Innovative R&D by NTT

Nanophotonics technology toward optical logic circuits

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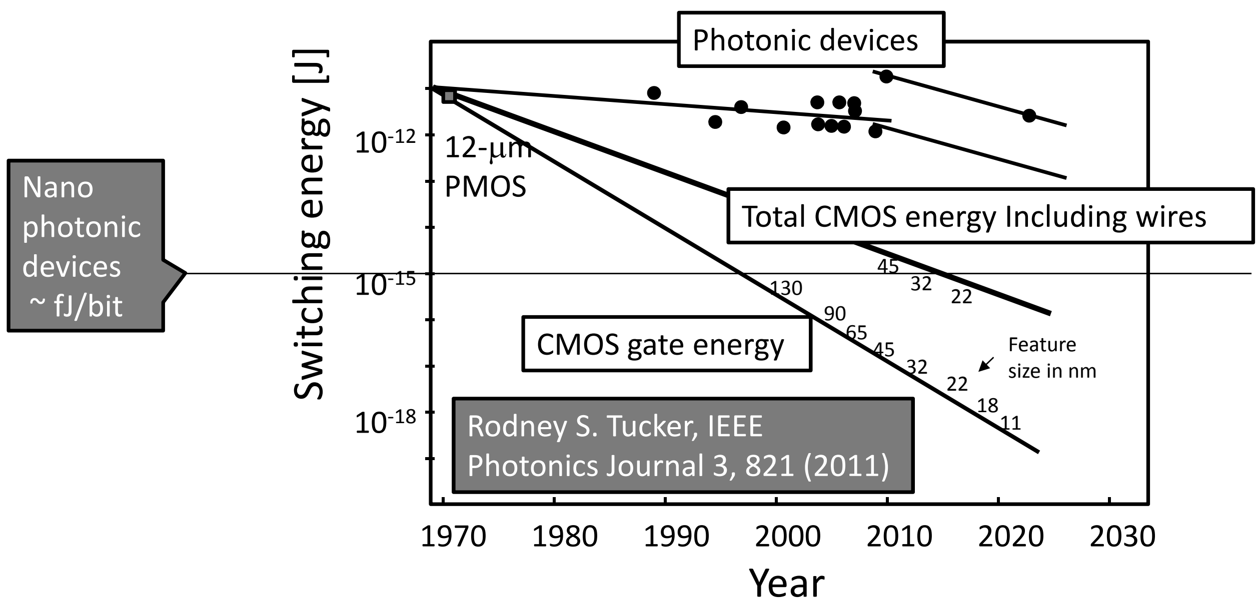
MPSoC'15, Ventura Beach Marriott, CA, USA

Progress in photonics

Electronic vs All-optical signal processing



Nanotechnologies reduce the energy cost in photonics devices to almost the same level as in electronics.
Computing with photonics can greatly develop electronic computing.

Why photonics ?

Problems in electronics

Delay time for data transmission has become a more serious problem than switching time of gates.

Essential problems

(1) Electromagnetic induction (CR limitation)
Bandwidth limitation of metal wire

(2) Basic configuration of a computer
Von Neumann bottleneck
Memory cannot be accessed at the same time.
Throughput is much smaller than the rate at which the CPU can work.

Advantages of photonics

(1) Very high, spatial and temporal bandwidth.
(2) Free space interconnect. (Two-dimensional parallel processing, transmission.)
(3) No physical interaction among optical signals.
(4) Switching of picosecond order.

Limitation of optical logic (photon-level computing)

Required average number of photons (m) ~ 100

$(1-P_0)^\beta \geqq 1-\alpha$	
$P_0 = e^{-m}$:	Minimum probability that "0" and "1" can be distinguished
$\alpha = 10^{-20}$ [1/s]:	Reliability of the system
$\beta = N \times T = 10^{18}$ [1/s]:	Complexity of the system
$N = 10^6$:	Gate number
T = 1ps:	Operating cycle of the logic element

Switching time ~ 1fs

$\Delta E \Delta t \geq h/2\pi$:	Uncertainty principle
ΔE ~ 1eV:	Energy gap between two state levels
Δt:	Switching time

Energy cost/gate: ~ 13 aJ

$m \times \hbar\omega$

Power consumption of the system: 13 W

10T [bit/s]	Clock: $\Delta t \times 100$
10% :	Active elements in N Gates

Tohoku Univ., S. Noguchi, IPSJ 26, 970 (1985)

History of optical computing (1980 -1990)

☐ Opto-electronic computer (digital computing with optics)

Bit serial computing/programmable logic array (PLA) and table look up (LUT) based system.
Use light for signal communication.
Almost the same basic configuration/operation concept as the electronic computer.
Basically, optical-electrical (OE) conversion was required.

Speed and power consumption, overheads due to O/E and E/O conversions.

☐ Optical parallel computer

Optical phenomena (Fourier transform, correlation operation, spatial filtering).
Analogue phenomena were accurately analyzed via binary arithmetic.
Programmability via parallel optical interconnect and spatial light modulation element.

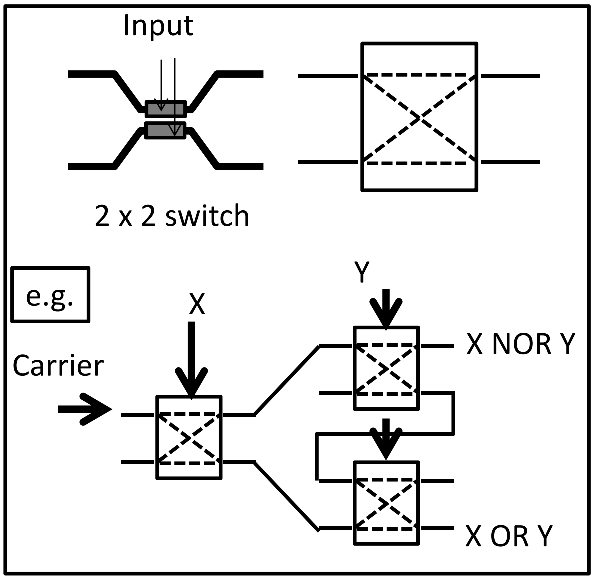
Lower resolution, response speed, controllability.

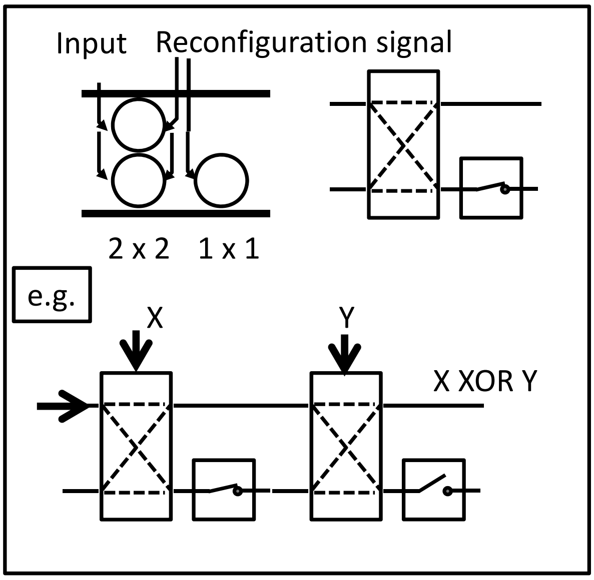
Very successful in information systems (e.g. communications, memories).
Relative failure in computing.

http://www.hindawi.com/journals/aot/2010/372652/

Recent studies in computing with optics

Optical circuit based on pass transistor logic





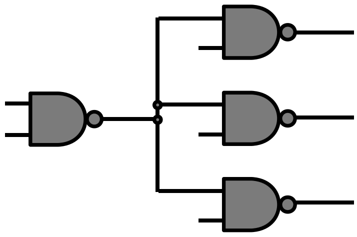
Idaho State University, J. Hardy,
OPTICS EXPRESS 15, 150 (2007)

Rice University, Q. Xu,
OPTICS EXPRESS, 19, 5244 (2011)

Difficulties in opto-electronic computing

☐ Logic functionality

AND, OR, NOT, etc



☐ Cascadability

Retain logic levels when cascading multiple devices

☐ Fan-in, Fan-out

Device output can drive input of at least two devices

Typical fan-out for CMOS ~ 10

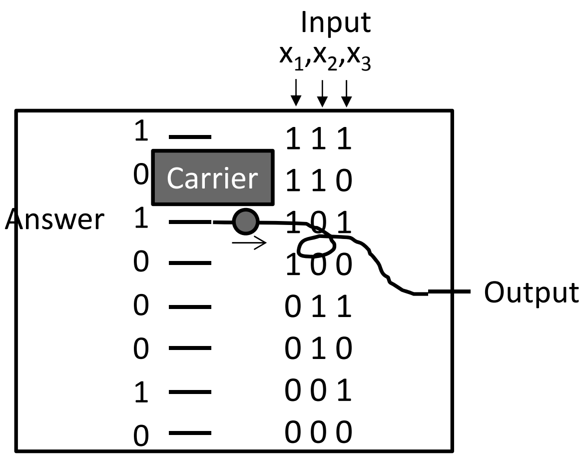
Rodney S. Tucker, IEEE Photonics Journal 3, 821 (2011)

What is role of computing element?

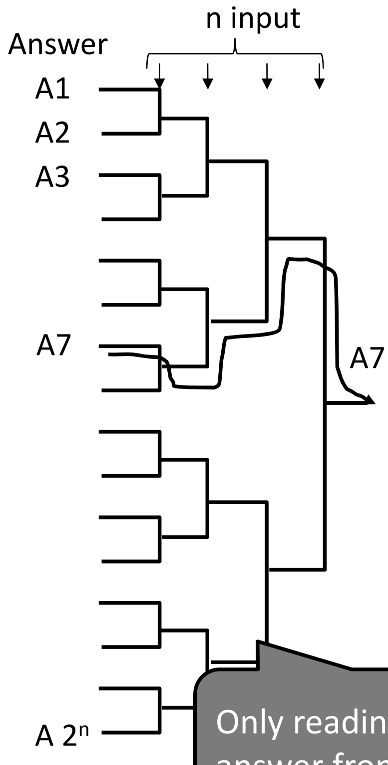
Enter the combination of "0" and "1" and output "0" or "1"

$F(x_1,x_2,x_3,\cdots)$ = "0" or "1" @x_i="0" or "1"

Connecting "Output" port and appropriate "Answer" depending on the input pattern
Calculation can be done by carrier propagation through the connected pathway.



Circuit configuration based on pass transistor logic



Three operation processes

(1) Preparation of 2^n pattern answer for n inputs.
(Answer list is kept in memory)

(2) Construction of output path via two-branch switch.
(Simultaneous gate switching [ps])

(3) Outputting the answer through the pathways.

In electronics

(1) Huge memory switch available
(2) Fast (~ 10 ps)
(3) Very slow (limited by CR constant $\propto n^2$)

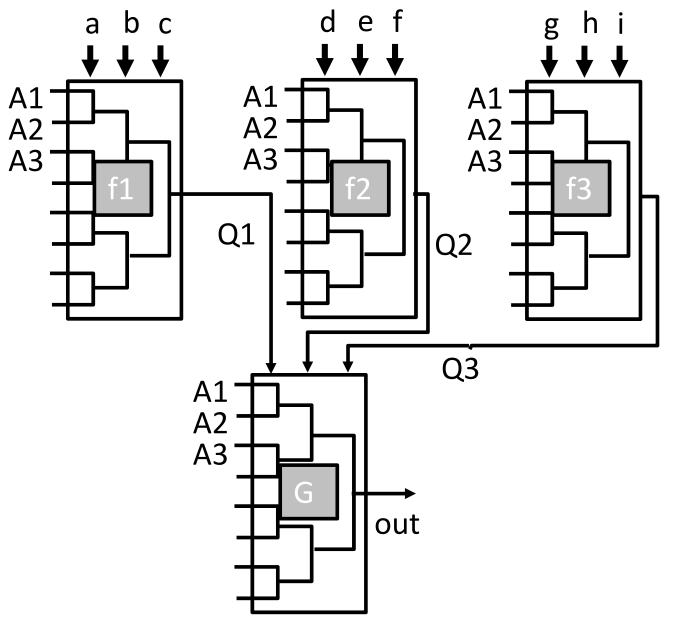
Improvement by photonics

(3) No CR limitation

Only reading out the answer from the list!

Calculation with light propagation speed!

Cascade connection



Merits

Flexibility in circuit design.

Out = F(a,b,c,d,e,f,g,h,i)
↓
Q1 = f1(a,b,c)
Q2 = f2(d,e,f)
Q3 = f3(g,h,i)
Out = G(Q1,Q2,Q3)

Demerit

No appropriate photonic device for this connection.

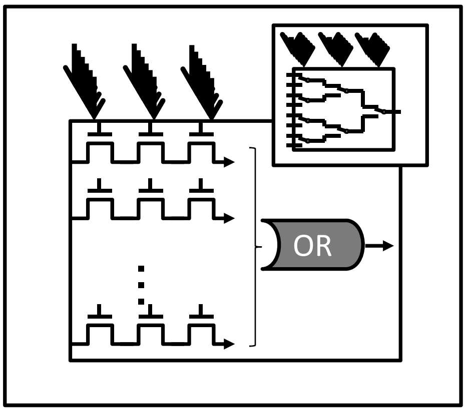
Throughput (data transfer rate)

	Size	Bandwidth	Path delay (data transmission)	State delay (state change)	High throughput Application
Photonics	Large (bulky)	**Wide band** No CR limitation **Multiplexity** Frequency Phase Polarization Mode shape	**Light speed**	few ps	**Multiplex commun.**
Electronics	**Small**	Narrow band CR limitation	Slow	few ps	**Parallel computing** Expand the "operation" to "space"

Target: Calculation of multiplexed signal while keeping optical throughput

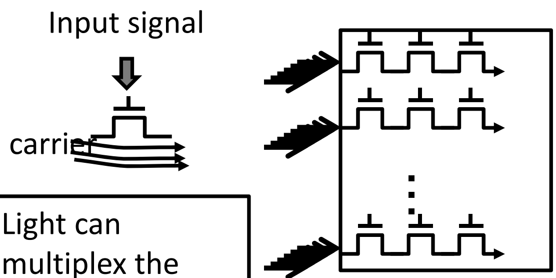
Calculation of multiplexed signal

Required function



Multiplexed signal

Feasible function in photonics



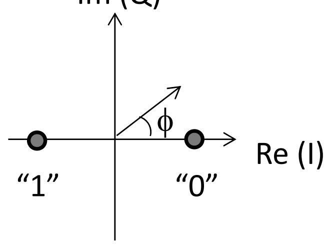
Light can multiplex the carrier signal.

Carrier
Electrical signal = A ("0" or "1")
Optical signal = $A_\theta e^{i(\omega t + \phi)}$
A: Amplitude θ: polarization
ω: frequency ϕ: phase

Phase/Polarization Shift Keying

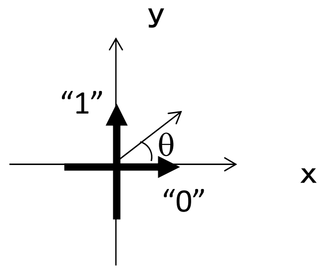
Signal = $A_\theta e^{i(\phi)}$

PSK (Phase Shift Keying)



Widely used in digital coherent optical communication

POLSK (POLarization Shift Keying)

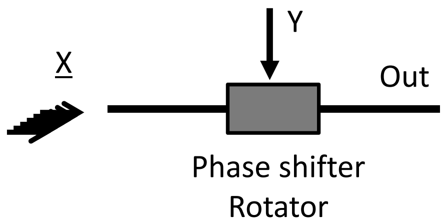


MIT, S. Benedetto, IEEE TRANSACTIONS ON COMMUNICATIONS 40, 708 (1992)

Very simple "NOT" operation (rotating ϕ or θ)

Boolean functions (AND/ OR/ NOT/ XOR)

Phase shifter / Polarization rotator

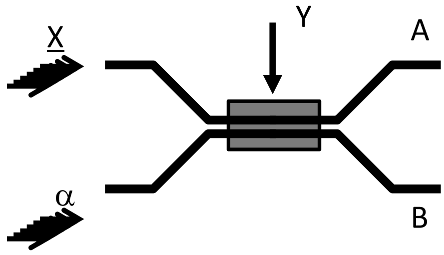


X	Y	out
"1"	1	"0"
"0"	1	"1"
"1"	0	"1"
"0"	0	"0"

Out = X XOR Y

Out = NOT X   Y=1

Directional coupler



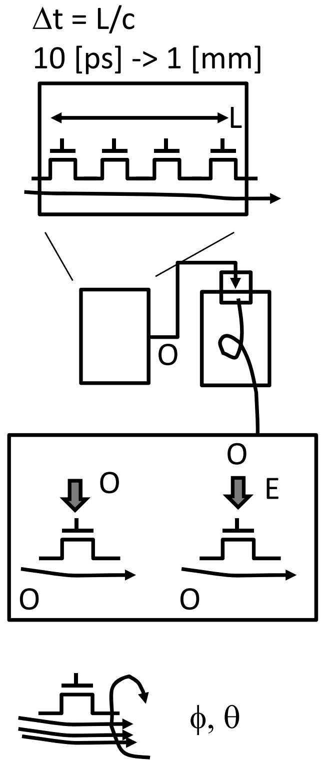
X	Y	A	B
"1"	1	α	"1"
"0"	1	α	"0"
"1"	0	"1"	α
"0"	0	"0"	α

A = X OR Y   α = "1"

B = X AND Y   α = "0"

Short summary

- Pass transistor based logic circuit
  - Only pass the light through many gates.
  - Create complex logic functionalities.
    Calculation time = Light propagation time
    Importance of nanophotonics to minimize device size.
- Cascade connection offers flexibility in circuit design.
  It requires gate operation via light signal.
- Calculation of multiplexed signal for more throughput
  Possible candidate: PSK or POLSK.

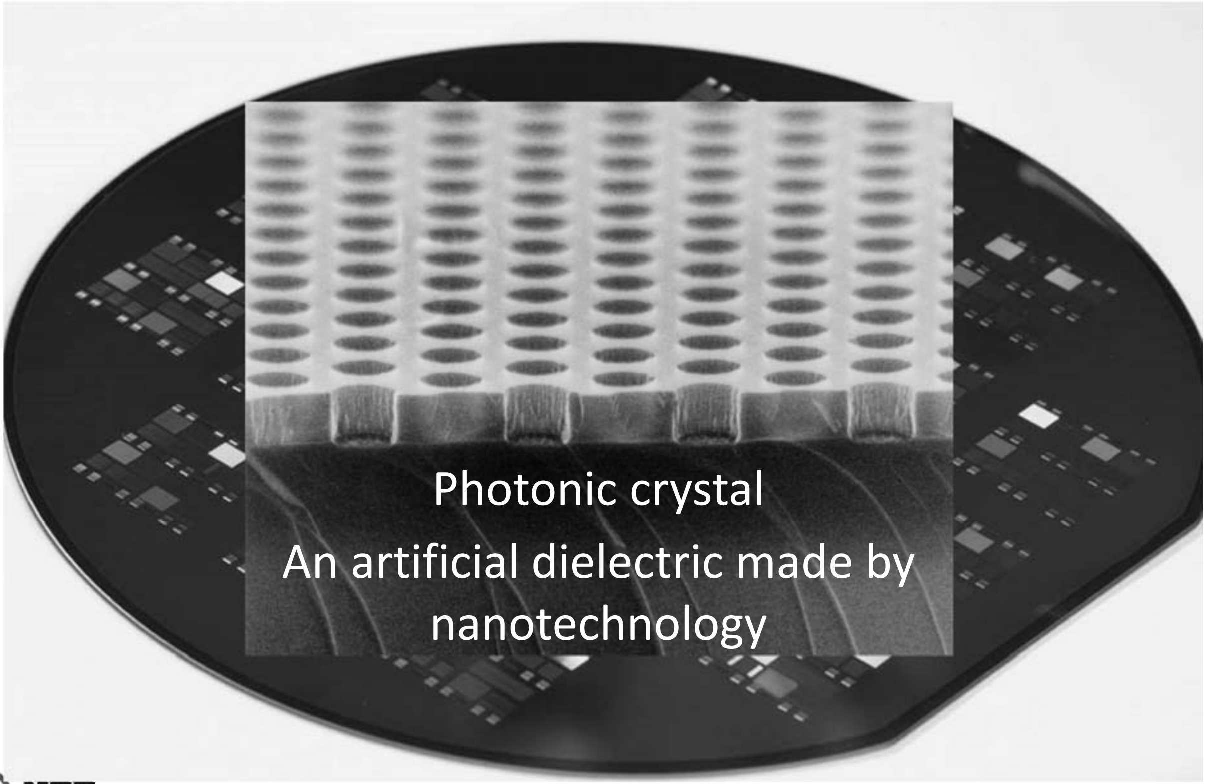


Required nanophotonic devices

For light speed computation

- Light source + Photo detector
- Short switching device (L < 100 μm (1ps path delay))
  - Pass gate type selector to use pass-transistor logic
  - Small size device for small path delay
  - Cascade connection for flexibility in circuit design
  - Wide band device for WDM.
  - PSK or POLSK compatibility for multiplexed carriers

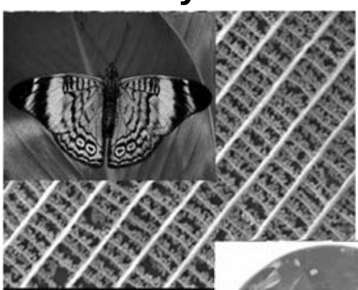
Photonic crystal



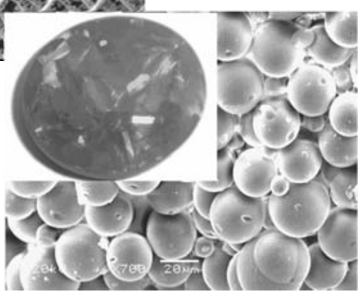
What is photonic crystal?

Natural photonic crystal

Butterfly

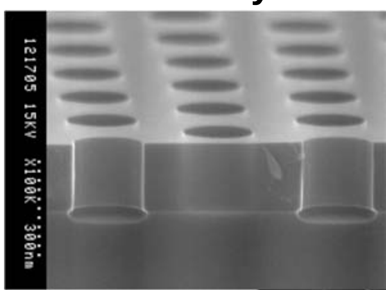


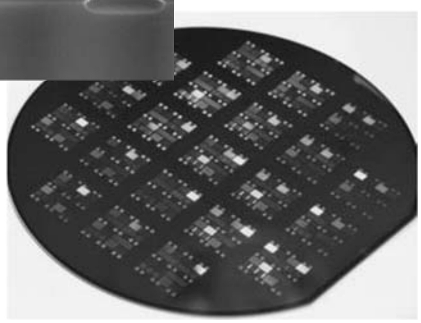
Opal



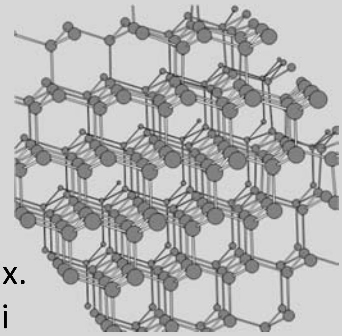
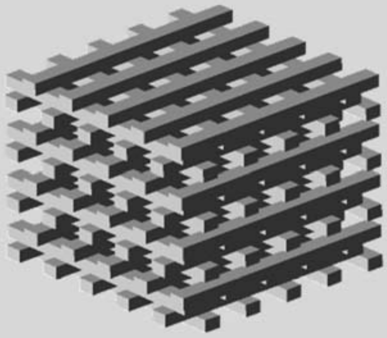
Artificial photonic crystal

Photonic crystal on Si wafer



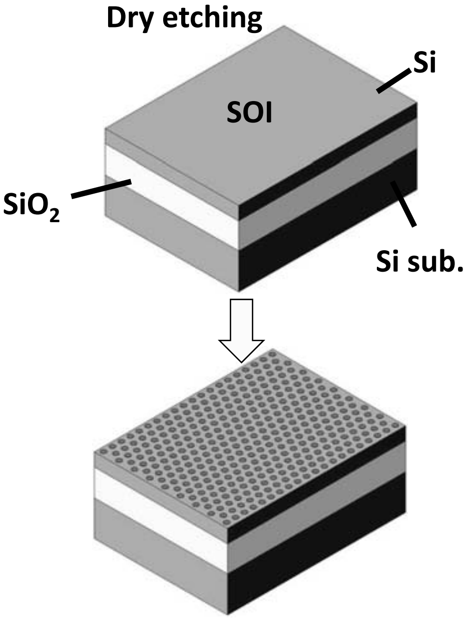


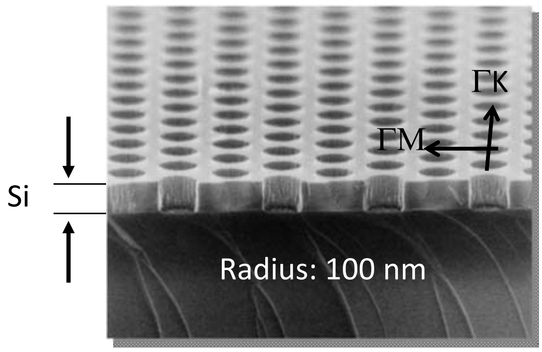
Analogy between electronic and photonic crystal

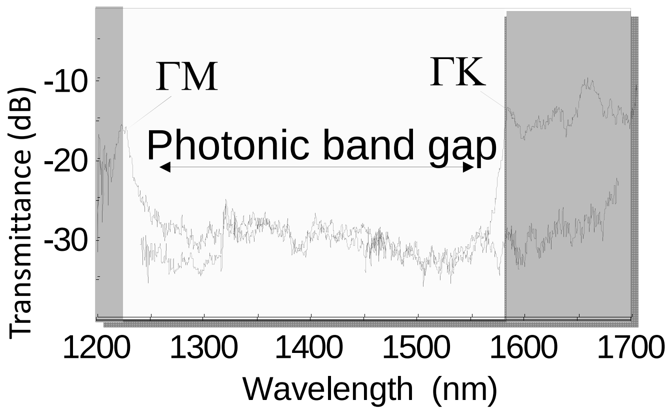
Electronic crystal	Photonic crystal
 Ex. Si	
Period ~ 0.1nm = Electronic wavelength	Period ~ 100 nm = Optical wavelength
Various electrical properties ● Conductor ● Semi conductor ● Insulator	New optical properties ● Optical insulator ● Slow light ● Negative refraction

2D photonic crystal

Electron beam lithography
&
Dry etching

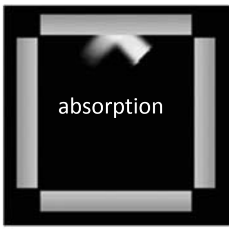


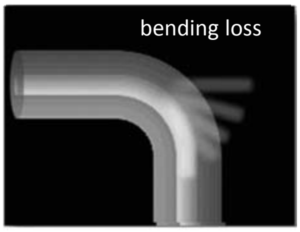




Why photonic crystal?

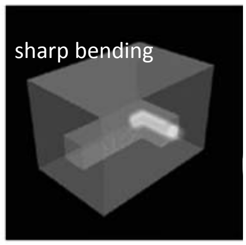
Metal mirror	Fiber



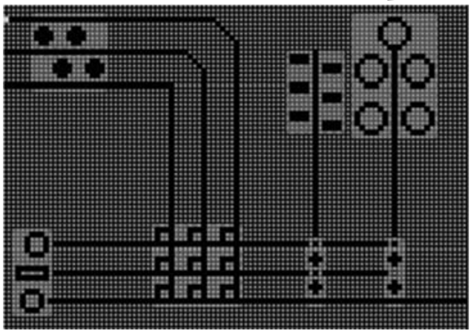


Optical absorption — Leakage at bends

Photonic crystal



Light is completely confined



Large-scale
photonic integration

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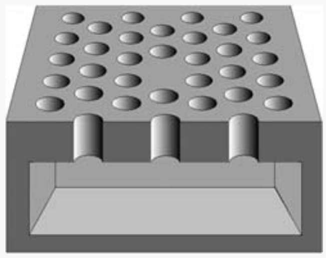
What can photonic crystals do?

Toroid cavity	Micro-disk	Micro-post	**Photonic Crystal**



Toroid cavity	Micro-disk	Micro-post	Photonic Crystal
V = >100(λ/n)^3	V = 6(λ/n)^3	V = 5(λ/n)^3	**V = 0.5-1.5 (λ/n)^3**
Q = 10^8	Q = **10^3 -10^6**	Q = **10^3**	**Q = 10^5-10^6**

(λ/n): light wavelength in cavity

Ultrasmall high-Q cavity

Small footprint (~ μm²)
Strong light-matter interaction

→ **fJ/bit and Mbit photonics**

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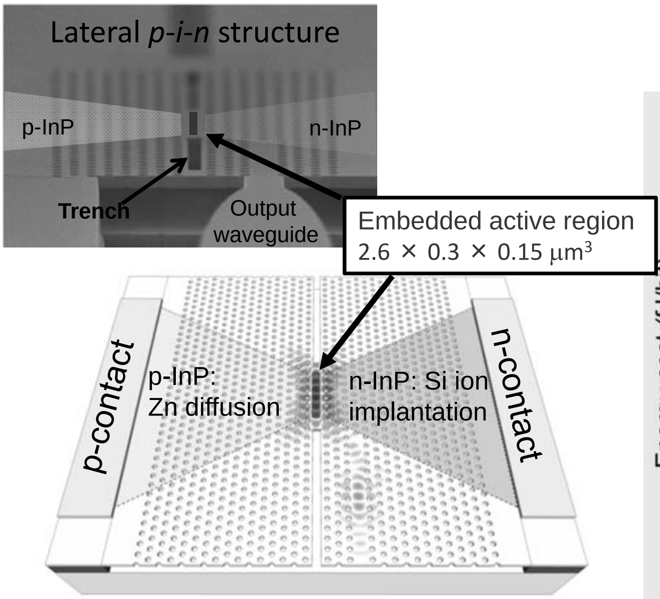
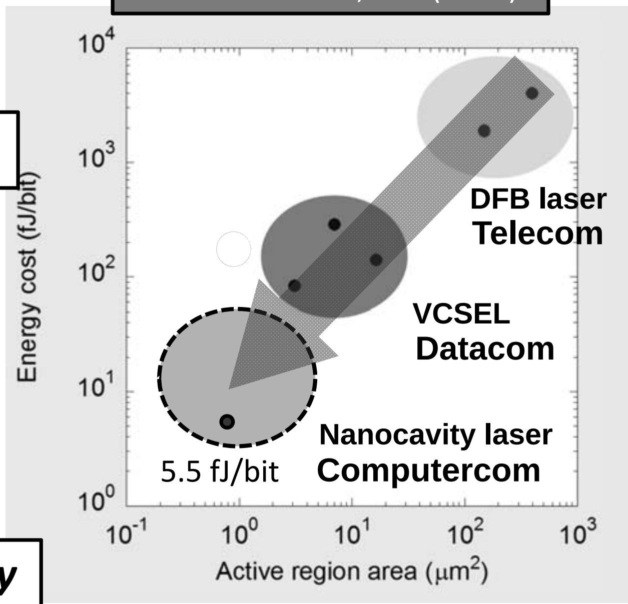
Ultralow-threshold Laser

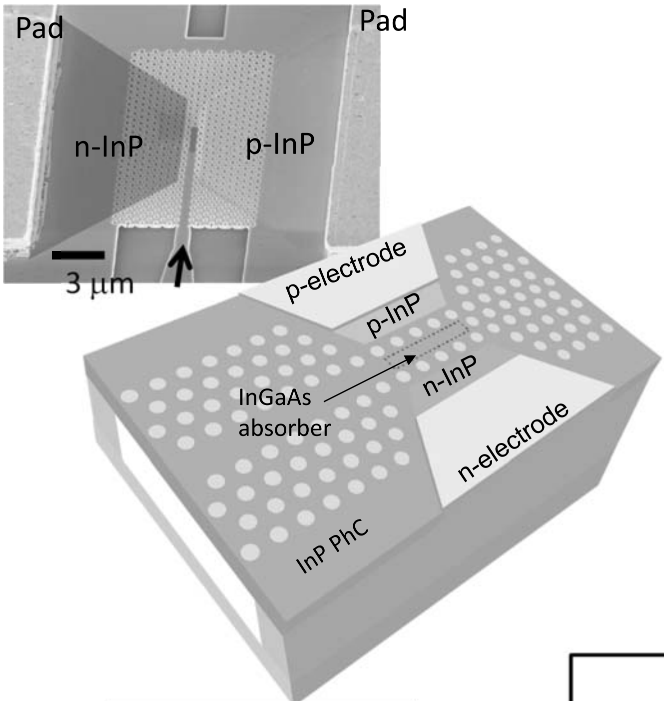


NTT, Takeda et al.
Nature Photon. 7, 569 (2013)



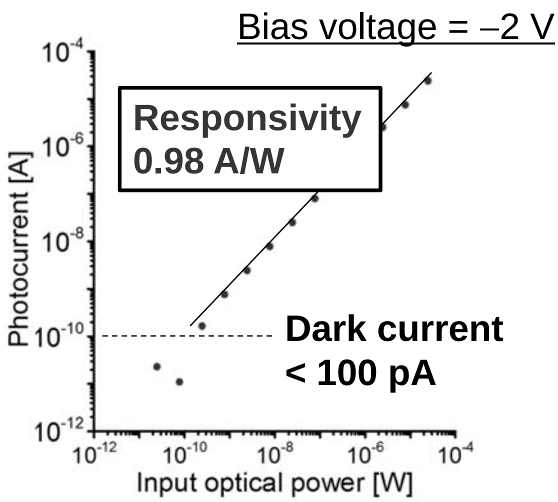
World's lowest threshold for any type of laser diode

High-responsivity Detector



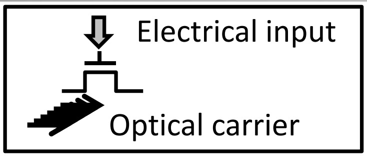
C_{theory} = 0.3~0.5 fF

Nozaki et al., OPTICS EXPRESS 21, 19022 (2013)



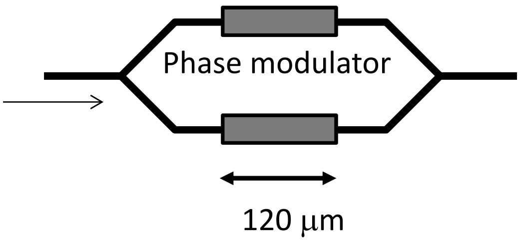
Best candidate for receiver-less photodetector

Very small EO modulator (Phase modulator)



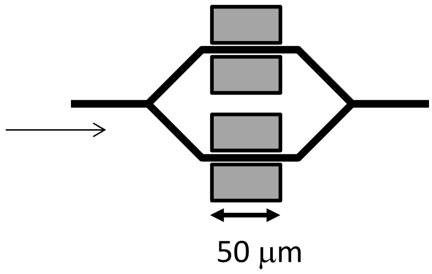
Path delay (data transmission)
Glass: 1~10 [cm] -> 100~1000 [ps]
Si Ph.: 1 [mm] -> 10 [ps]

Silicon photonics



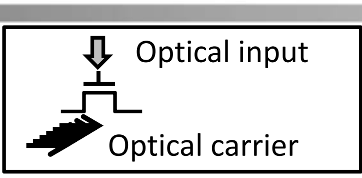
NEC, J. Fujikata,
OFC 2010

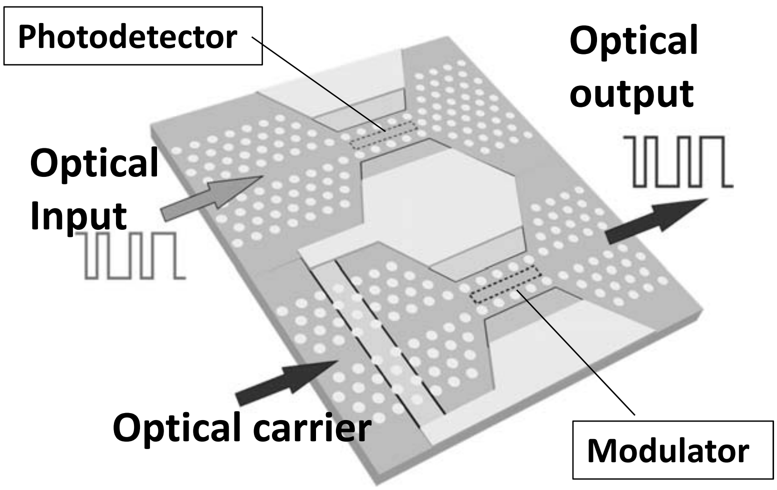
Photonic crystal



Yokohama Univ., Hong C. Nguyen,
OPTICS EXPRESS 20, 22465 (2012)

Ultracompact O-E-O convertor





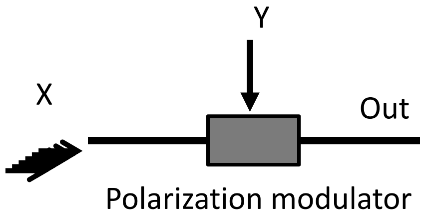
Simulation

Size : <10 × 10 μm^2
Speed: ~ 40 Gb/s
Energy : 13 fJ/bit (light)
aJ/bit (bias)

NTT, K. Nozaki
JSAP spring meeting, 13a-A10-10 (2015)

Very short Polarization modulator

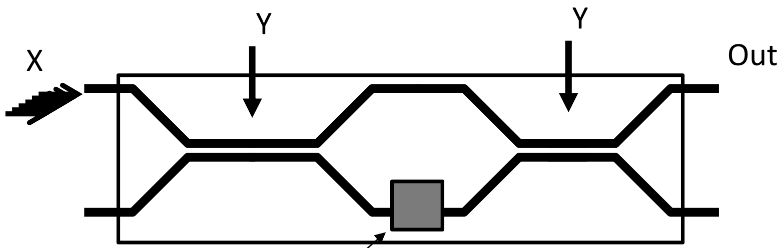
Polarization rotator

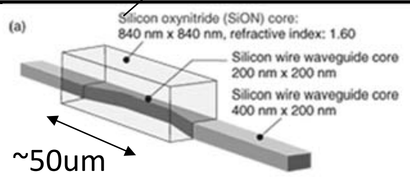


X	Y	out
“1”	1	“0”
“0”	1	“1”
“1”	0	“1”
“0”	0	“0”

Out = X XOR Y

Out = NOT X   Y=1





Polarization rotator

NTT, H. Fukuda, Optics Express 16, 2628 (2008)

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Summary

- ☐ Pass transistor based photonic logic circuit
  - Only passes light through many gates.
  - Creates complex logic functionalities.
  - Enables light speed computation!

- ☐ Requirements for switching device
  - Short gate length
    Path delay is determined by light propagation speed.
  - Cascade connection of logic block
    It offers flexibility in circuit design.
  - Calculation using multiplexed signal
    It can improve throughput (data transfer rate).

⇓

Nanophotonic devices technology

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