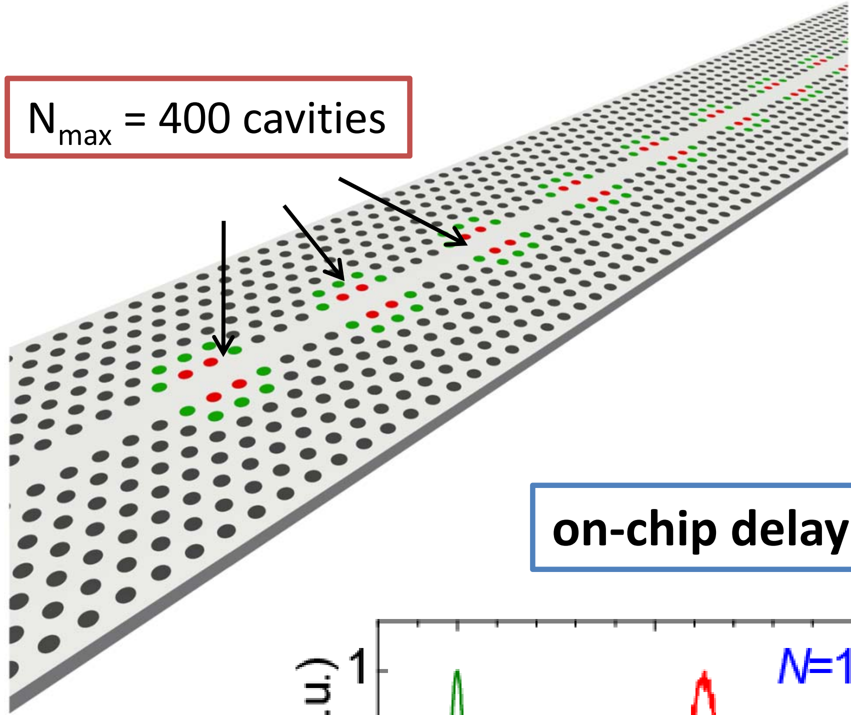


T. Shoji et al., Electron. Lett. 38, (2002)

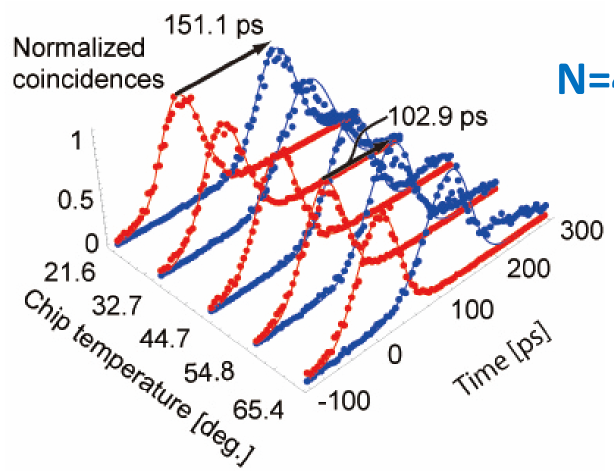
Connection Loss～ 3dB

Large-scale array of coupled-nanocavities

N_{max} = 400 cavities

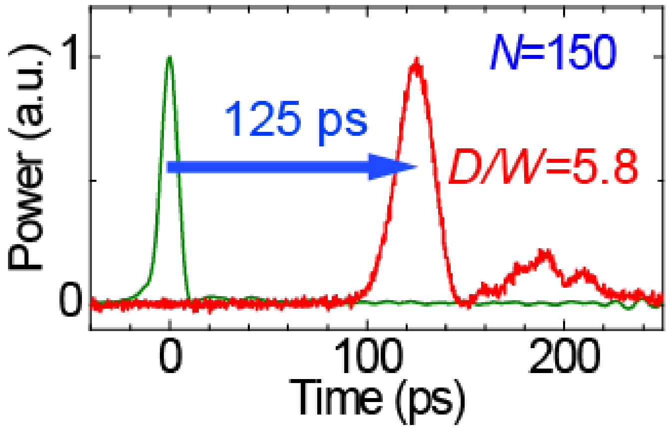


On-chip quantum buffer



Takesue et al. Nature Commun. (2013)

on-chip delay line

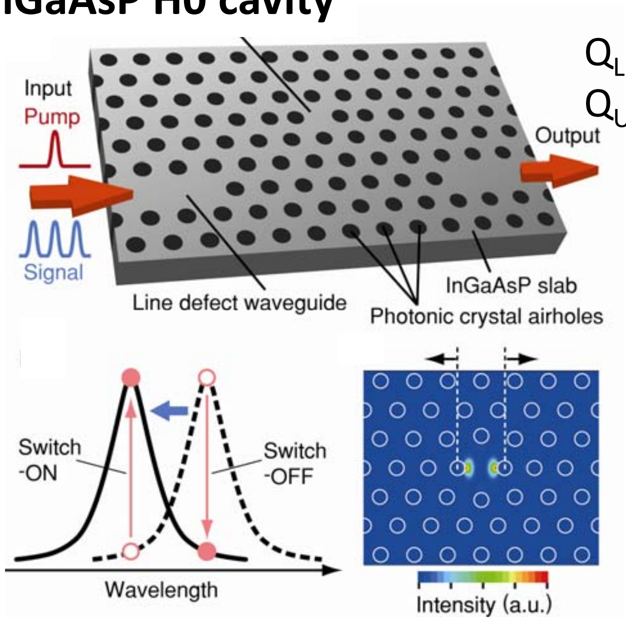


Notomi et al. Nature Photonics (2008)

Ultralow-energy All-optical Switch

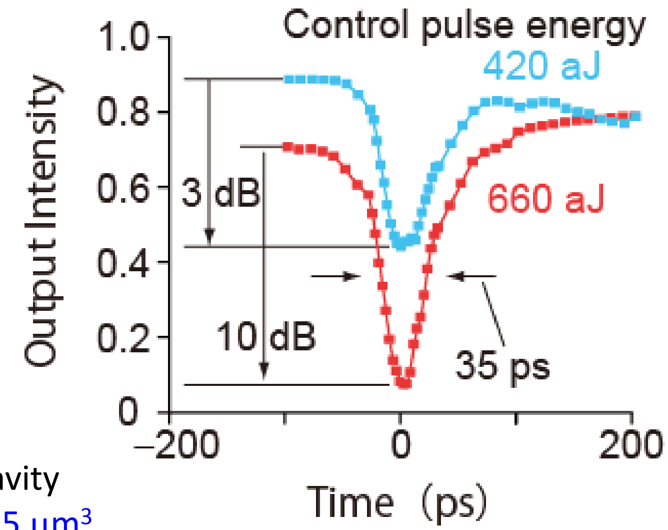
Nozaki et al. Nature Photonics (2010)

InGaAsP H0 cavity



Q_L=6500
Q_{UL}=22000

Ultrasmall H_0 nanocavity
$V = 0.26(\lambda/n)^3 = 0.025\ \mu m^3$



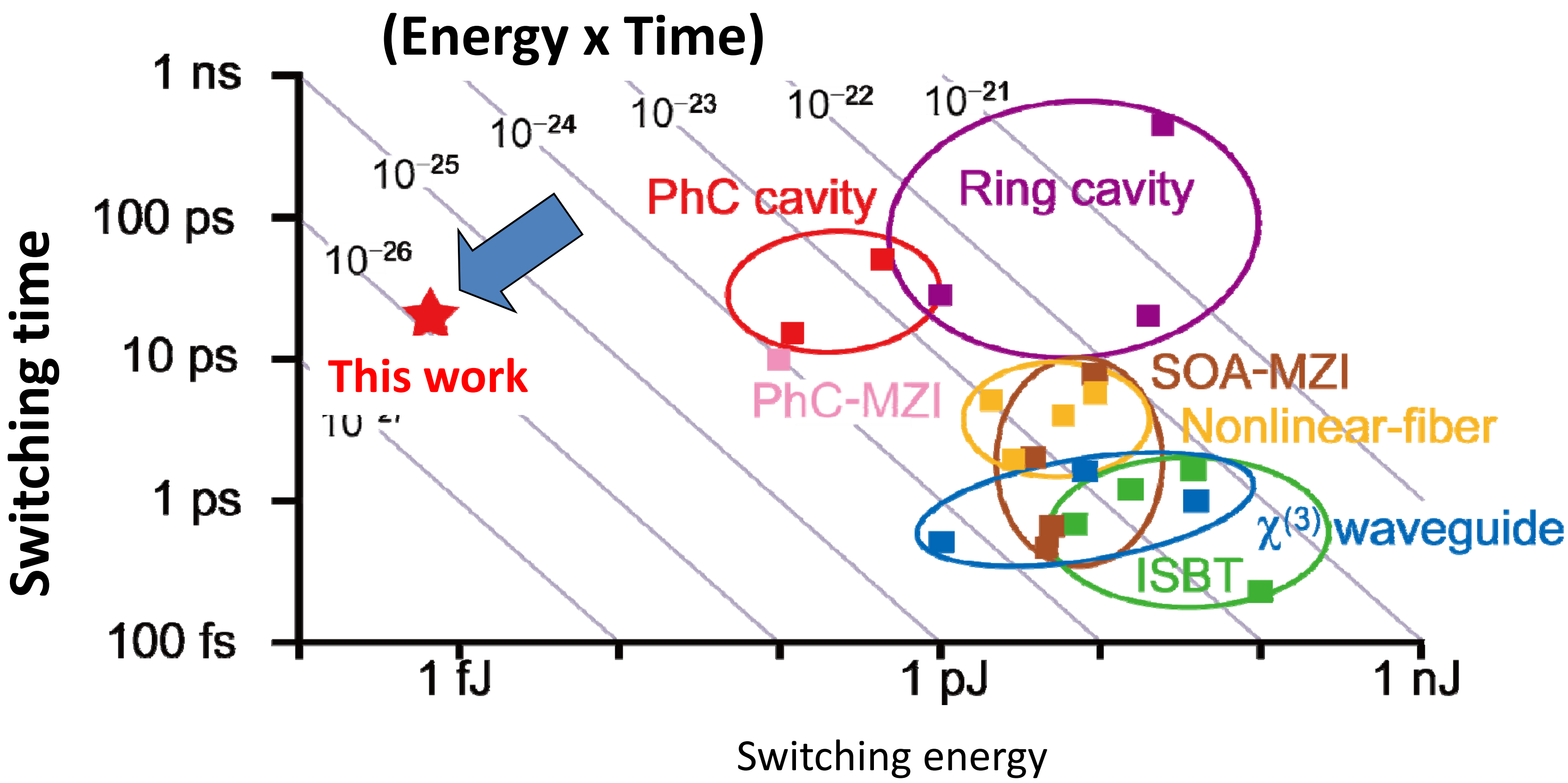
World's lowest energy consumption in attojoule region
[aJ] = 10^{-18}[J]

U= 420 [aJ] @3 dB
U= 660 [aJ] @10 dB
T = 20~35 [ps]

< 10 μW @ 10 Gbps

NTT

Operation Speed vs. Energy Consumption



Overcome the trade-off of the device limitation

Summary

Limitation of E-Interconnect

The most power is lost during the electric communication
Electronics is not good at high bit/s communication

Photonic network into a chip

Photonic data transmission energy is extremely smalls
Photonics is good at broadband communication.

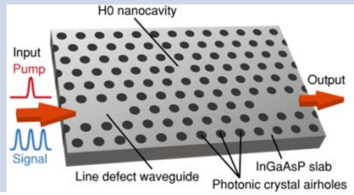
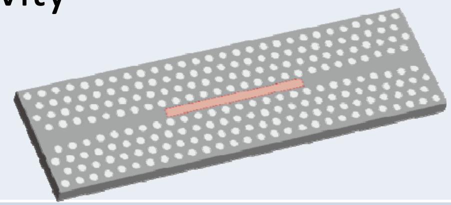
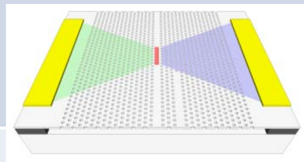
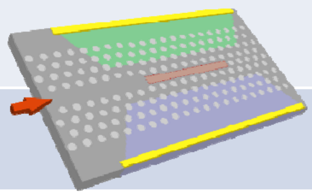
Integrated Nanophotonics

We will need integratable nanophotonic devices with ***ultralow power consumption***

Energy cost: ≈ fJ/bit
Footprint: ≈10 μm^2

Summary

PhC integration technology is rapidly progressing.

Device		Key technology
Switch	Low switching energy: 420 – 660 [aJ] Fast switching speed: 20~35 [ps]	H0 cavity 
Memory O-RAM	Low threshold power: < 30 nW 4-bit spatial addressing 32-bit wavelength addressing	BH cavity 
Laser	Low threshold: 4.8uA Low energy cost: 5.5f J/bit	PIN junction 
Detector	High Responsivity : 0.7-1.0 A/W, Small capacitance: possibly of < fF	
Link	Low energy cost (LD) = 28.5 fJ/bit	