フォトニック結晶による光閉じ込めと光制御

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自己紹介: 納富雅也(のうとみ まさや)

1988 東京大学工学部物理工学科(修士課程修了)
「一次元電気伝導体の電荷密度波状態のダイナミクス」
1988 日本電信電話㈱入社 NTT光エレクトロニクス研究所配属
半導体量子細線、量子ドットデバイスの研究
1996-1997 Linkoping University (スウェーデン) 客員研究員
1997 工学博士 (東京大学)
「半導体量子細線における2次元量子閉じ込め効果の研究」
1998 フォトニック結晶の研究開始
1999 NTT物性科学基礎研究所へ異動。
現在 同所上席特別研究員、フォトニックナノ構造研究グループリーダ

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何か質問があればいつでもe-mailで

(1) What is photonic crystal?

(2) Ultrastrong light confinement

(3) Slow light in a chip

(4) Adiabatic tuning of light

(5) Optomechanics

(6) Ultralow power device operation

(1) What is Photonic Crystal?

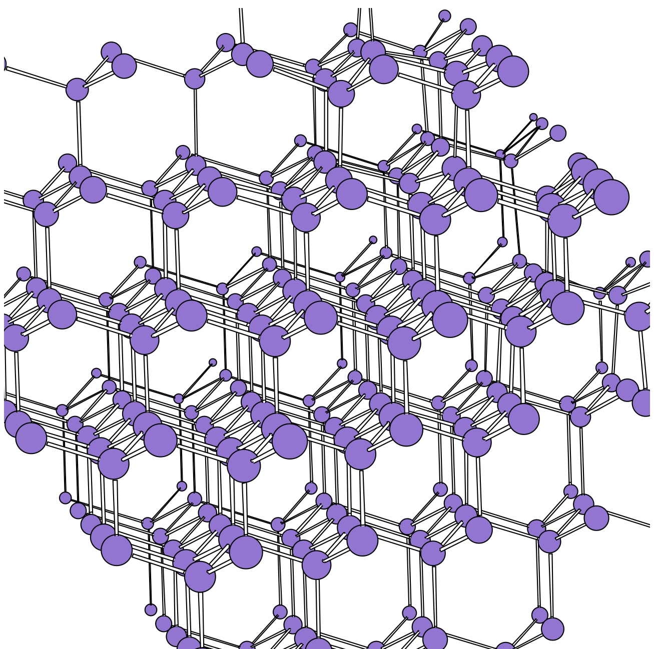
What is Photonic Crystal?

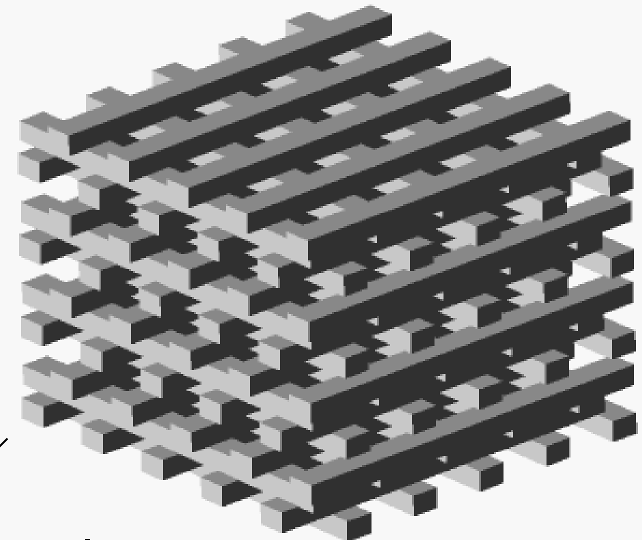
A structure whose refractive index is periodically modulated in 2D or 3D

period ~ λ/n

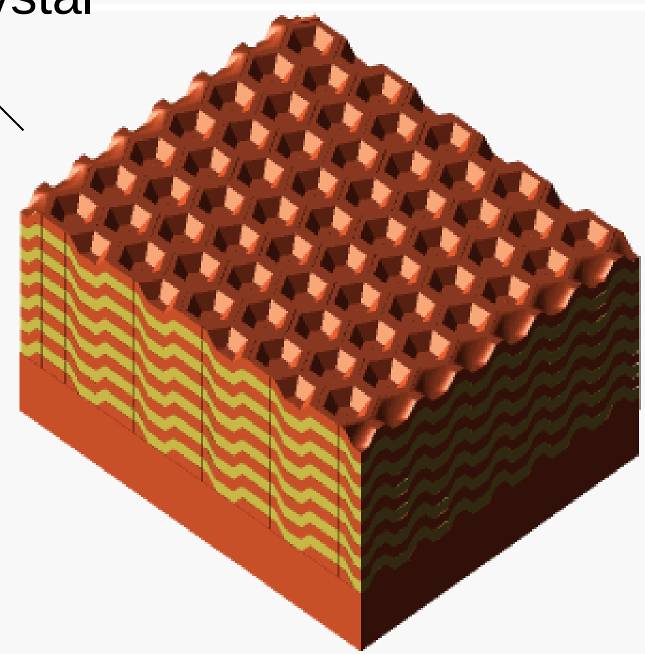
(typically 0.2 ~ 0.5 μm for semiconductors)

e.g., Si



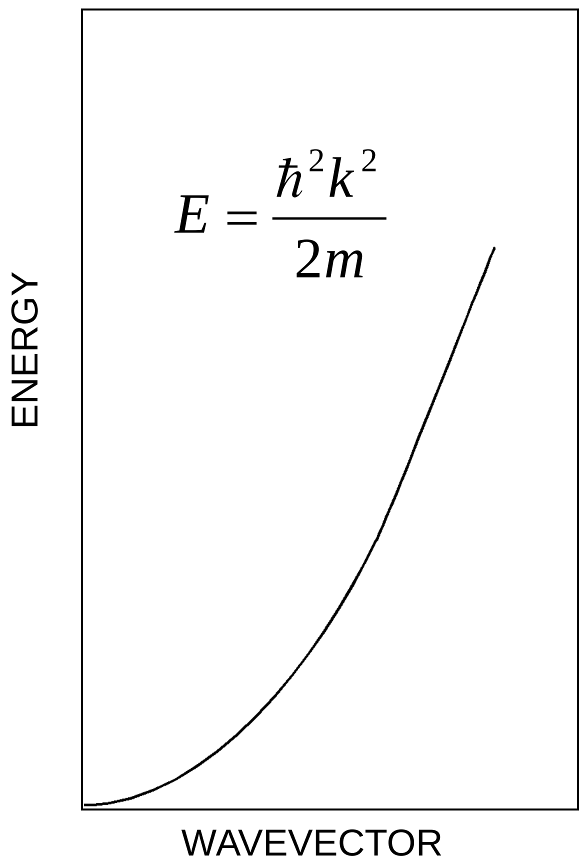


photonic crystal



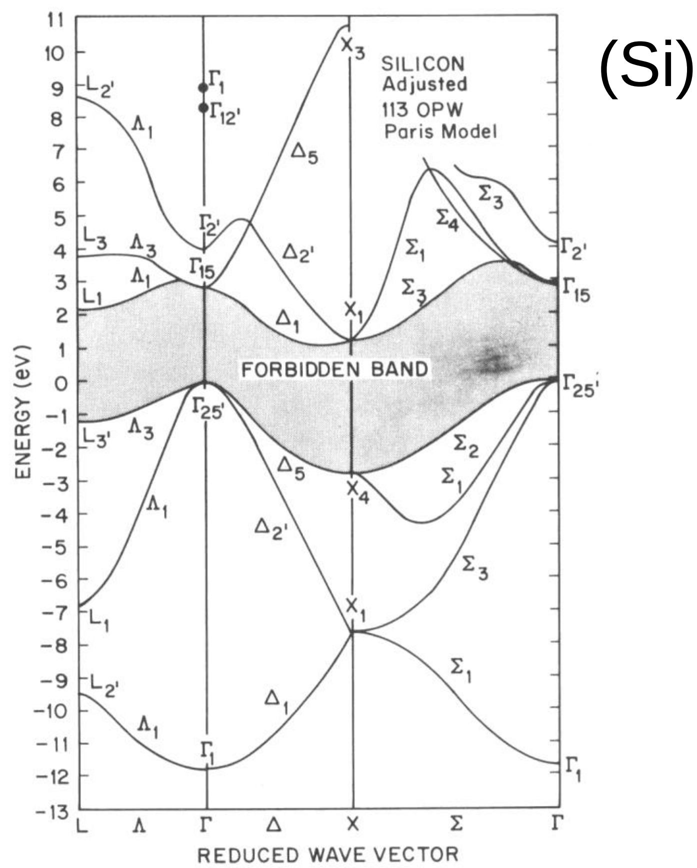
Electronic Band Structure and Bandgap

Free Electrons



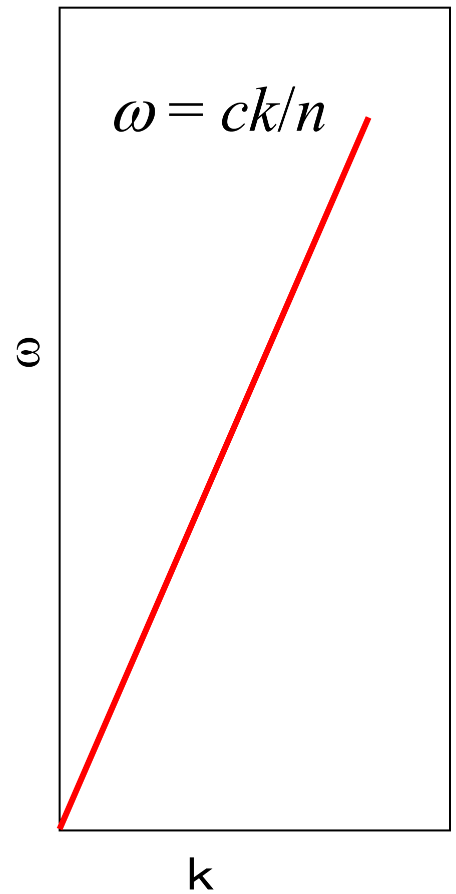
$$E = \frac{\hbar^2 k^2}{2m}$$

Band Electrons

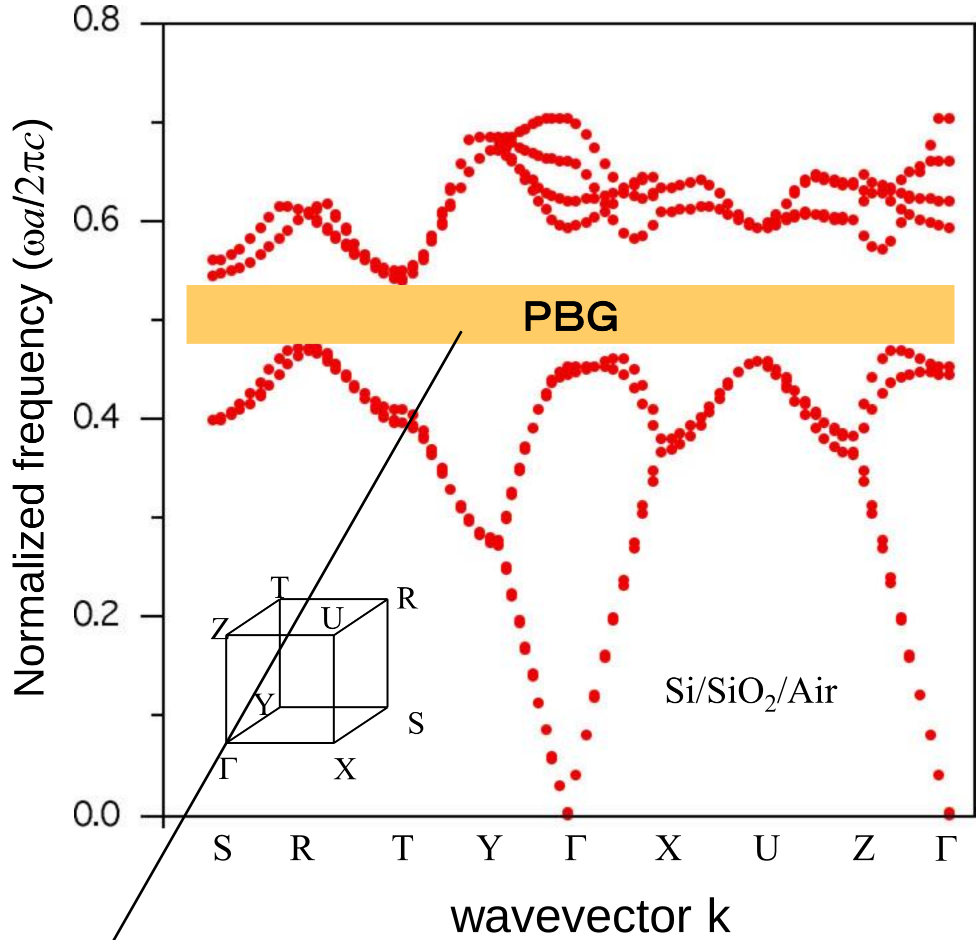


Photonic Band Structure and Bandgap

Dispersion of light in media



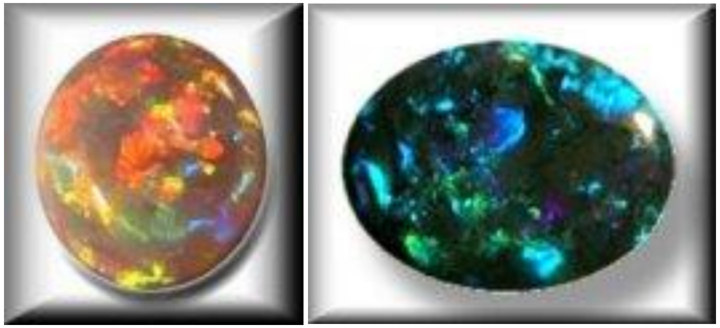
Dispersion of light in photonic crystals

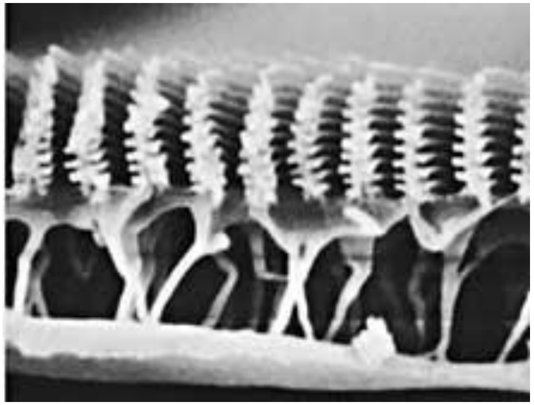


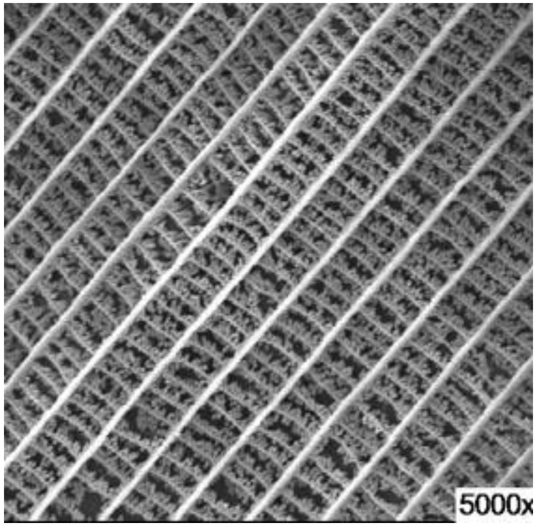
photonic insulator

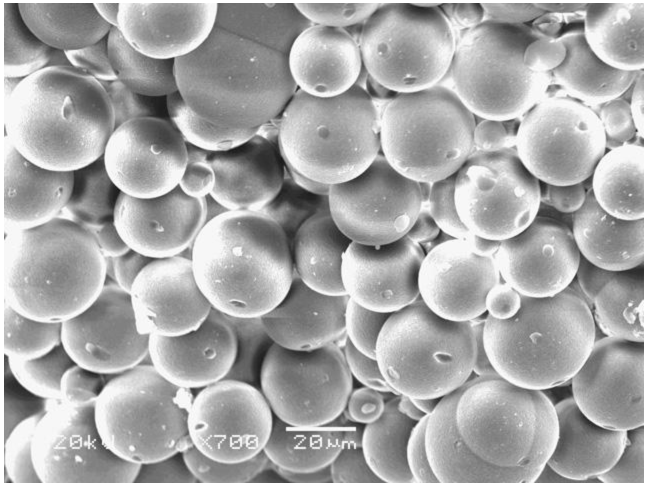
Natural Photonic Crystals

opal







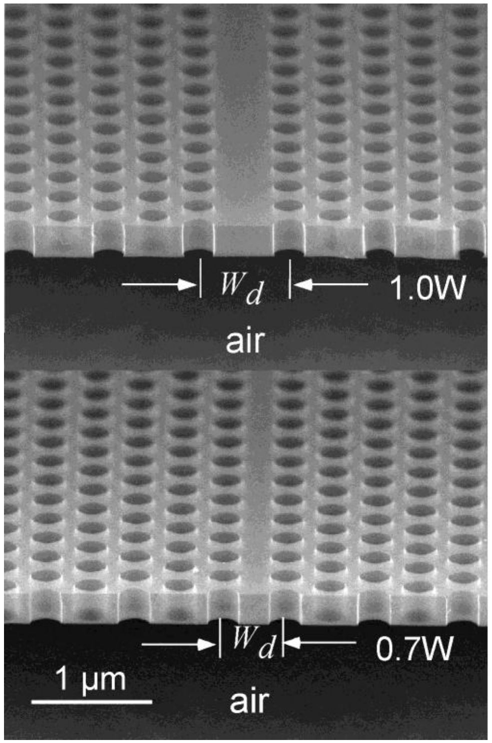


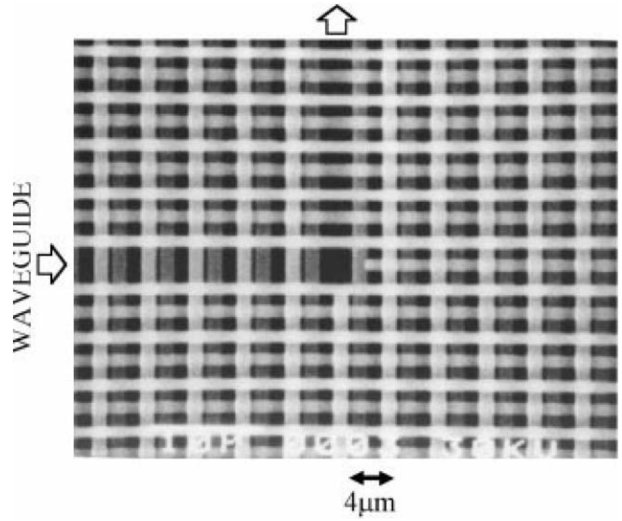
Refractive Indices of Materials

Air	1.0
SiO_2	1.46
NaCl	1.54
Al_2O_3	1.70
MgO	1.74
Polymer	1.4-1.6
GeO_2	2.00
TiO_2	2.72
InP	3.1
GaAs	3.6
Si	**3.5**
Ge	4.1
Te	4.9 / 6.37

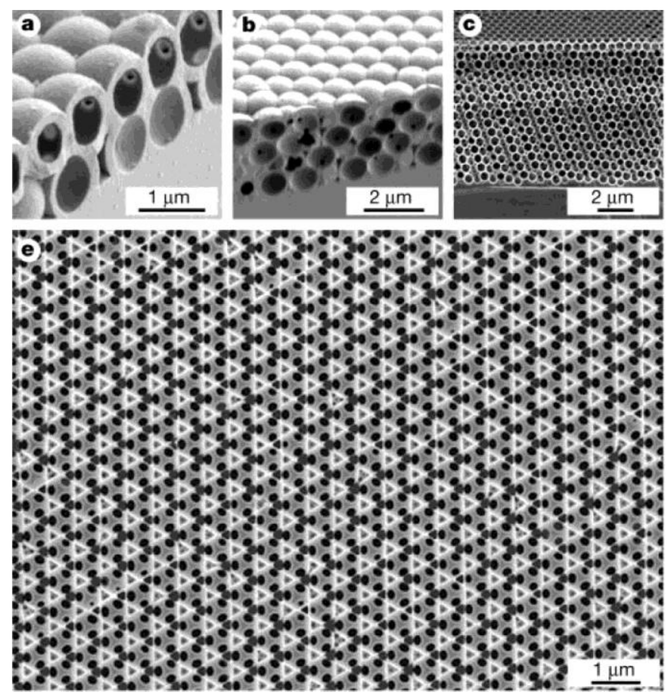
Artificial Photonic Crystals

2D SOI PhC





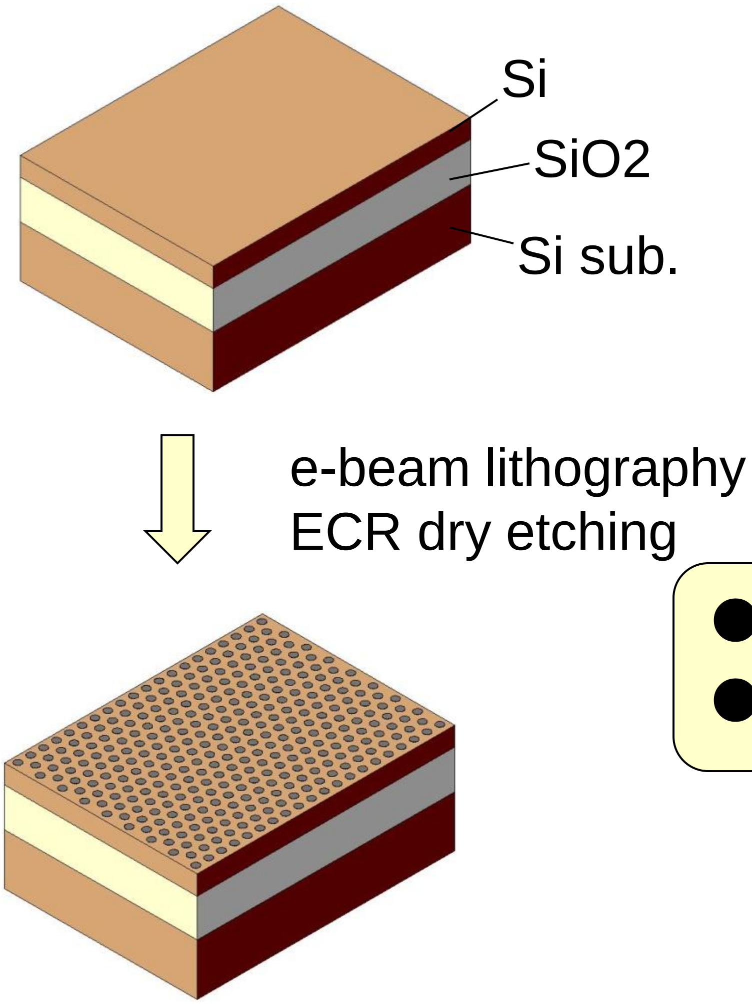
3D woodpile PhC

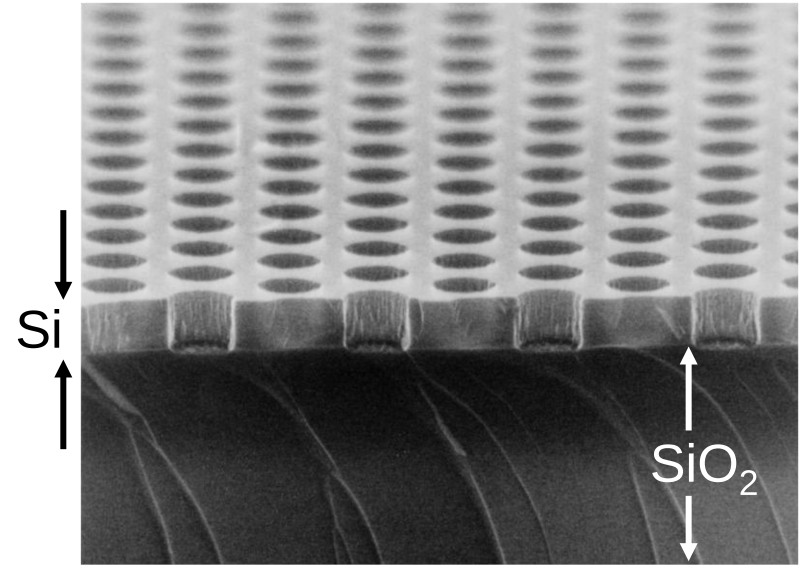


Si inverse-opal

2D Photonic Crystal Slabs

Silicon-On-Insulator (SOI) sub.

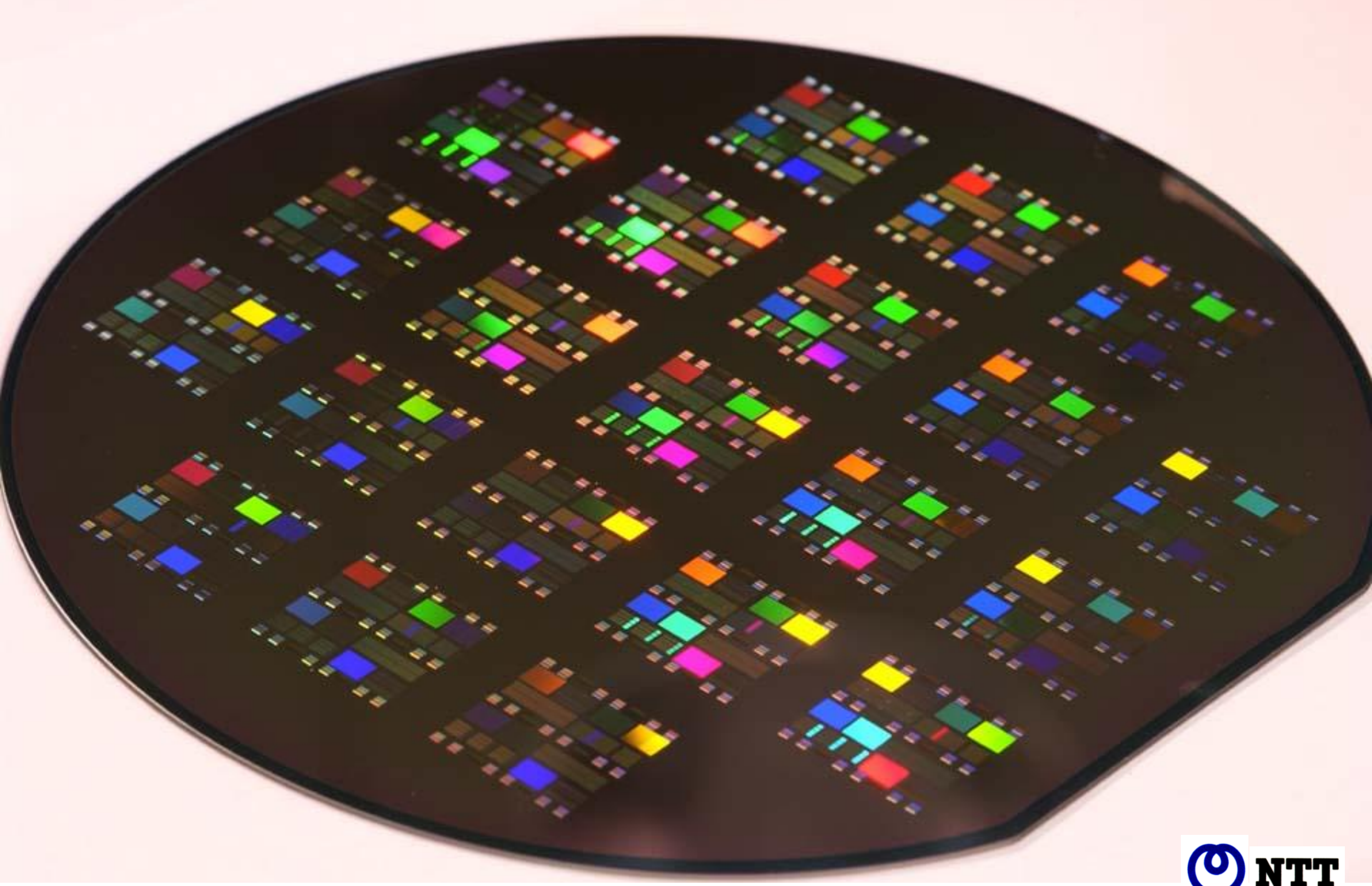




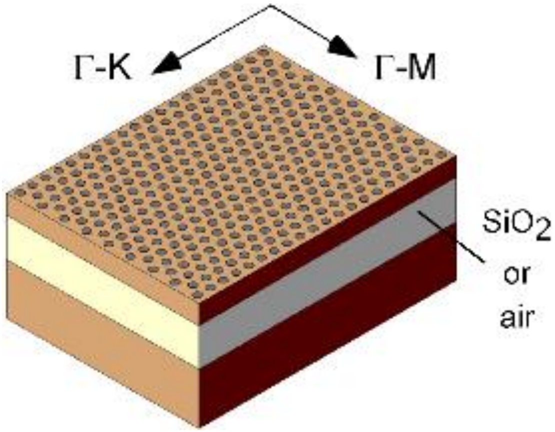
- high-quality and homogeneous sub.
- future large-scale integration

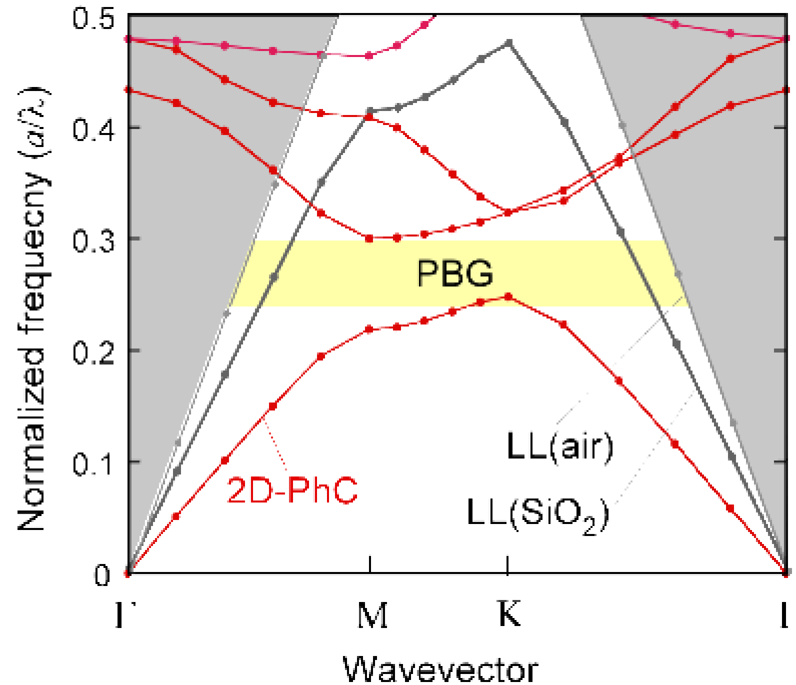
possible platform for PhC-based photonic LSIs

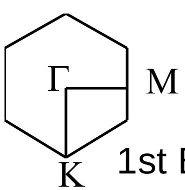
2D Photonic Crystals on SOI wafer



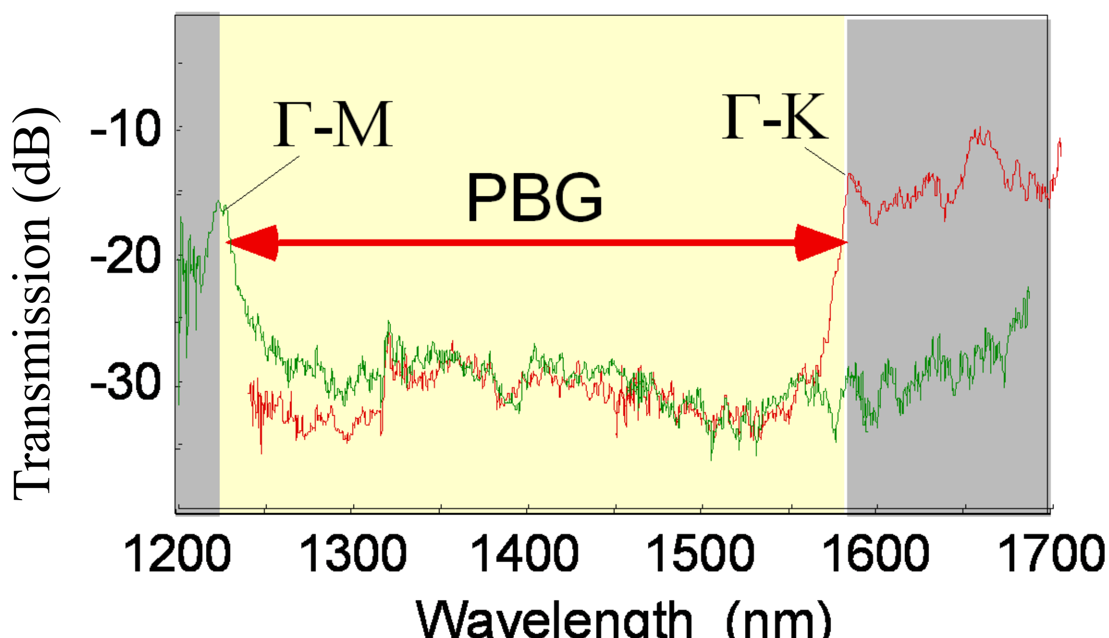
2D PBG in PhC slab







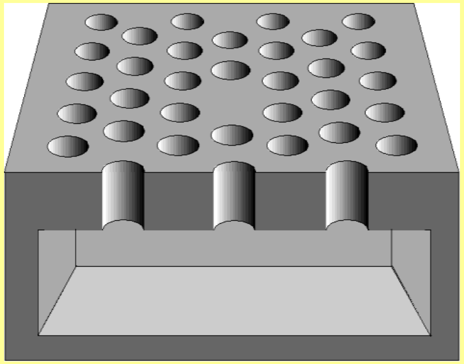
1st Brillouin zone



(2) Strong light confinement

in λ-sized volume

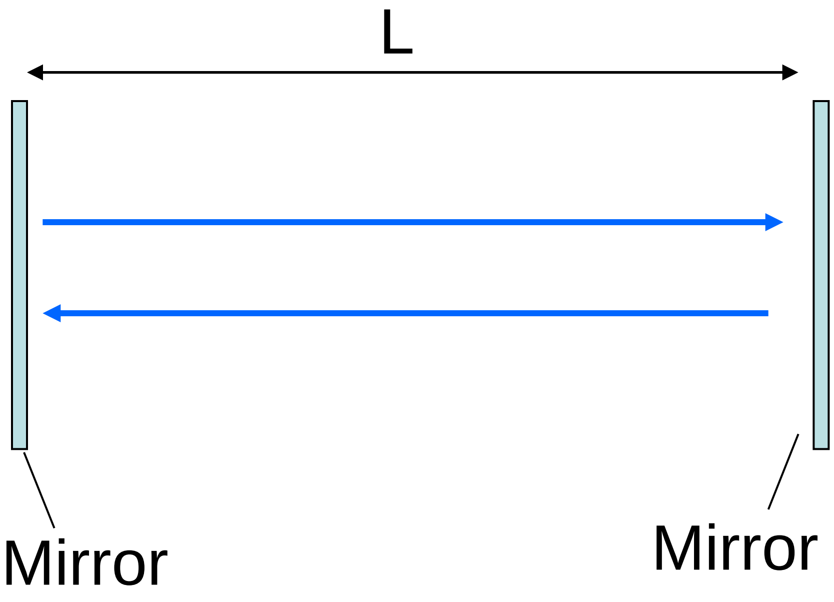
Optical Microresonators

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

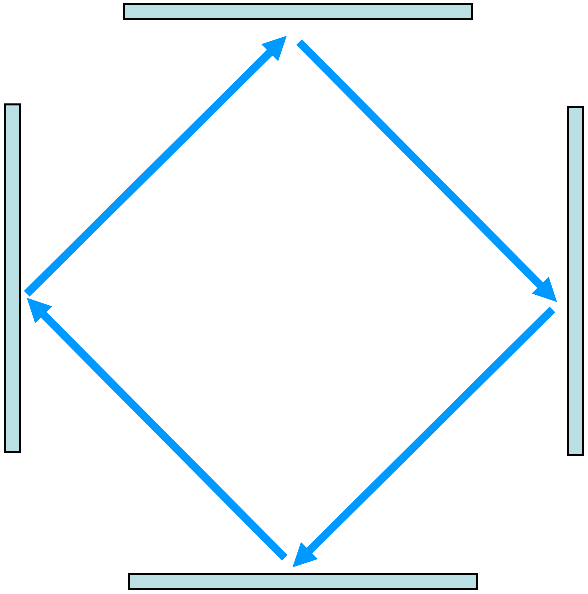
wavelength-sized ultrahigh-Q cavity

How small can an optical resonator be?

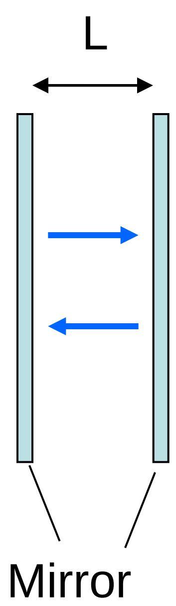
Fabry-Perot Resonator



Ring Resonator



Can we use a conventional mirror?



Cavity Quality factor (Q)

$$Q = \omega\tau = \omega(NL/c)$$

N: allowed number of reflection

Q becomes small in proportional to L

Example: A metallic mirror cavity with L=1 μm

round trip time of light ＝6.7 fs

R~0.95 (Ag)	N~7, photon lifetime =47 fs	Q~60
R~0.99	N~35, photon lifetime = 233 fs	Q~150

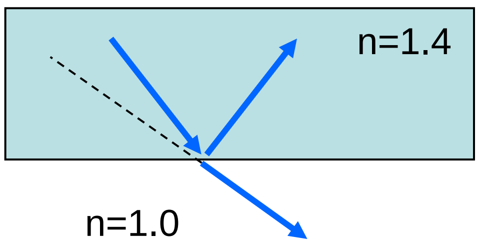
A cavity with $Q=10^6$

L= 1mm, N=150000, → R~0.99999 ⇨ Impossible for plasma reflection

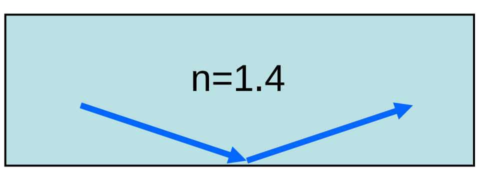
Total Internal Reflection (TIR)

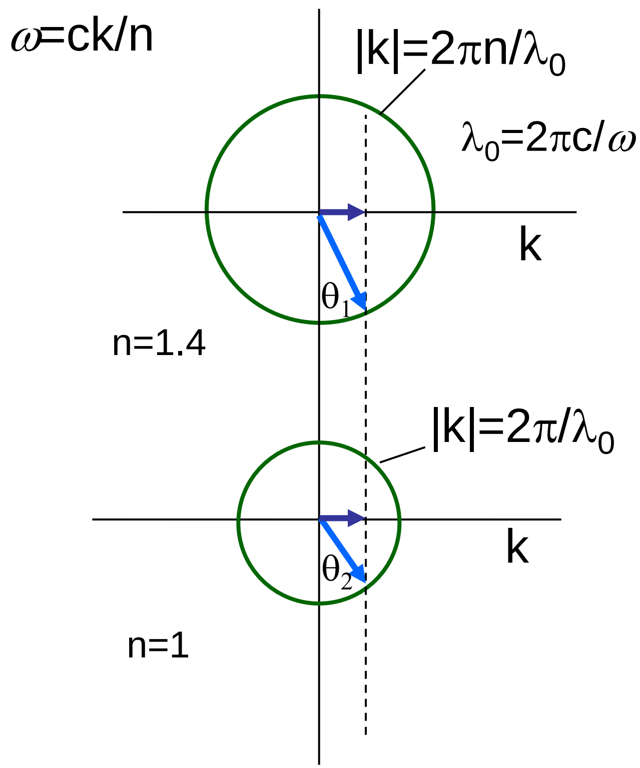
tangential components are conserved

refraction/reflection



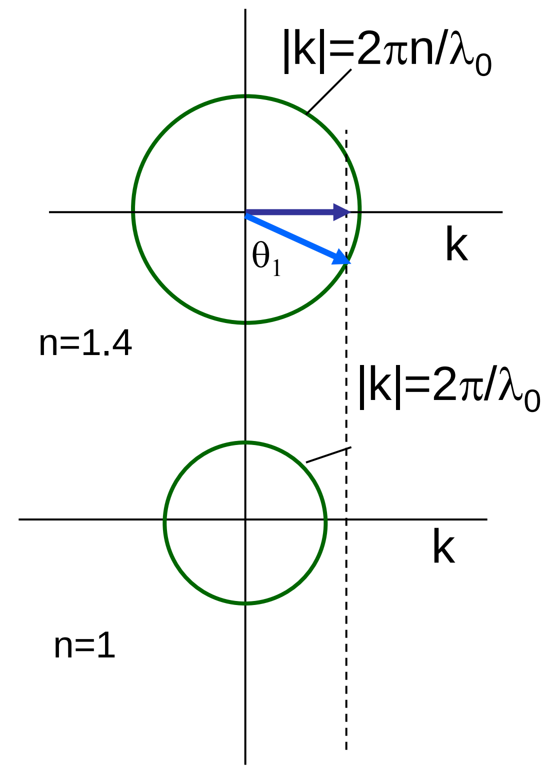
TIR





$n\sin\theta_1 = \sin\theta_2$

refraction/reflection



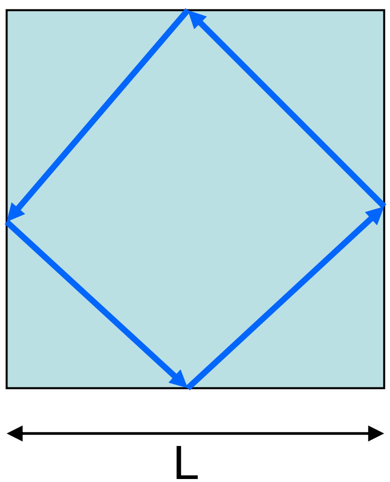
$n\sin\theta_1 \neq \sin\theta_2$

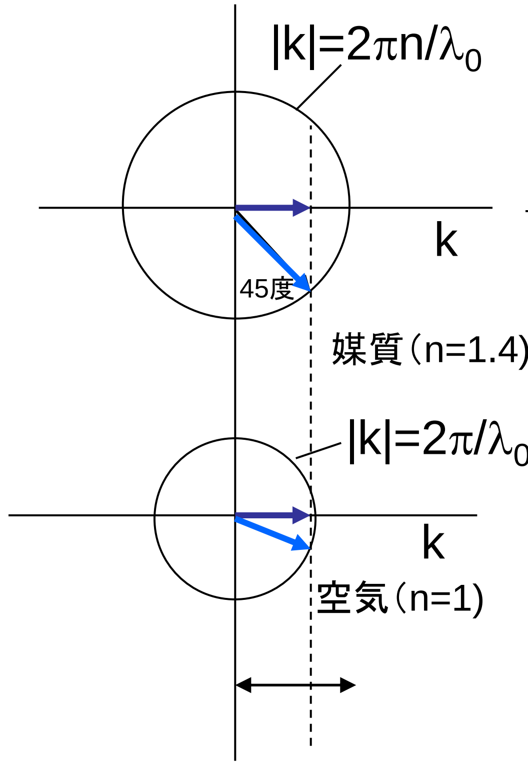
TIR

R_{TIR} = 100%, theoretically

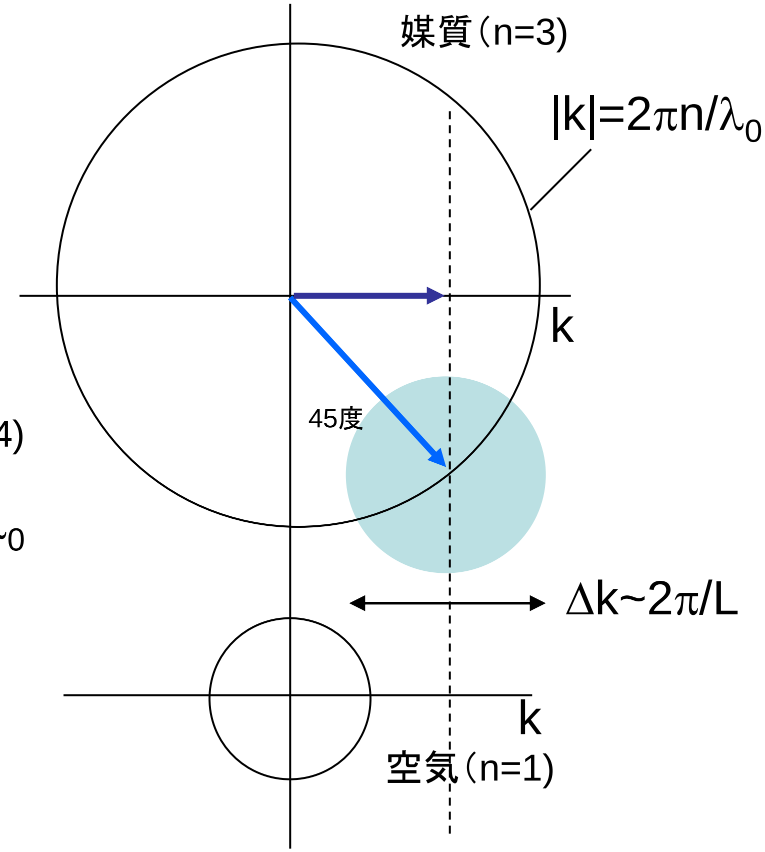
TIR in a small cavity

Ring cavity





no TIR

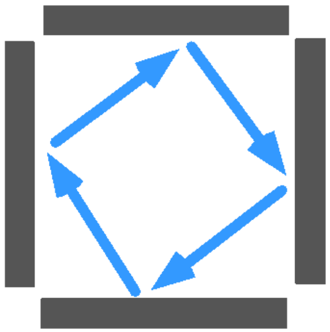


TIR condition is satisfied, but affected by k-space broadening

Light confinement is deteriorated by k-space broadening

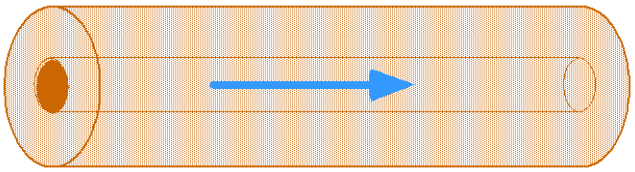
How to confine light?

Plasma reflection



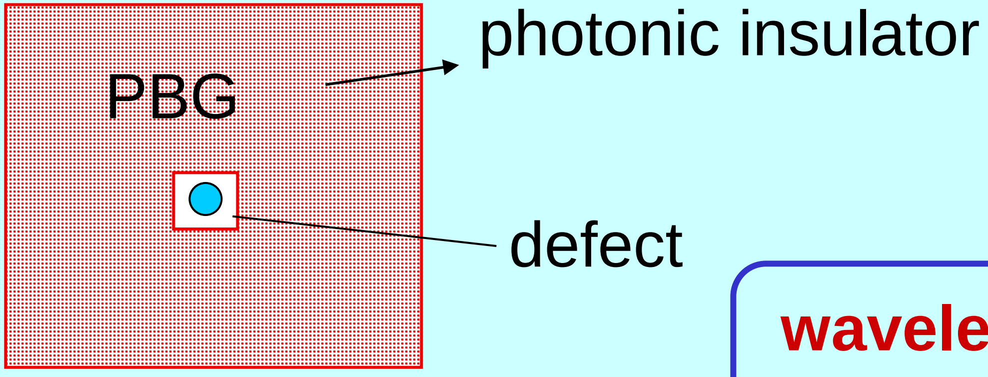
R_{max} is limited

TIR confinement



k-space broadening

PBG confinement



wavelength-size confinement $\sim(\lambda/n)^3$ is possible

3D PBG Photonic Crystals

- Yablonovitch (1987)

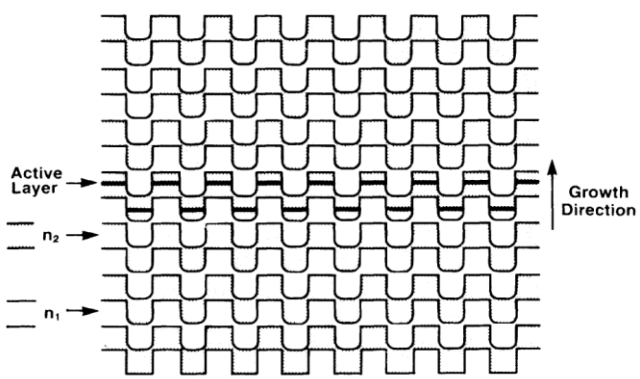
VOLUME 58, NUMBER 20 PHYSICAL REVIEW LETTERS 18 MAY 1987

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

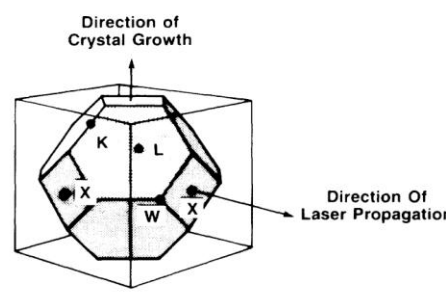
Eli Yablonovitch
Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701
(Received 23 December 1986)

It has been recognized for some time that the spontaneous emission by atoms is not necessarily a fixed and immutable property of the coupling between matter and space, but that it can be controlled by modification of the properties of the radiation field. This is equally true in the solid state, where spontaneous emission plays a fundamental role in limiting the performance of semiconductor lasers, heterojunction bipolar transistors, and solar cells. If a three-dimensionally periodic dielectric structure has an electromagnetic *band gap* which overlaps the electronic *band edge*, then spontaneous emission can be rigorously forbidden.

PACS numbers: 42.50.−p, 42.55.Bi, 78.45.+h



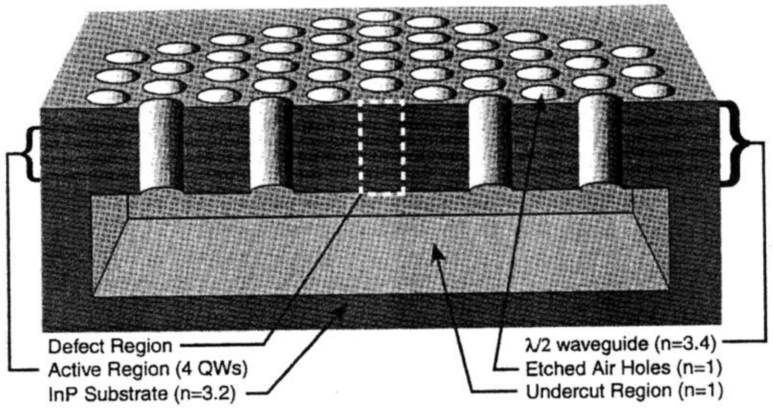
(b)



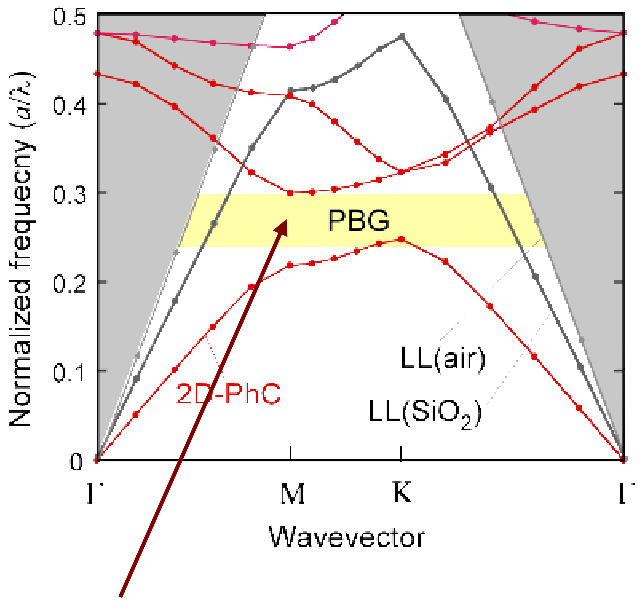
(c)

Can We Confine Light by 2D PBG？

First PhC laser with $(\lambda/n)^3$ volume



O. Painter et al. (Caltech) 1999



V=0.3 $(\lambda/n)^3$, but Q<1000

2D PBG is not perfect

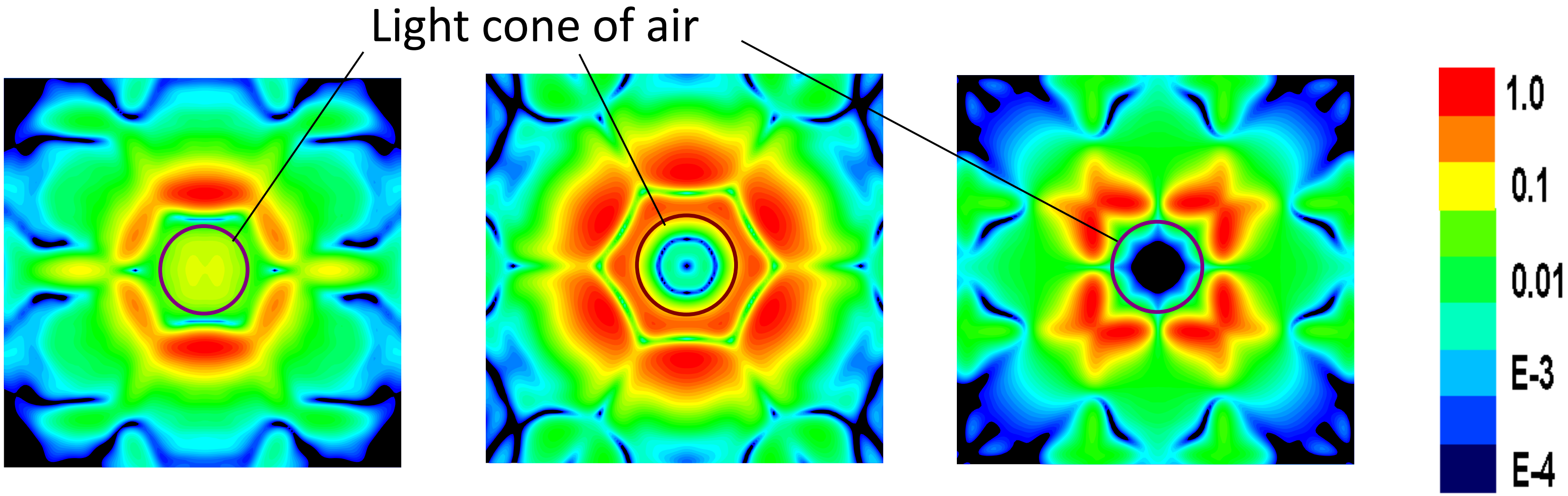
No PBG in the vertical direction

2D PBG cavity in k space

$$P_{\mathrm{rad}} \propto \iint_{|\boldsymbol{k}_\parallel|\le\omega/c} d\boldsymbol{k}_\parallel |\boldsymbol{E}(\boldsymbol{k}_\parallel)|^2 = \iint_{|\boldsymbol{k}_\parallel|\le\omega/c} d\boldsymbol{k}_\parallel |FT[\boldsymbol{E}(\boldsymbol{r})]|^2$$

Reduction of $|E(k)|^2$ inside the line cone → High vertical Q factor

Vuckovic et al., QE 38, 850 (2002)., Srinivasan et al., OpEx 10, 670 (2002).



Dipole mode

Q = 300

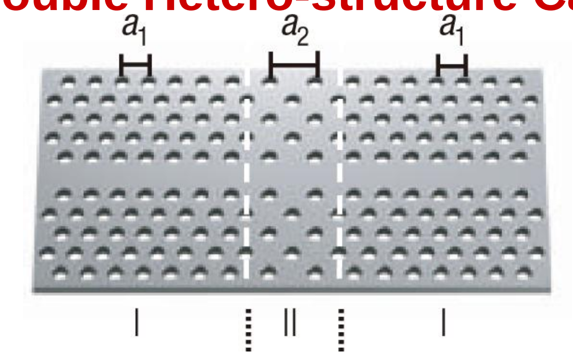
Monopole mode

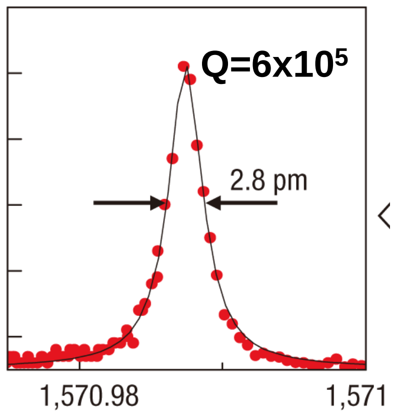
Q = 16000

Quadrupole mode
(square lattice)
Q = 52000

Modulated Line-Defect Cavity (Modulated Mode-gap Cavity)

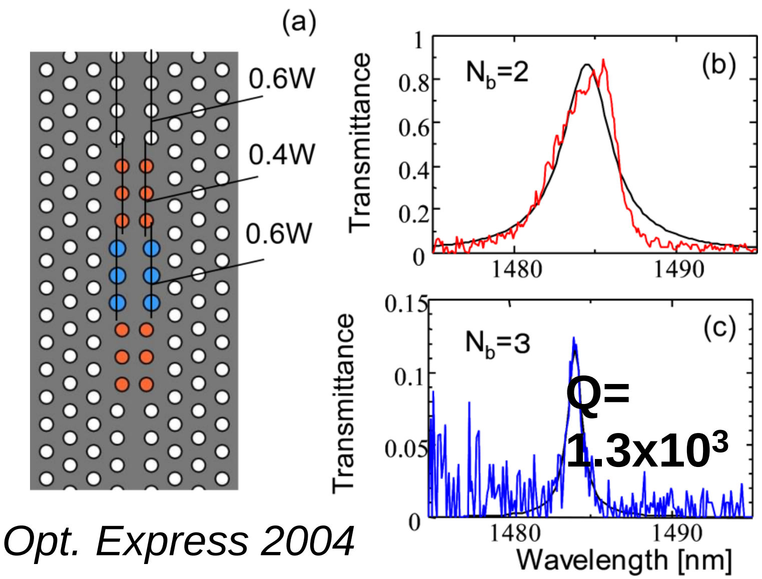
Double Hetero-structure Cavity



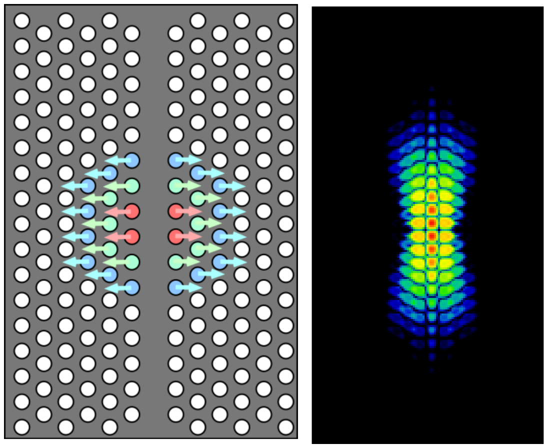


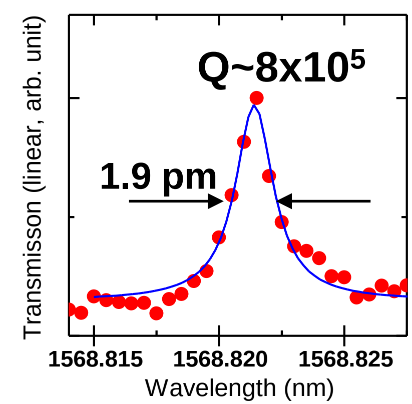
Kyoto Univ., Nat. Mat. 2005

Width-modulated Cavity



NTT, Opt. Express 2004



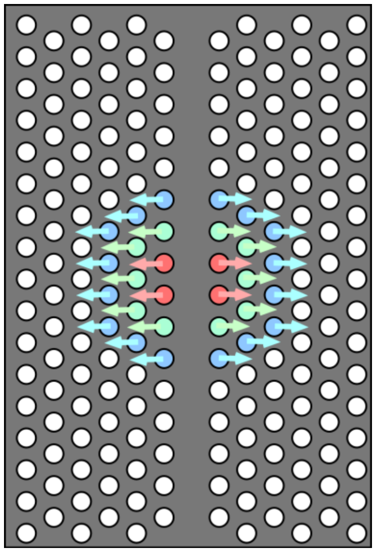


NTT, APL 2006

local modulation of the mode gap produces light confinement.

Demonstration of Ultrahigh Q

Tanabe et al. Nature Photonics, 1, 49 (2007), Tanabe et al. Opt. Express (2007)



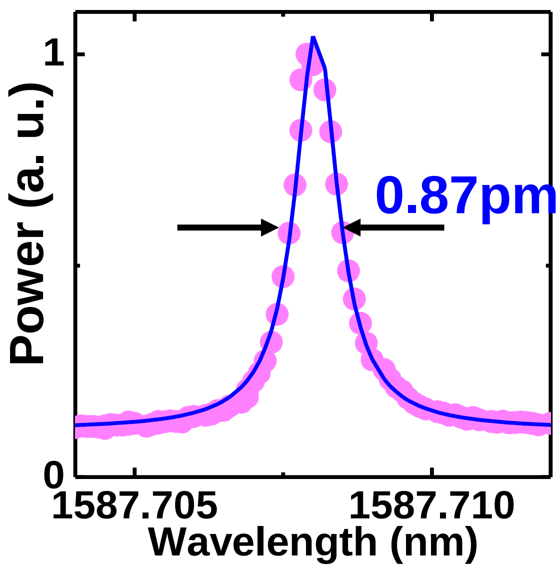
Q_{cal}~ 1.5 x 10^8

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

shift= 9, 6, 3 nm

Spectral measurement

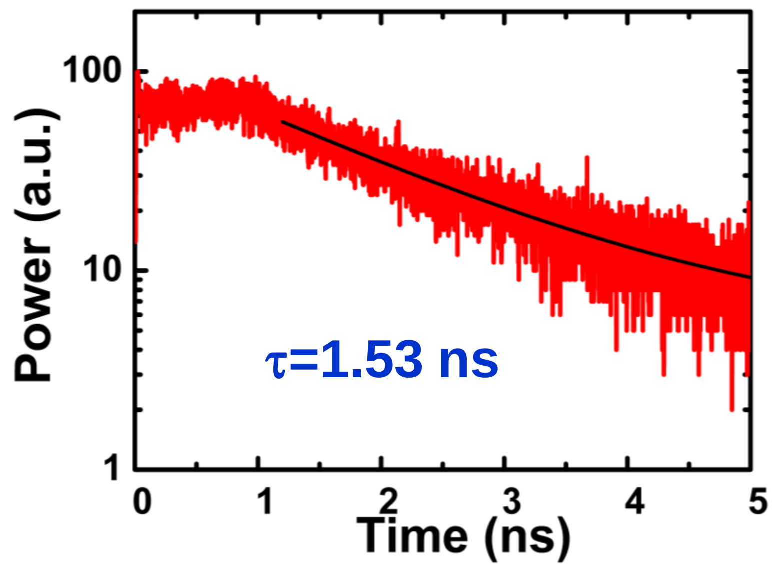
$Q = 1.8 \times 10^6$



(accuracy <0.06 pm)

Time-domain measurement

$Q = 1.8 \times 10^6$

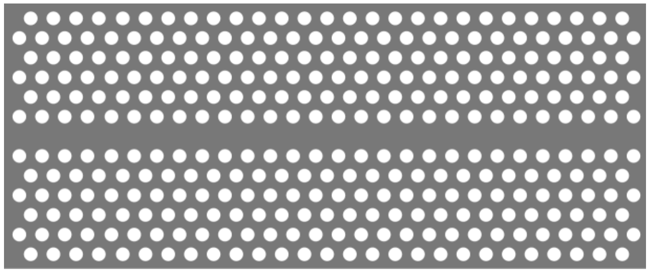


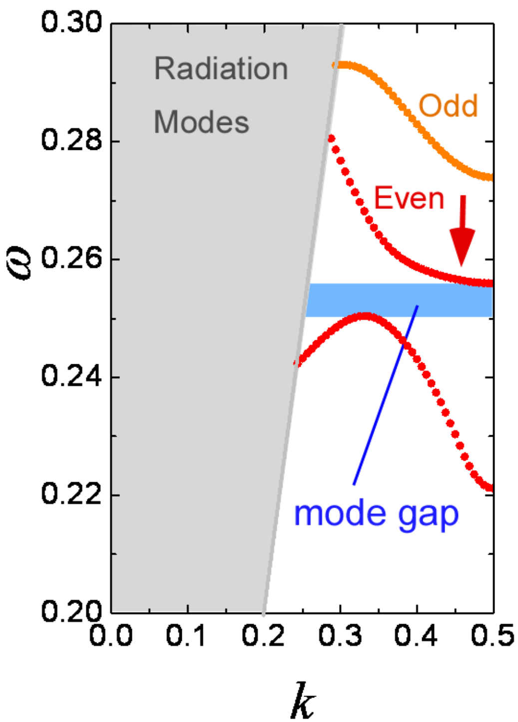
$Q_{unloaded}$~2 x 10^6

Q~ 3.9 x 10^6 was recently achieved in double-hetero cavities by Noda's group

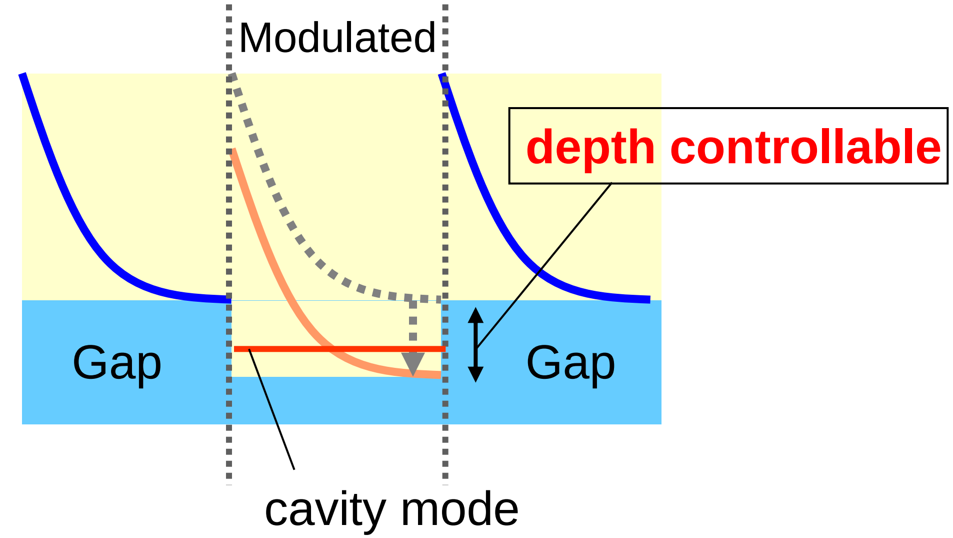
Taguchi et al. Opt. Express (2011)

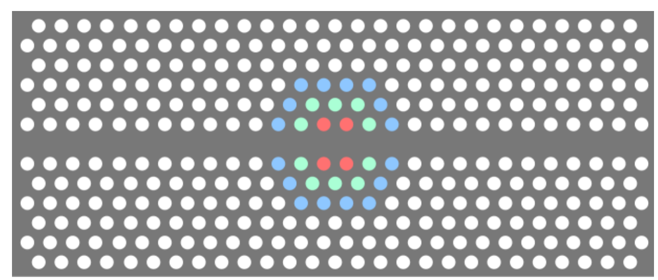
Line Defect Waveguide





Modulated Modegap Cavity

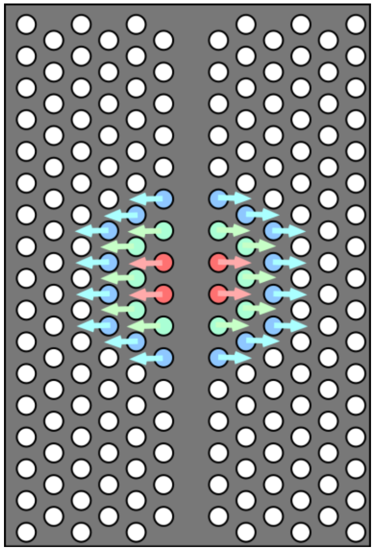




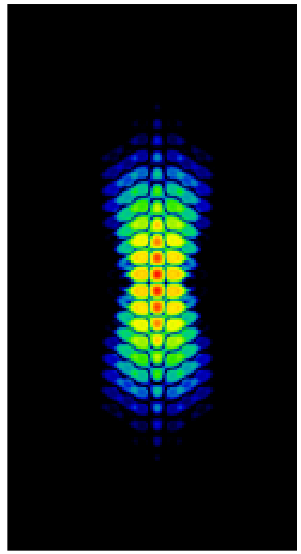
small structural perturbation

→ smaller broadening in k space

Modulated Line Defect Cavity in k-space



Holes shifted by 9, 6, 3 nm



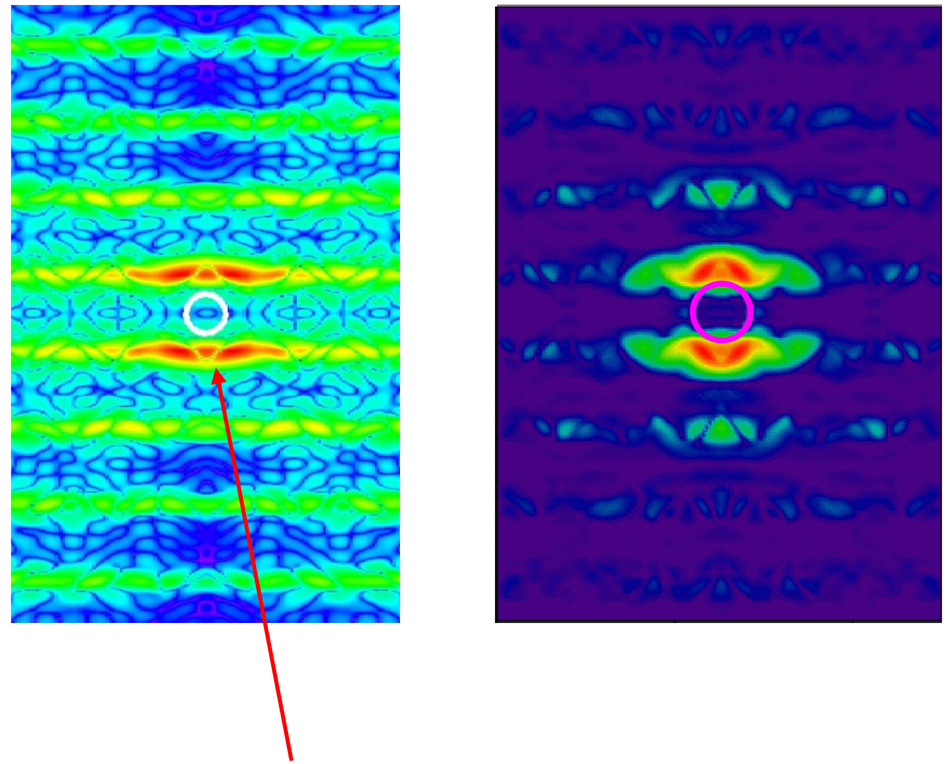
V_{eff}=1.5 $(\lambda/n)^3$

Q=1.5 x 10^8

(calculation)

Modulated Cavity

e.q. Terminated Cavity



optical mode is squeezed in k space

ultrahigh Q

Features of Modulated Modegap Cavities

(1) Ultrahigh Q with V of ~$(\lambda/n)^3$

best performance as wavelength-sized cavity

➡ advantageous for enhancing light-matter interaction
(low-power optical devices, cavity QED, etc.)

(2) Small modification makes ultrastrong light confinement

unique among any types of cavity

➡ novel forms of cavity realization, cavity manipulation

It is worth noting that this cavity formation is closely related to John's original proposal of photon localization employing photonic band edge.

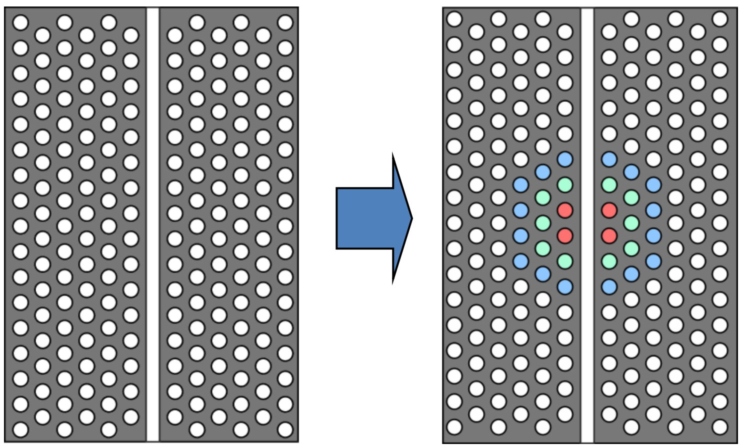
Variation 1

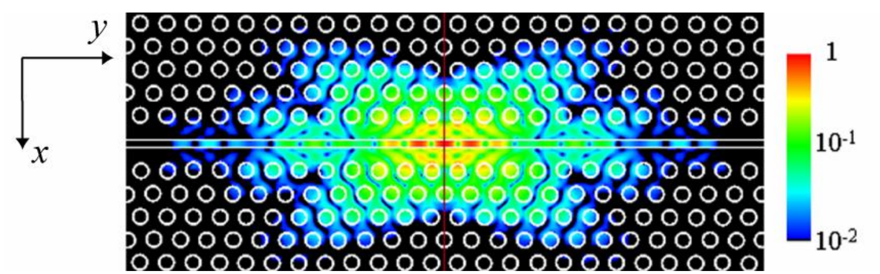
Ultrahigh-Q Air-Core Cavities

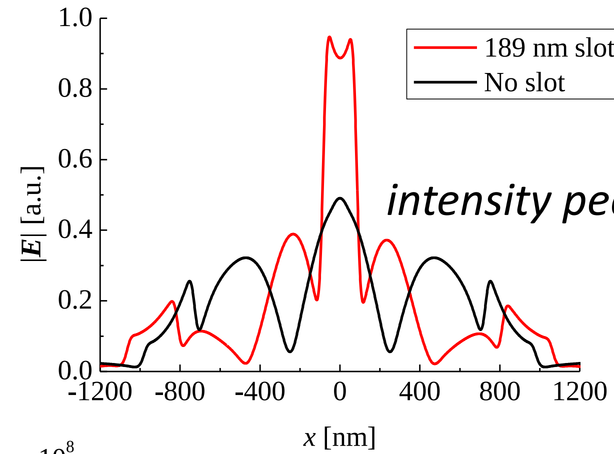
Ultrahigh-Q Air-core cavity in 2D PBG? **cavity QED, gas sensor, radiation force etc...**

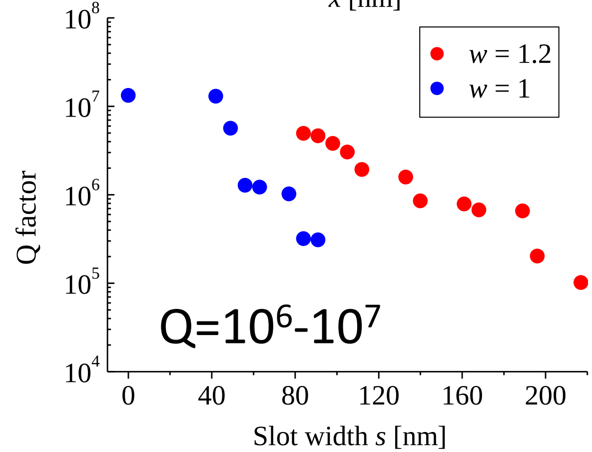
Width-modulated air-slot cavity

based on Air-slot waveguide







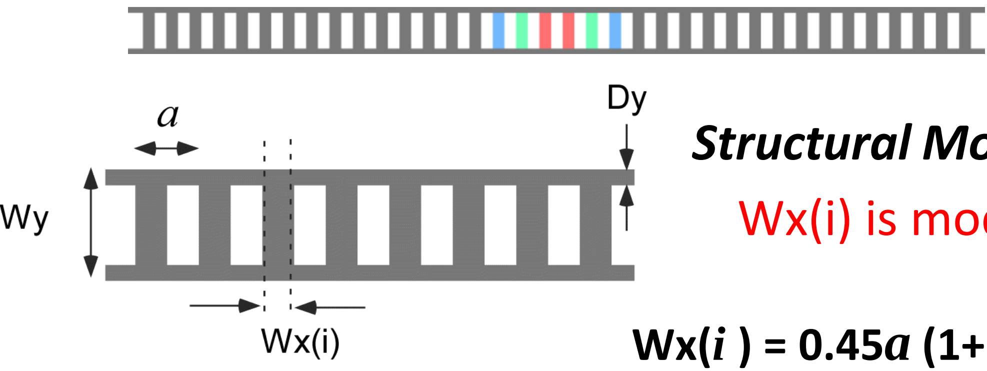


Q_{cal}= 6 x 10^6 V: 0.03 $(\lambda)^3$

Yamamoto et al. Opt. Express 16, 13809 (2008) / Taniyama et al. Phys. Rev. B78, 165129 (2008)

Variation 2

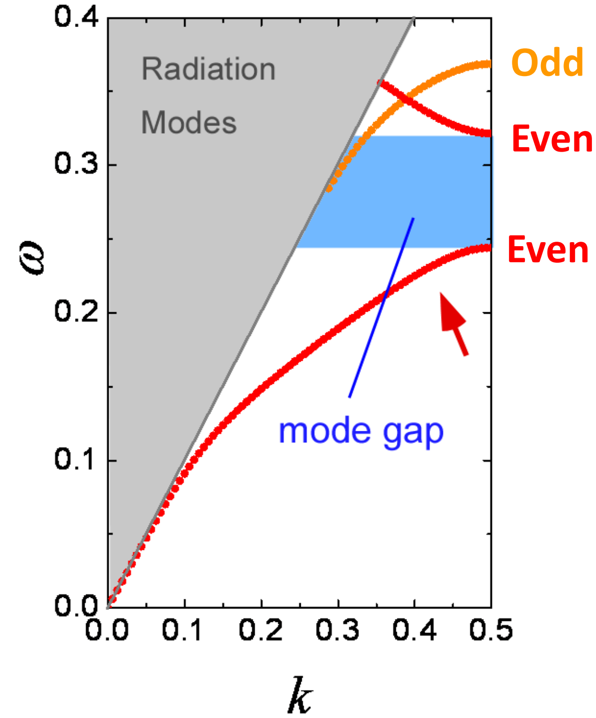
Modulated Mode-Gap Cavities in 1D PhCs

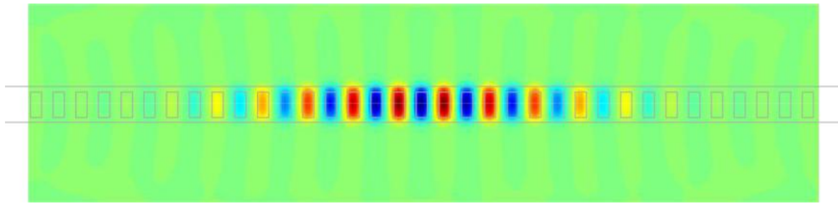


Structural Modulation

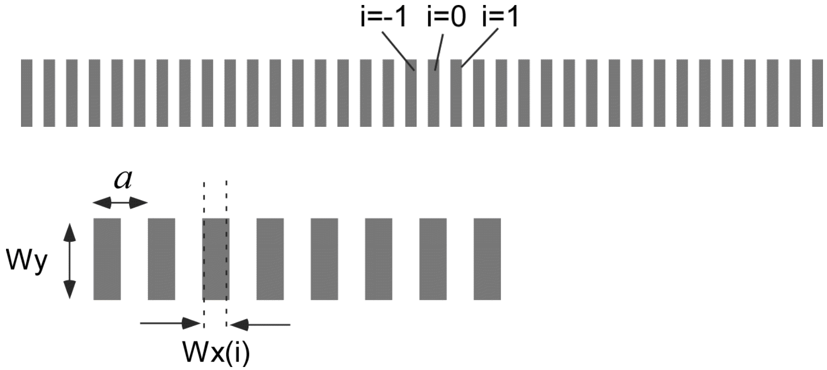
Wx(i) is modulated

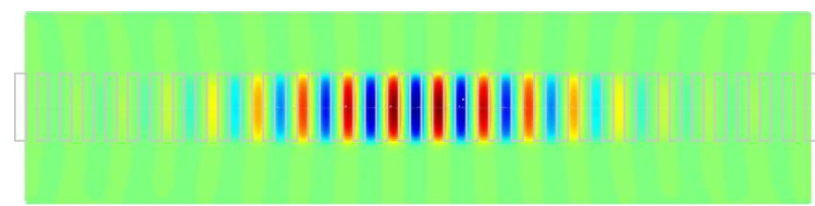
$$Wx(i) = 0.45a\,(1+(i/30)^2)$$





Q = 2.0 x 10^8, V = 1.4 $(\lambda/n)^3$





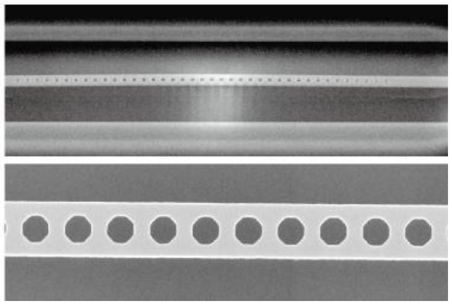
Q = 6.3 x 10^7, V = 2.1 $(\lambda/n)^3$

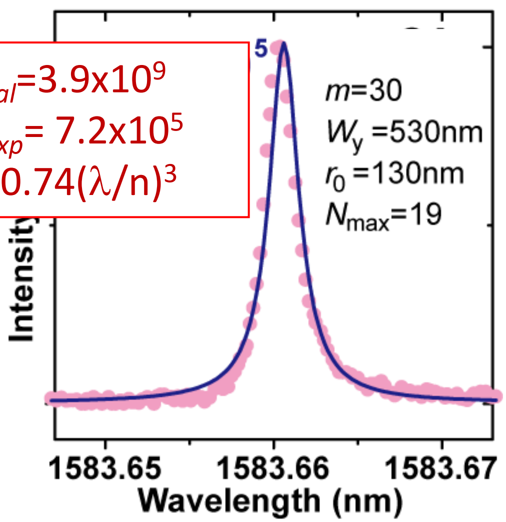
Notomi, Kuramochi, Taniyama, Opt. Express 16, 11095 (2008)

Evolution of 1D Photonic Crystal Nanocavities

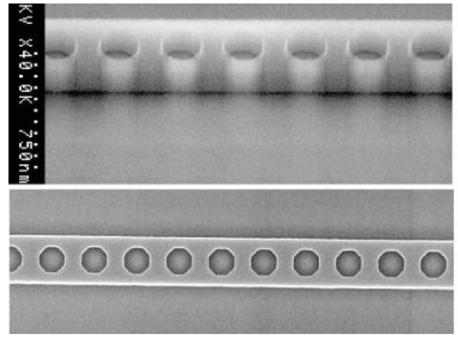
Air-bridge cavity

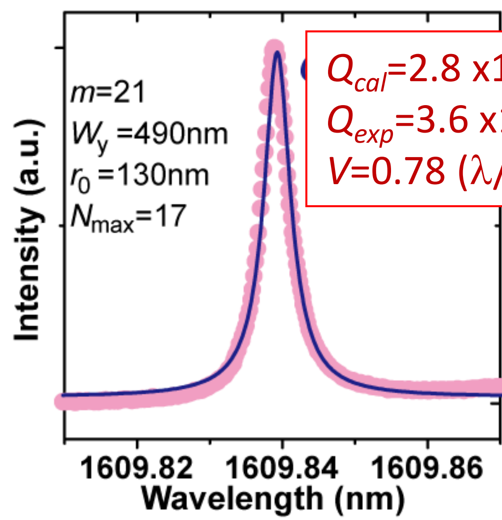
Kuramochi et al. Opt. Express (2010)





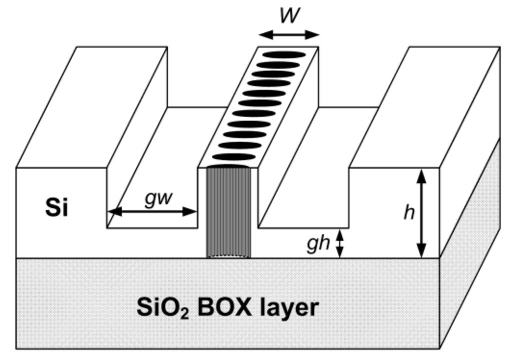
SiO_2-clad cavity

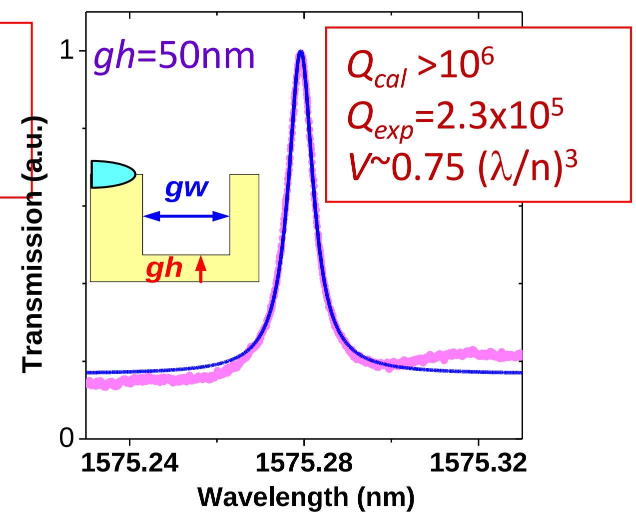




Side-slab cavity

Kuramochi et al. To be submitted





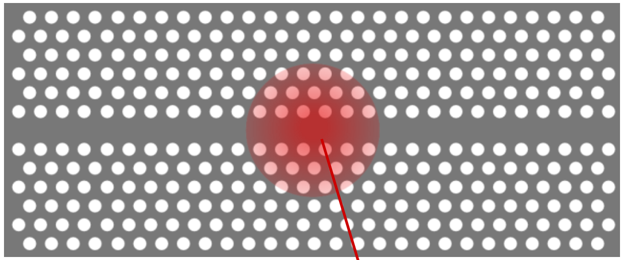
1D PhC cavity is now better than 2D

(1) with SiO_2 clad / (2) as small V / (3) for beam configuration

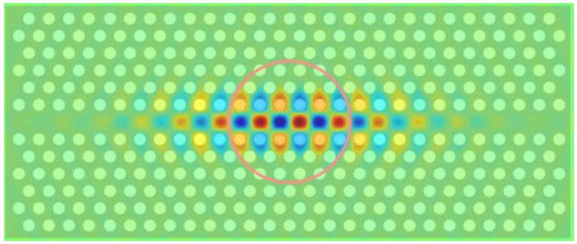
Variation 3

Index-Modulated Mode-gap Cavities

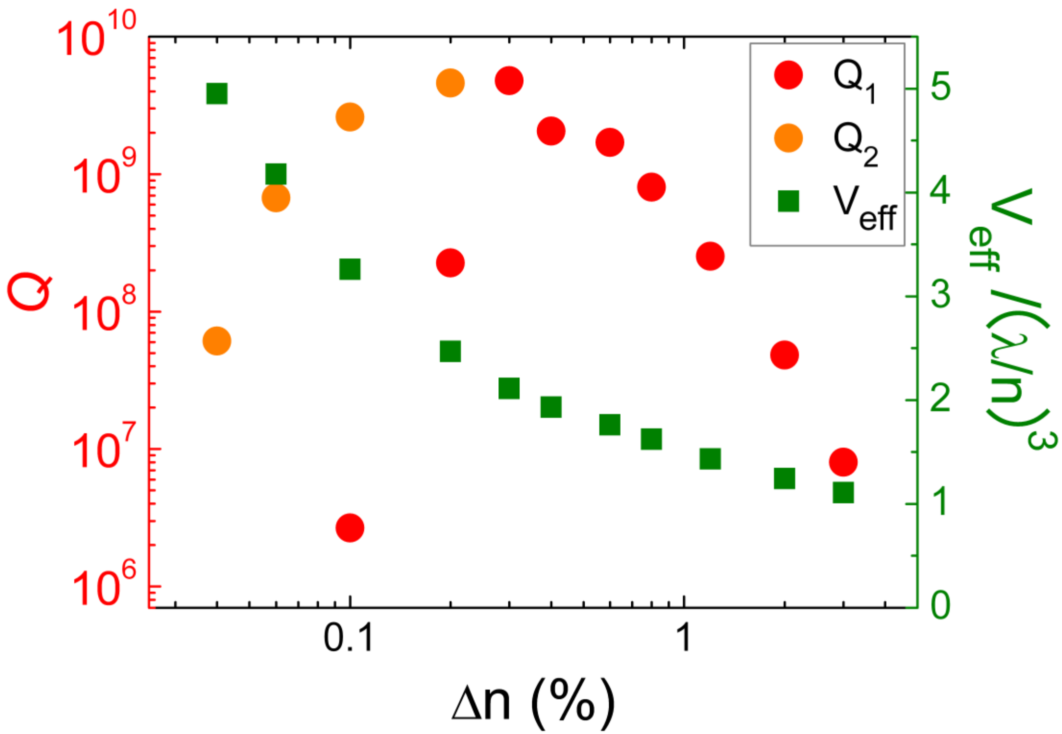
Index Modulated Mode-Gap Cavity



n **is modulated by optical pump**



$\Delta n/n$ = 0.3%, Q = 4.8 x 10^9

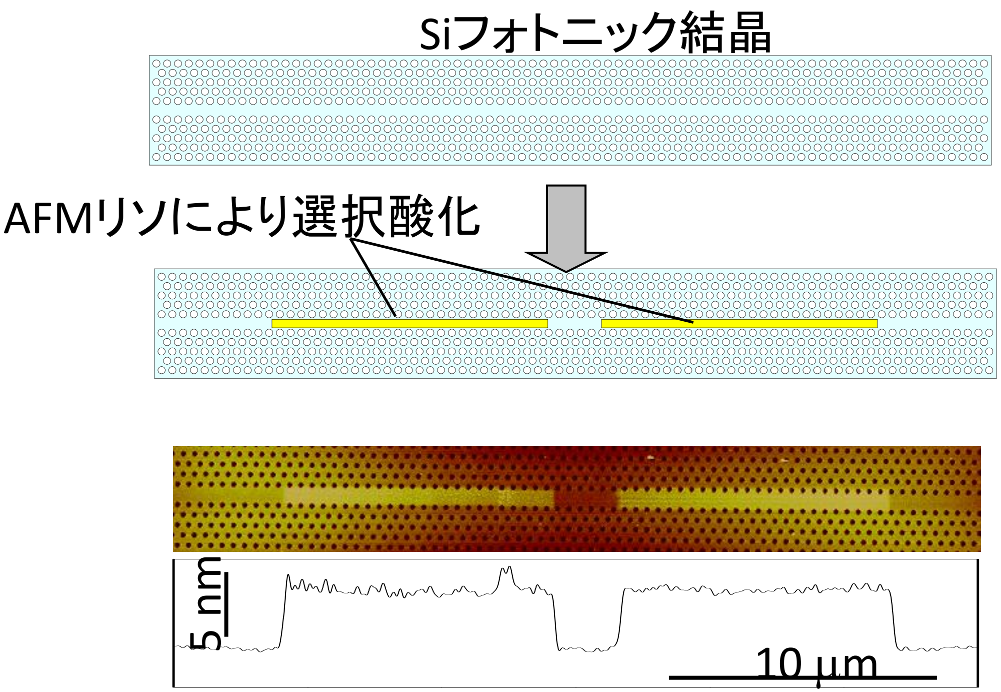


Very small Δn is enough for ultrahigh Q!

Notomi, Taniyama, Opt. Express 16, 18657(2008)

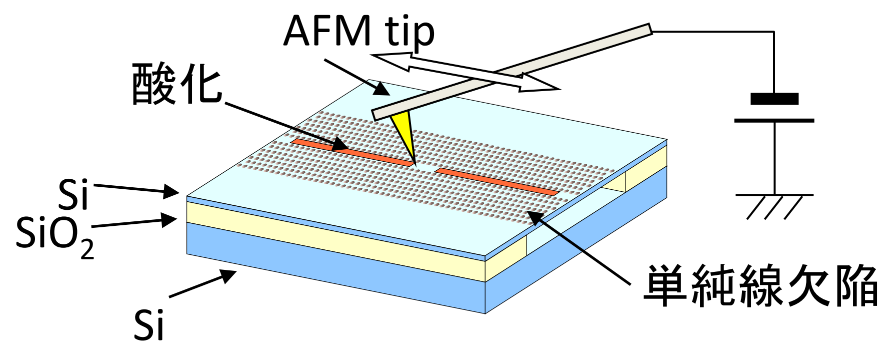
Ultrahigh-Q nanocavity written by a nano-probe

Yokoo et al. Nano Lett. (2011)

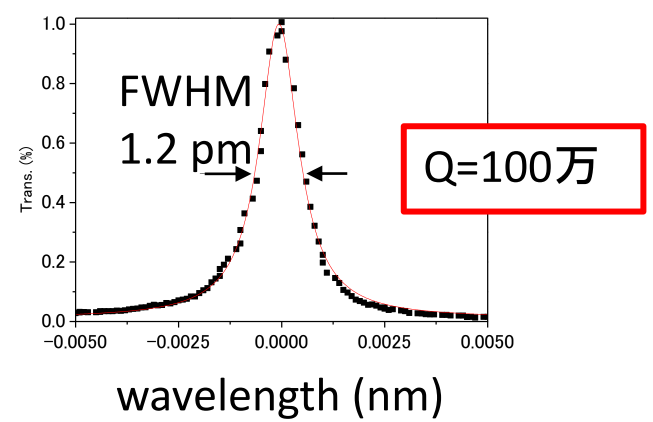


nano-probeによる選択酸化

電流印加による陽極酸化反応によりSi表面を酸化



測定結果： 超高Q共振器の形成を確認



ポストプロセスによって任意の場所に
超高Qモードギャップ変調共振器を形成

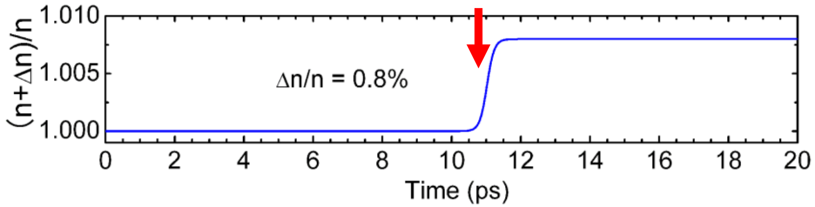
微小な屈折率変化で超高Q共振器が形成
できる特徴を利用

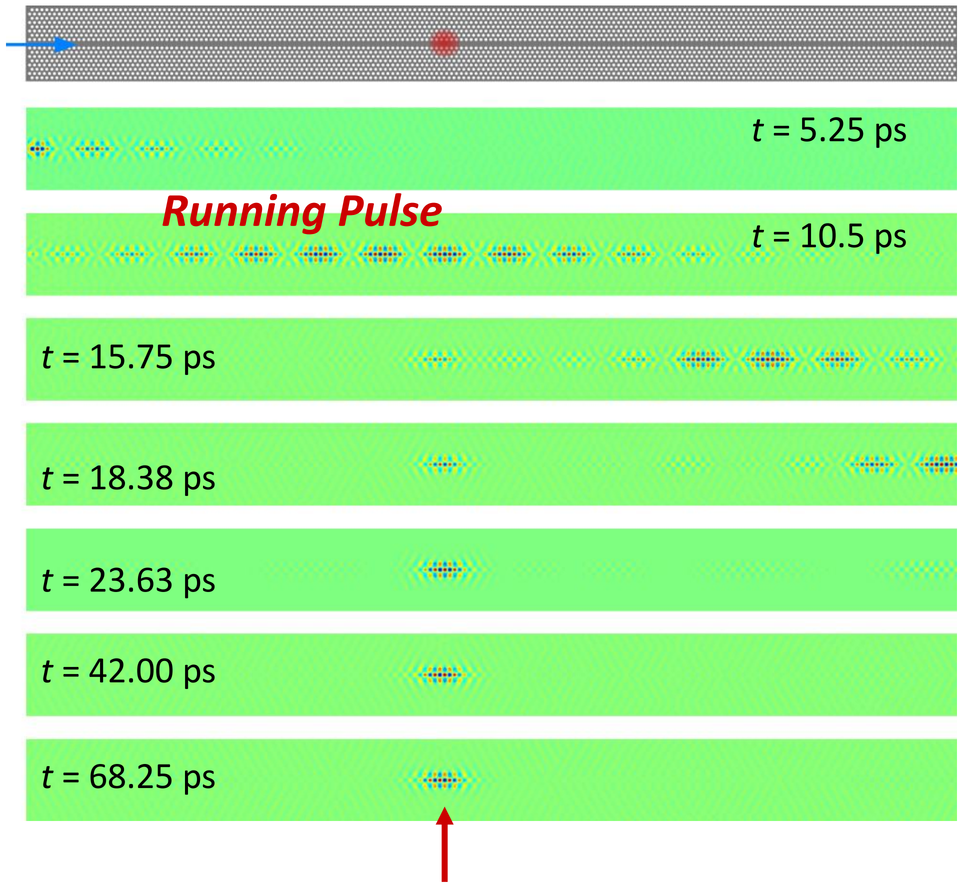
Variation 4

Dynamic Modulation of Light Confinement

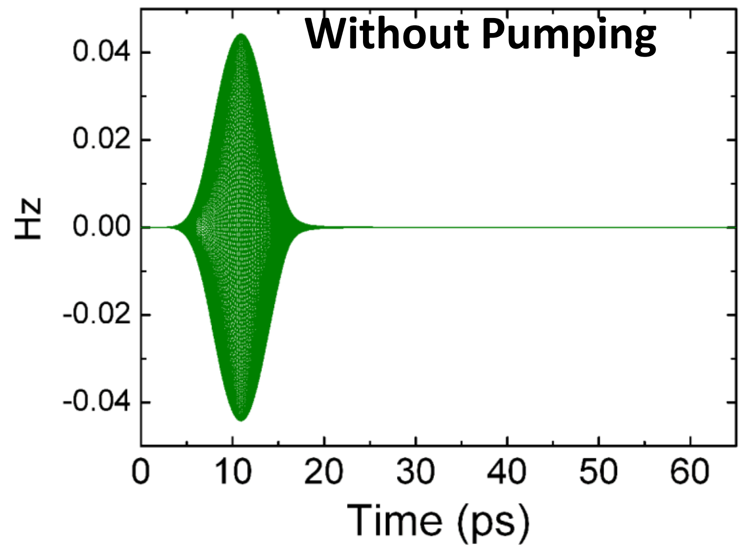
pump

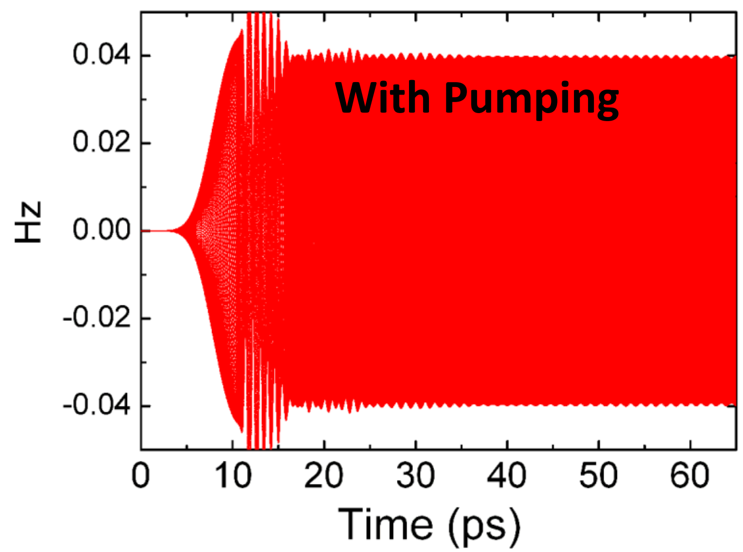
Photon Pinning





Pinned Pulse



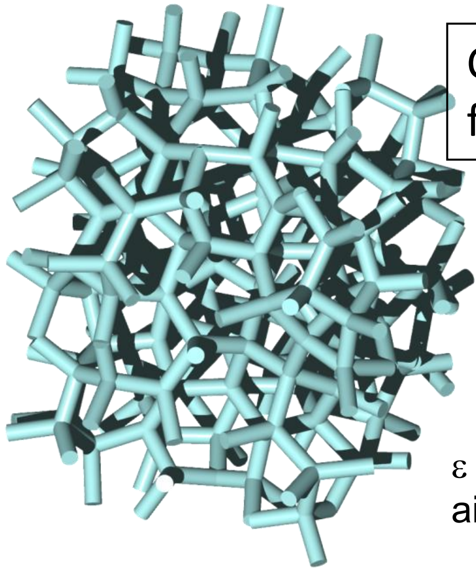


Notomi, Taniyama, Opt. Express 16, 18657(2008)

3D Photonic Amorphous Diamond

Edagawa et al. Phys. Rev. Lett. (2008)

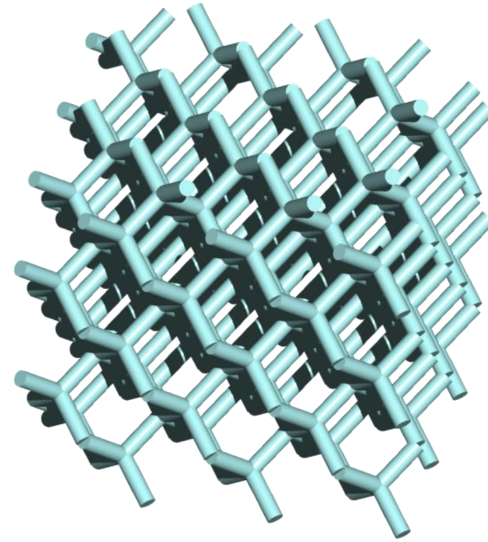
Photonic Amorphous Diamond (PAD)



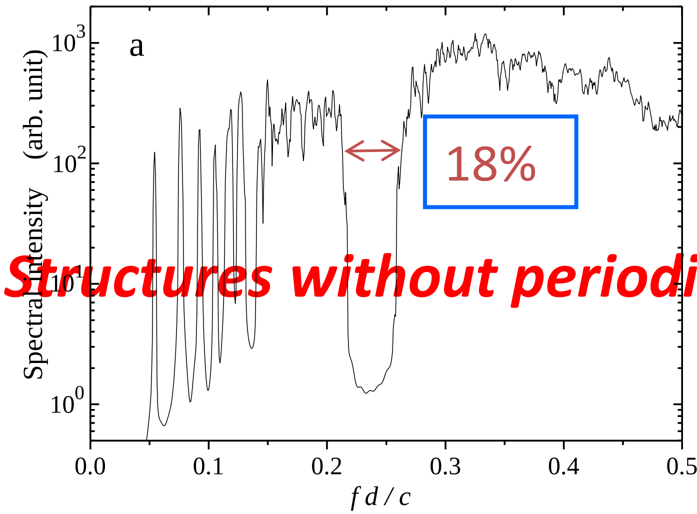
CRN model for a-Si

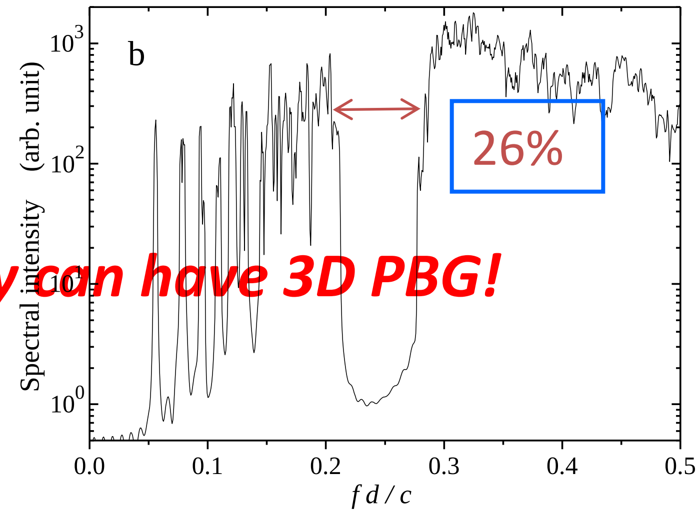
ε =13/1
air-fraction 78%

Photonic Crystal Diamond (PCD)



ε =13/1
air-fraction 78%

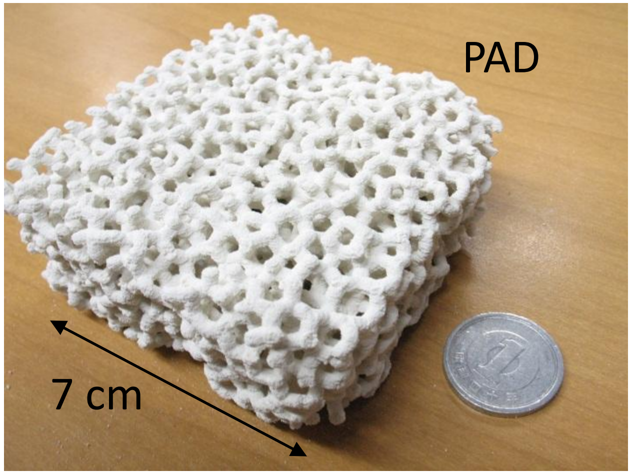


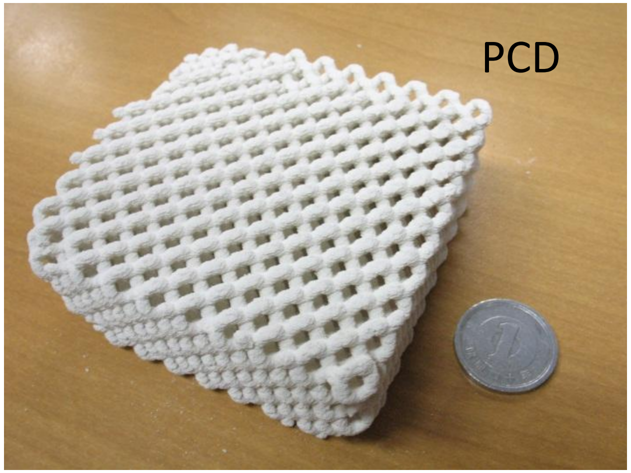


Structures without periodicity can have 3D PBG!

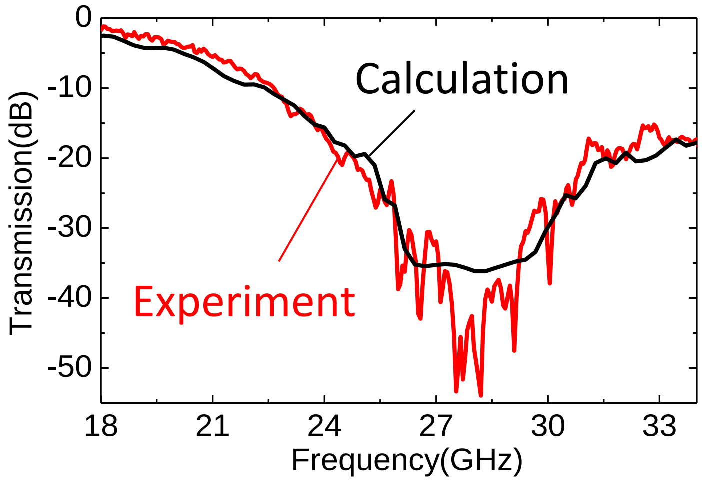
RF-PAD fabricated by Selective Laser Sintering

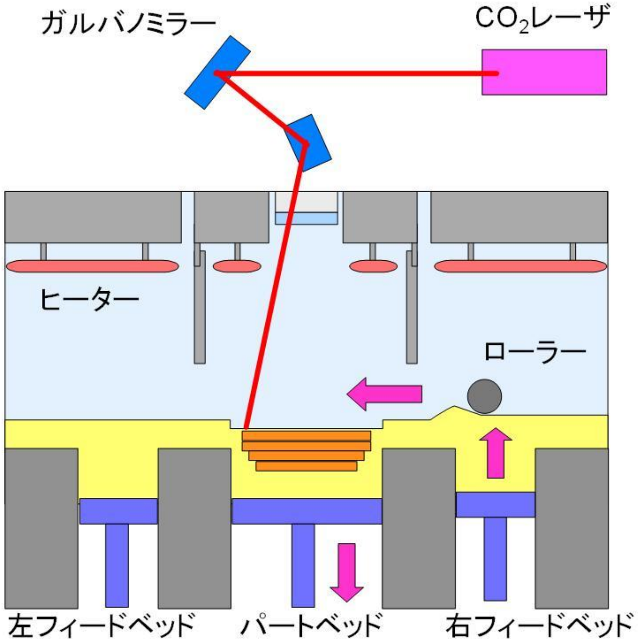
Imagawa et al. PRB (2010)





$\varepsilon_1/\varepsilon_2=10/1$ d= 3mm, r=0.26d

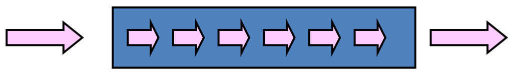




(3) Slow Light in a Chip

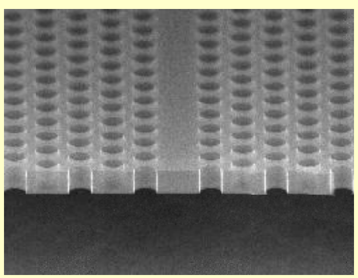
Slow light in Photonic Crystals

スローライト

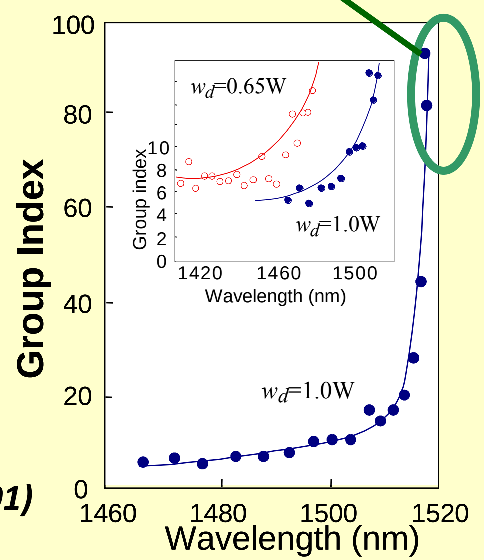


光が遅く進むと (1) 相互作用が増強
(2) 光信号のバッファリング

強分散導波路による光遅延 (2001)



群屈折率～100

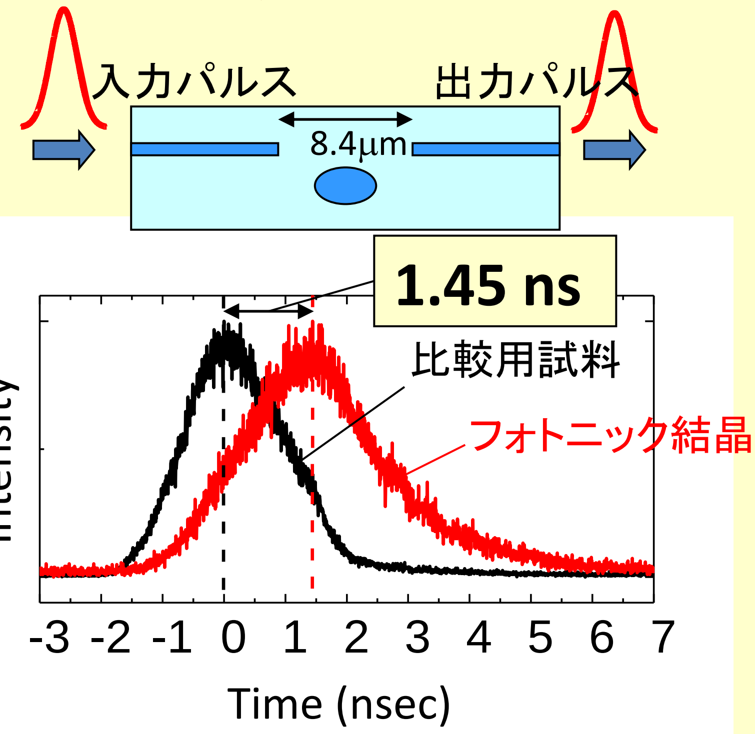


光速が1/100に

Notomi et al. PRL (2001)

Tanabe et al. Nature Photonics (2007)

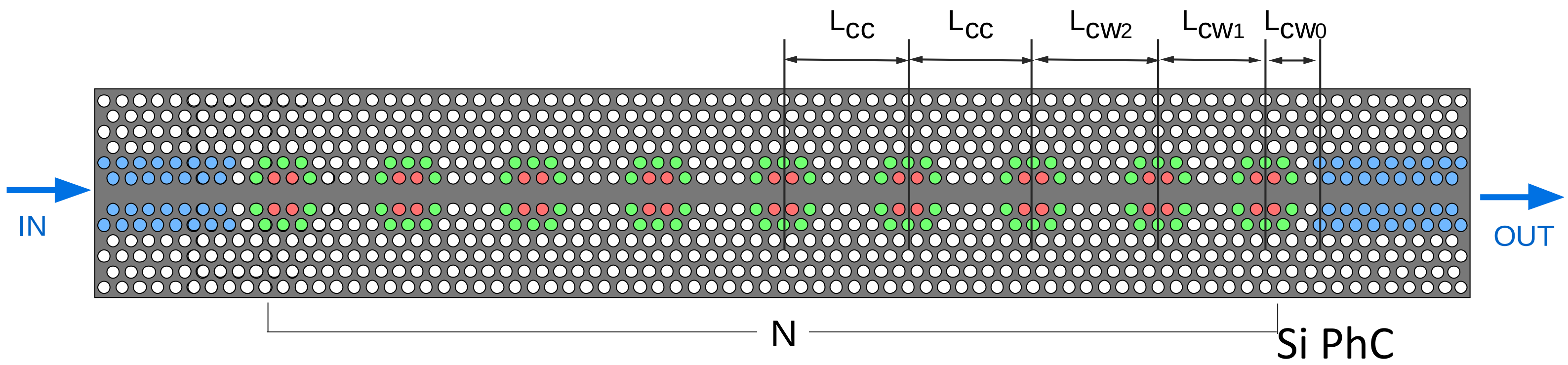
高Qナノ共振器による光遅延



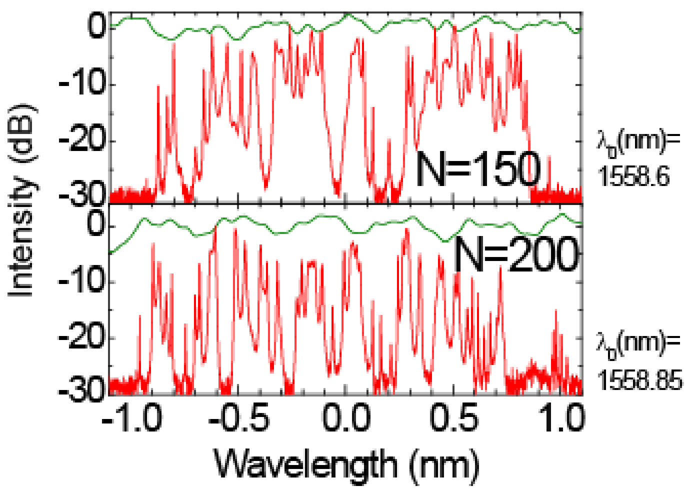
パルス伝播速度=5,800 m/s

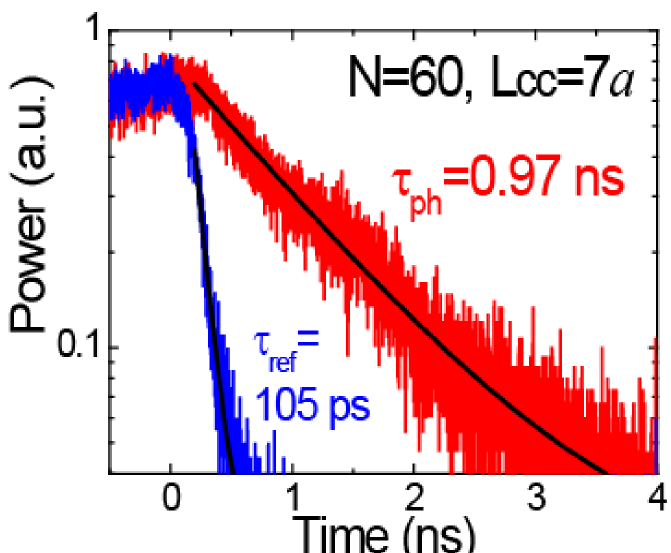
光速が 50,000分の1に

Coupled Nanocavities based on Modulated Modegap Cavities



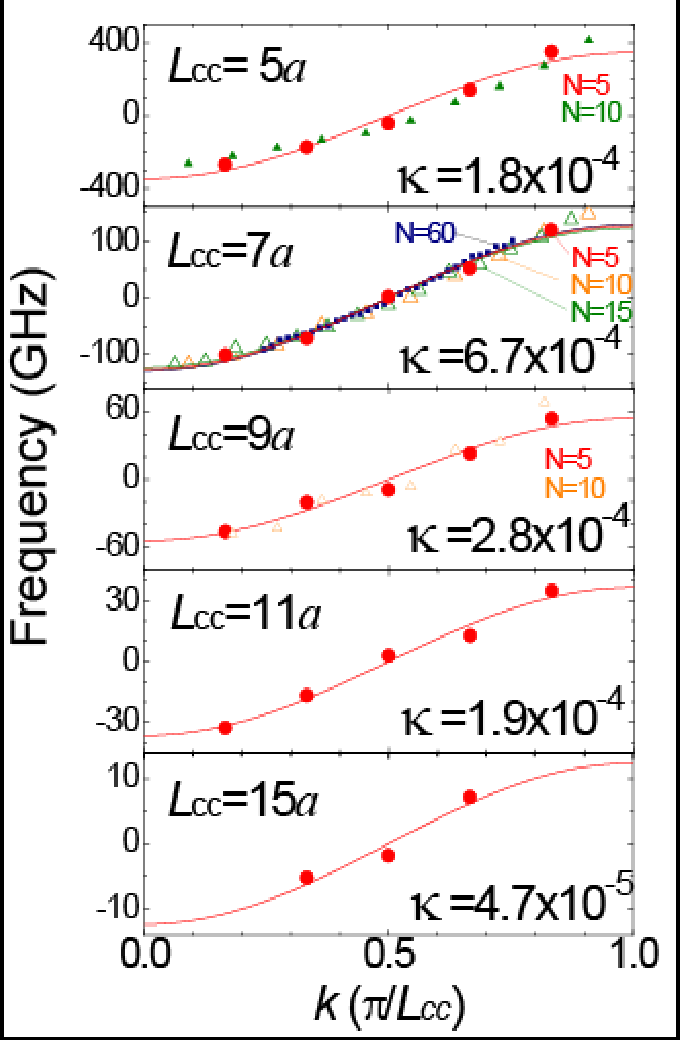
We fabricated large-scale coupled nanocavities (N up to 400)





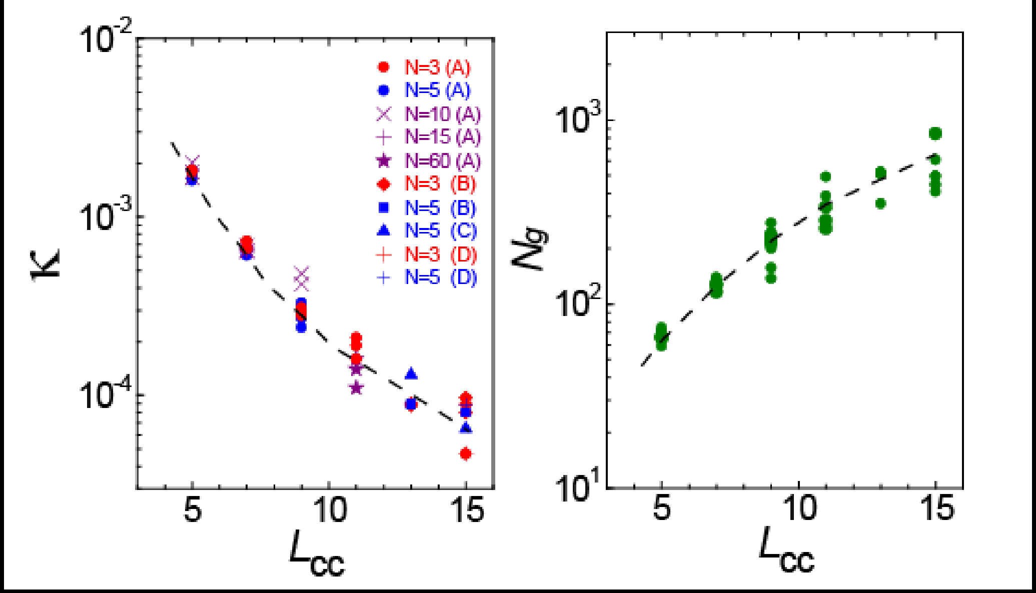
Notomi et al. Nature Photonics (2009)

Dispersion of Large-scale Coupled Nanocavity



➡ **Tight-binding behavior is confirmed**

$$\omega = \omega_0 (1 + \kappa \cos(k L_{cc}))$$



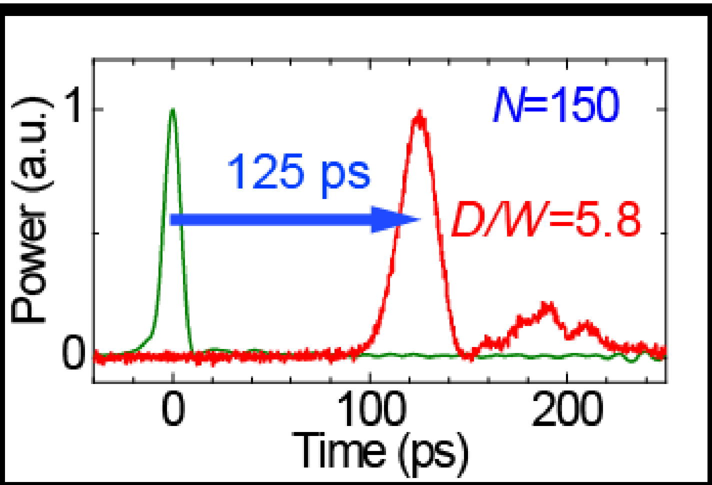
Vg is controlled by coupling strength

lowest Vg ~ c/600 **at center**

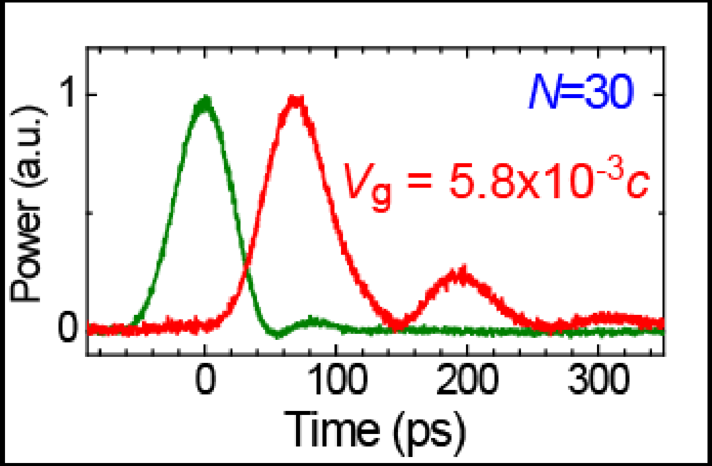
Notomi et al. Nature Photonics (2009)

Slow Light Propagation in Large-scale Coupled Nanocavity

Largest Delay/Pulse Width Ratio



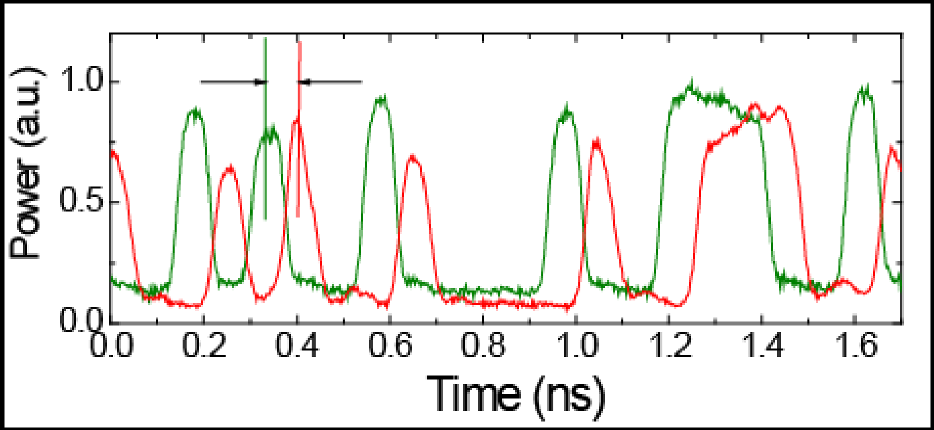
Slowest Vg (~c/170)



Note: Here, we used overcoupled samples having spectra flatter than previous ones.

1 bit delay in 12.5Gbps signal

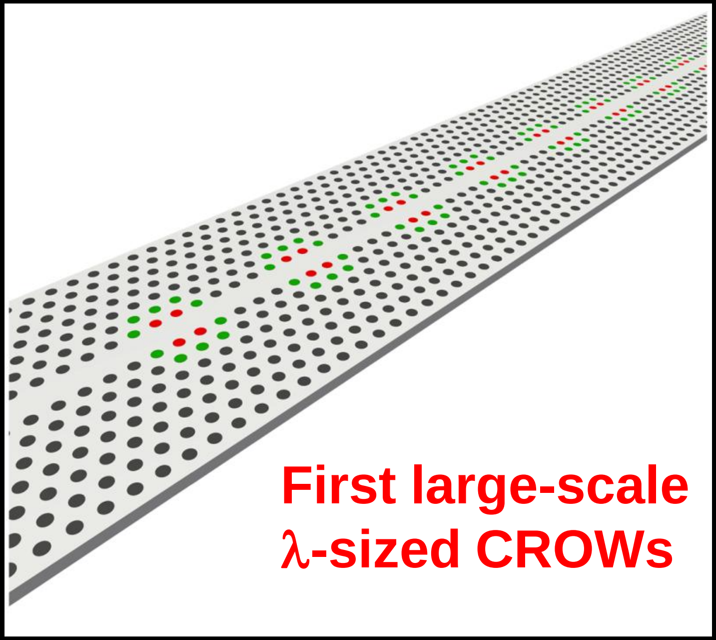
80 ps (=1bit@12.5Gbps)



Slowest Vg in CROWs

Notomi et al. Nature Photonics (2009)

Features of Photonic-Crystal Nanocavity CROW



small volume	$V \sim 1.6\ (\lambda/n)^3$
small period	$L_{cc} \sim 2.9\ \mu m$
large-scale	$N_{max} \sim 400$
ultrahigh-Q	$Q \sim 10^6$
long lifetime	$\tau_{ph} \sim 1$ nsec
low loss	< a few dB
low Vg	c/170 (for pulse)
	~ c/600 (in spectrum)

In comparison with previous CROWs,

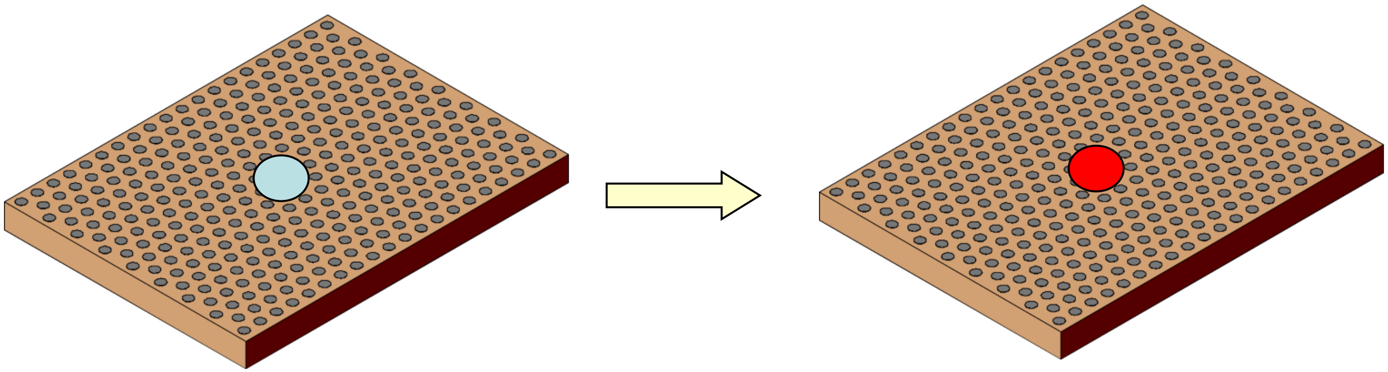
x10 shorter length, x100 smaller area, x10 higher Q, x5 slower Vg

only slow light waveguides that can transmit pulses with Vg < c/100

(4) Adiabatic Tuning of Light

Adiabatic Wavelength Conversion via Dynamic Tuning

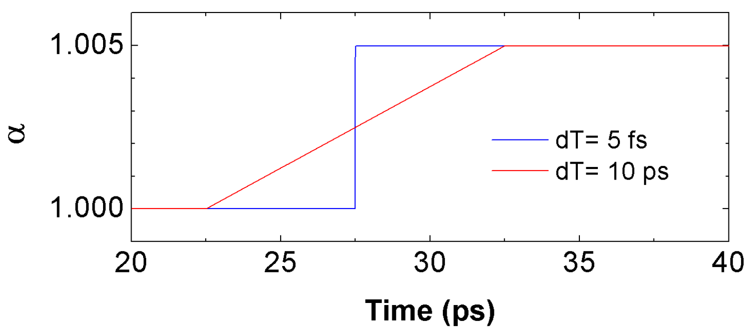
Ultrahigh-Q & ultrasmall cavity: long photon lifetime

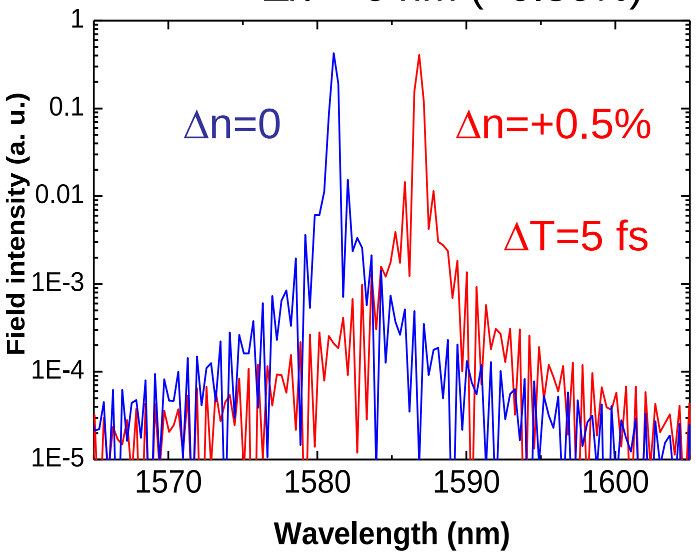


If we tune it within the photon lifetime, what will happen?

Notomi et al., PRA & PRL (2006)

⇨ ***Wavelength Conversion***

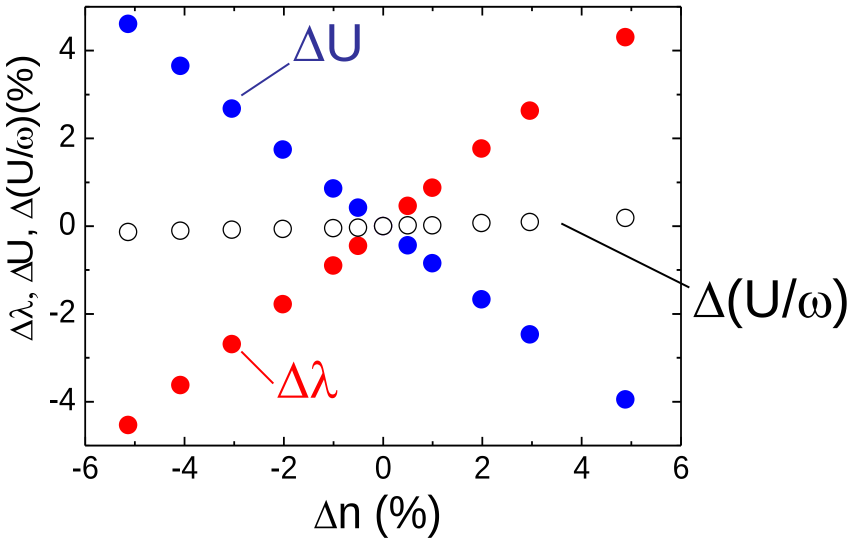




Δλ does not depend on tuning rate

Conversion Mechanism : Adiabatic Tuning of Classical Oscillation

Electromagnetic energy in the cavity



$\Delta U \sim 1/\,\Delta n \sim 1/\,\Delta\lambda \;\; \sim \Delta\omega$

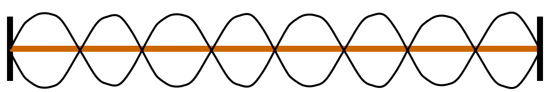
U/ω is conserved

$$J = \frac{1}{2\pi}\oint dpdq = \frac{U}{\omega}$$

→ action integral (adiabatic invariant)

Similar to ...

- twisting the peg after picking a string of a guitar

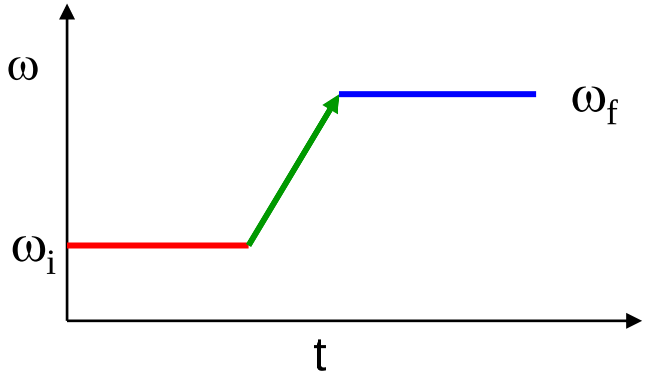


Notomi et al., PRA (2006)

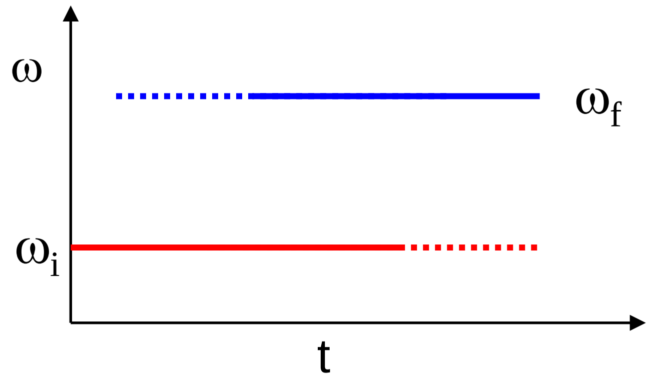
Comparison with conventional wavelength conversion

Adiabatic Conversion	Conventional Conversion
▪free of material choice	▪need to use $\chi^{(2)}$ or $\chi^{(3)}$ materials
▪Linear→not depend on intensity	▪Nonlinear→depend on intensity
▪high efficiency (~100%)	▪low efficiency
▪single photon can be converted	

▪always single frequency (adiabatic process)



▪two waves coexist

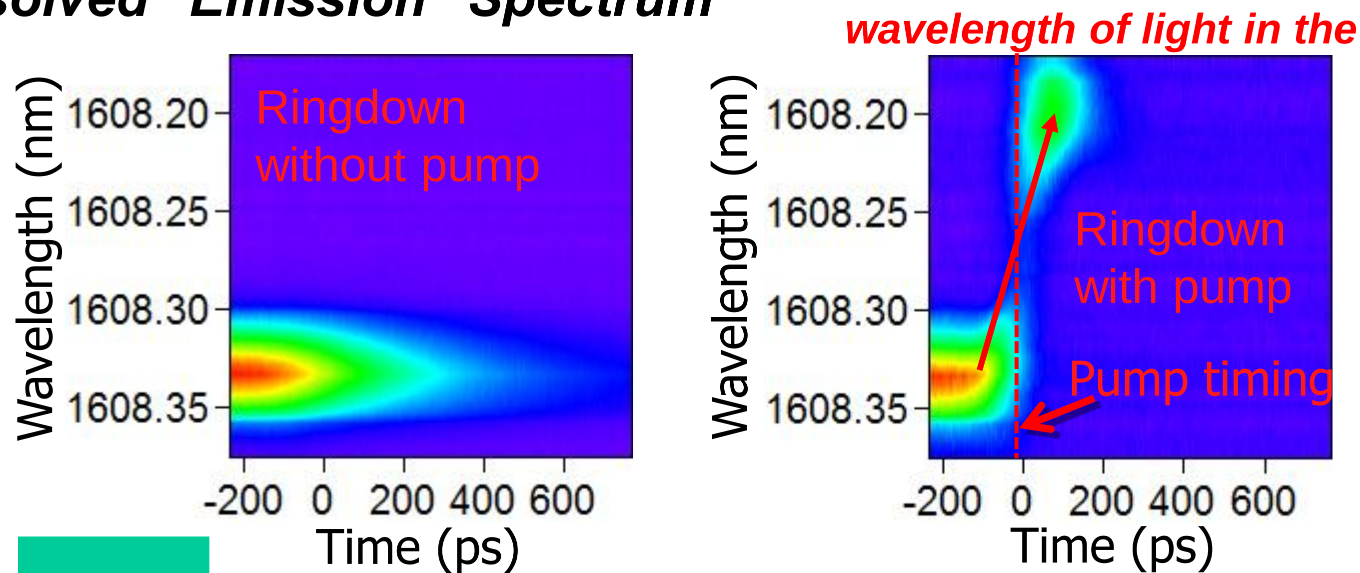


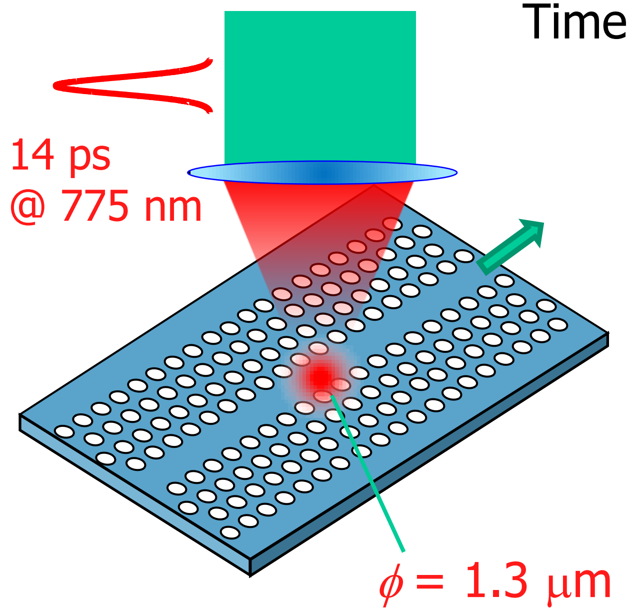
unambiguous confirmation has not be done

Demonstration of Adiabatic Wavelength Conversion

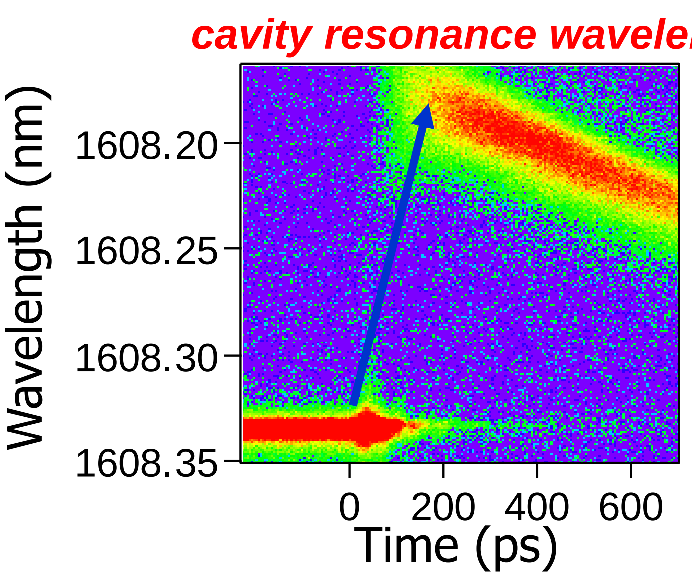
Time-resolved "Emission" Spectrum

Tanabe et al. Phys. Rev. Lett. (2009)





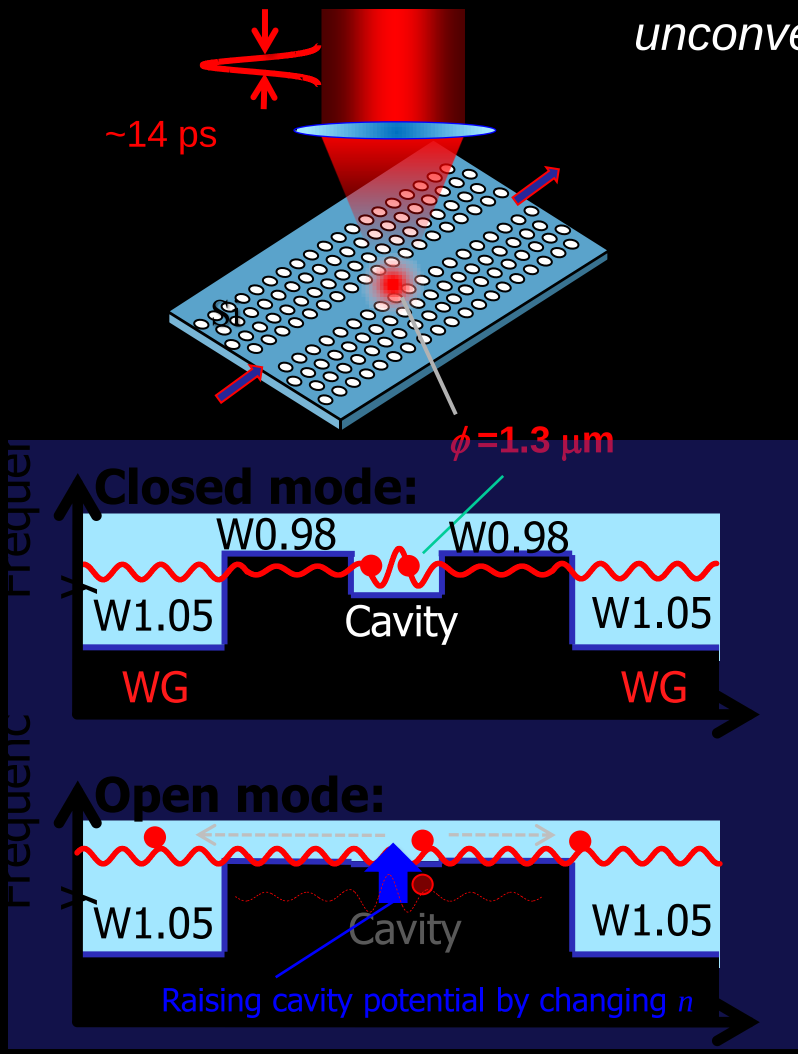
Time-resolved Transmission Spectrum

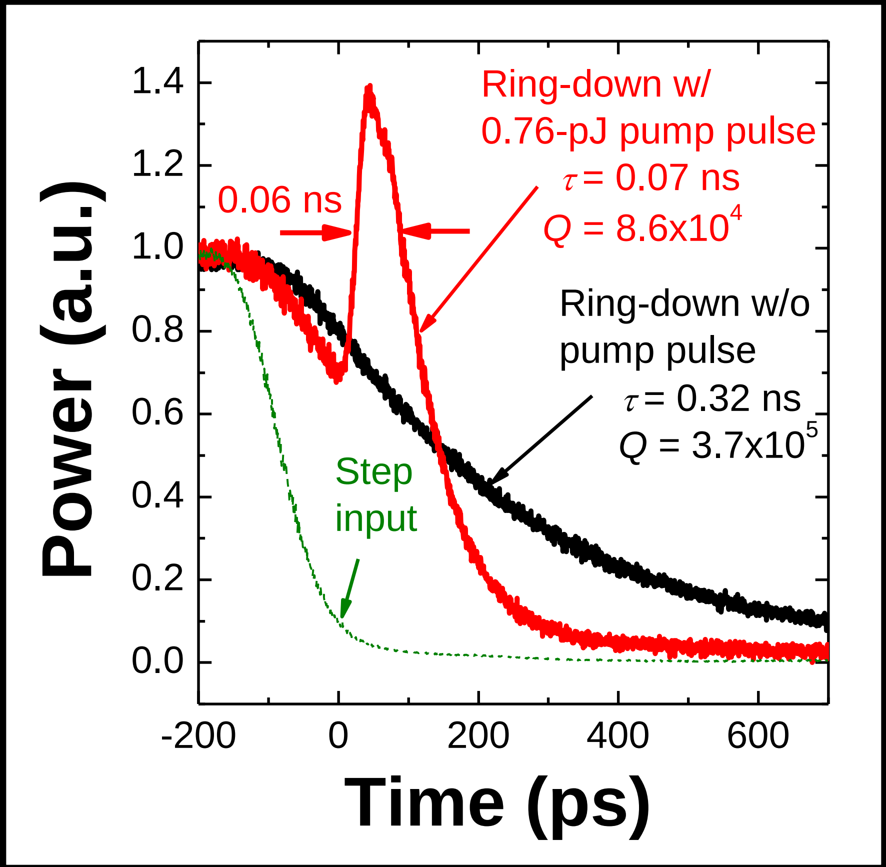


Dynamic Release of Trapped Light by Adiabatic Conversion

Adiabatic Frequency Shift of Light → Short pulse generation

unconventional device operation scheme in photonics
(similar to CCD operation)

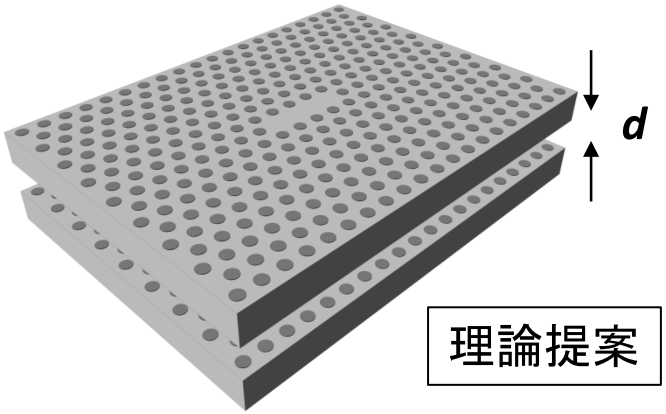


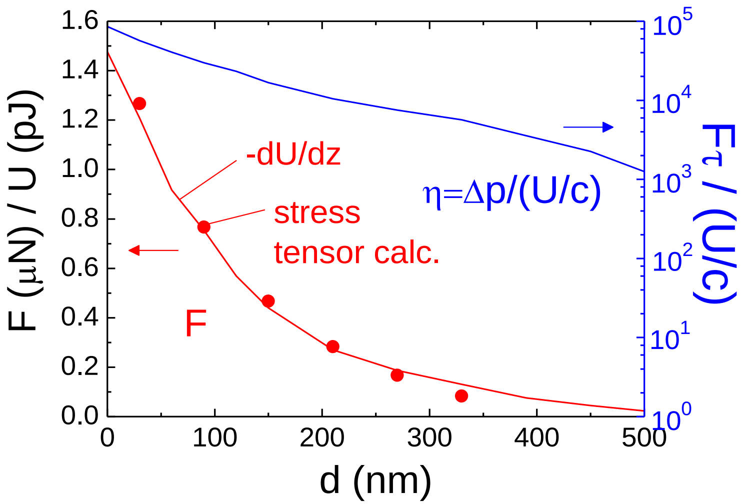


Tanabe et al. Phys. Rev. Lett. (2009)

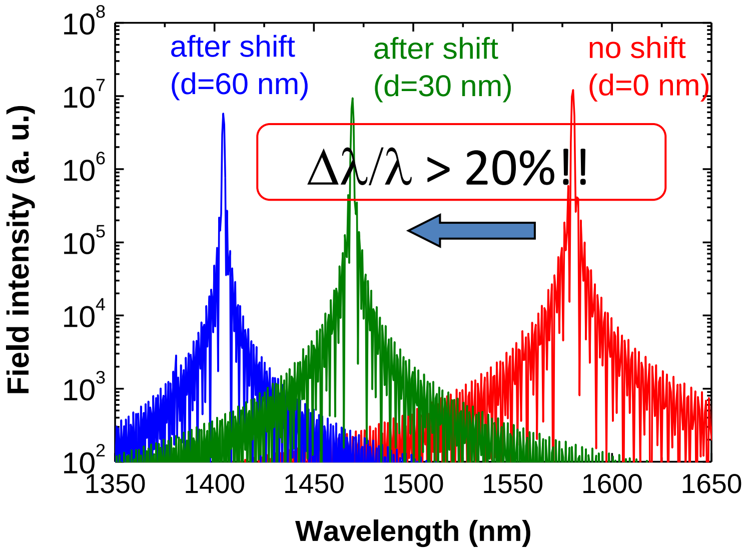
Bi-Layer Photonic Crystals for Optomechanics (proposal)

Notomi et al. PRL 97, 023903 (2006)





Optomechanical Wavelength Conversion



Very large radiation force F

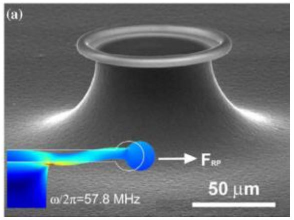
~ 1 μN per 1 pJ

Optomechanical Energy Conversion

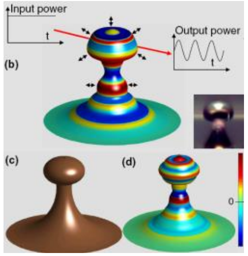
(5) Optomechanic application

Cavity Optomechanics with Various Microcavities

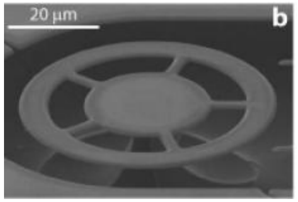
Mono-layer system



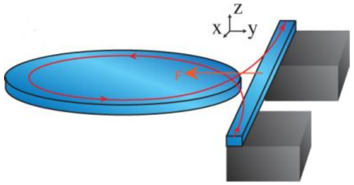
Kippenberg PRL (2006)



Cameron, PRL (2007)



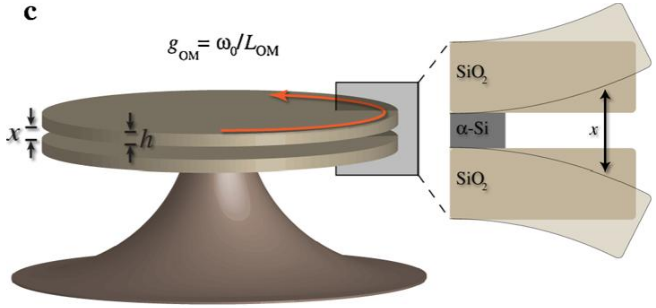
Nature Photon. (2009)



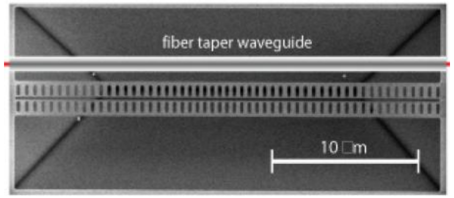
Li, PRL (2009)

Eichenfield, Nature (2009)

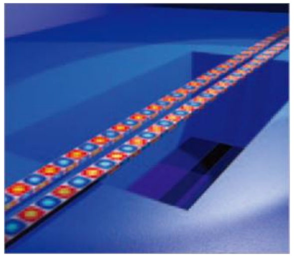
Bi-layer system



Lin, PRL (2009)



Eichenfield, Nature (2009)



Li, Nature Photon. (2009)

Radiation Force in Double-Layer PhC Cavities

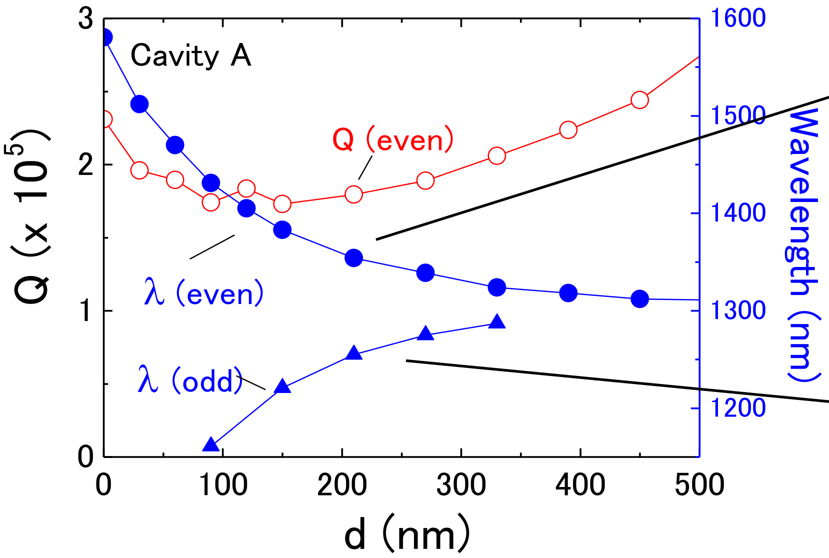
Radiation Force

$$F = -\frac{\partial U}{\partial z} = -\frac{U}{\omega}\frac{\partial \omega}{\partial z}$$

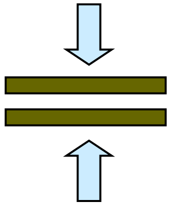
adiabatic invariant

This term is very large in DL-PC Cavities

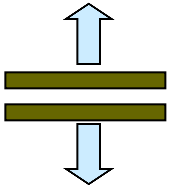
If the process is adiabatic, DL-cavities shows extraordinarily large radiation force.



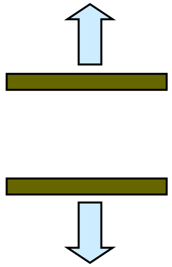
attractive force (even)



repulsive force (odd)



Fabry-Perot cavity

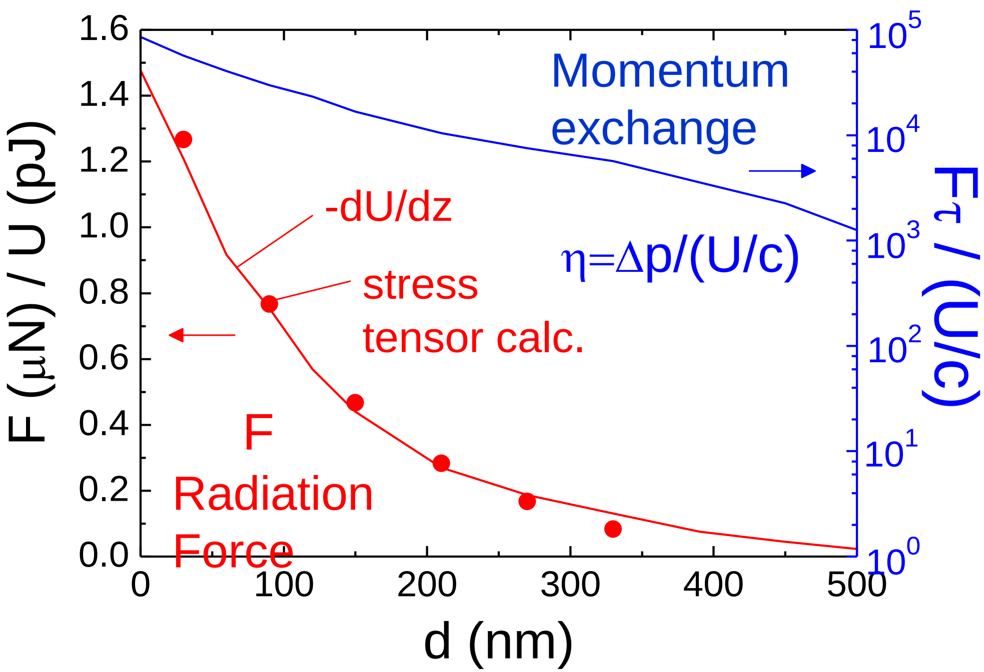


always repulsive

(1) The force direction can be designable.

(2) The force itself is very large.

Radiation Force and Mechanical-momentum Exchange



$$F = -\frac{\partial U}{\partial z} = -\frac{U}{\omega}\frac{\partial \omega}{\partial z}$$

adiabatic invariant

Very large radiation force F

~ 1 μN per 1 pJ

due to smallness (1/V)

Very large impulse (Ft) (momentum exchange)

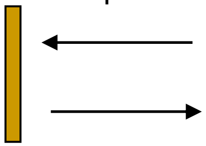
due to long photon lifetime (Q)

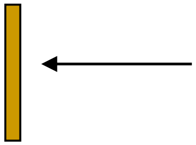
$\Delta p/p_{pw} = 10^3 - 10^5$

Normally, momentum of light is

$p_{pw} = U/c$

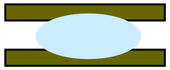
reflection: $\Delta p/\ p_{pw} = 2$ absorption: $\Delta p/\ p_{pw} = 1$





Energy Conversion from Optical to Mechanical

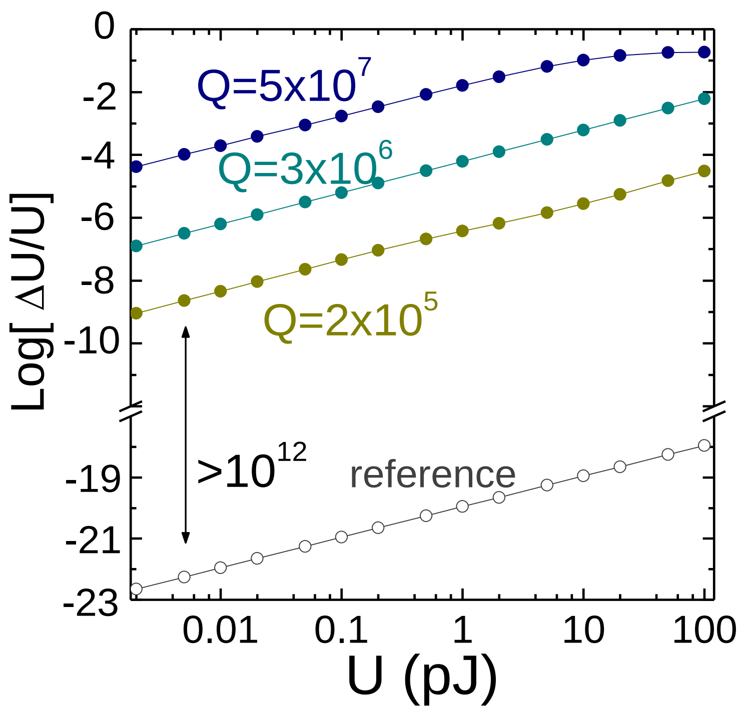
Notomi et al. PRL 97, 023903 (2006)



$$\frac{d^2z}{dt^2} = \frac{F(z)}{m}$$

z(0)=z'(0)=0

We solved the nonrelativistic equation of motion for DL-PC cavities to deduce ΔU/U and the induced slab shift.



ΔU/U can be up to ~10^{-1}

Mechanical to Optical

Wavelength converter

$\Delta\lambda$

Reverse process

Optical to Mechanical

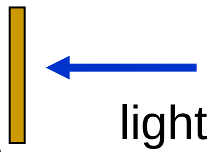
MEMS

ΔU

Extremely large energy conversion efficiency!

Energy Conversion from Optical to Mechanical

Why is this energy conversion inefficient?



light having energy U

mirror

How large energy portion can be transferred to the mirror?

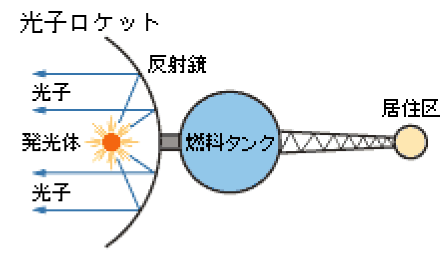
$$\frac{\Delta U}{U} = \frac{U}{mc^2/2} + 2\frac{v_0}{c} \sim \frac{U}{mc^2/2} \quad <<1$$

e.g.) ϕ20-μm polystyrene sphere

$mc^2 = 1.8 \times 10^6 [J] \longrightarrow$ 1 mW laser over 30 years

ΔU/U can be close to unity only when U is comparable to mc^2 of the mirror.

⇨ This is the case for photon rockets!

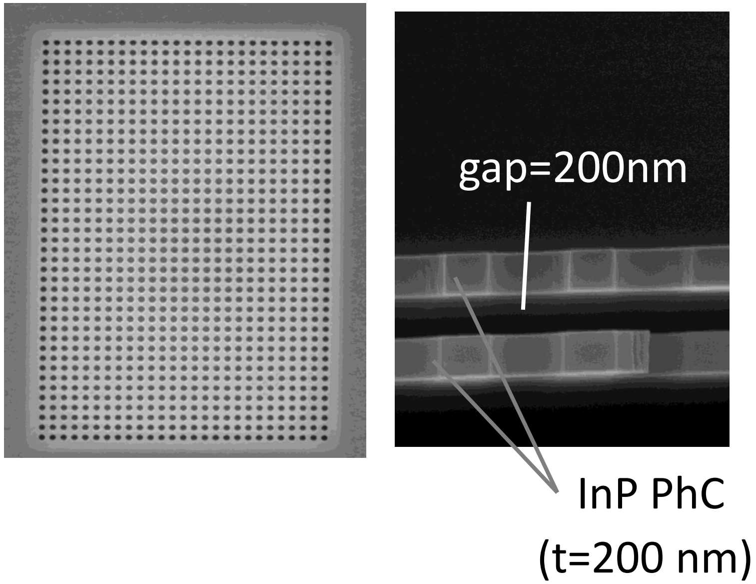


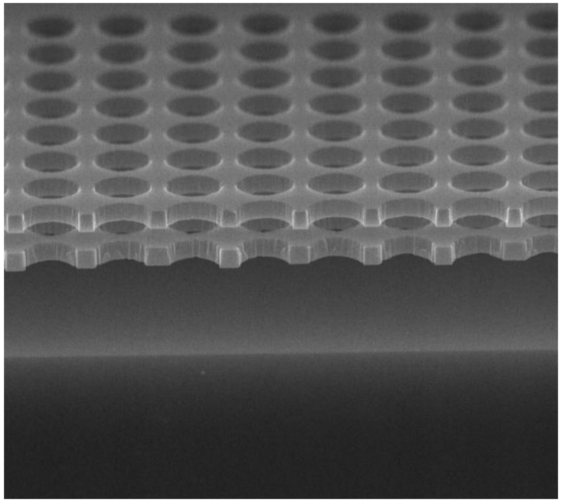
photon rocket

Bi-Layer Photonic Crystals for Optomechanics (experiment)

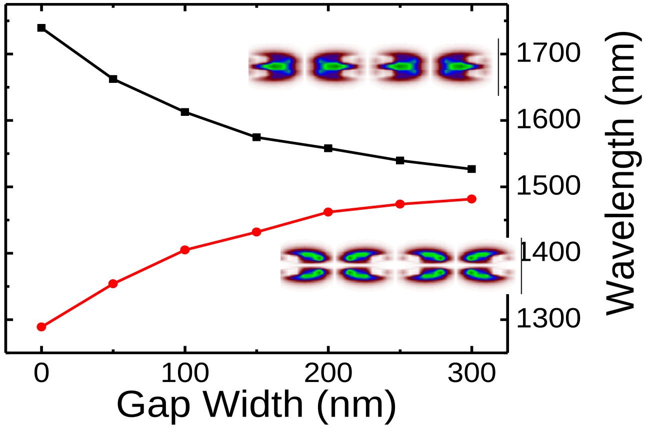
Roh et al. Phys. Rev. B (R) (2010)
Editor's suggestion

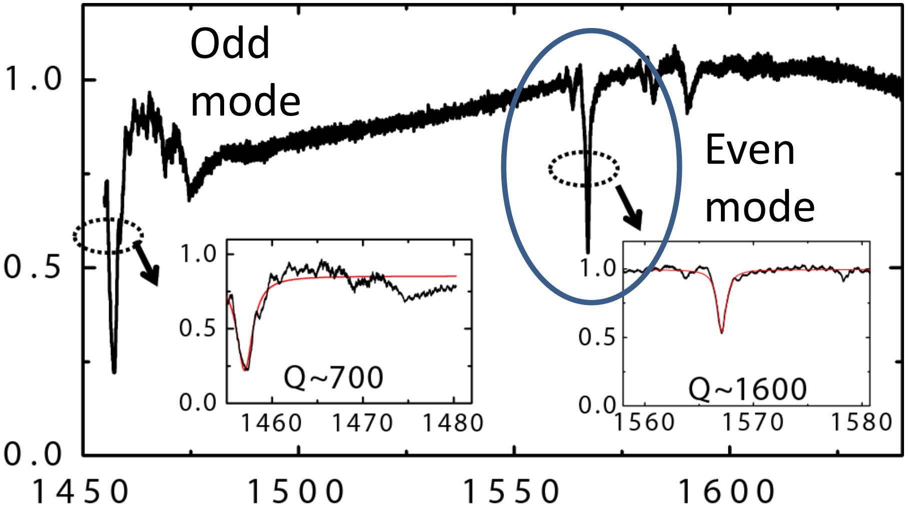
Bi-layer Photonic Crystal



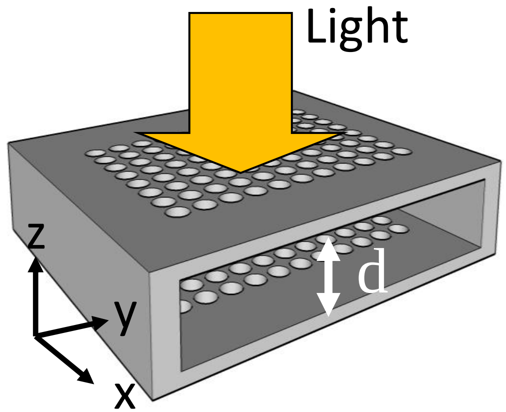


Band edge modes (even / odd)



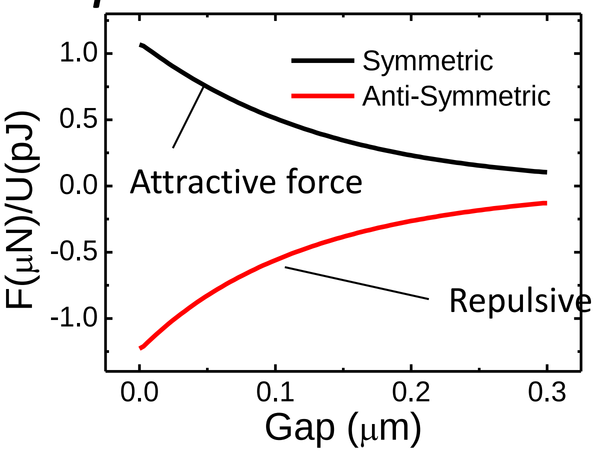


Observation of Large Radiation Force

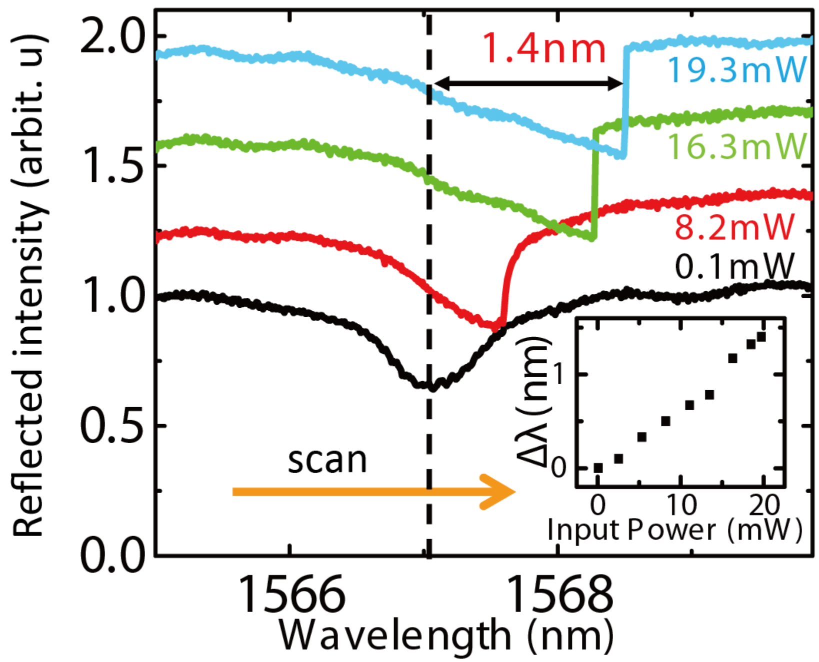


$$F/U = -\frac{1}{\omega}\frac{d\omega}{dx} = \frac{1}{\lambda}\frac{d\lambda}{dx}$$

Expected Radiation Force



Reflectance vs. Power



Radiation Force

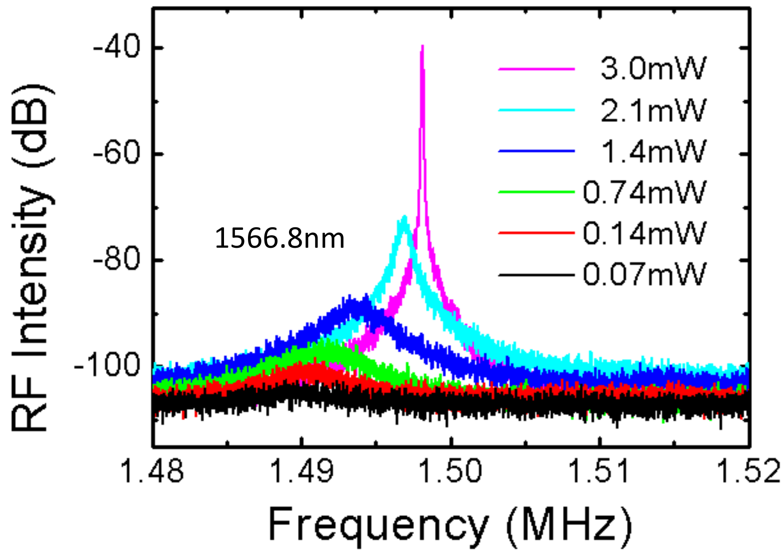
F = 10.8nN

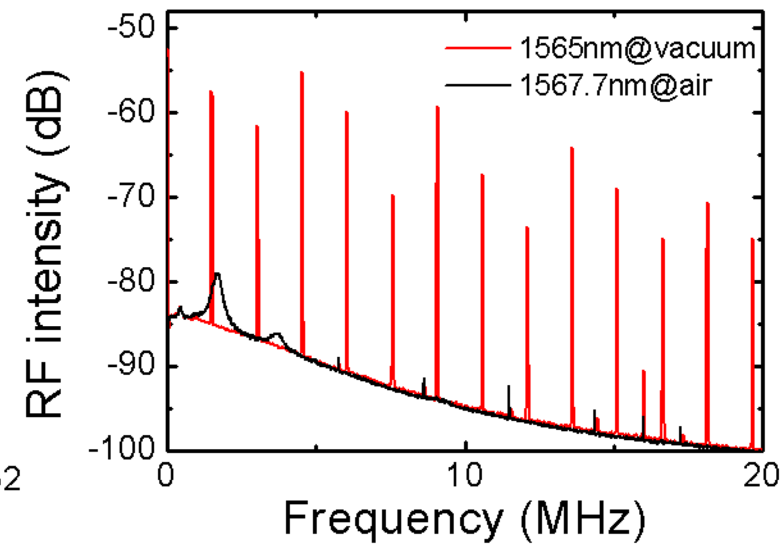
(F/U ~ 0.4uN/pJ)

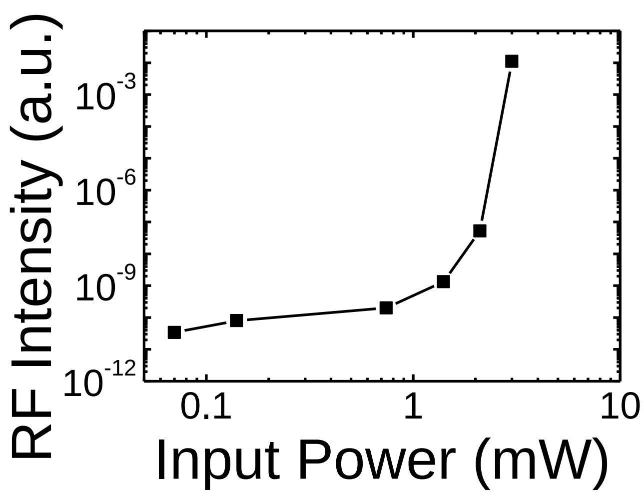
Roh et al. Phys. Rev. B (R) (2010)

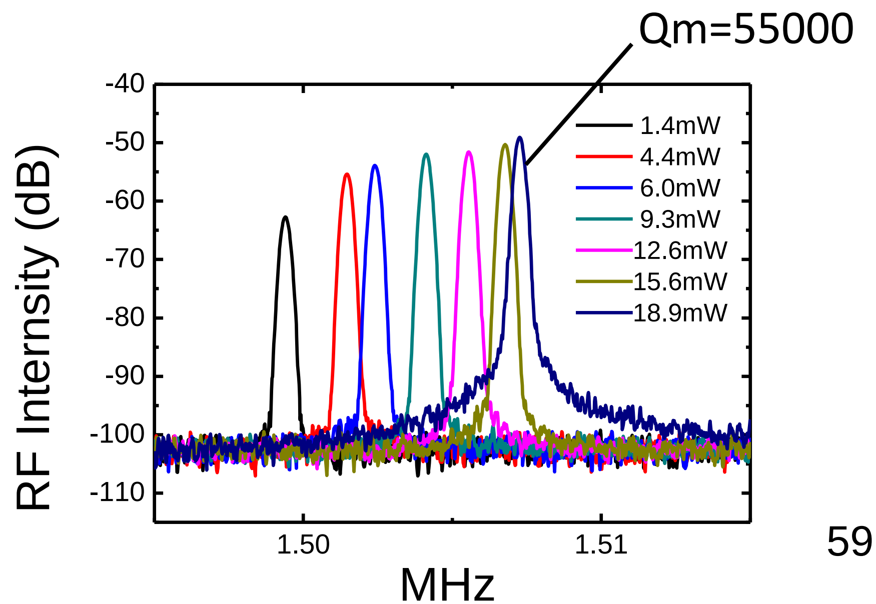
Editor's suggestion

Mechanical Lasing in Vacuum (self oscillation)









(6) Ultralow Power Device

Q/V scaling in various device operations / phenomena

Purcell factor

$$F_P = \frac{3}{4\pi^2}\frac{Q}{V}\left(\frac{\lambda}{n}\right)^3$$

light intensity per unit input power
interaction time per unit volume
photonic DOS per unit volume

~Q/V

Switching energy

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

Consumption power 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

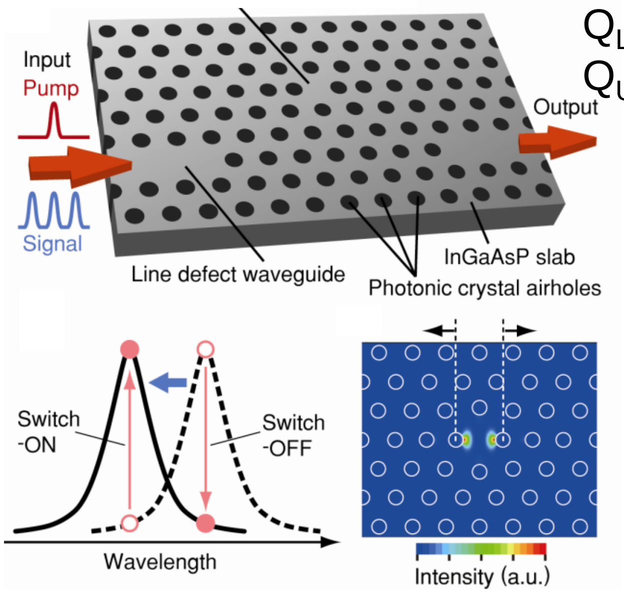
$$I_{\mathrm{mod}} \approx \frac{en}{\sigma\tau_c}\frac{V}{Q}$$

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

Demonstration of Atto-Joule Switching

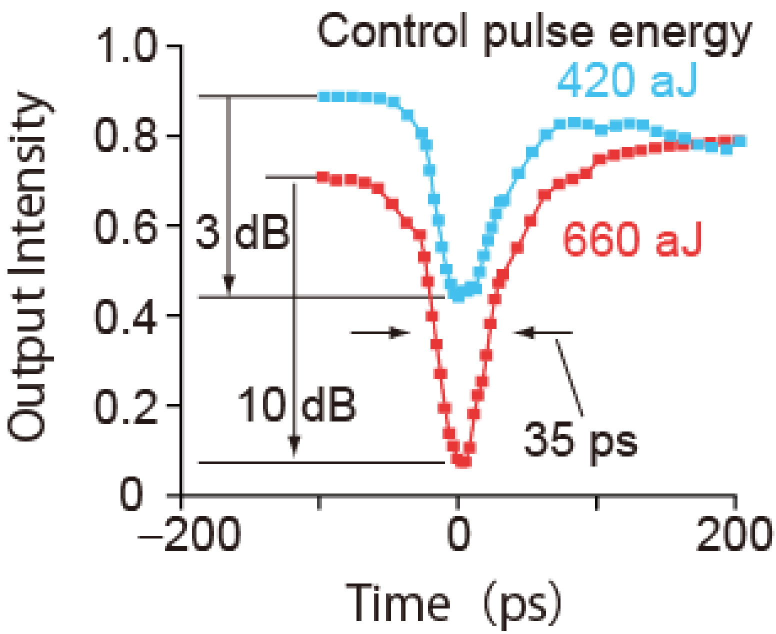
InGaAsP H0 cavity

Nozaki et al. Nature Photonics (2010)



Q_L=6500
Q_{UL}=22000

Room temperature



First all-optical switching in Atto-joule regime

U= 420 aJ @3dB

U= 660 aJ @10dB

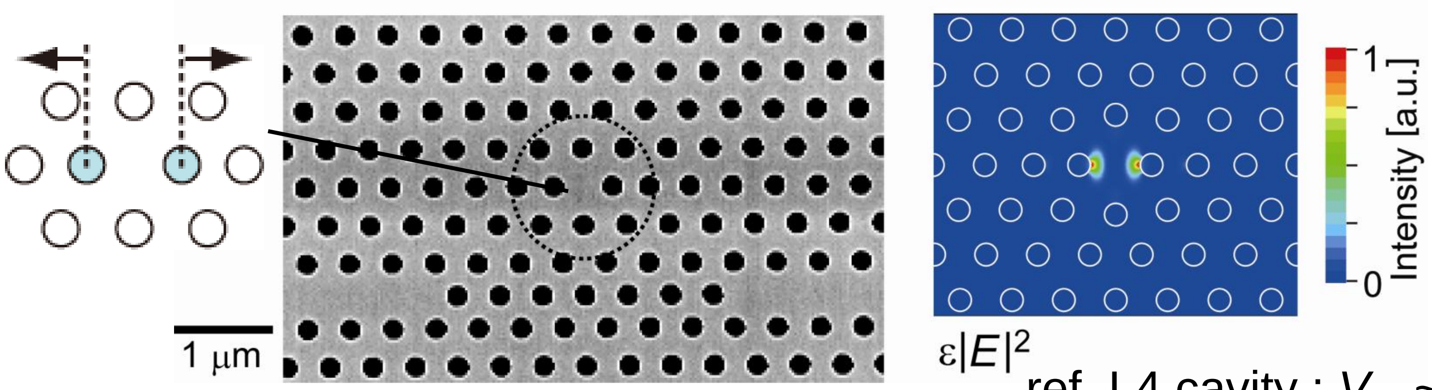
We have also achieved
Pulse extraction from 40 Gbps data stream

T= 20 ~35 ps

Our Choice of Cavities

Nozaki et al. Nature Photonics (2010)

H0 cavity (Zero-cell): Smallest dielectric-core nanocavity



Zhang,Qiu
OpEx (2004)

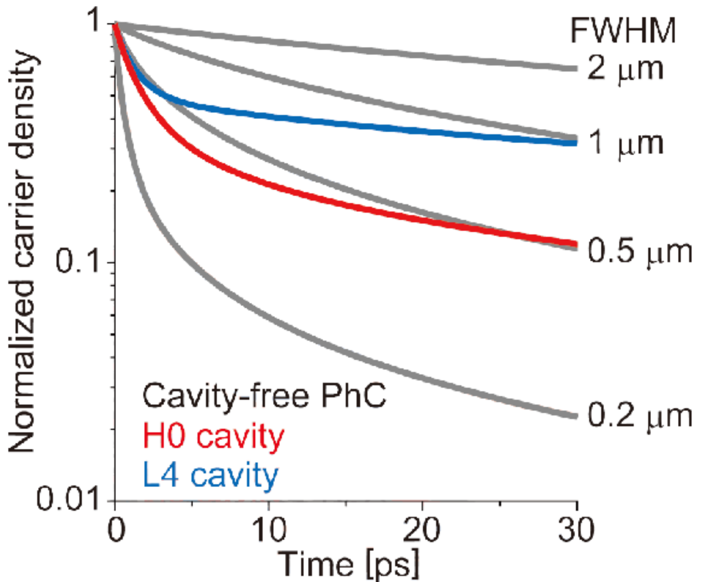
$V_{\mathrm{eff}} \sim 0.02\ \mu\mathrm{m}^3$

ref. L4 cavity : $V_{\mathrm{eff}} \sim 0.1\ \mu\mathrm{m}^3$
Ring cavity : $V_{\mathrm{eff}} > 1\ \mu\mathrm{m}^3$

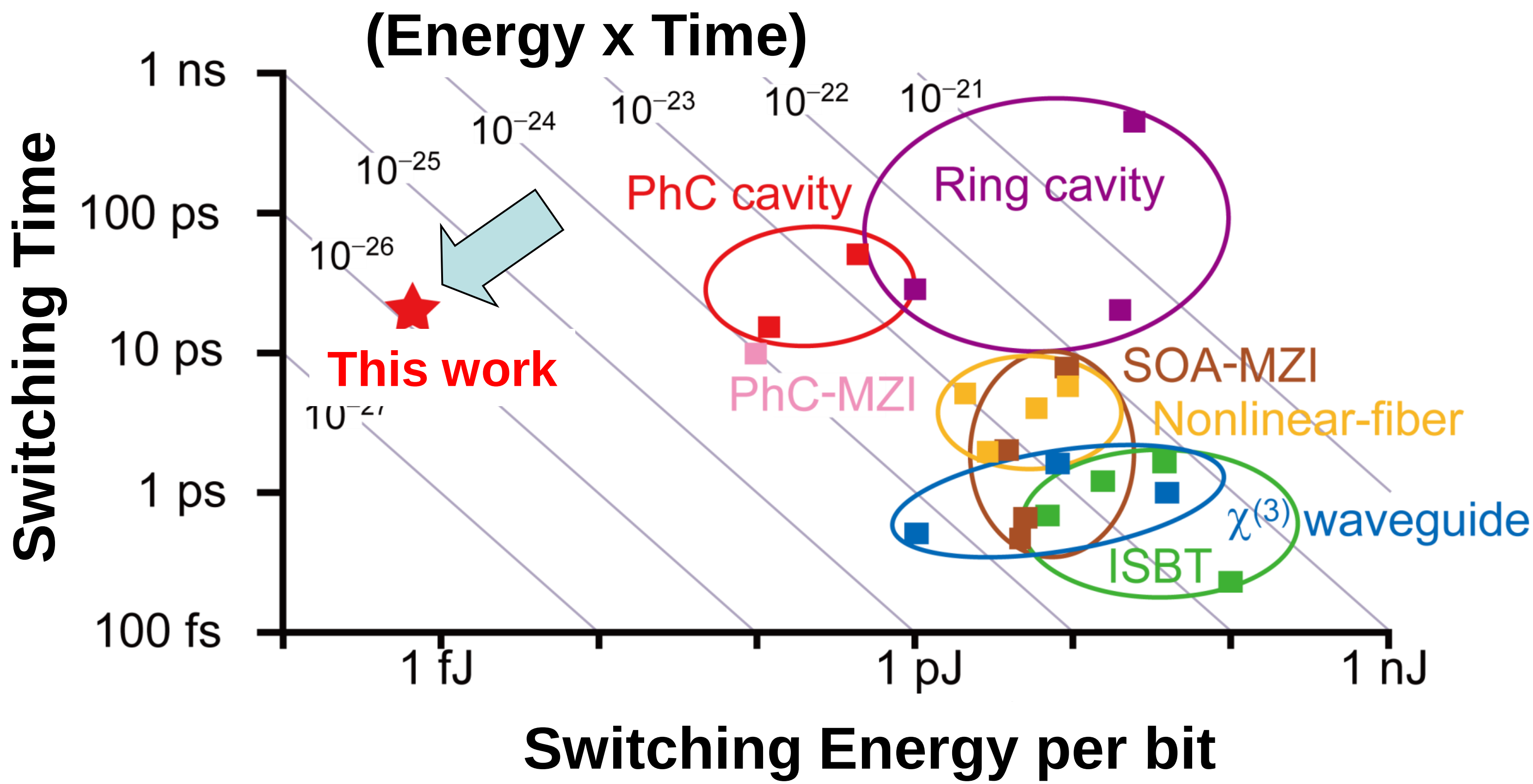
(1) "Small" is "Green" (low switching energy)

$$U_{\mathrm{switching}} \propto (Q/V)^{-1}$$

(2) "Small" is "Fast" (fast carrier diffusion)



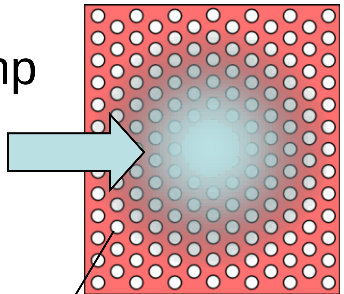
Speed vs. Energy



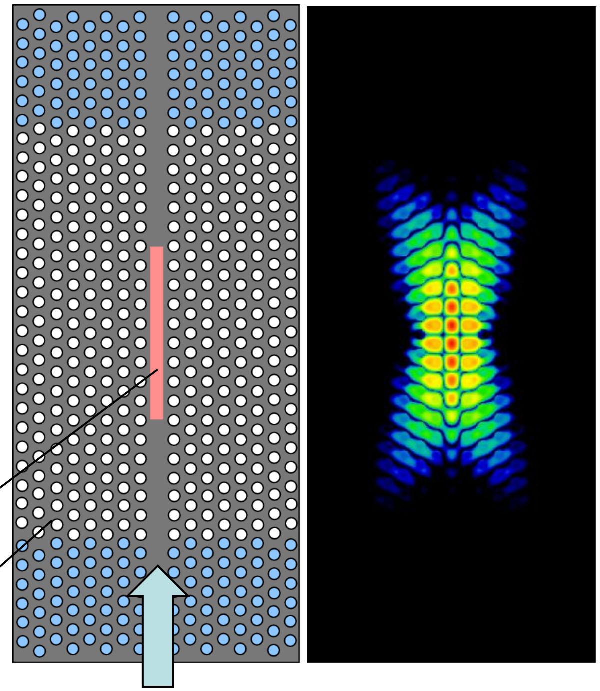
Ultrasmall BH Cavity Lasers

Matsuo et al.
Nature Photonics (2010)

Previous PhC Laser



BH-induced Cavity
(BH: Buried-Hetero)



Cavity
(Photon Confinement)

$Q > 10^6$

$V_{eff} \sim 0.2\ \mu m^3$

BH
(Carrier Confinement)

$V_{BH} \sim 0.18 \mu m^3$

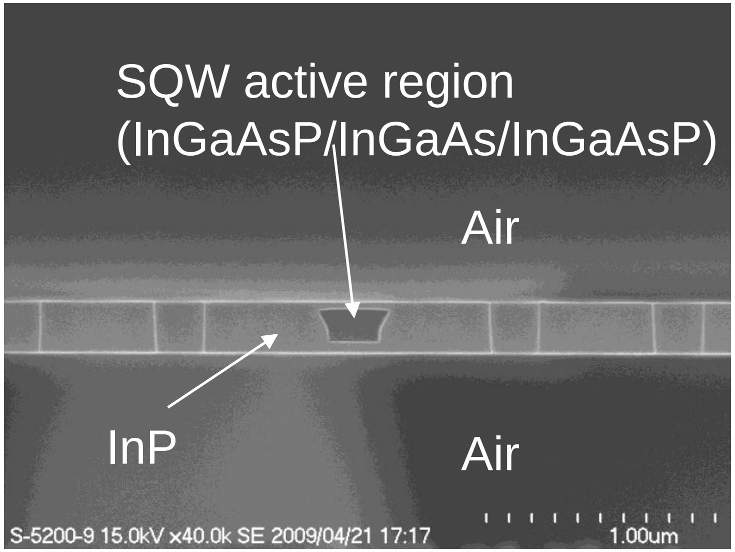
$L_{BH} \sim L_{abs}$

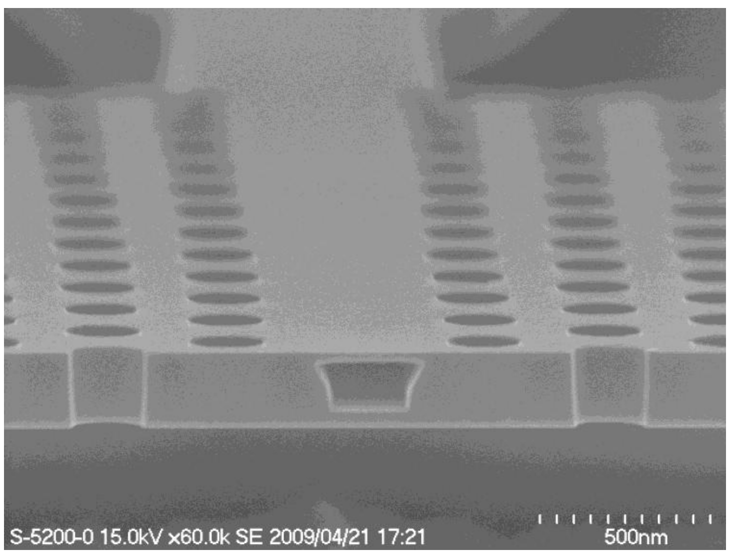
1) *Low heat resistance*
2) *High pumping efficiency*
3) *Strong carrier confinement*

⇨ *Ideal for laser*

Fabrication and Lasing of Ultrasmall BH Lasers

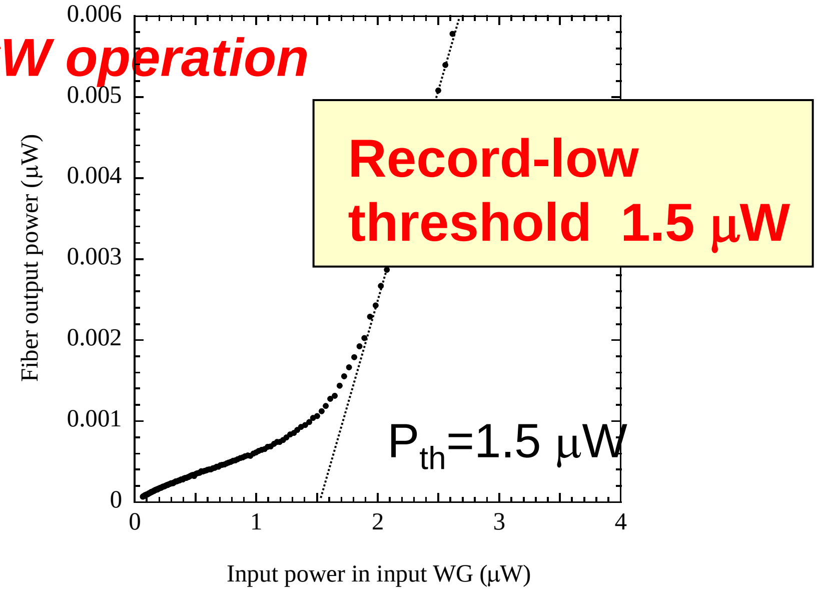
Matsuo et al. Nature Photonics (2010)

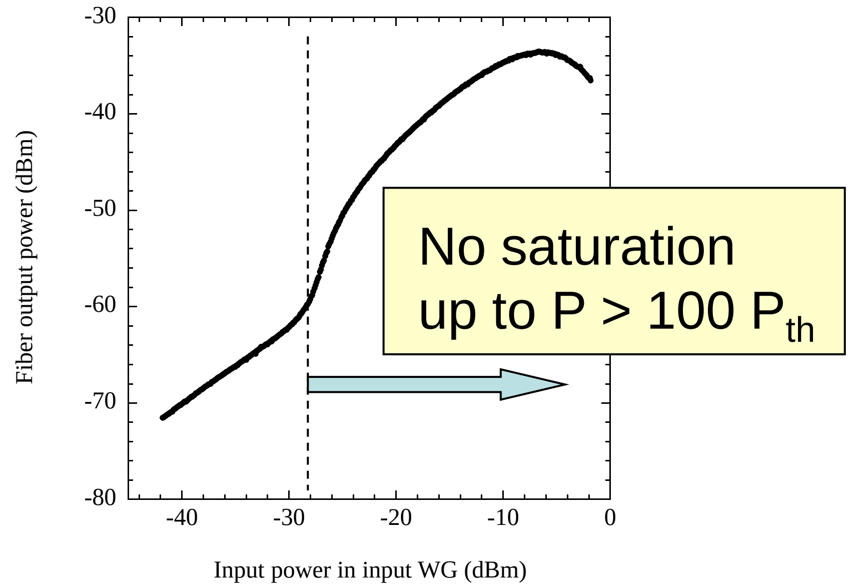




Pump laser:
1310-nm DFB

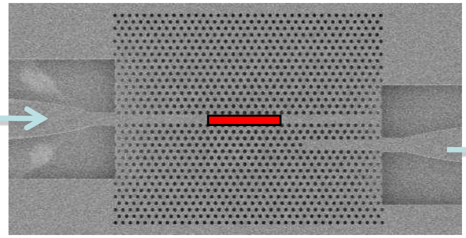
RT CW operation





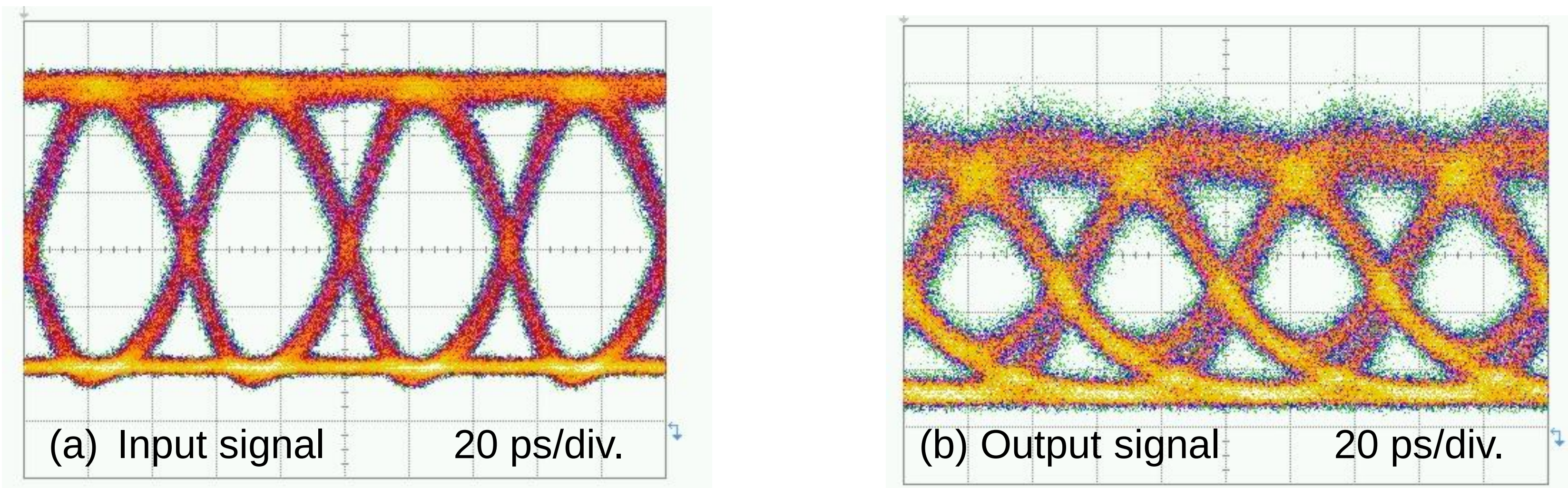
Dynamic characteristics at 20Gbps modulation

Matsuo et al. ECOC 2010 PD

1.3-μm pump laser → LN modulator (← PPG) →  → Fiber amp. → Optical filter → Osc.

20 Gbit/s NRZ signal
PRBS=31

RT-CW

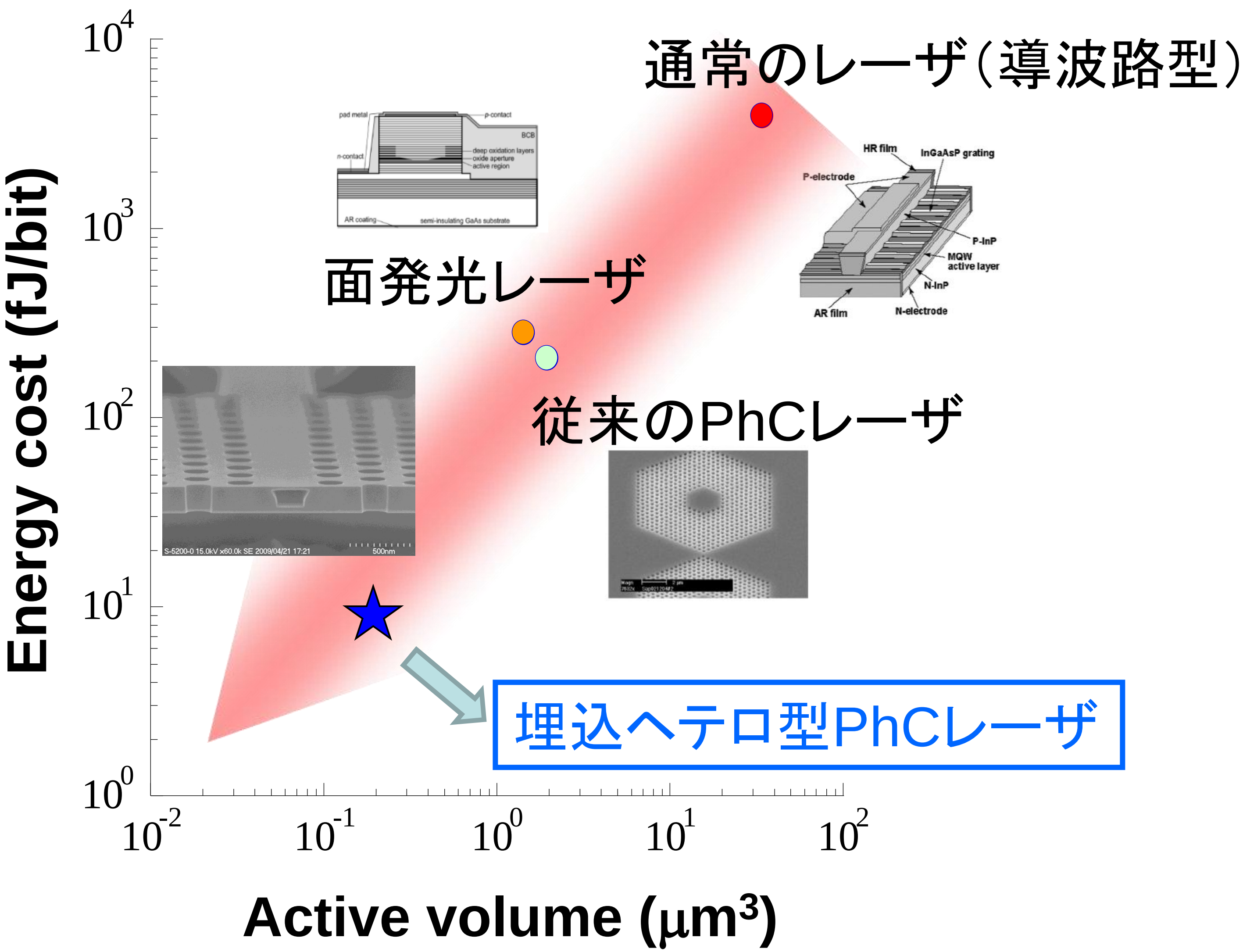


Input power 30 ↔ 208 μW

Estimated absorbed power 175.2 μW
(α=6000 cm^{-1}, Γ=0.616)

→ Energy cost for 1 bit transmission
8.8 fJ/bit

消費エネルギー / サイズ　比較　（レーザ）



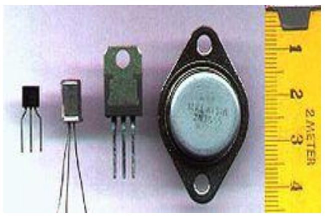
Impact of photonic crystals

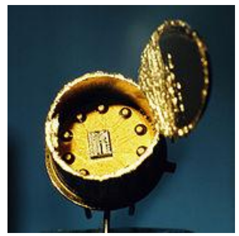
Electronics Integration vs. Photonics Integration

electronics

present | future

vacuum tube → **transistor** → **IC** → **LSI**



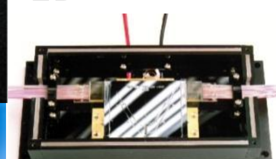


?

photonics

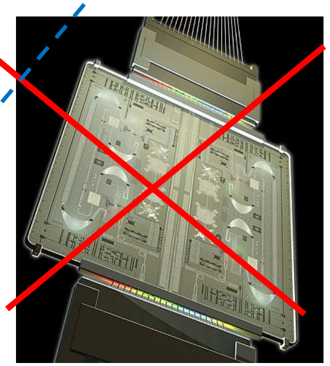
LD

EDFA



PLC

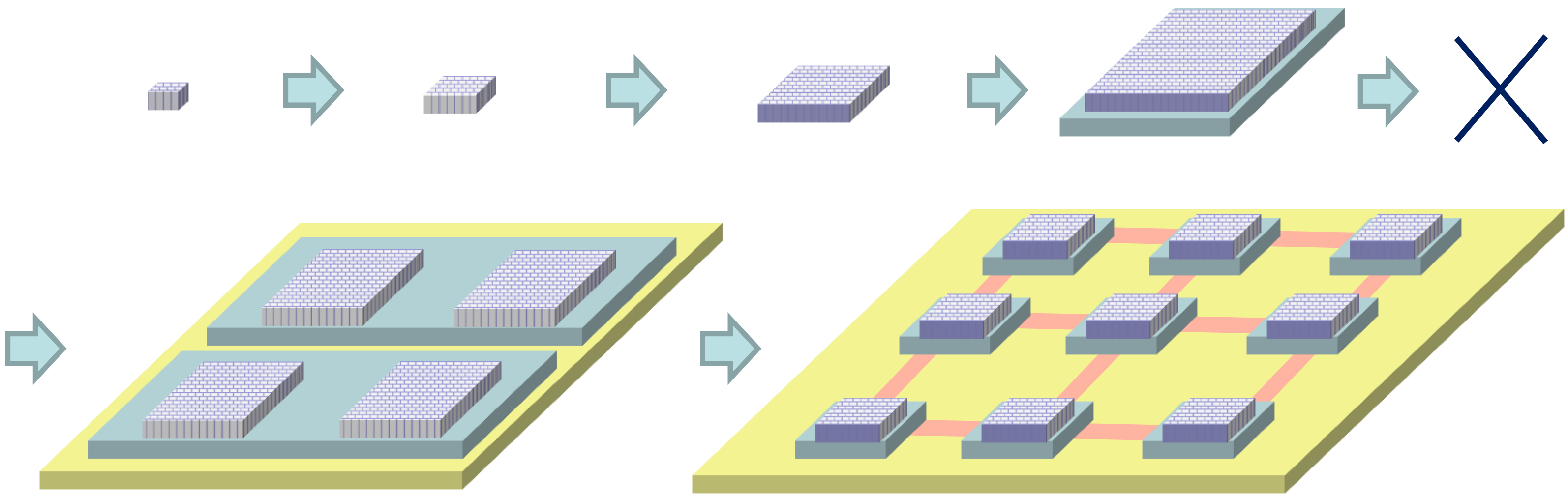
?



?

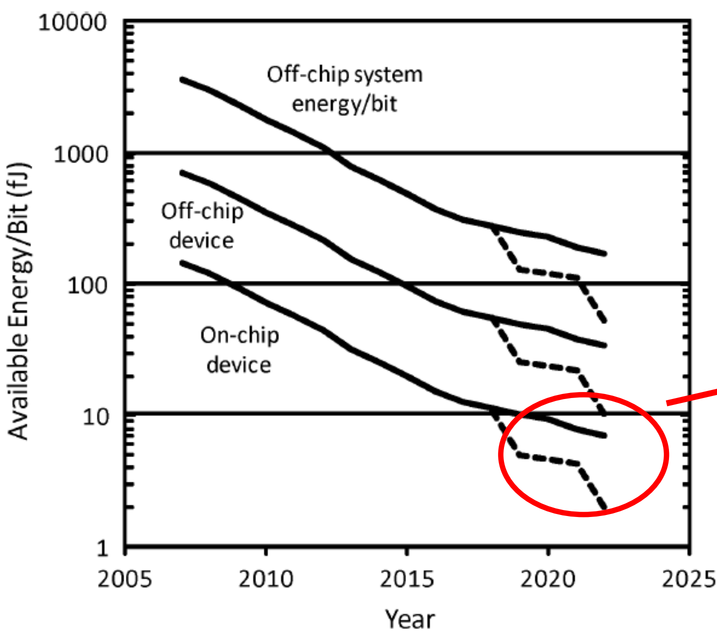
Large-scale photonic integration

Evolution of Chips



Multi-CPU/ Many-core

Optical interconnect



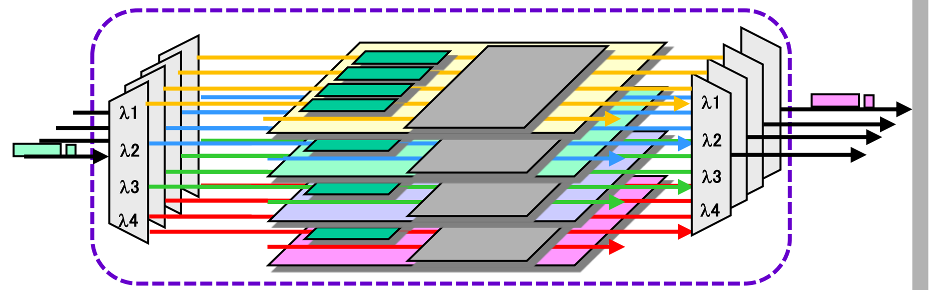
Most of energy will be consumed by electric signal transport (mainly due to charging energy)

Energy cost <10 fJ/bit @2020

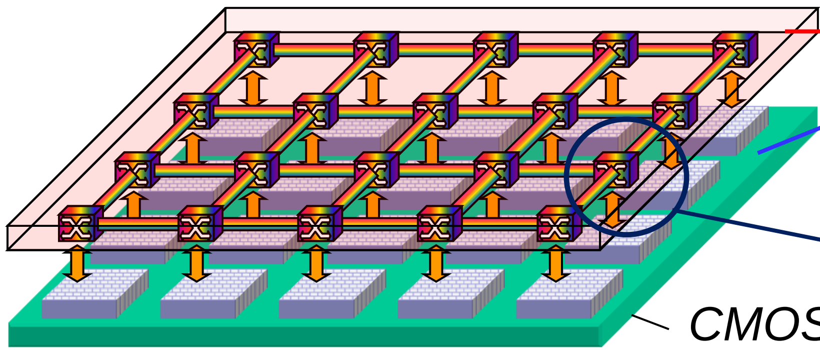
出展： D.A.B. Miller, *Proc. IEEE* (2009).

Photonic Network into Chip

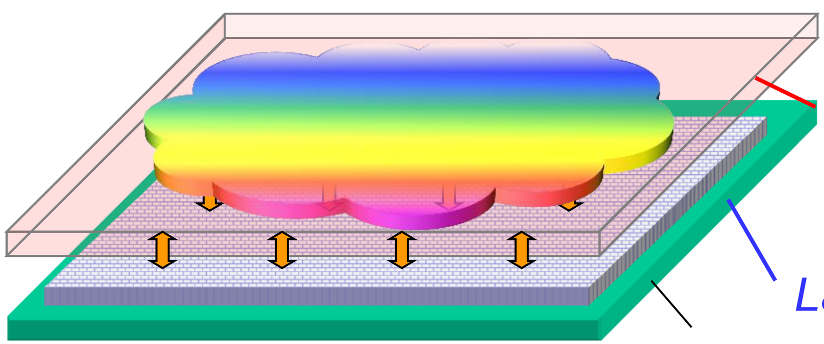
One-chip photonic routing processor



Photonic routing network on CMOS

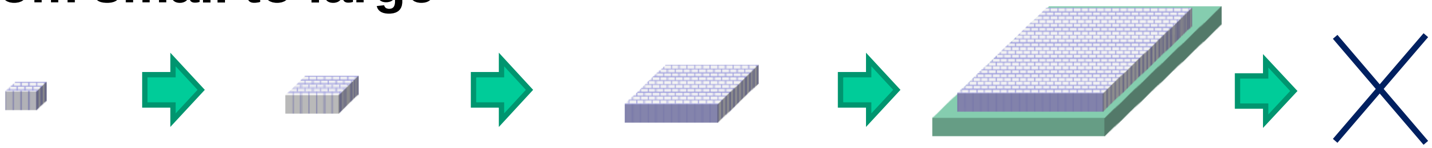


Large-scale MPU unified with photonic network

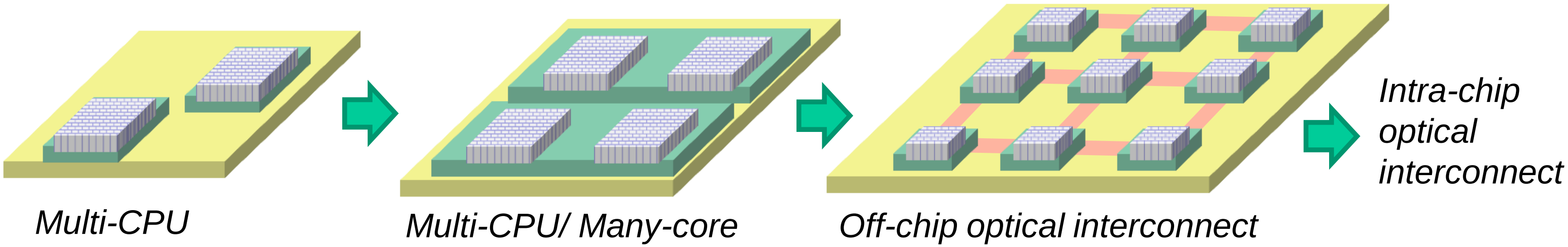


Evolution of Chip in Future

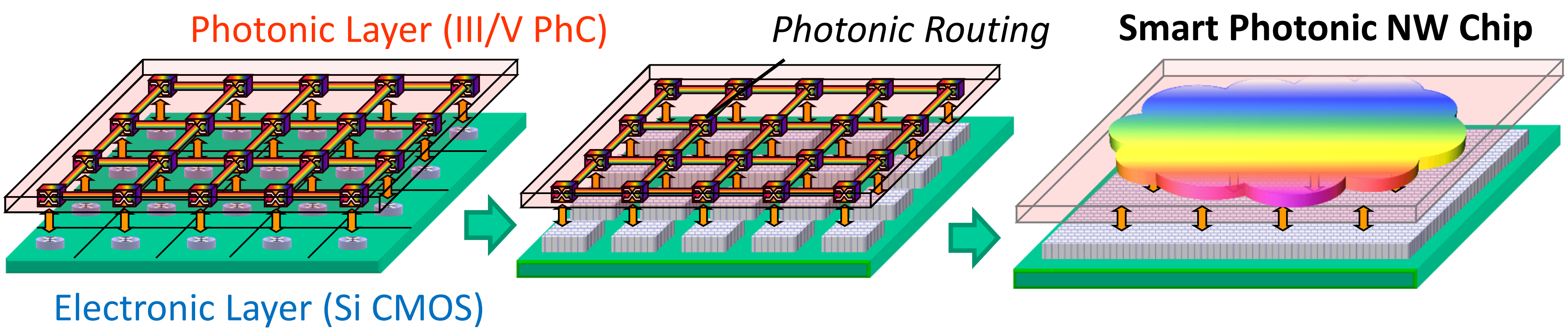
1: From small to large



2: Divide and connect



3: Networking by photonics



Summary

Photonic crystals have enabled

-- Strong light confinement / slow light
-- Control of strong light confinement

⇩

-- Ultralow power devices and integration
-- Adiabatic control of light
-- Enhancement of light-matter interaction

“Photonic crystal” is a technology for ultimate photonic integration.

Photonic LSI ?
On-chip quantum information circuit?
On-chip optomechanics?

Ref) M. Notomi , “Manipulating light with strongly-modulated photonic crystals”, Rep. Prog. Phys. (2010)