Nanophotonics for low-latency optical integrated circuits

Akihiko Shinya
NTT Basic Research Labs., Nanophotonics Center,
NTT Corporation

MPSoC'17, Annecy, France

Outline

Low latency optical circuit

BDD-based optical circuit

Cascaded-BDD

Optical matrix multiplication

Photonic crystal technology

Small capacitance optical devices

optical gate, light source, receiver

Computing at light speed!

Target

Light-speed processor

・Eliminating latency bottleneck

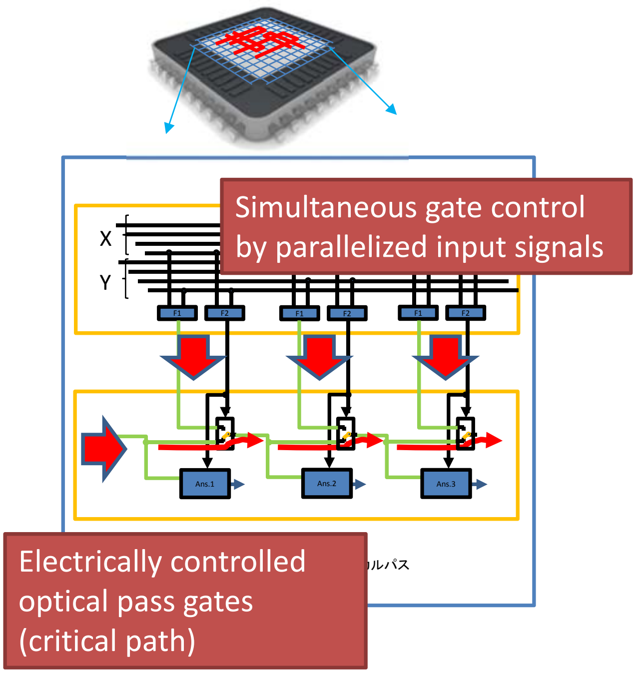
・New optical computing technology

Approach

Replacement of critical path with photonic devices.

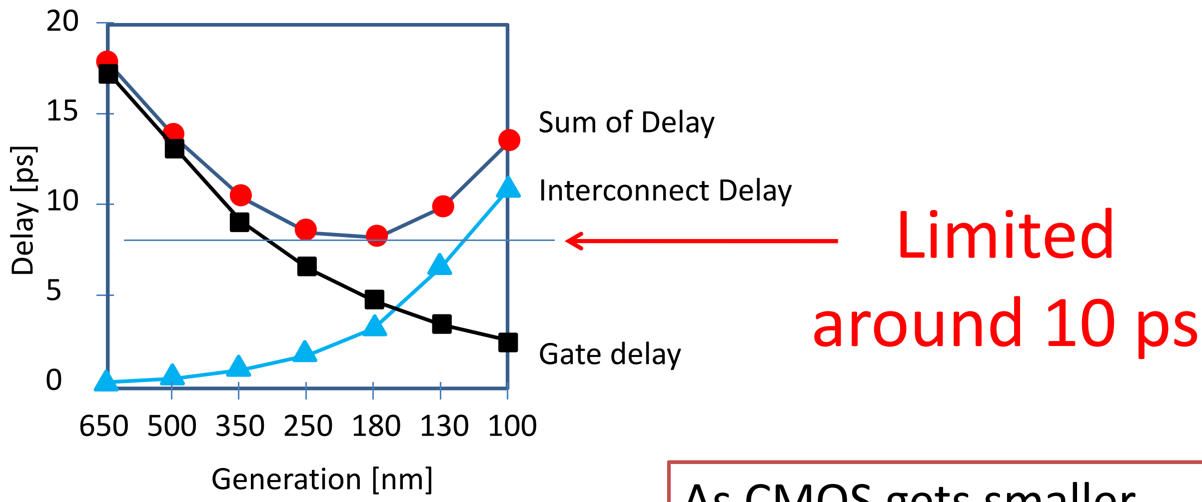
Calculation simply by propagating the light through the electrically controlled optical pass gates.

Nanophotonics for shortening the critical path



Critical path = signal route determining calculation time

RC-delay in CMOS circuit

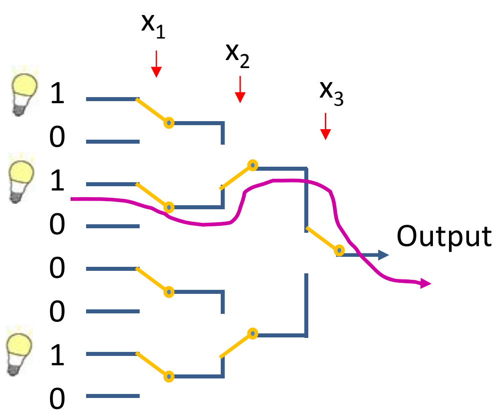


SIA, National technology roadmap for semiconductors, 1997 edition

As CMOS gets smaller,
Gate delay decreases,
Interconnect delay increases

BDD based optical circuit

BDD (Binary Decision Diagram)

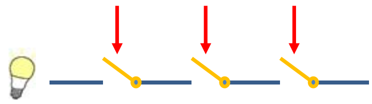


Merits

(1) Instantaneous construction of output path via simultaneous gate control [ps]

(2) Calculation simply by propagating the light through the pathway.

(3) Calculation with light propagation speed!



Optical signal is not affected by RC!

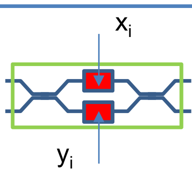
The shorter the gate, the faster the calculation.

NTT

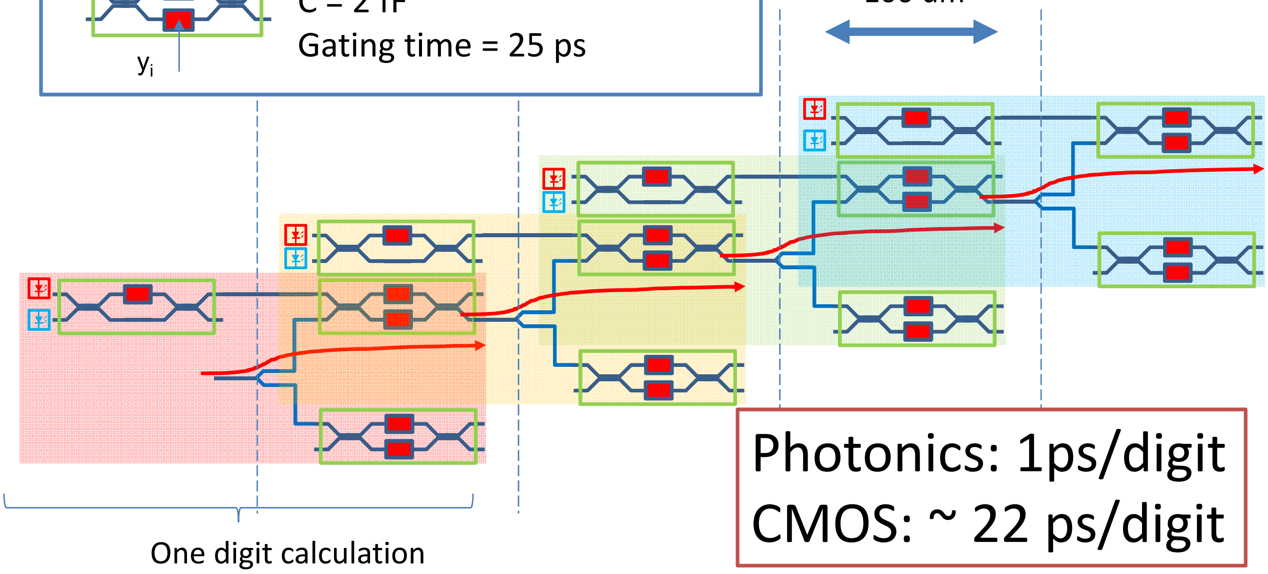
Optical parallel adder

Proposed by Dr. Ishihara, Kyoto Univ.

Mach–Zehnder interferometer



L = 100 μm (pass delay = 1ps)
C = 2 fF
Gating time = 25 ps

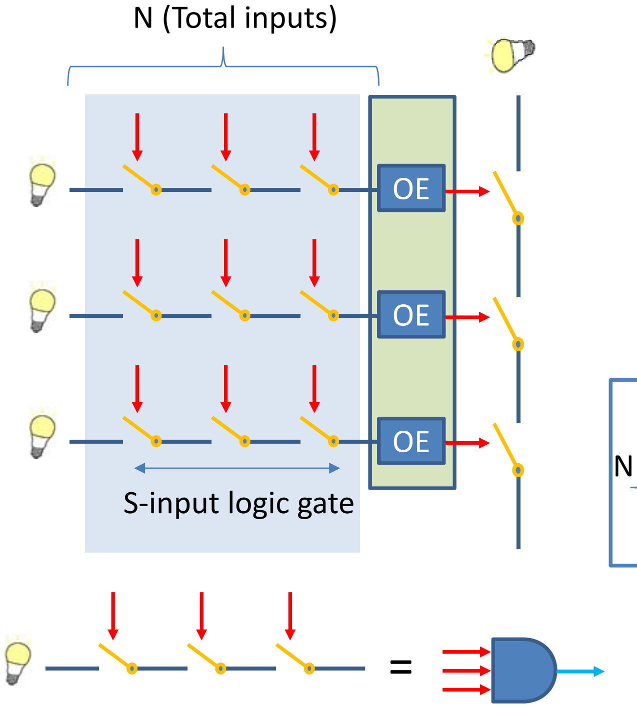


Photonics: 1ps/digit
CMOS: ~ 22 ps/digit

The shorter the gate, the faster the calculation.

NTT

Cascaded-BDD

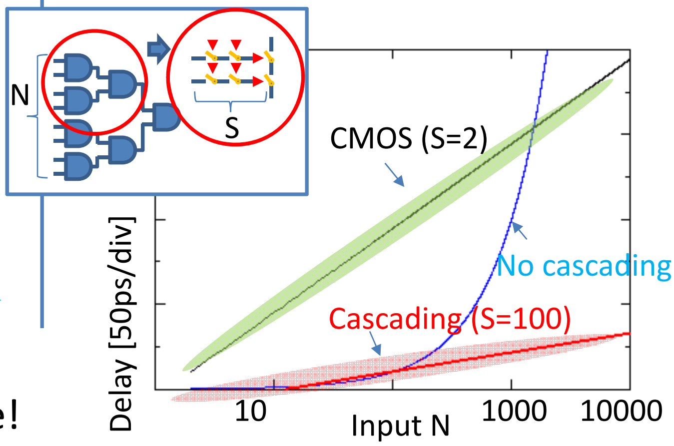


Multi-input function via serially connected gates (S>4) is available!

Merits

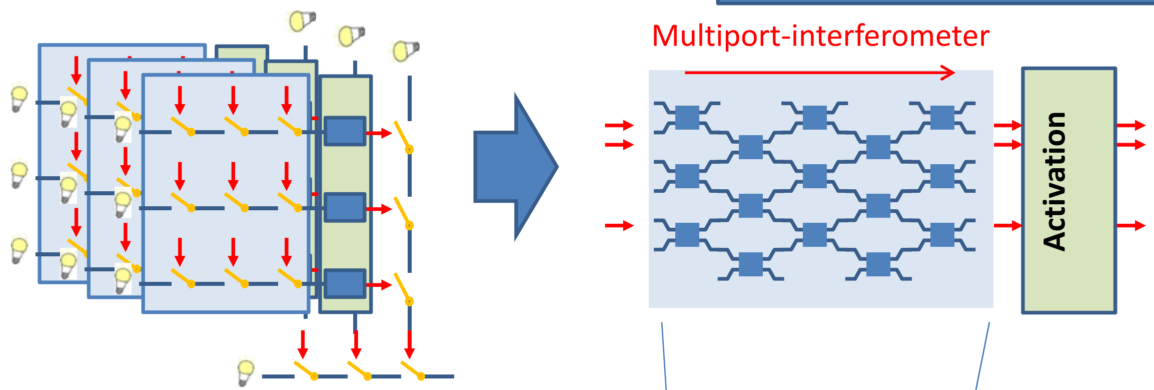
(1) Multi-input logic gate with very large number of input (S > 4) is available.

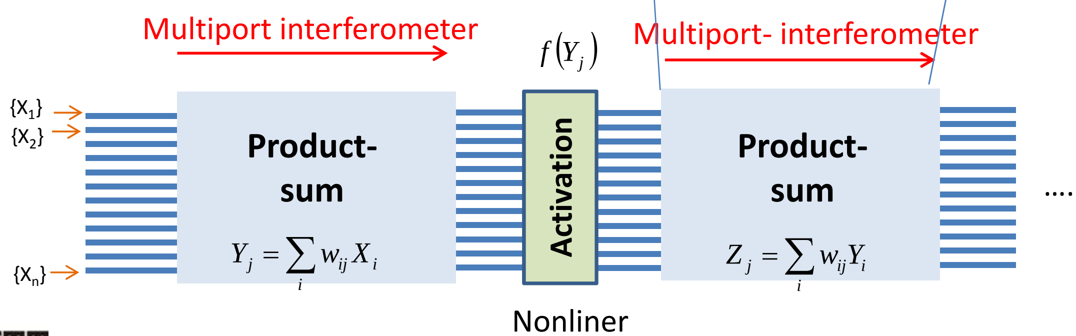
(2) Cascading of multi-input gate dramatically reduces the calculation step from N to $\log_S(N)$.



Optical matrix multiplication

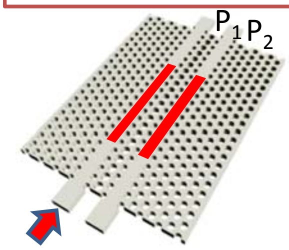
Oxford Univ., W. R . Clements et al., Optica 3, 1460 (2016)





Building blocks for on-chip optical circuit

Electrically driven ultrashort gate



<u>Serially connected gates (S ~ 10^2)</u>

Fast Multi-input logic functionality.

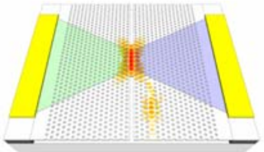
No CR-limitation for propagating light.

<u>Cascading of serially connected gates</u>

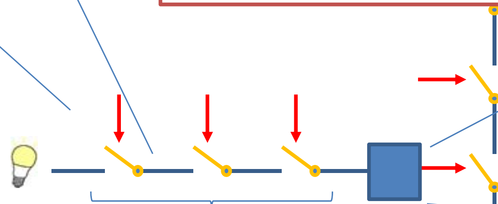
Reduction of cal. step from N to $\log_s(N)$

Requirements

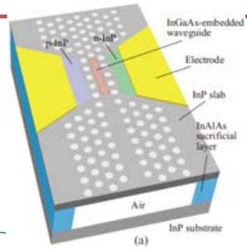
- Very short optical gate
- High efficiency EO/OE convertor (light source, receiver)



Ultralow-threshold laser



S-input logic gate



High-efficiency O/E conversion w/o electrical amplifier

NTT

Toward low-capacitance optical device

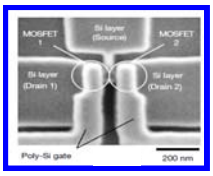
10 aF | 100 aF | 1 fF | 10 fF | 100 fF | 1 pF

(high loss)

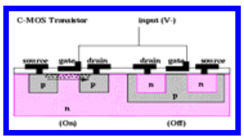
Plasmonics

Photonics

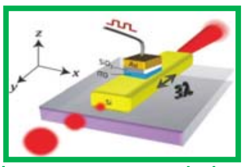
Electronics



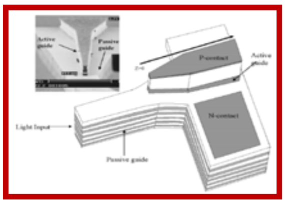
Single electron (~10 aF)



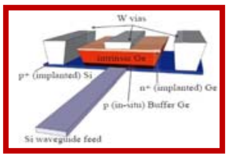
CMOS gate (~ fF)



Plasmonic modulator (5 fF)



Conventional InGaAs receiver (200 fF)



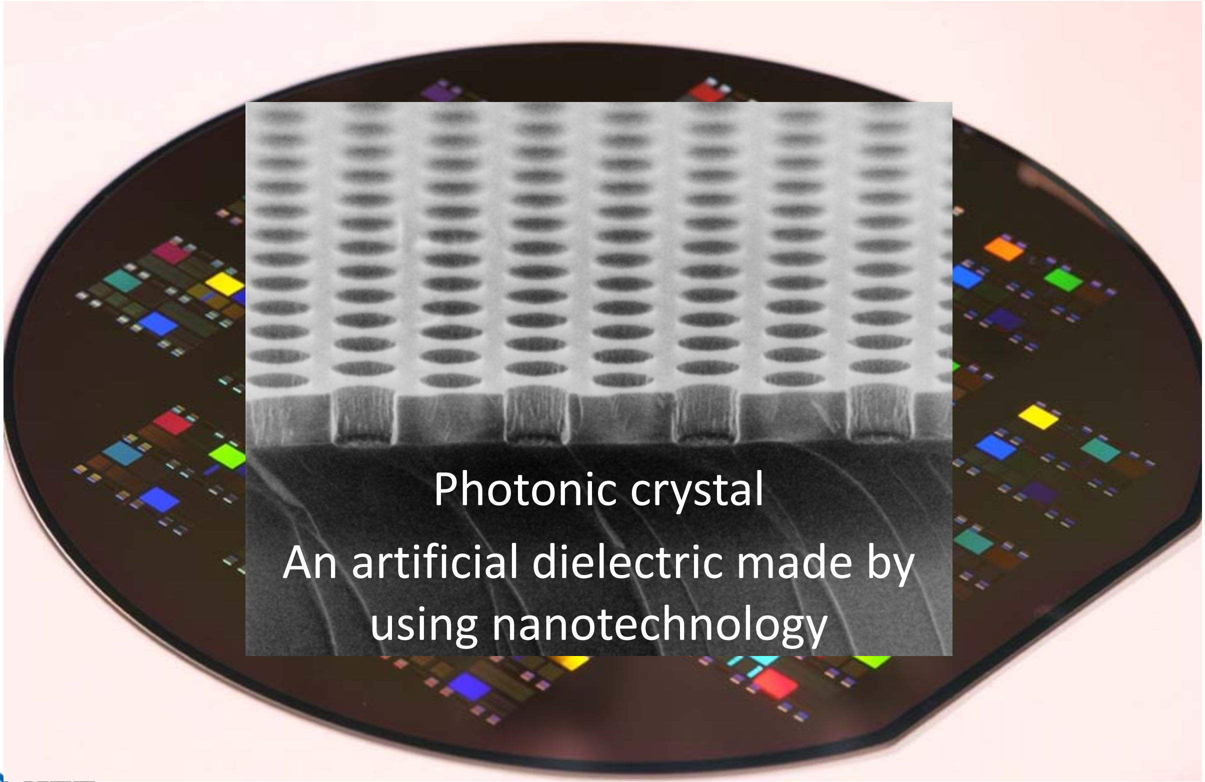
Si photonics Ge receiver (4 – 5 fF)

Photonic crystal

(<1 fF)

Size (C)
Latency (RC)
Energy (CV^2)

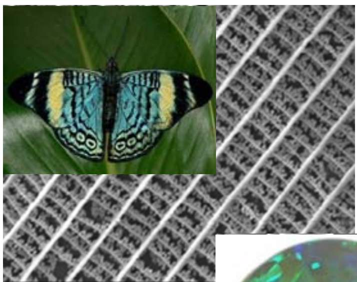
Photonic Crystal



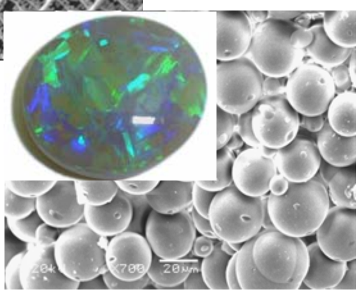
What is photonic crystal?

Natural Photonic Crystal

Butterfly

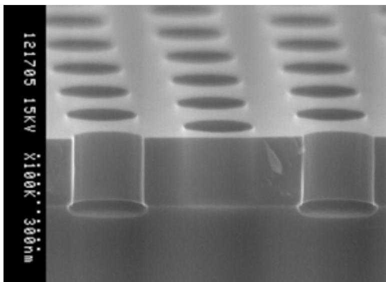


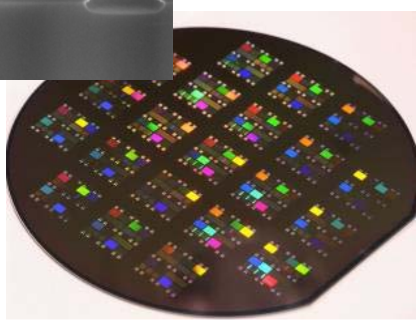
Opal



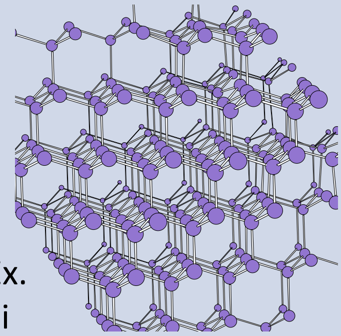
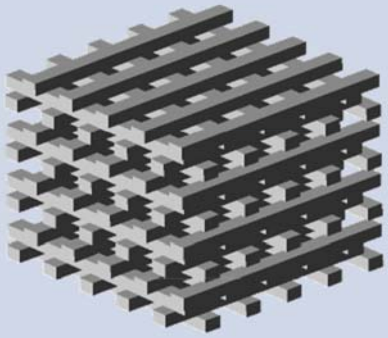
Artificial Photonic Crystal

Photonic crystal on Si wafer





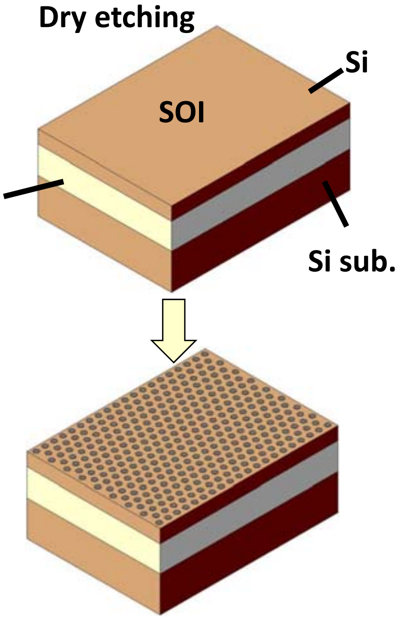
Analogy between Electronic and Photonic Crystal

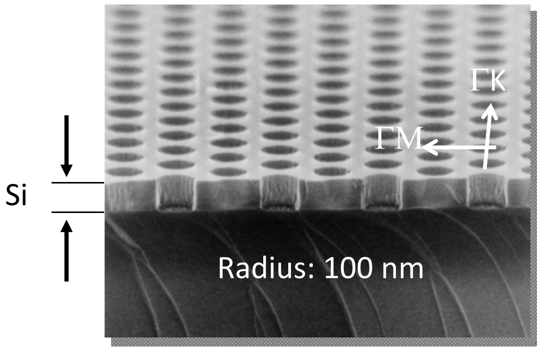
Electronic crystal	Photonic crystal
 Ex. Si	
Period ~ 0.1nm = electronic wavelength	Period ~ 100 nm = optical wavelength
Various electrical properties ● Conductor ● Semi conductor ● Insulator	New optical properties ● Optical insulator ● Slow light ● Negative refraction

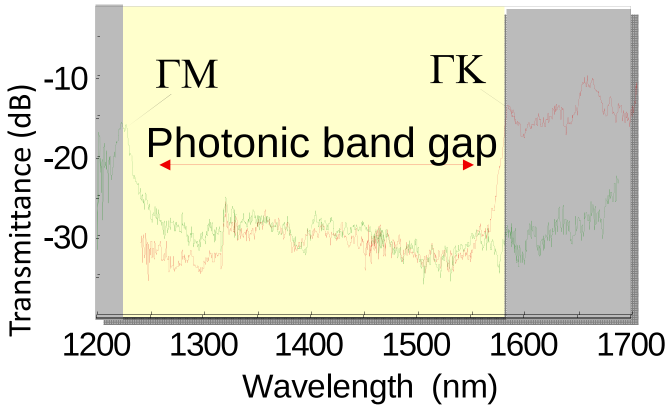
NTT

2D Photonic Crystal

Electron beam lithography
&
Dry etching



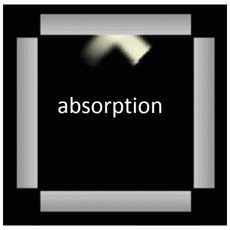




NTT

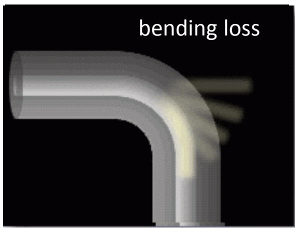
Why photonic crystal?

Metal mirror



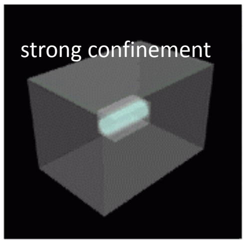
Optical absorption

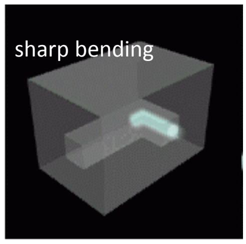
Fiber



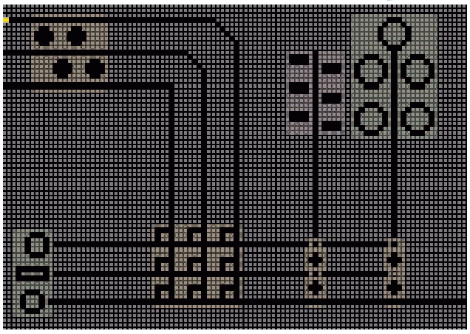
Leakage at bending

Photonic crystal



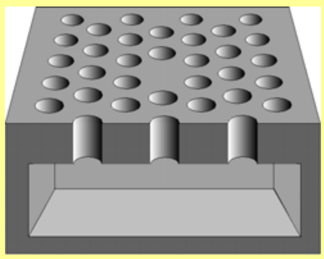


Light is completely confined



Large-scale
photonic integration

What can photonic crystals do?

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

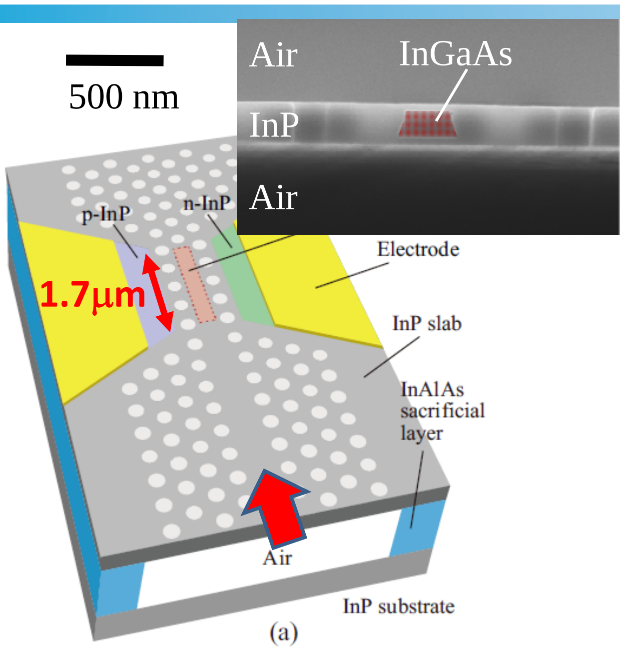
(λ/n): light wavelength in cavity

Ultrasmall high-Q cavity

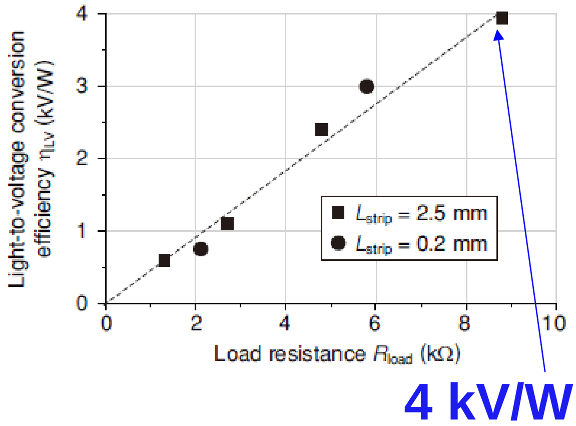
Small footprint (~ μm²)
Strong light-matter interaction

→ **fJ/bit & Mbit photonics**

High-efficiency light-to-voltage conversion w/o amplifier



NTT, K. Nozaki et al., Optica 3, 483 (2016)



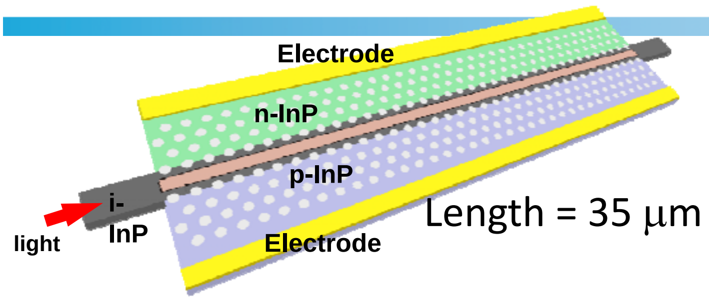
C_{theory} = 0.3~0.5 fF
f_{3dB} = 28.5 GHz

Best candidate for amplifier-free photodetector

Typical amp. = 400 fJ

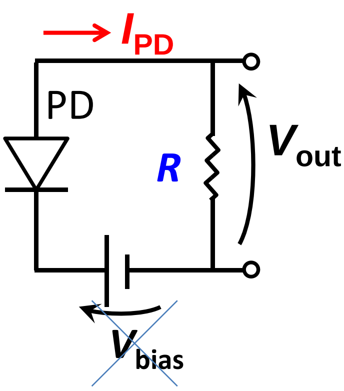
NTT

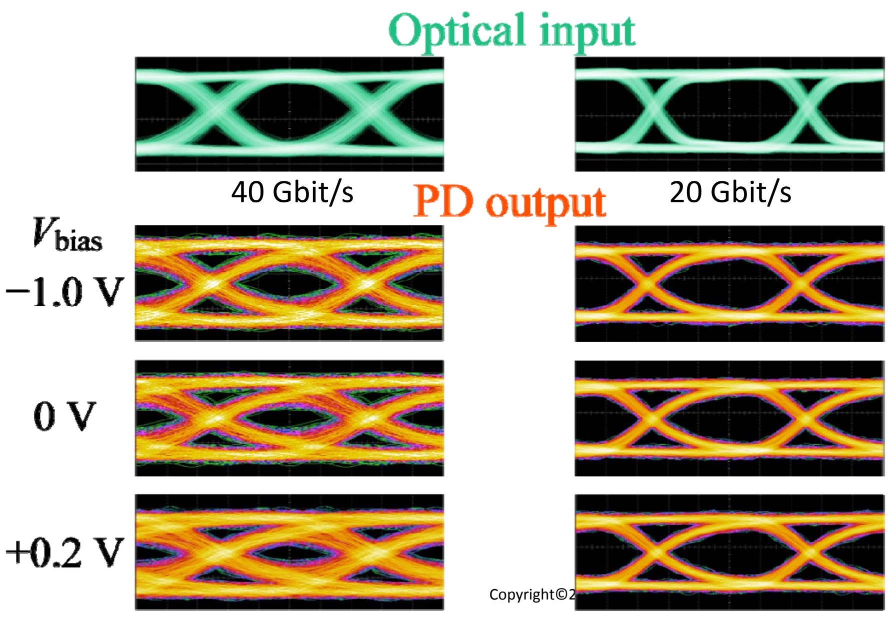
Bias-free operation



Length = 35 μm

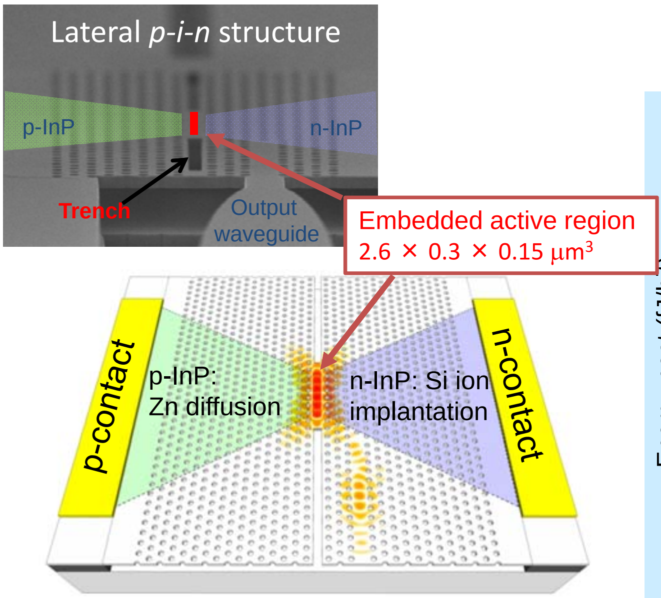
NTT, K. Nozaki et al., CLEO, STh4N.1 (2017)



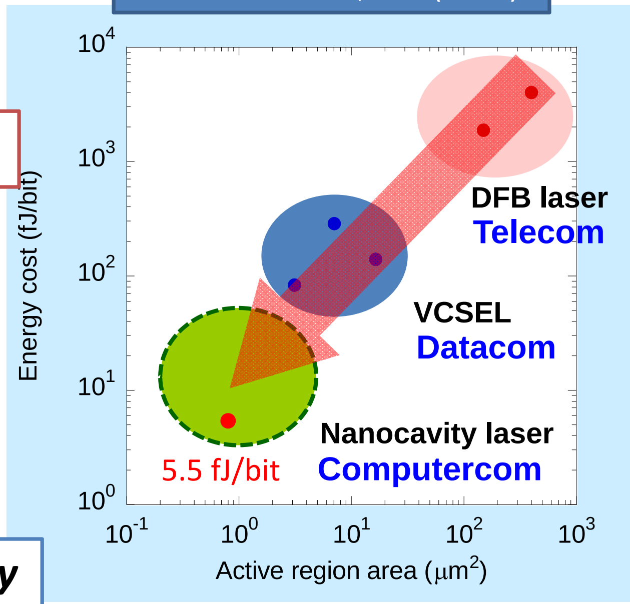


NTT

Ultralow-threshold laser



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

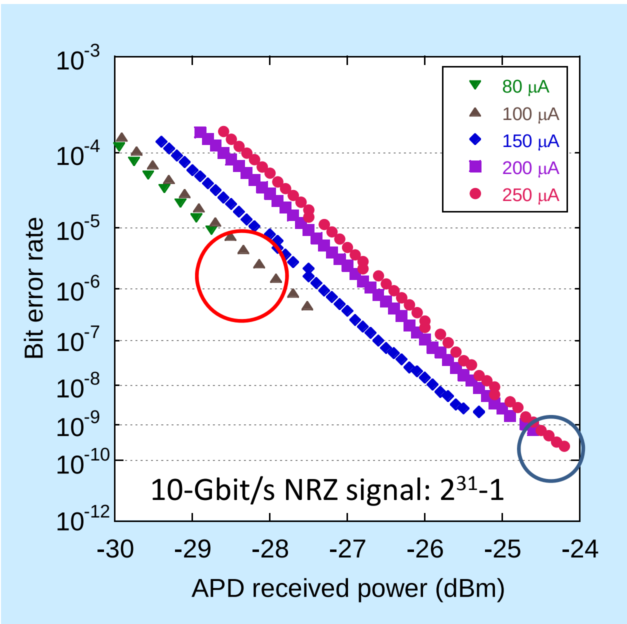


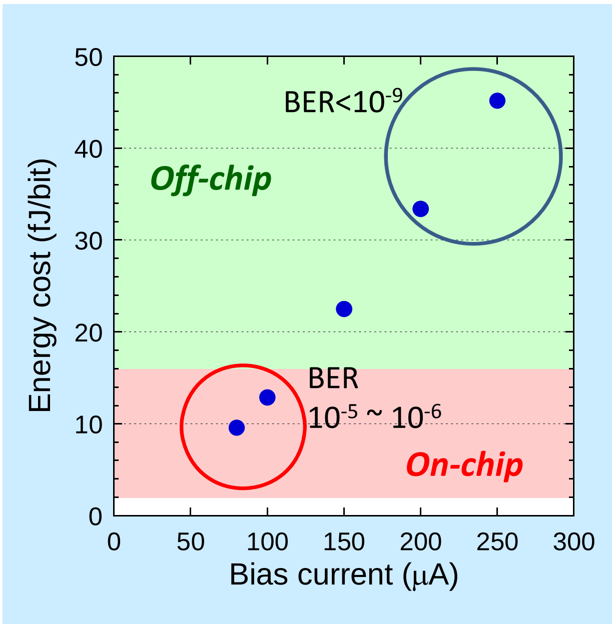
World's lowest threshold for any type of laser diode

NTT

Bit Error Rate Measurement

w/o 50-Ω termination & optical amplifier





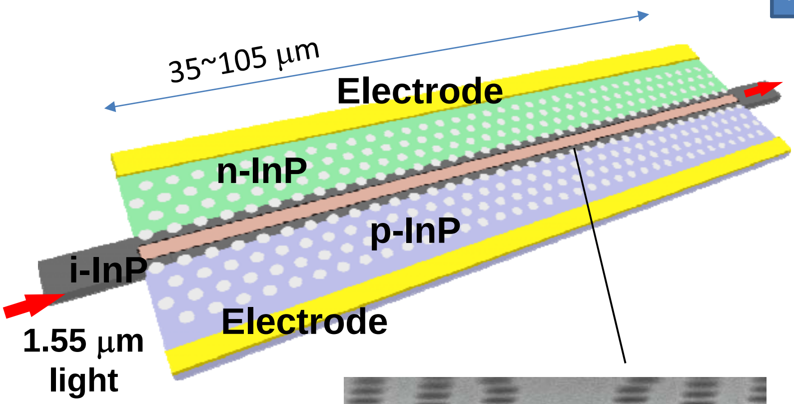
- ✓ ***BER < 10^{-9}*** @ 200&250 μA
- ✓ Limited by coupling loss

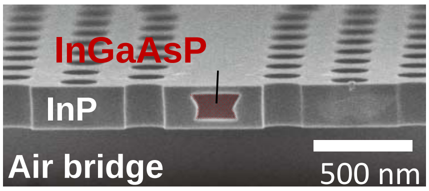
- ✓ ***Energy cost < 50 fJ/bit***

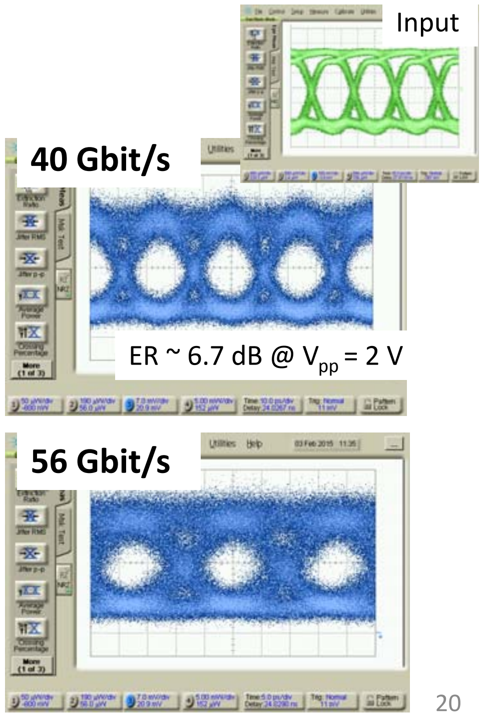
Ultra short pass/block gate

EAM: electrical amplitude modulator

NTT, K. Nozaki et al., APL Photonics 2 , 056105 (2017)







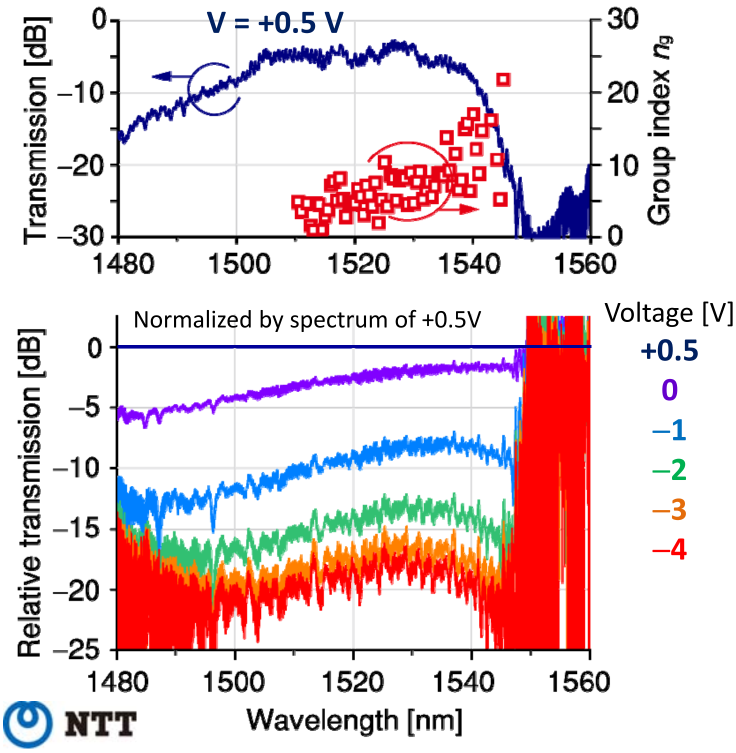
C_{theory} = 13 fF
Energy = 1.8 fJ/bit
@105um

Pass delay ~ 1 ps/100μm

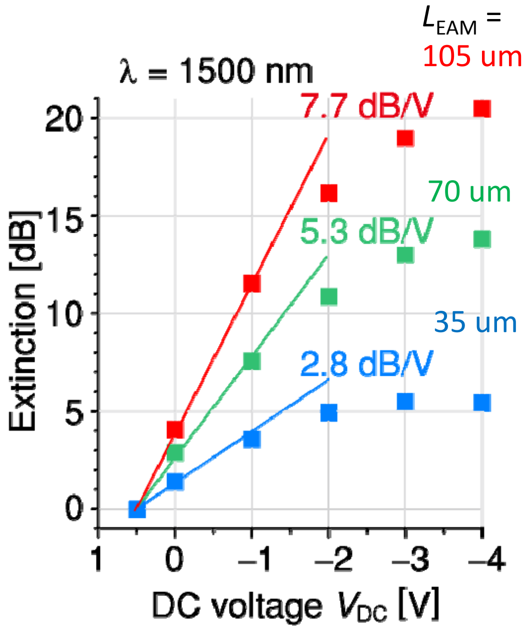
NTT

Extinction vs Voltage

EAM length L_{EAM} = 105 um



Extinction vs Voltage

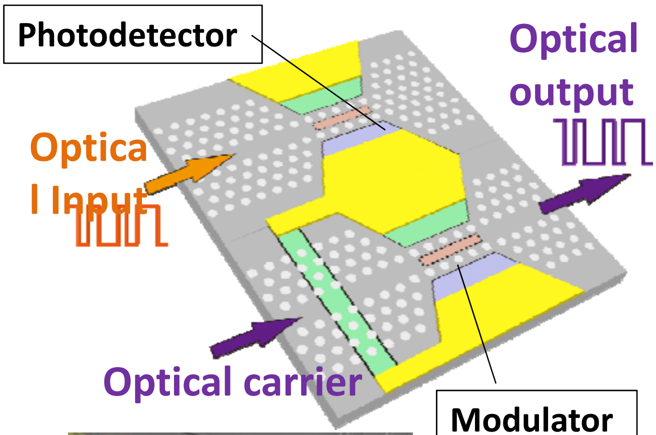


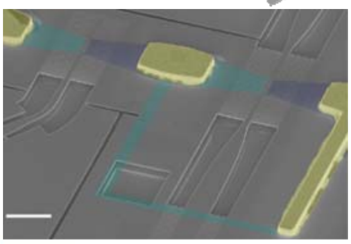
NTT

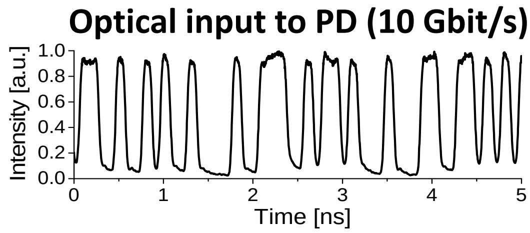
Ultracompact O-E-O convertor

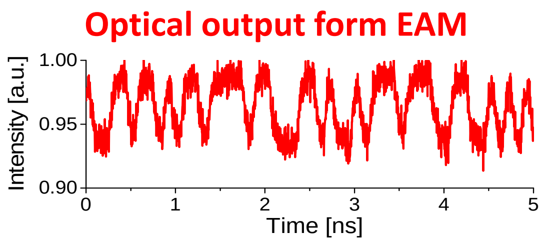
Direct combination of PD and EAM

NTT, K. Nozaki, IPC, TuD3.1 (2015)









NTT

Summary

- ☐ Computation at light speed
  - BDD-based circuits and their cascading enable very low latency calculation.
  - If optical pass gate is 10 - 100 μm long, 10 - 100 times faster than CMOS (potentially).

- ☐ Requirements for photonic device
  - Short optical pass gates
  - Highly effective E/O, O/E and O/E/O conversion

⇩

Nanophotonic device technology

This work was supported by CREST, JST.

NTT