

Photonic Crystals and Si Photonics

Toshihiko Baba

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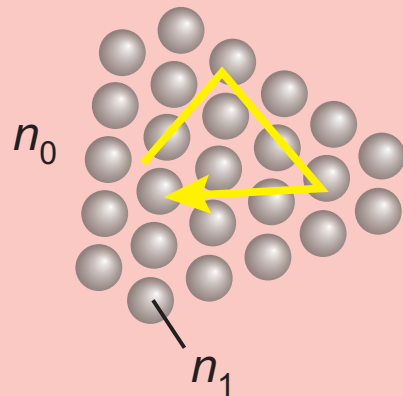
Yokohama National University

<http://www.dnj.ynu.ac.jp/baba-lab/babalabe.htm>

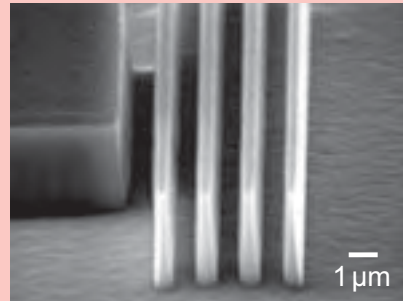
Photonic Nanostructures

Photonic Crystals: PC

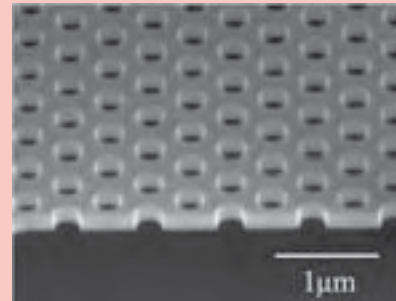
Bragg reflection
Bragg scattering



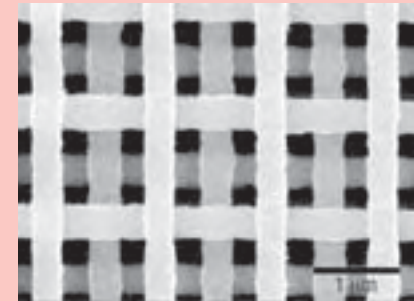
1D



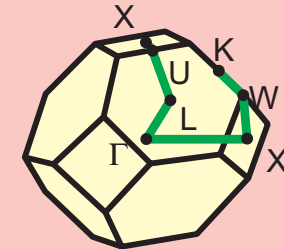
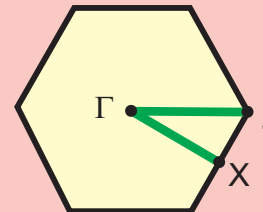
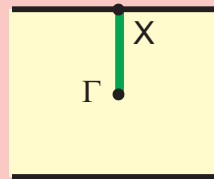
2D



3D

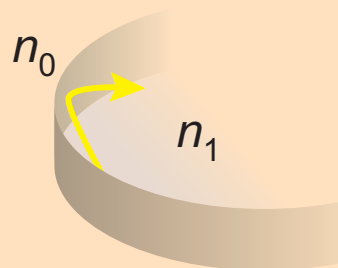


Brillouin zone

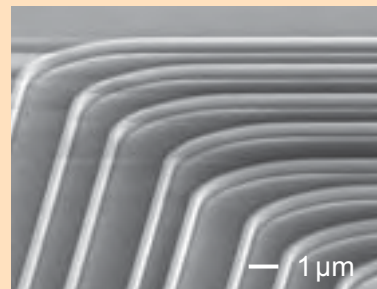


High Index Contrast Structure: HIC

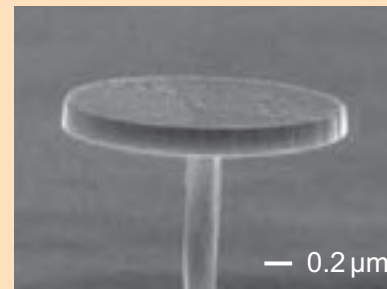
Total reflection



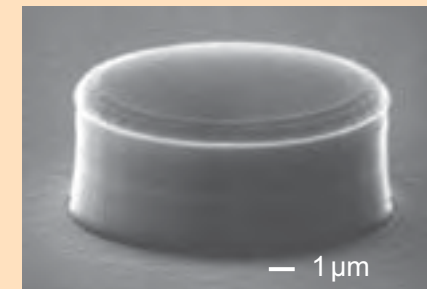
Wire



Disk



Mesa



Innovation in Photonic Integration by Photonic Nanostructures

Holey fiber with small mode size

Mode size converter

Nanocavity drop switch

Slowlight buffer

Slowlight amplifier

Nanocavity cross-connect

Nanocavity λ -converter

Nanocavity add switch

Electronics

Integrated isolator

Nanolaser for λ -converter

Nanolaser signal source

MUX by super prism and superlens

Resonant photodetector

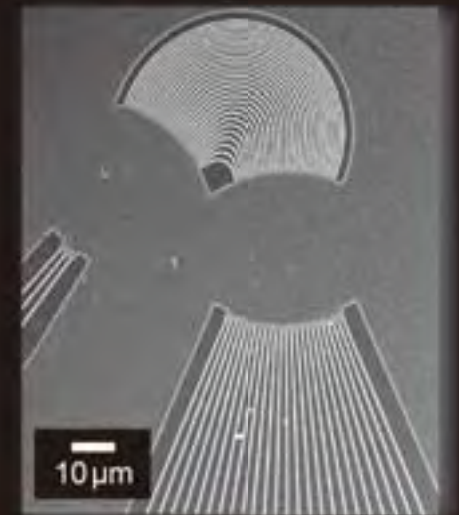
Photonic crystal slowlight waveguide

1 μm

500nm

Photonic crystal nanocavity device

- Nanolaser, nanocavity, slow light waveguide, negative refractive optics, etc. realize novel light emitters and light control devices
- PC and HIC Silicon photonics allow densely integrated advanced photonic chip



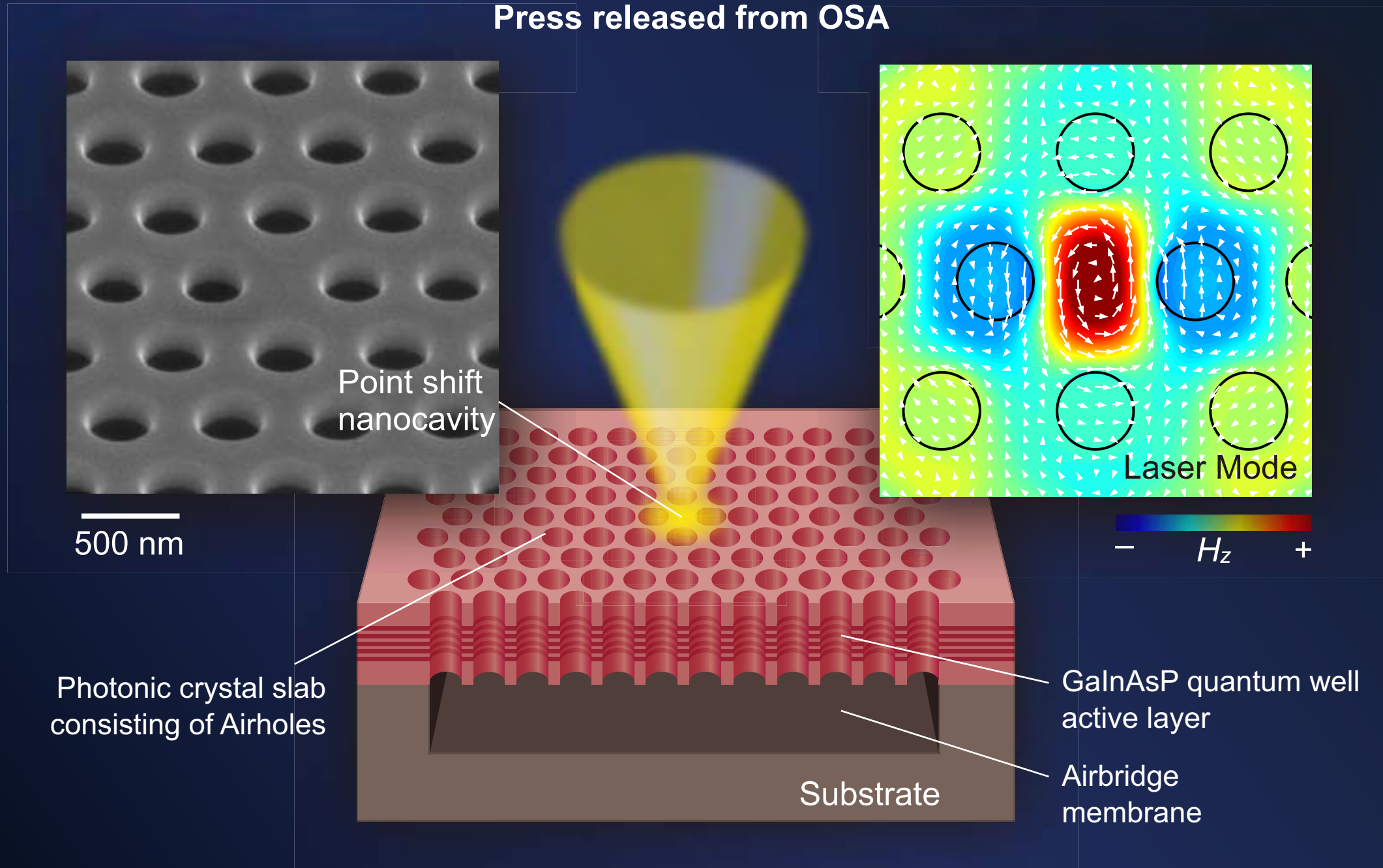
Silicon photonics devices

T. Baba, *nature photonics* 1, 22 (2007)

Room Temperature CW Photonic Crystal Nanolaser

Nozaki et al. *EL* **41**, 15843 (2005); *APL* **88**, 211101 (2006); *OE* **15**, 7506 (2007)

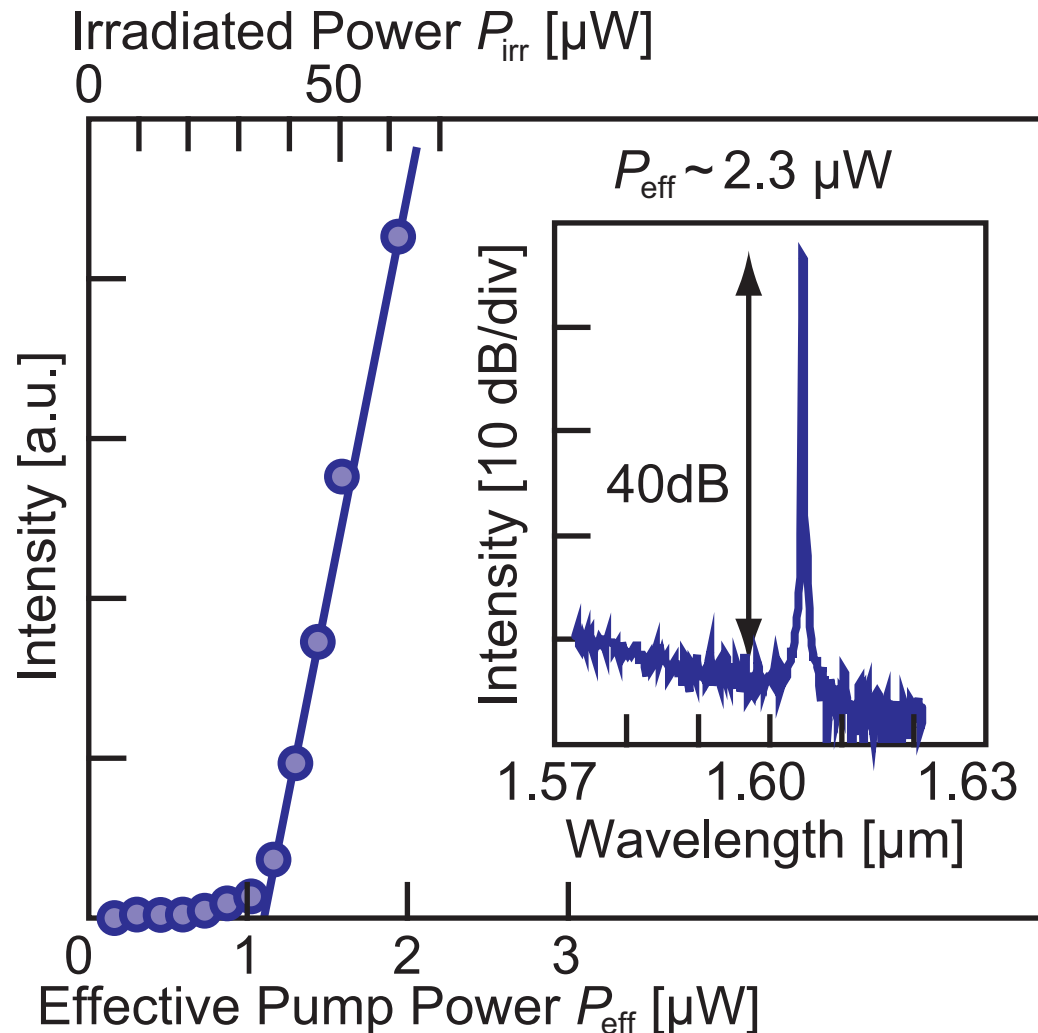
Press released from OSA



High Performance PC Nanolasers

RT, CW Lasing

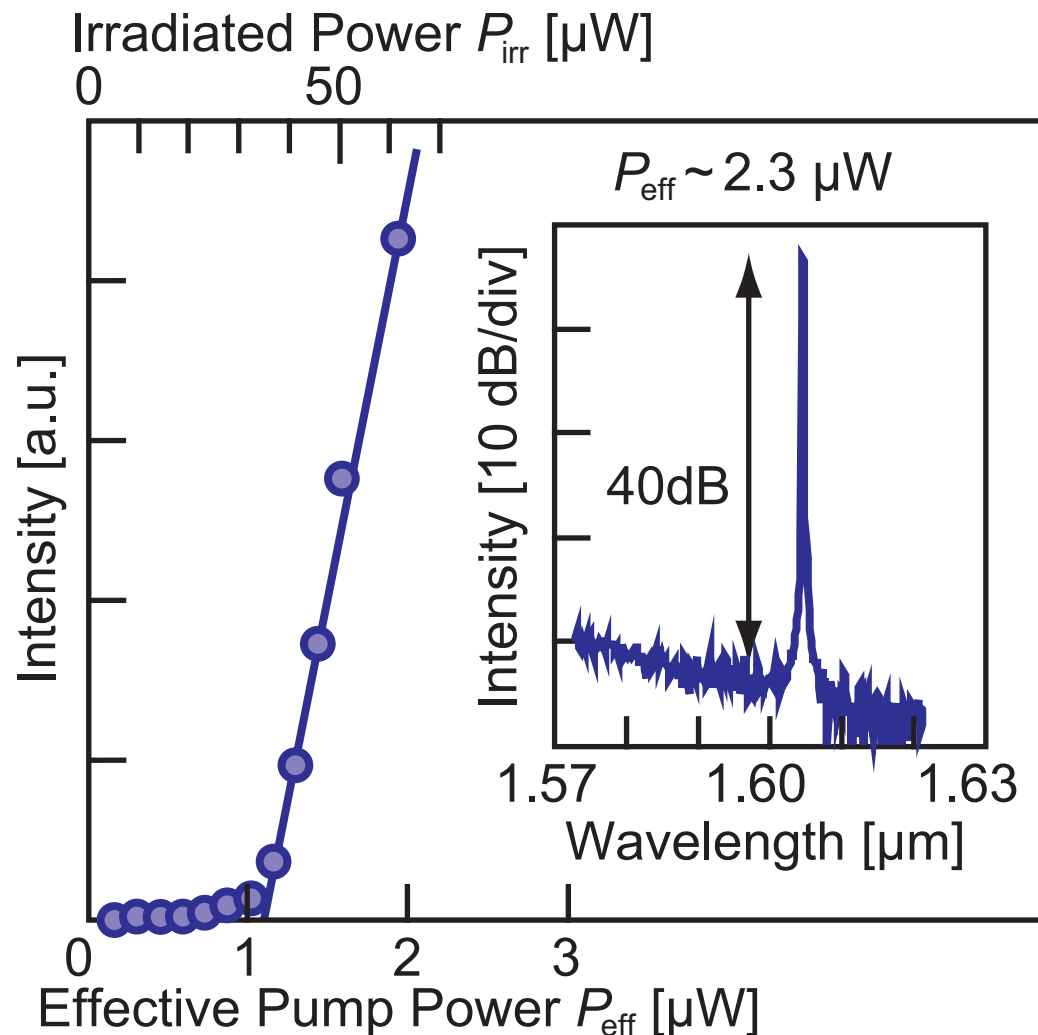
(Nozaki, Kita and Baba, *OE* **15**, 7506 (2007))



High Performance PC Nanolasers

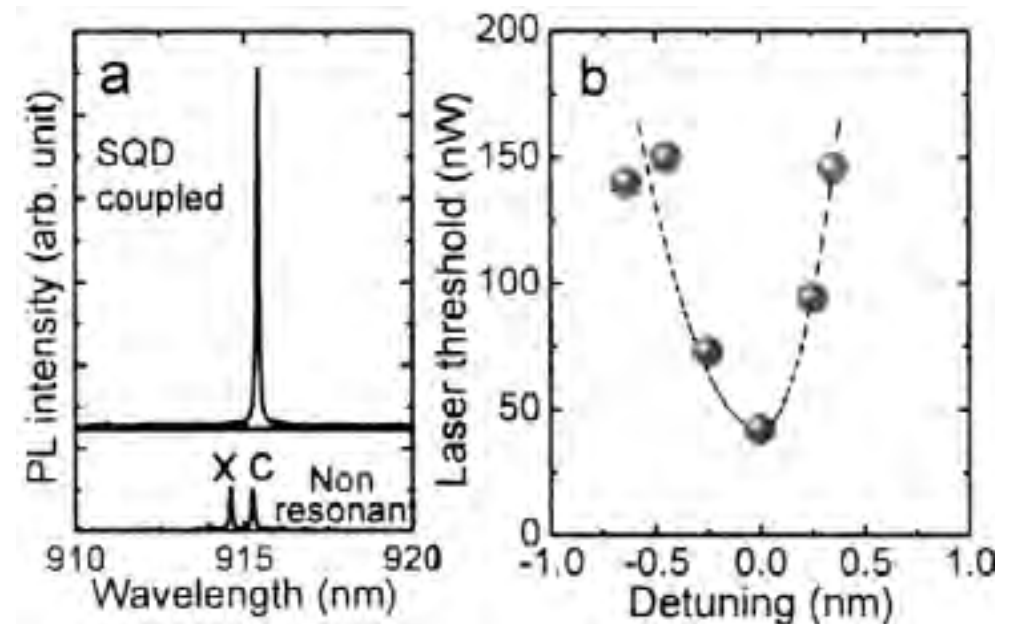
RT, CW Lasing

(Nozaki, Kita and Baba, *OE* **15**, 7506 (2007))



Single QD Lasing (LT)

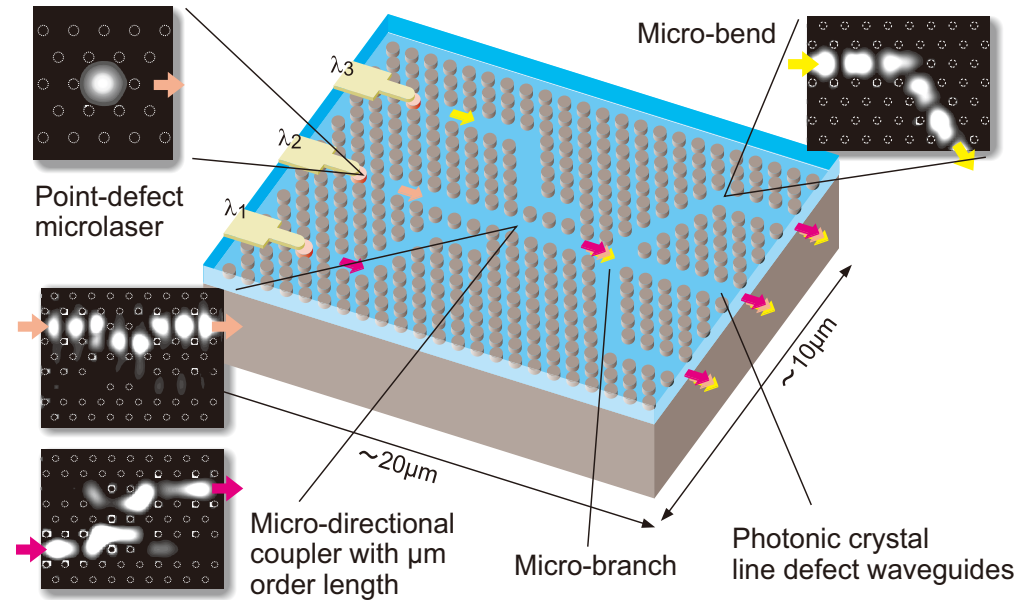
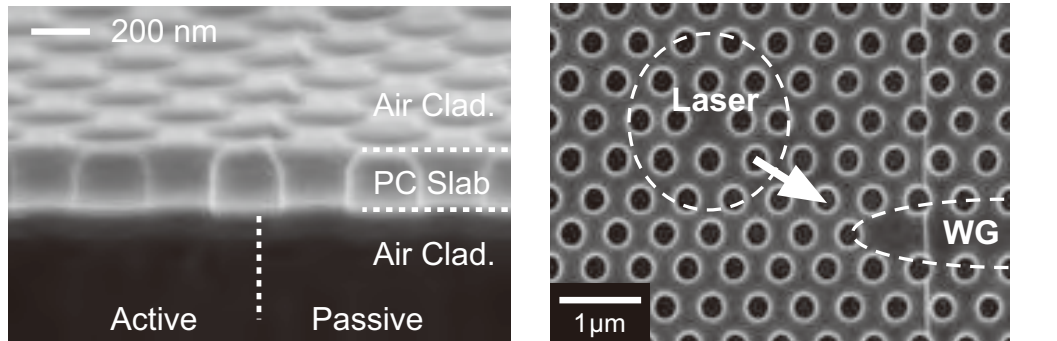
(Nomura et al., *JSAP* 31p-ZN-1 (2009))



Applications of Nanolaser

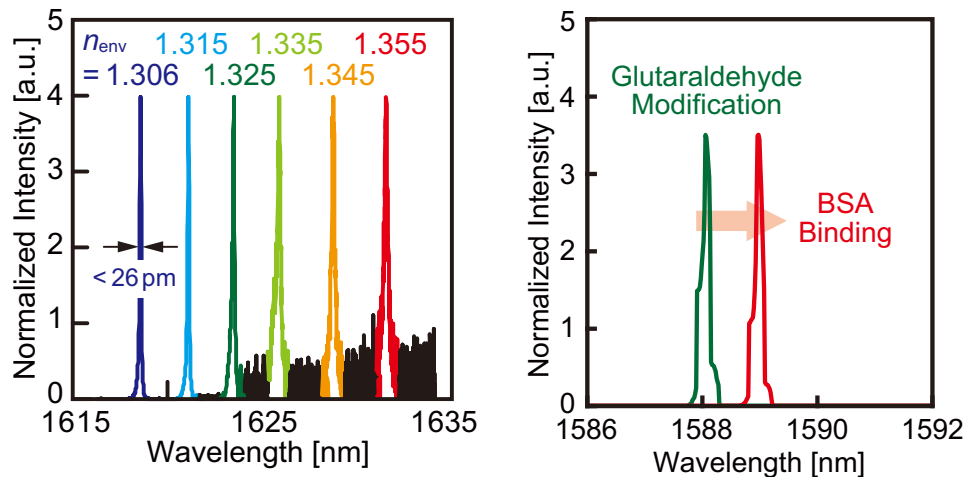
Light Source for Photonic IC

(Watanabe and Baba, *OE* **16**, 2694 (2008))



Chemical and Bio-Sensing

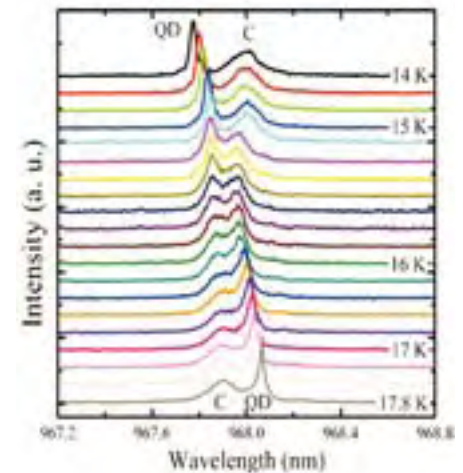
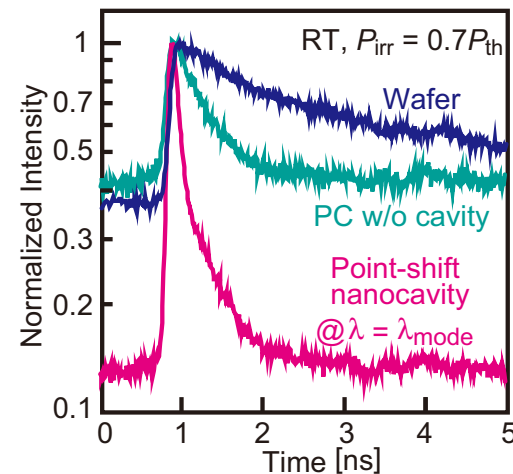
(Kita et al., *OE* **16**, 8174 (2008); *IPNRA*, JMB3 (2009))



Included in MEXT GCOE program operated by YNU and collaborated with Univ. Oulu

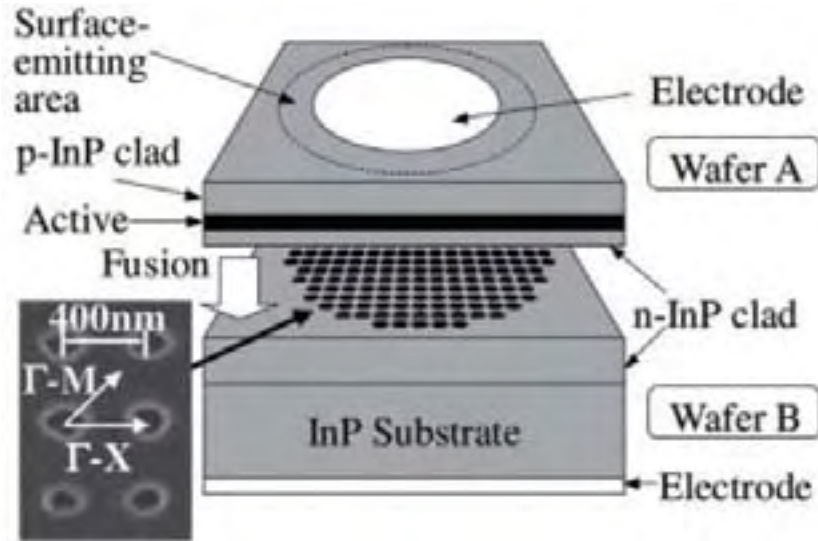
Cavity QED (Purcell enhancement, Rabi splitting, single photon emission, quantum information)

(Baba et al. *APL* **85**, 3989 (2004); Ota et al. *APL* **94**, 033102 (2009))



High-Power Singlemode PC Bandedge Lasers

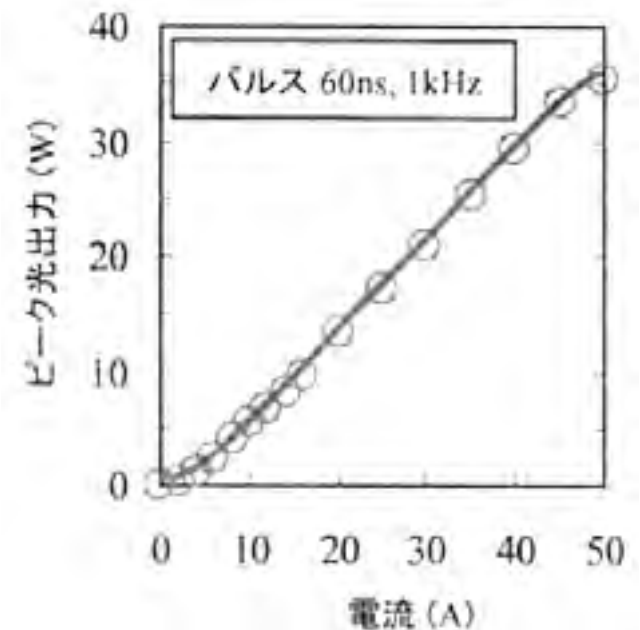
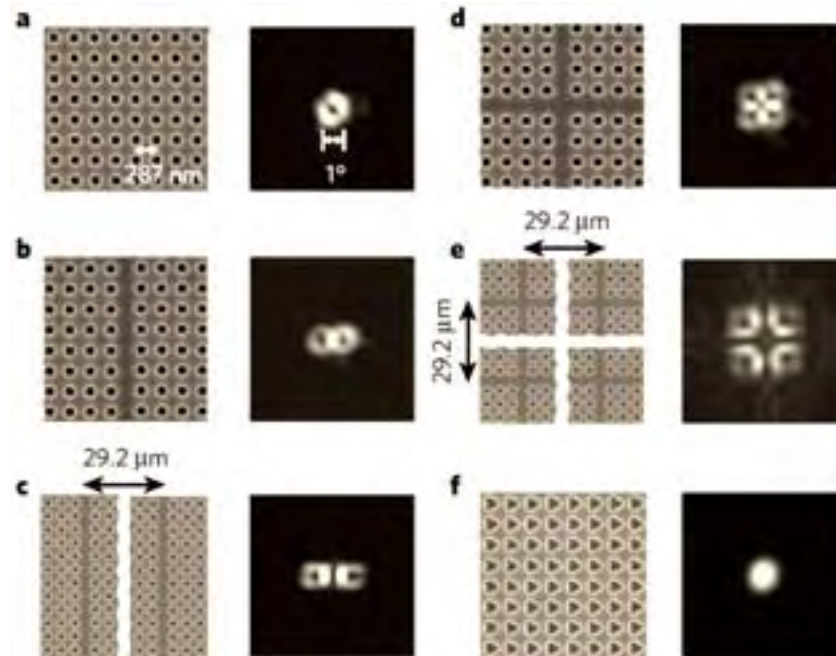
(Noda et al., *Science* **293**, 1123 (2001); *Nature* **441**, 946 (2006); *Science* **319**, 445 (2008); *JSAP* 31a-ZN-1 (2009))



2D DFB PC allows over 30 W singlemode lasing in large areas

Narrow beam profiles controllable by PC engineering

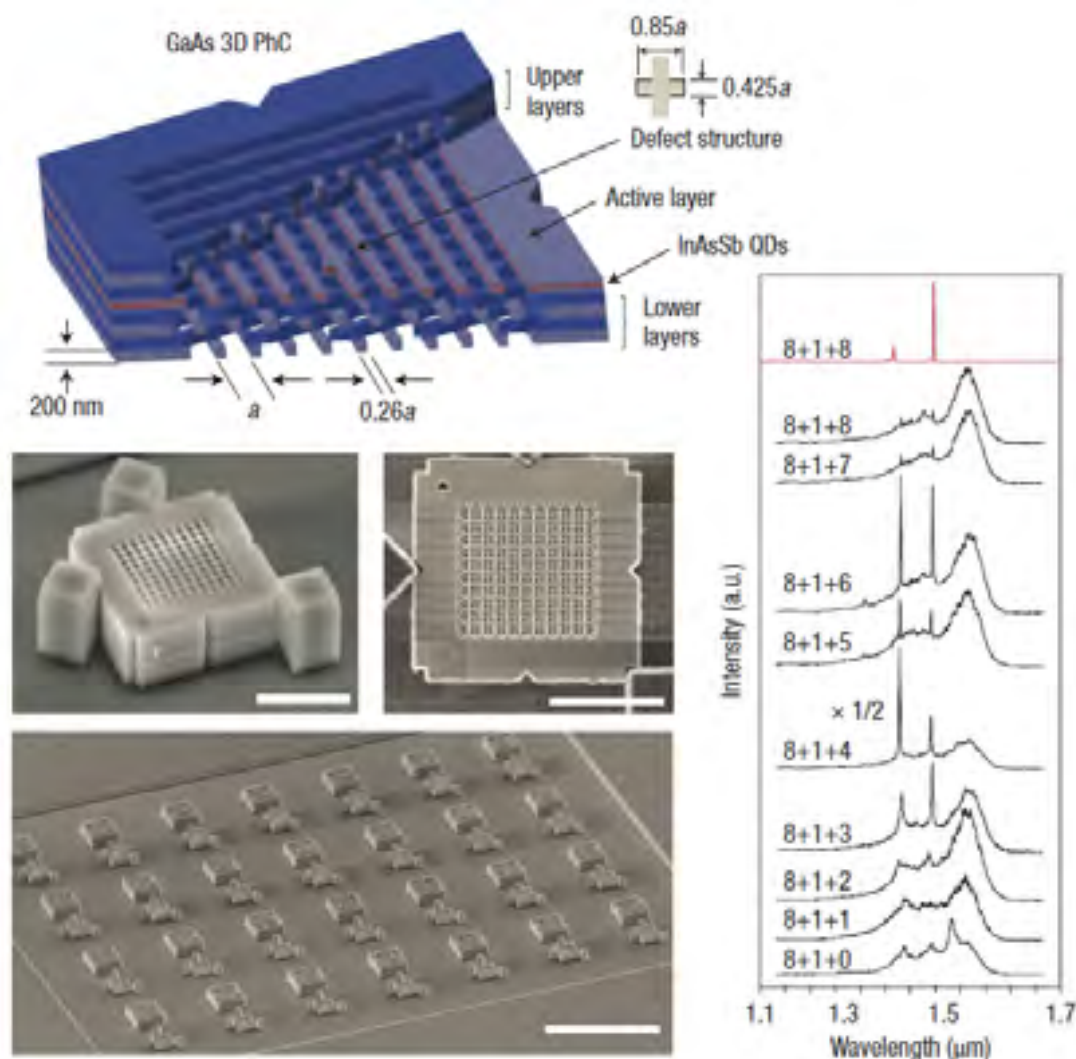
Ring shape FFP applicable to photon twister and tight focusing over the diffraction limit



Fabrication of 3D Photonic Crystals

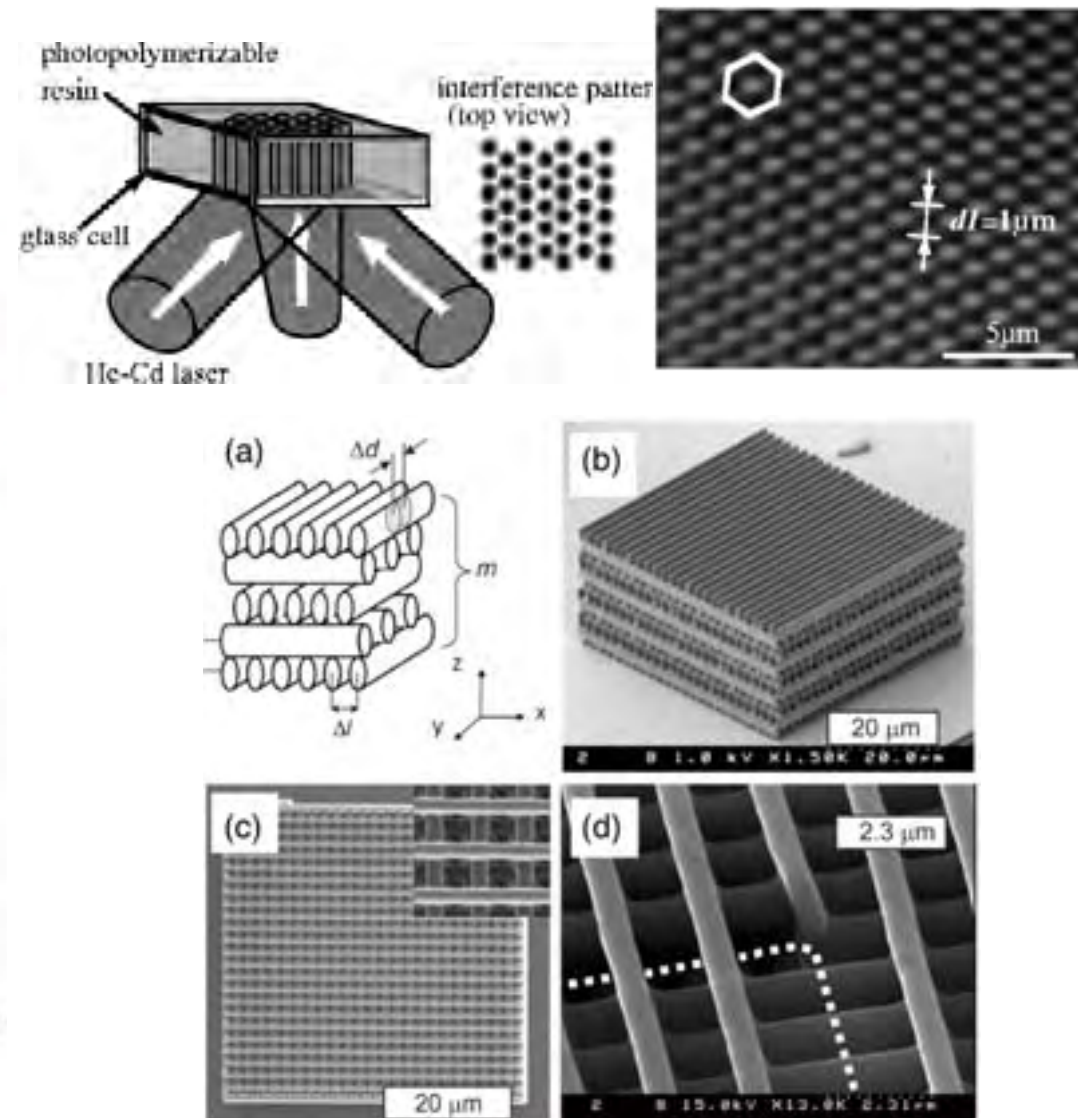
Top Down Approach (Micromanipulation)

(Aoki et al. *Nat. Mat.* **2**, 117 (2003); *Nat. Photon.* **2**, 688 (2008))



Bottom Up Approach (Lithographic Tech.)

(Shoji et al. *APL* **76**, 2668 (2000); Mizeikiz et al. *OL* **29**, 2061 (2004))

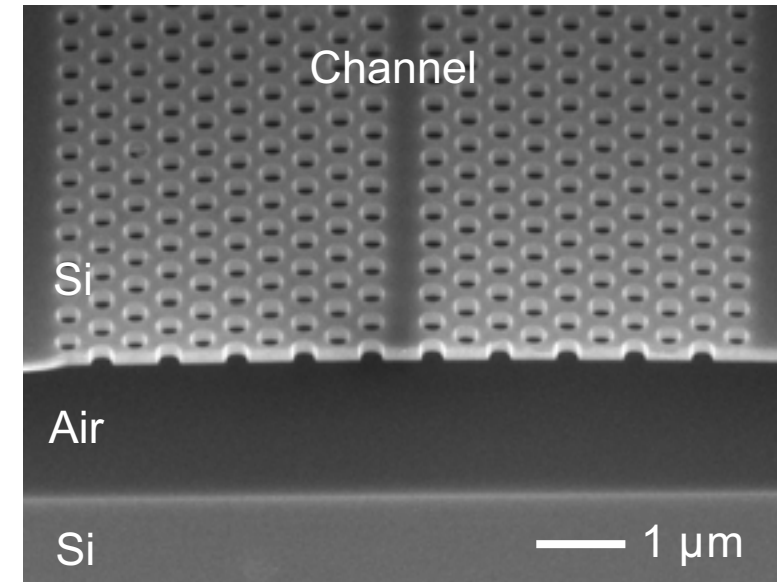


Slow light in photonic crystals

T. Baba, *Nature Photonics* **2**, 465 (2008)

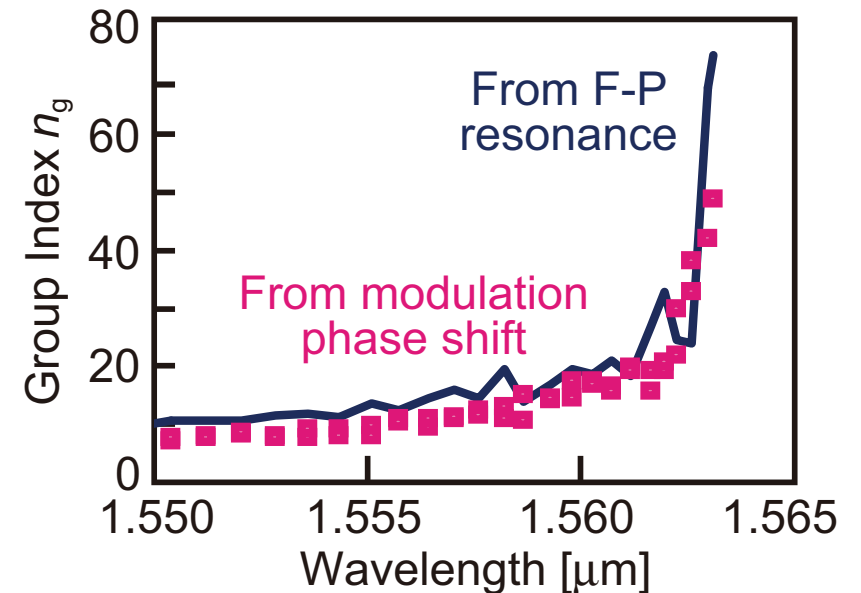
PC Line Defect Waveguide

(after Baba et al., *EL* **35**, 654 (1999))



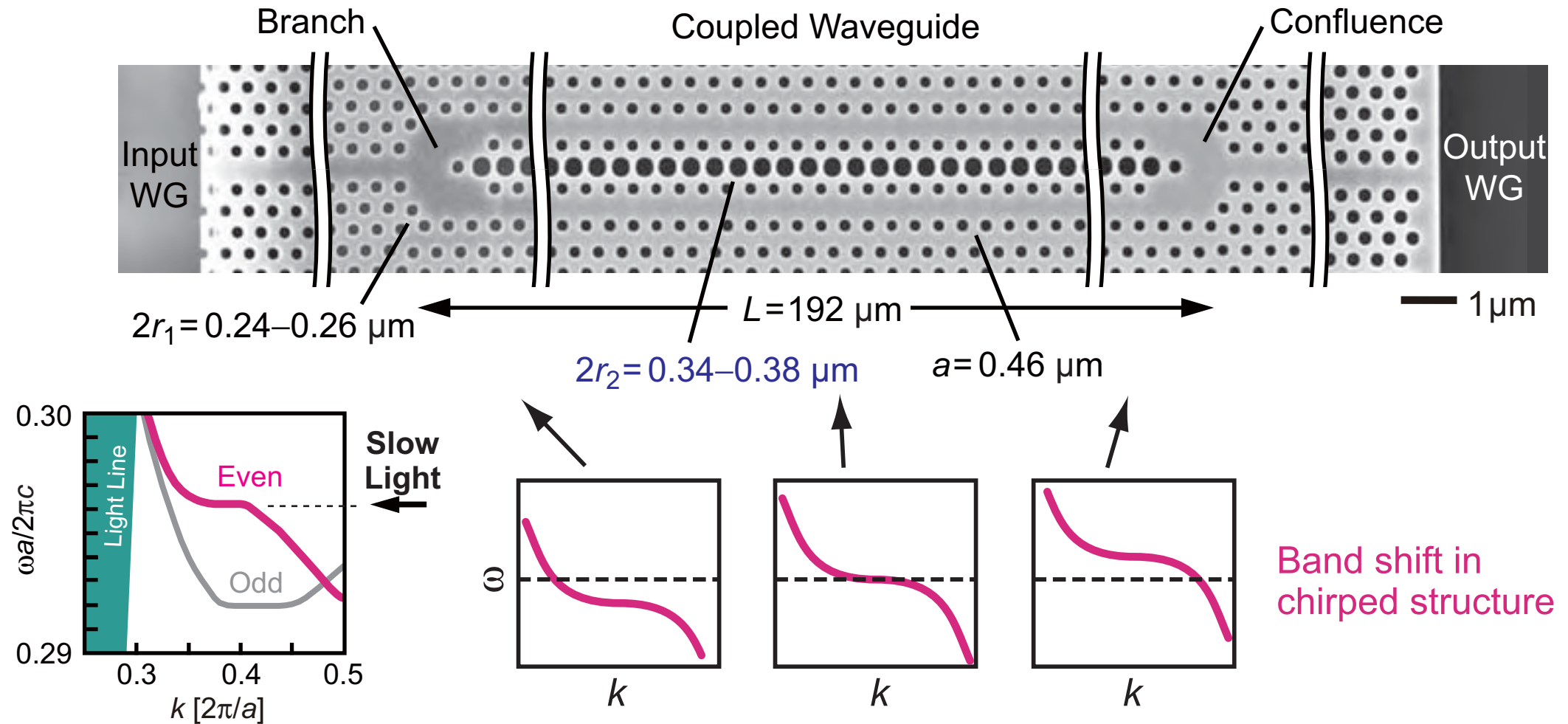
Observation of slow light

(after Notomi et al., *PRL* **87**, 253902 (2001))



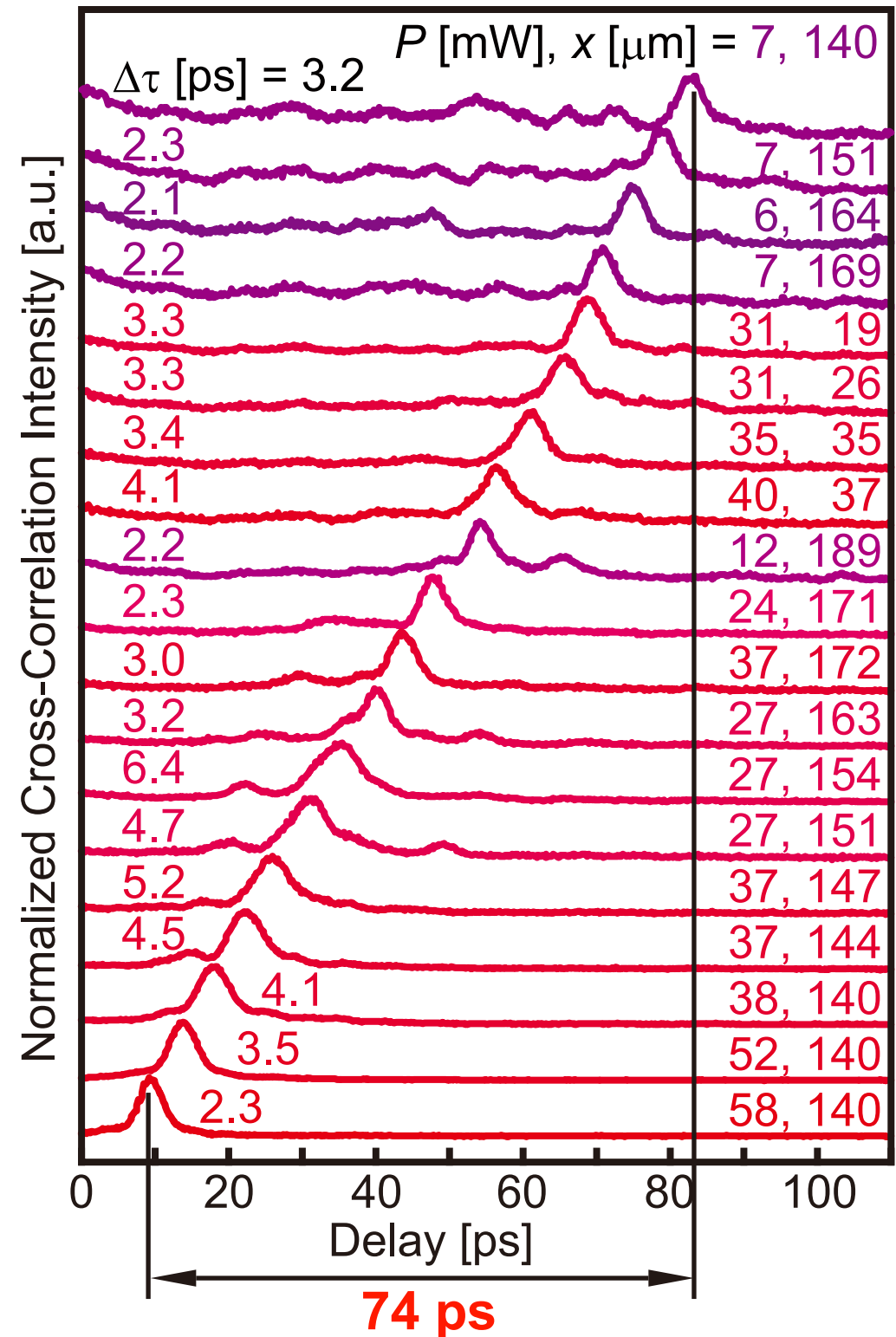
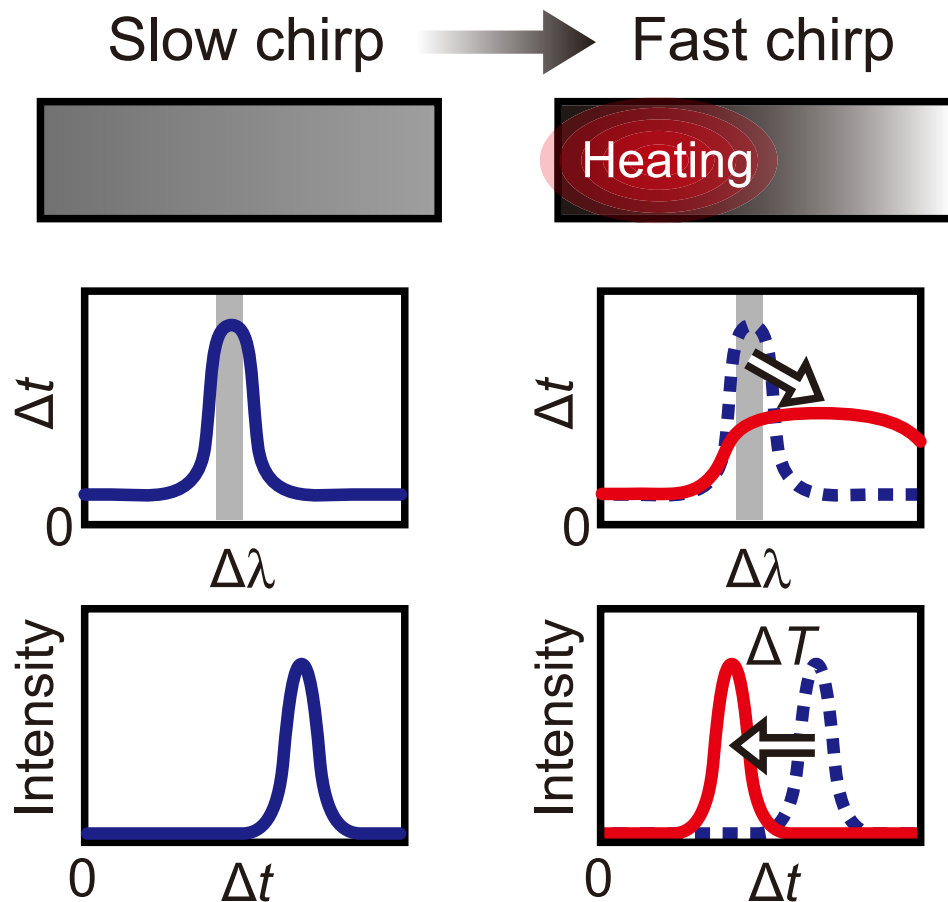
Photonic Crystal Coupled Waveguides (PCCW)

(Mori et al. *OE* **13**, 9398 (2005); Kawasaki et al. *OE* **15**, 10274 (2007))



Tunable Delay in Slow Light Pulse

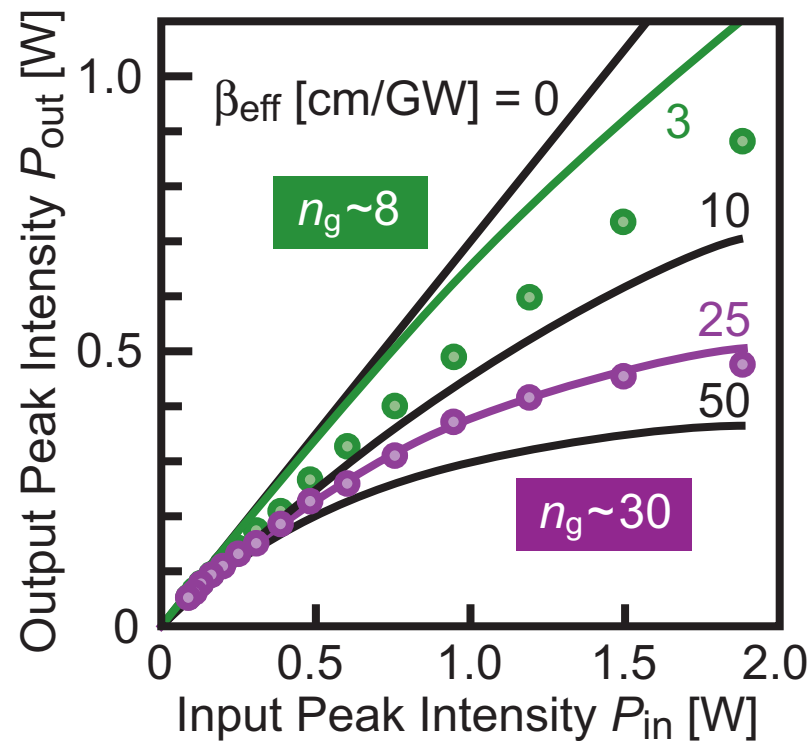
(Baba et al., *OE* **16**, 9245 (2008);
 Baba et al., *Nature Photon.* **2**, 465 (2008);
 Adachi et al., *OSA SL, SWA1* (2009))



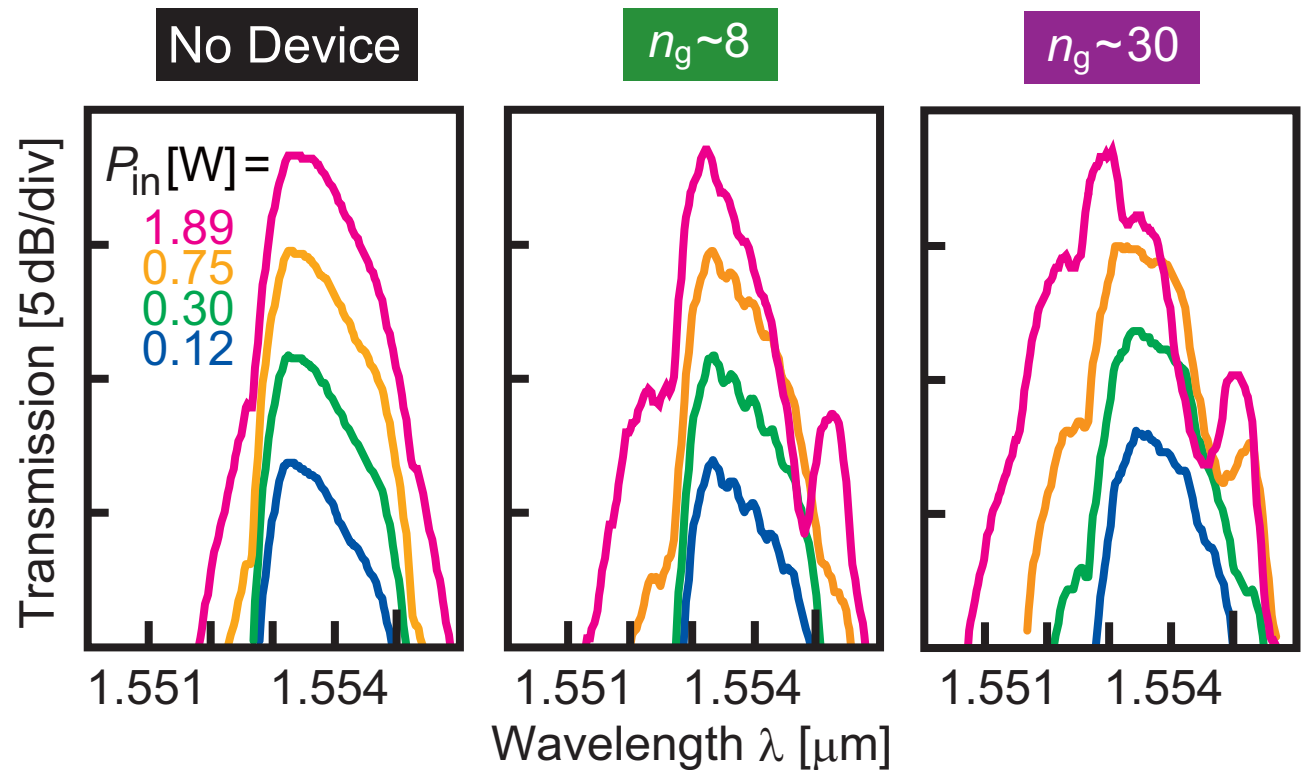
Optical Nonlinearity in LVLD Pulse

(Hamachi, Kubo, Baba, *OL* **34**, 1072 (2009))

Two Photon Absorption



Self Phase Modulation

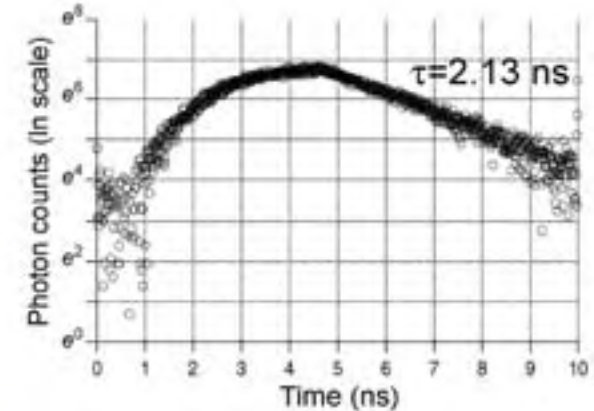
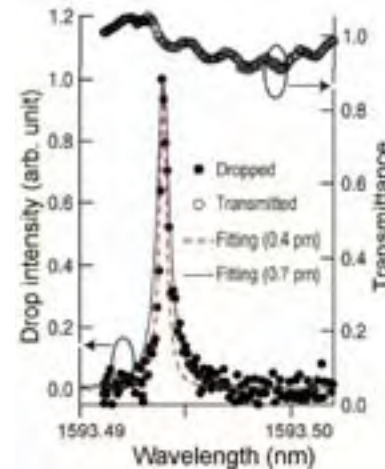
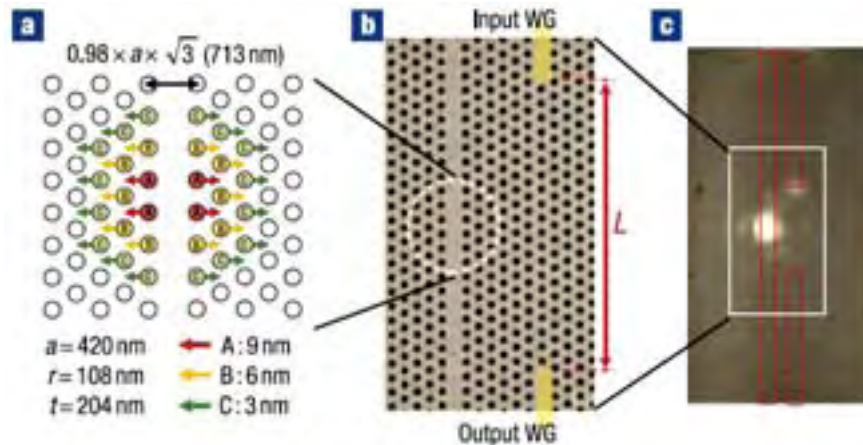


Nonlinearity is enhanced by SL pulse in LVLD waveguide (350 μm length)
TPA scales with n_g^2 and >40-fold higher than Si photonic wire waveguide

PC Nanocavity-Waveguide Coupled System

Ultrahigh-Q Nanocavity

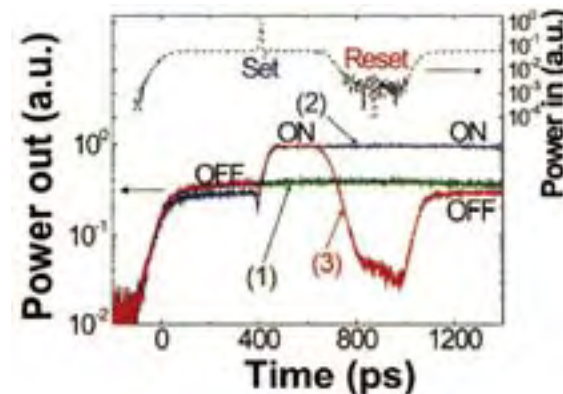
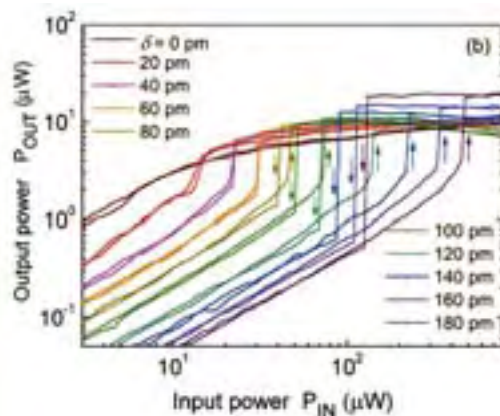
(Tanabe et al. *Nat. Photon.* **1**, 49 (2007); Takahashi et al. *OE* **15**, 17206 (2007))



Q factor up to 3,000,000 and photon storage of 2 ns

Nonlinear bistable switching

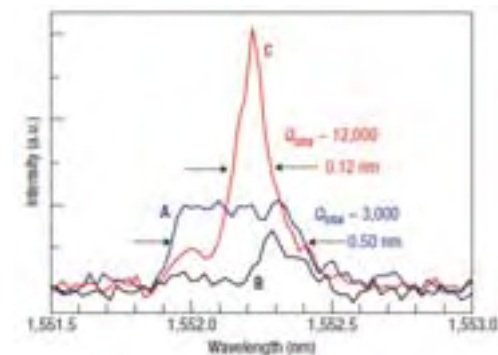
(Notomi et al. *OE* **13**, 2678 (2005); *OL* **30**, 2575 (2005))



Carrier-induced bistability, $\tau = 100$ ps, $W_{th} = 10$ fJ

Dynamic Tuning

(Tanaka et al. *Nat. Mat.* **6**, 862 (2007))



Stopping optical pulse observed

CHEMISTRY TODAY



Negative Refraction in Photonic Crystals

MRS
BULLETIN

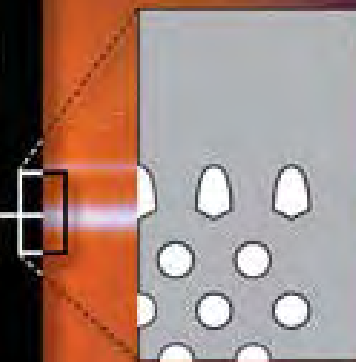
October 2008, Volume 33, No. 10

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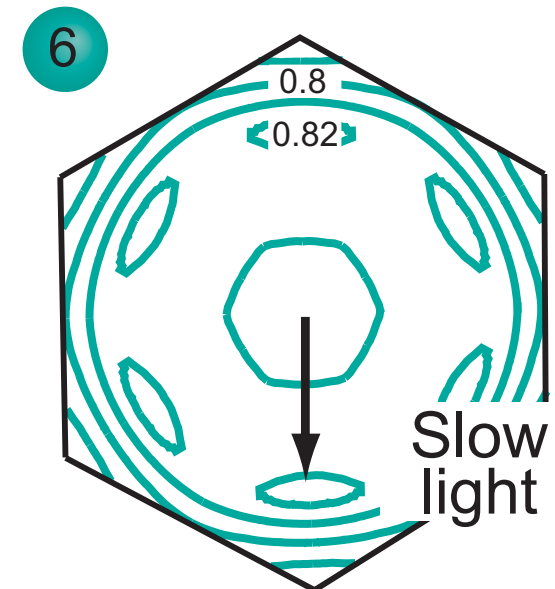
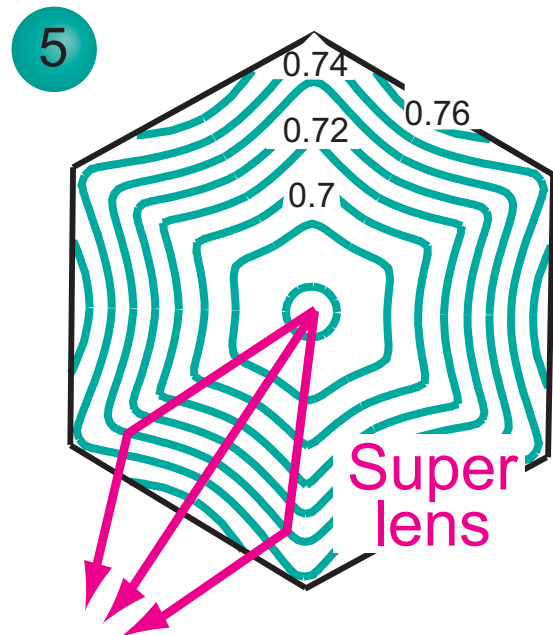
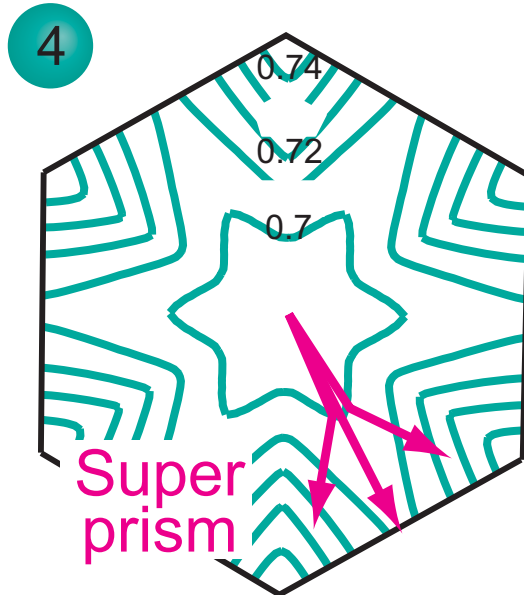
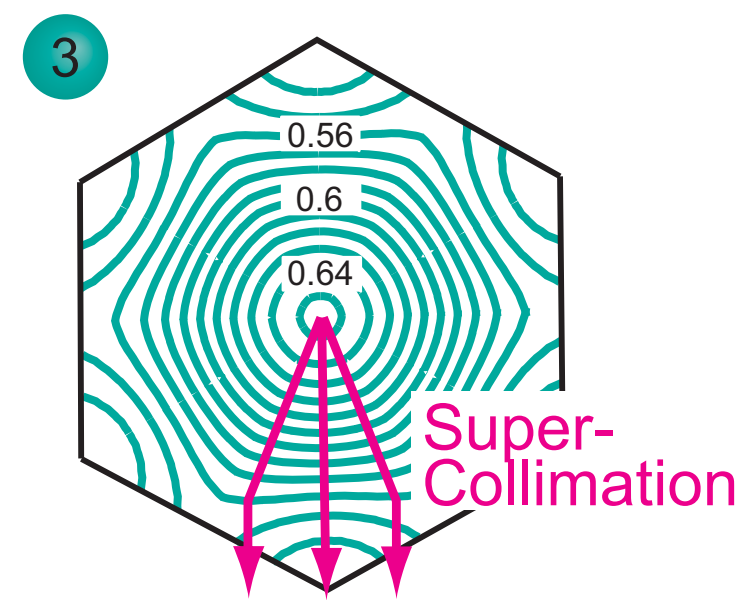
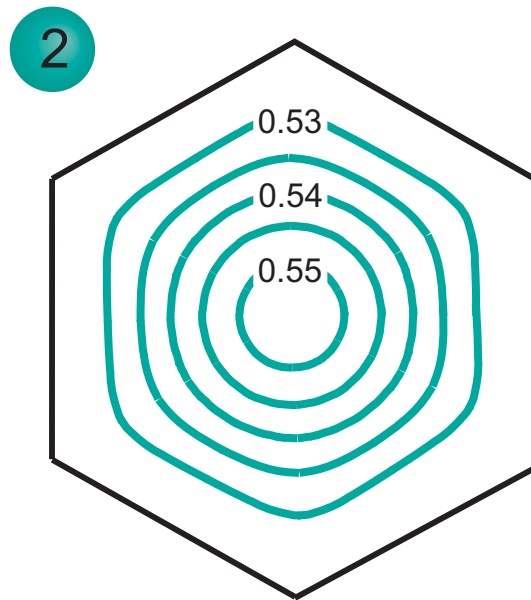
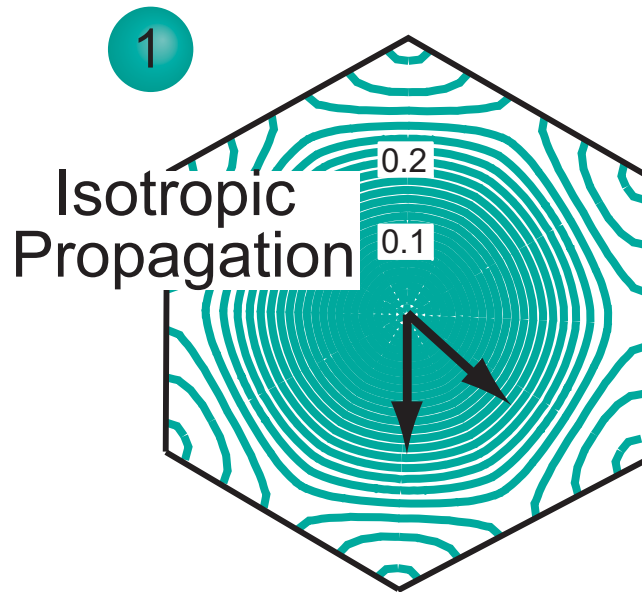


**Negative-Index
Materials**

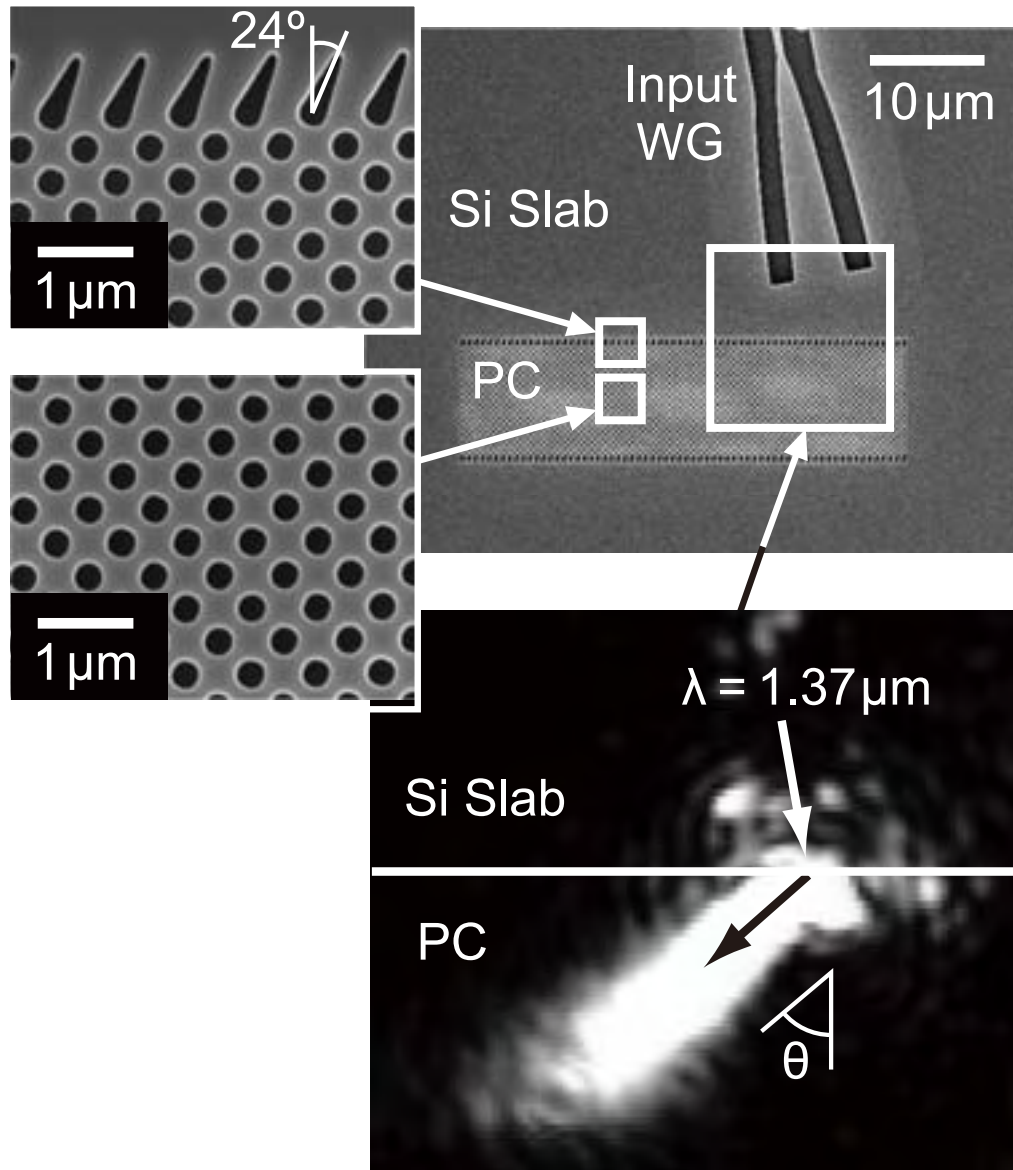


Functions Predicted from Dispersion Surfaces

(after Kosaka et al., *PRB* **58**, 10096 (1998))

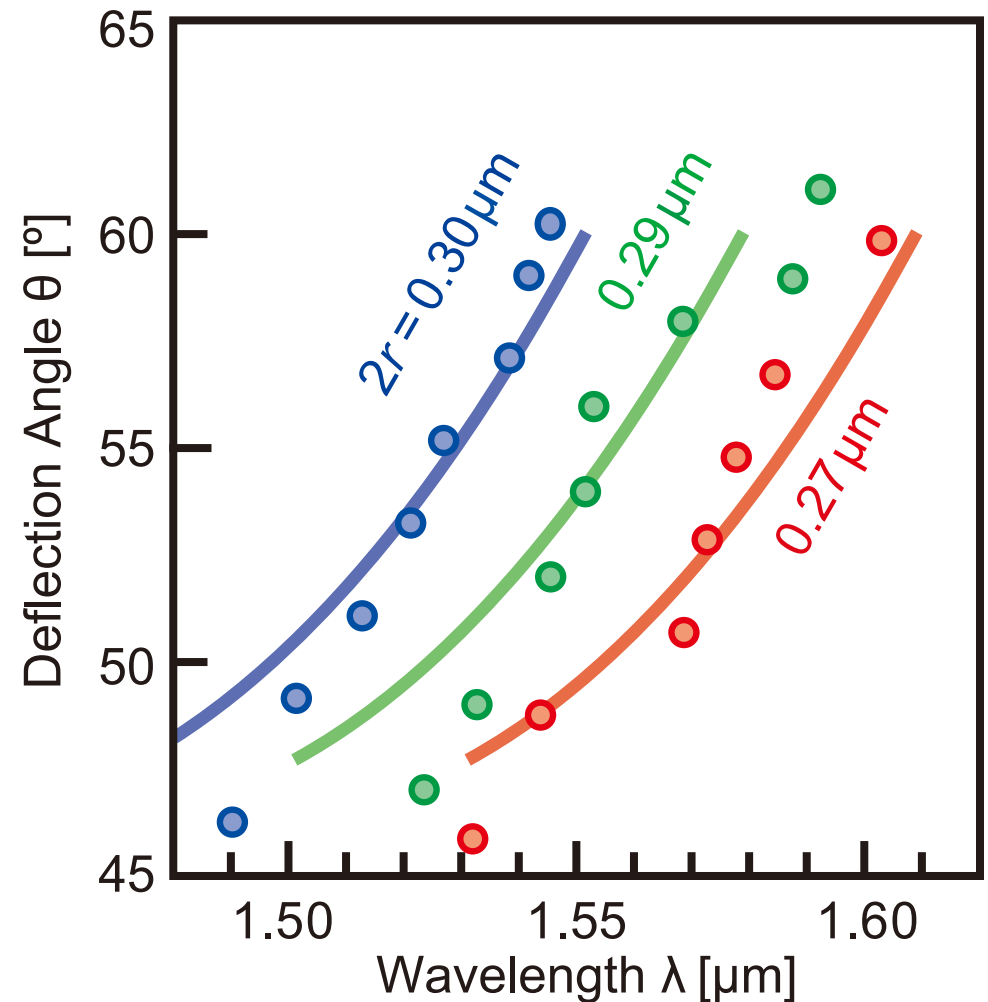


Observation of Negative Refraction



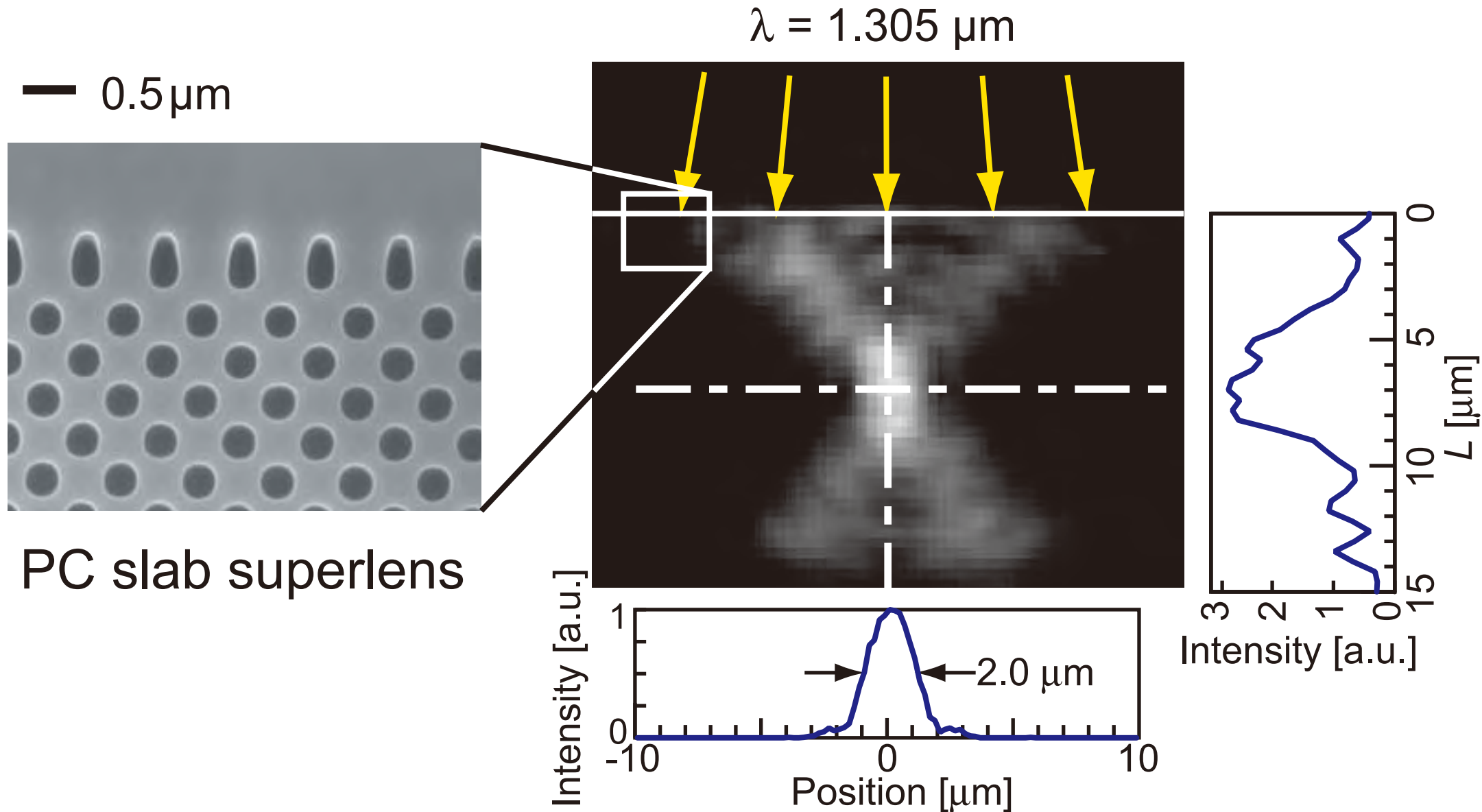
(Matsumoto et al., *APL* **91**, 091117 (2007))

Plot: Experiment, Line: FDTD



Light Focusing in PC Superlens

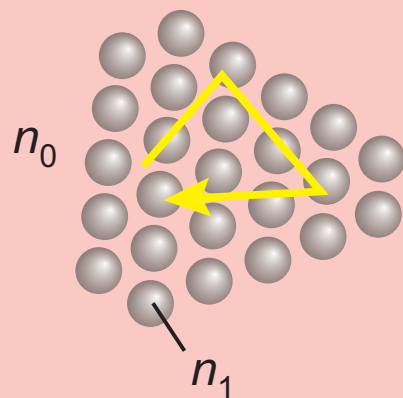
(Matsumoto, et al. *OL* 31, 2776 (2006))



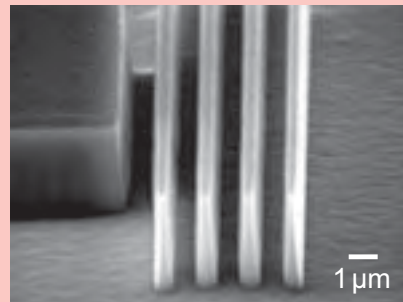
Photonic Nanostructures

Photonic Crystals: PC

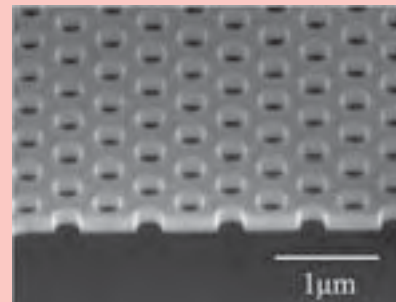
Bragg reflection
Bragg scattering



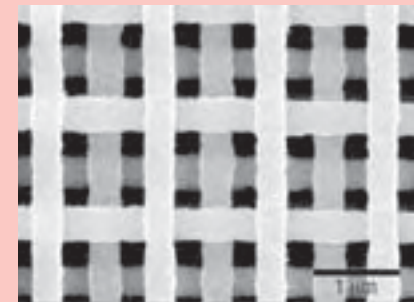
1D



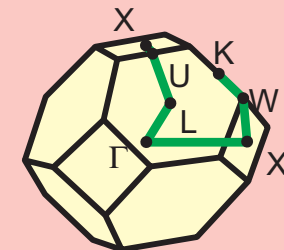
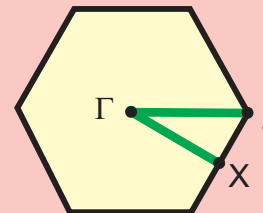
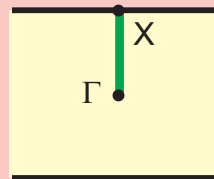
2D



3D

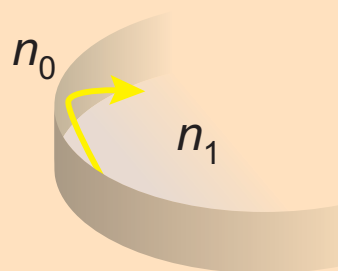


Brillouin zone

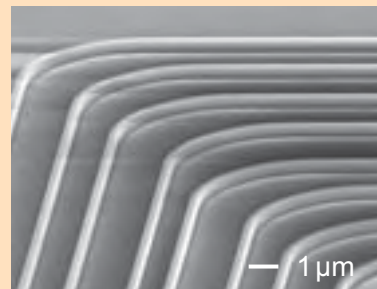


High Index Contrast Structure: HIC

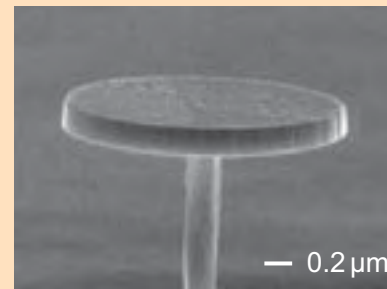
Total reflection



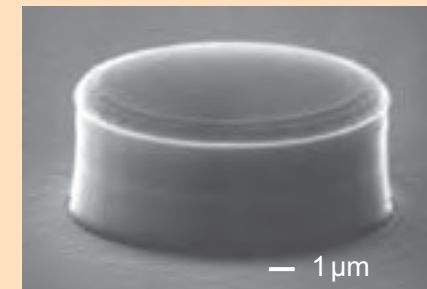
Wire



Disk



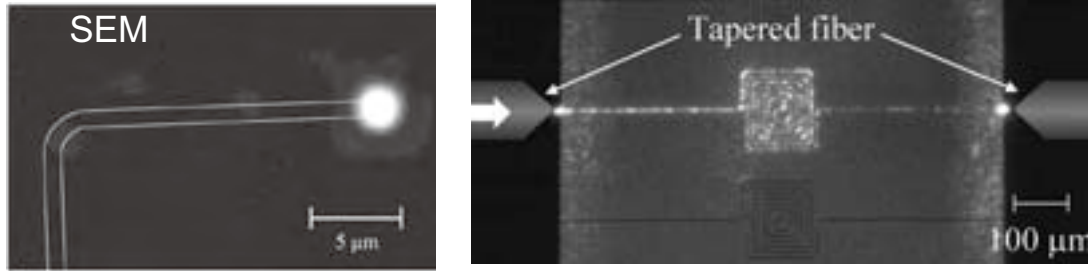
Mesa



Photonic Wire Waveguide Elements

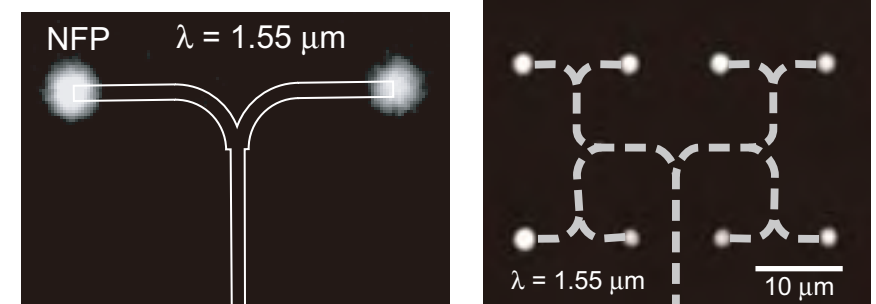
Bend

(Sakai et al. JJAP 40, L383 (2001)) (Yamada et al. IEEE JSTQE 12, 1371 (2006))



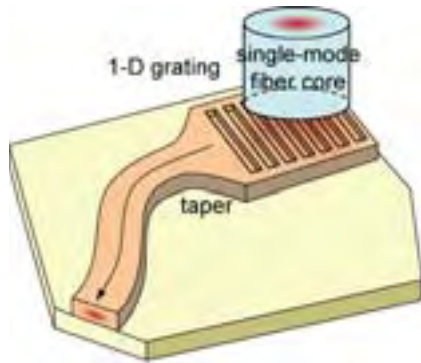
Y Branch and H-Tree

(Sakai et al. IEICE Trans.E85-C, 1033 (2002); JJAP 41, L1461 (2002))



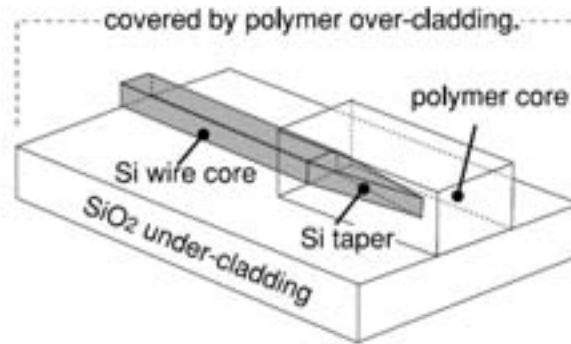
Grating Coupler

(Bogaerts et al. OE 12, 1583 (2004))



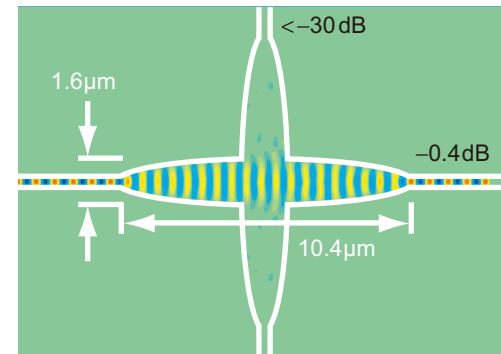
Spot Size Converter

(Tsuchizawa et al. EL 38, 1669 (2002))



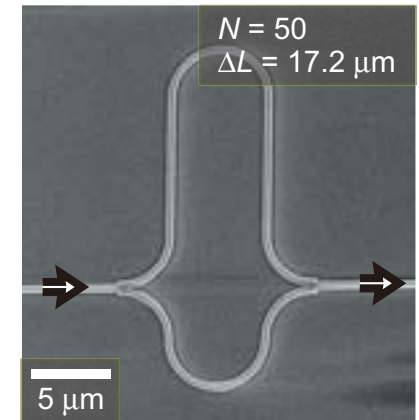
Intersection

(Fukazawa et al. JJAP 43, 646 (2004))



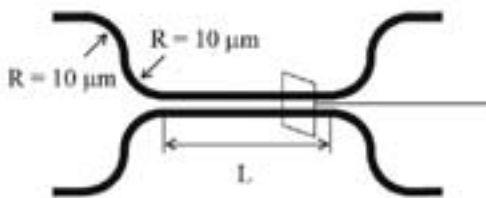
MZ Interferometer

(Ohno et al., JJAP 44, 5322 (2005))



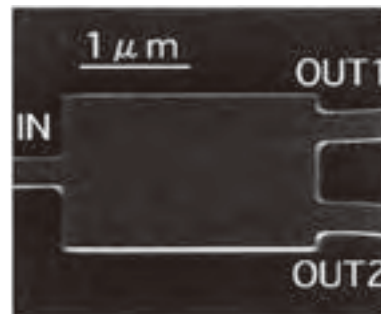
Directional Coupler

(Yamada et al., IEEE PTL 18, 585 (2005))



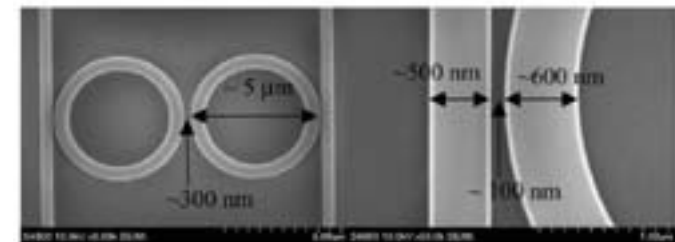
MMI Coupler

(Yamada et al. IEICE Trans.E87-C, 351 (2004))



Microring

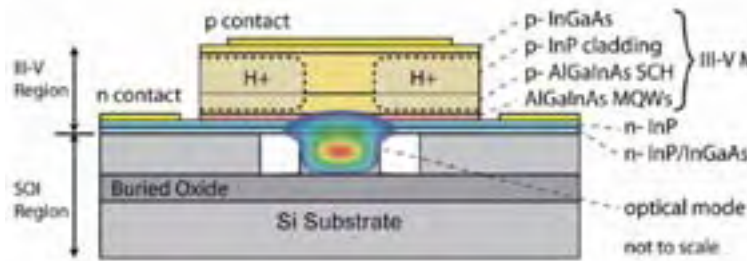
(Xiao et al., JLT 26, 228 (2008))



Si Photonics Functional Devices

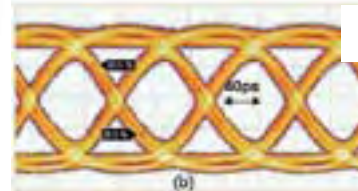
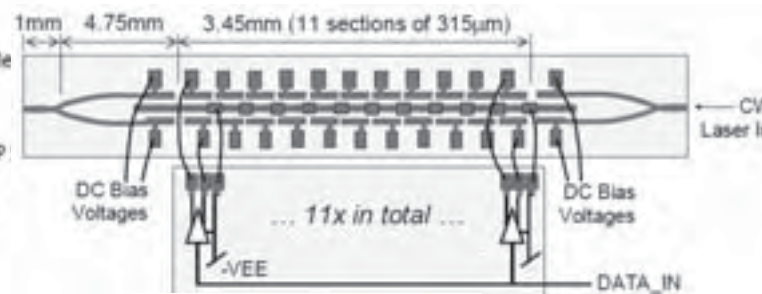
III-V Hybrid Laser

(Fang et al., OE 14, 9203 (2006))



Modulator

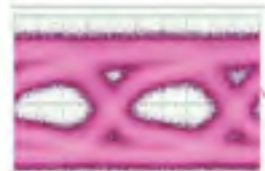
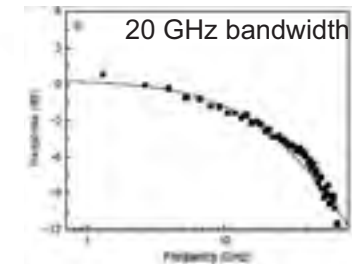
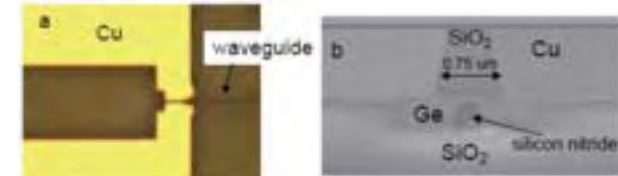
(Liao et al., OE 13, 3129 (2005))



10 Gbps
Eye Pattern

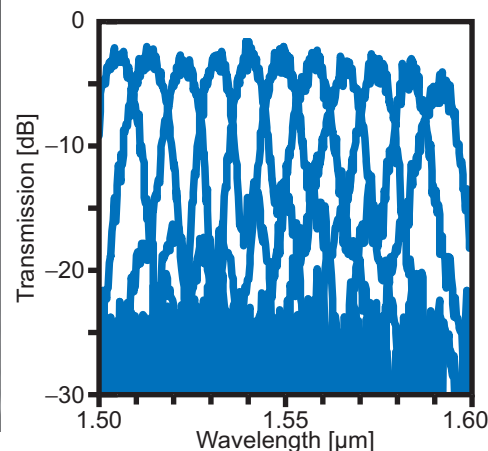
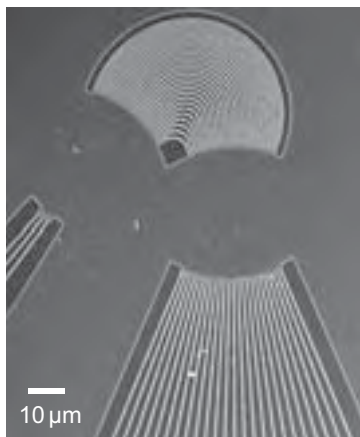
Epitaxial Ge Detector

(Liu et al. APL 87, 011110 (2005))



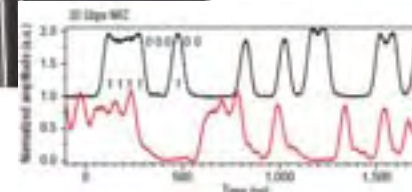
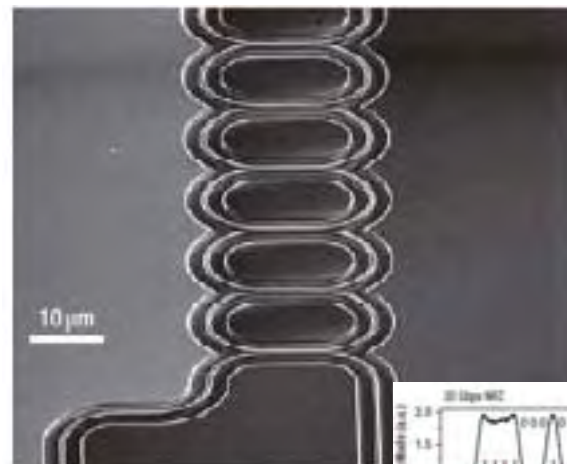
MUX/DEMUX (AWG)

(Fukazawa et al., JJAP 43, L673 (2004); JJAP 45, 6126 (2006))



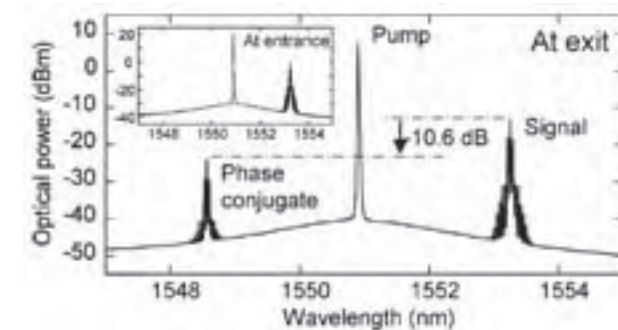
Delay Line and Optical Buffer

(Xia et al., Nature Photon. 1, 65 (2007))



Nonlinear Elements (FWM, Raman, TPA, SPM...)

(Yamada et al., IEEE PTL 18, 1046 (2006))



Open Foundry Now Available

	NTT-ATN (Japan)	Silicon Photonics MPW Prototyping/IME (Singapore)	ePIXfab / IMEC (Bergium)
started from	Sept. '08	May '08	Sept. '08 (pre. '06-)
lithography	e-beam 100 kV	photo. 248 nm	photo. 193 nm
WG width	> 80 nm	> 170 nm	> 120 nm
fiber coupling	facet with SSC (< 2.5 dB/facet)	facet with SSC (< 2.5 dB/facet)	facet with SSC, grating coupler (< 5.2 dB/facet)
lithography	?	available	available

JSPS Center of Si Photonics Prog.

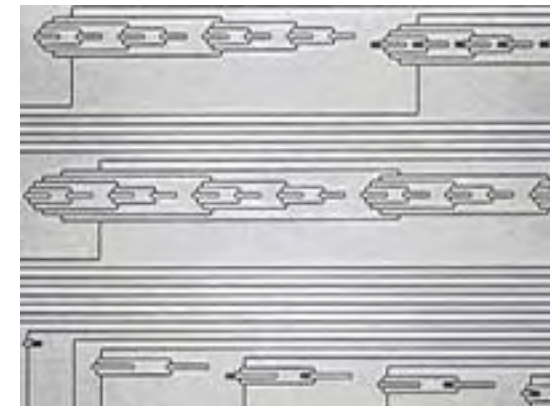
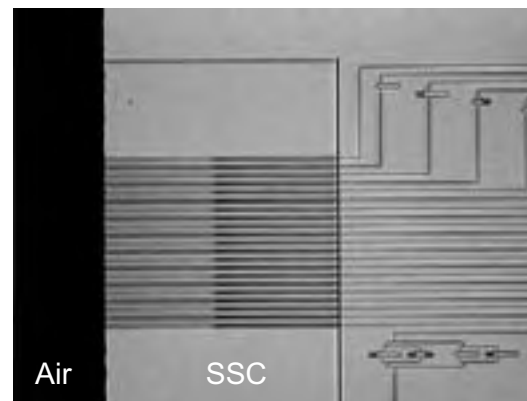
Japan: U.Tokyo, Yokohama U., etc.

USA: MIT, Rochester, etc.

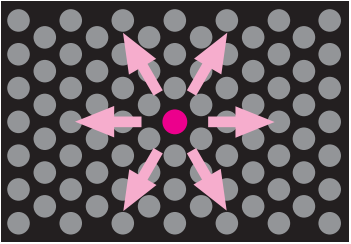
Europe: IMEC etc.

Test shuttle run by NTT-ATN

8000 USD / 2 chips, 6 dB loss inc. lens coupling

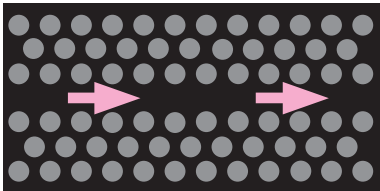


Topics



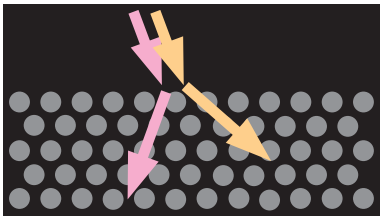
PC Nanolaser

Ultralow threshold RT CW lasing and Purcell effect
A/P integration for photonic integrated chip
High resolution sensing available



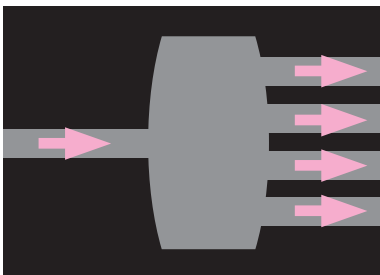
PC Slowlight waveguide

Wideband dispersion-free slow light pulse available
Tunable delay available by TO effect
Dynamic control expected for more delay



PC Negative refractive optics

Focusing, image formation, beam steering, collimating
Compensation of aberration possible



HIC Silicon photonics device

μ -components based on Si photonic wire waveguide
Functional devices, applications to opt. interconnects
Foundry service now available