

Photonic Crystal Devices

光子晶體元件

Chii-Chang Chen (陳啟昌)

Professor

Department of Optics and Photonics

National Central University

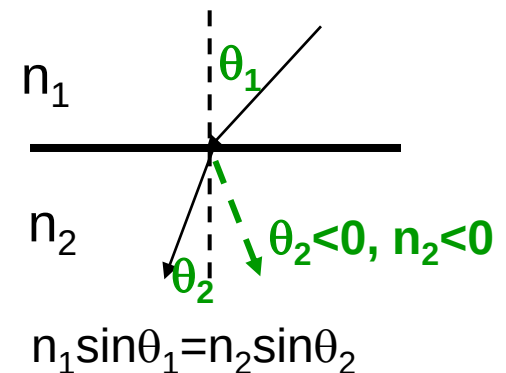
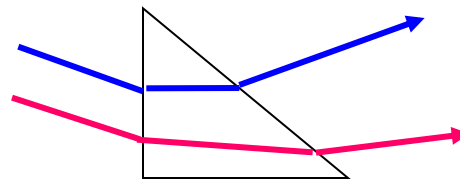
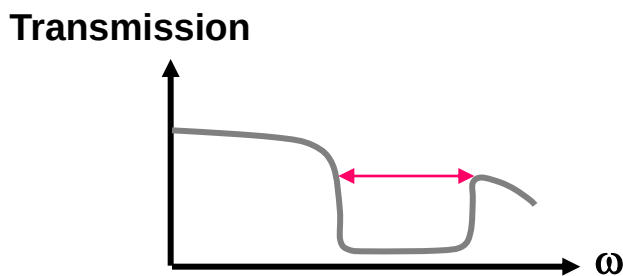
Taiwan

trich@dop.ncu.edu.tw

光子晶體(photonic crystals, PC)

空間中不同介電材料(折射指數)週期性分佈
所建構的結構

具有光子能隙 與 異常的色散與折射特性

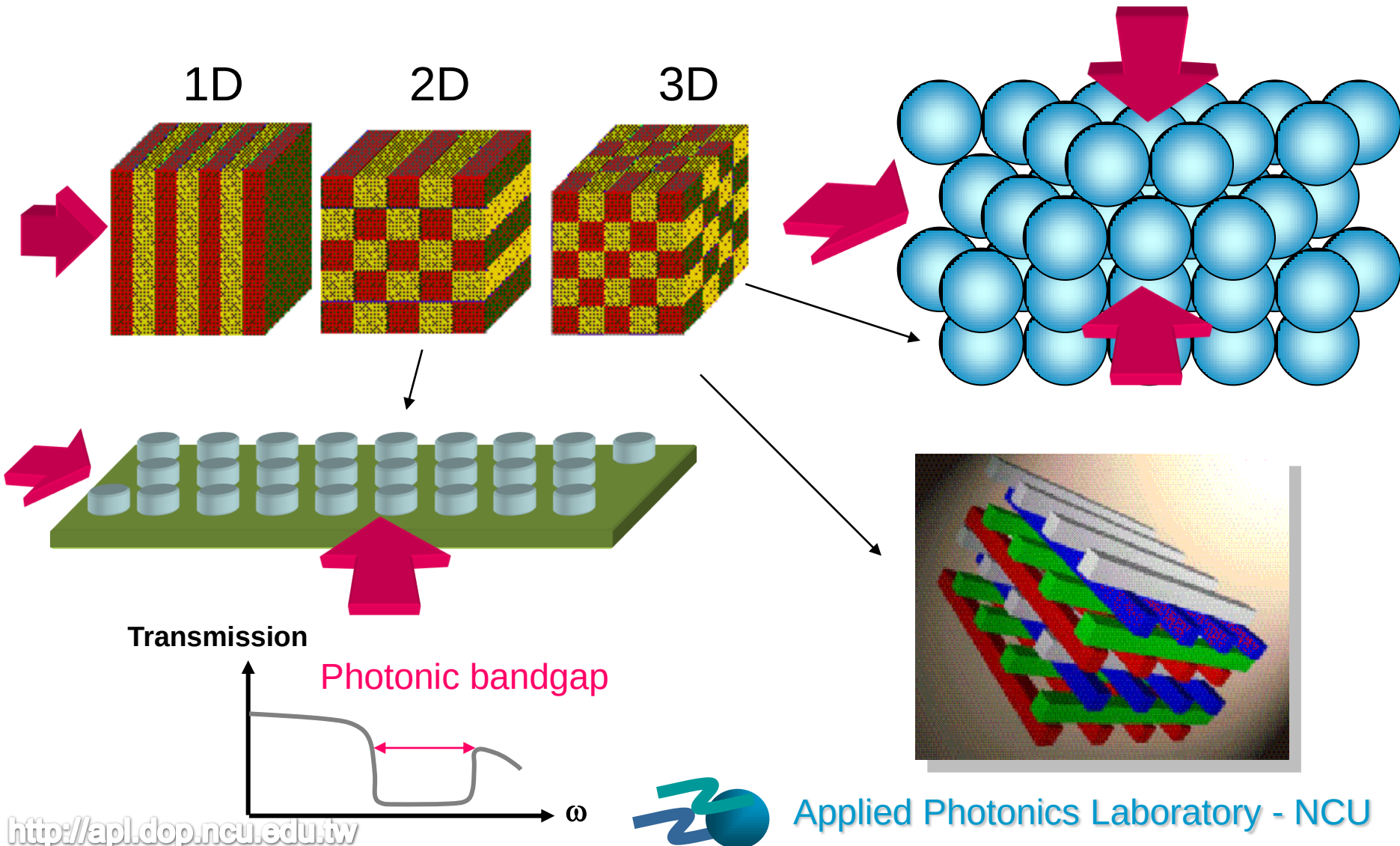


聲子晶體(Phononic crystals)

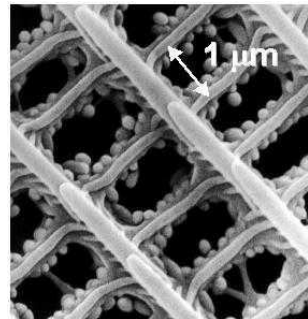
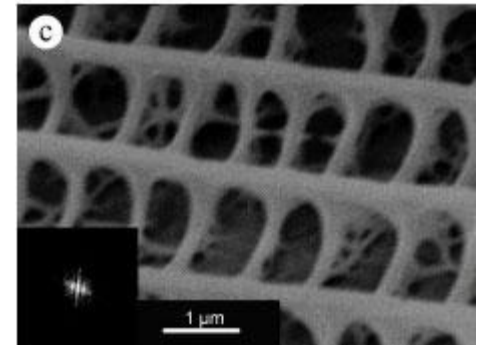
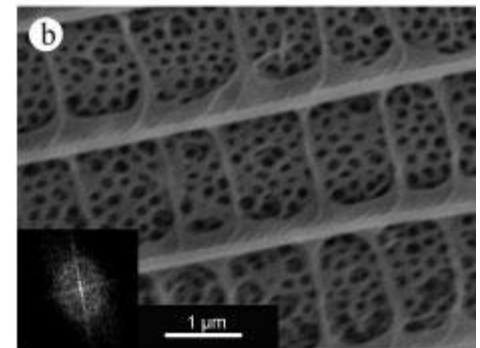
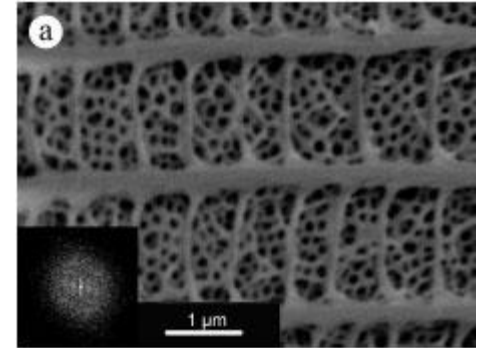
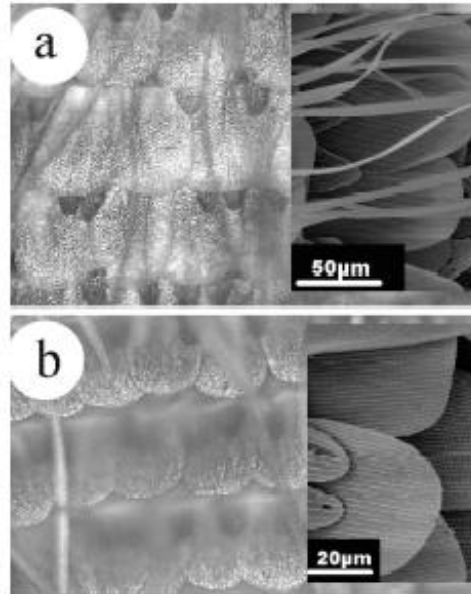
空間中不同密度及波速之週期性分佈所建
構的結構

具有聲子能隙 與 異常的色散與折射特性

1D, 2D and 3D photonic crystals



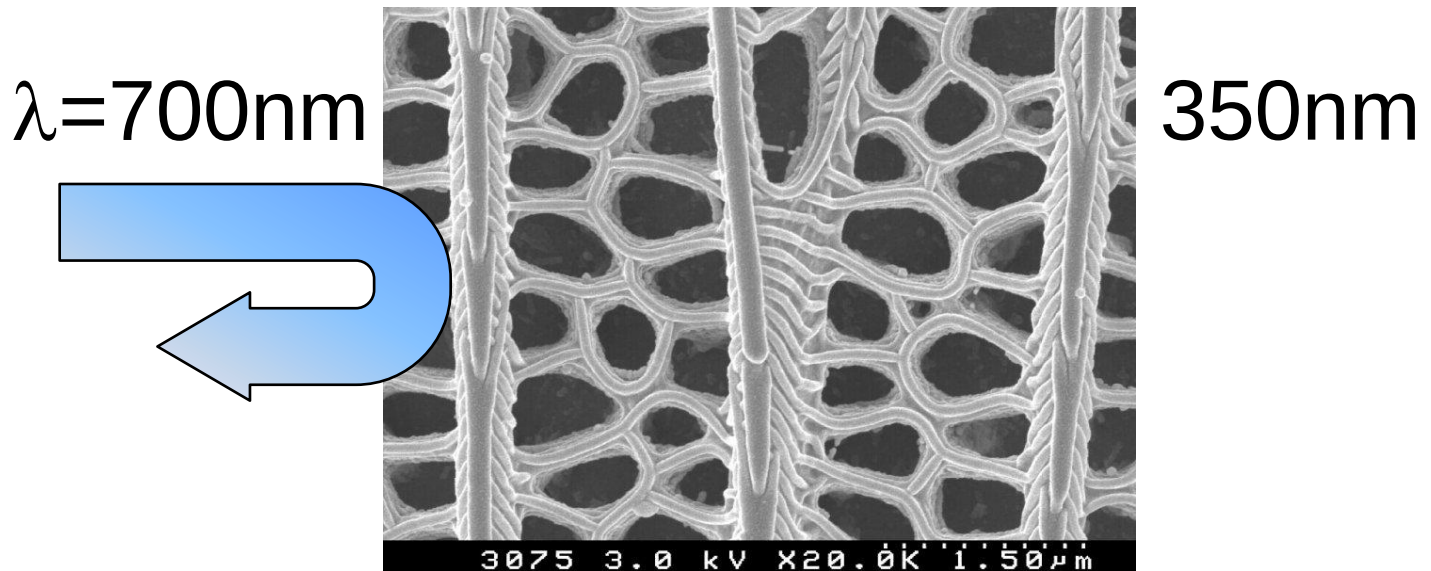
Butterfly crystals



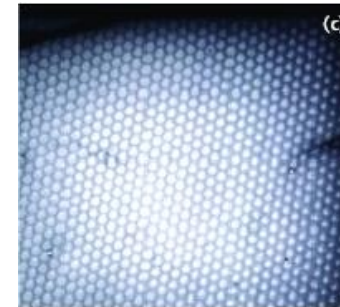
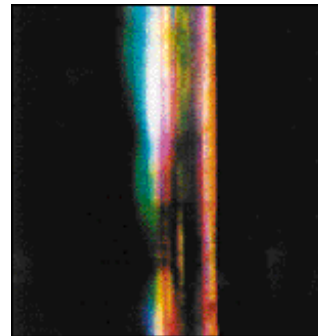
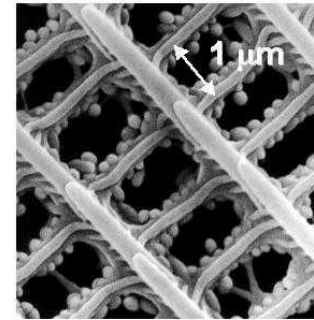
L. P. Biro, Zs. Balint, K. Kertesz, Z. Vertesy, I. Mark, Z. E. Horvath, J. Balazs, D. Mehn, I. Kiricsi, V. Lousse, J.-P. Vigneron, Phys Rev E.67.021907,2003

Wavelength & size

- Wavelength/2 $\approx$ Size



Natural photonic crystals



Famous People



Eli Yablonovitch

UCLA

(Bell Communication Research)

**Enhancement of spontaneous
emission**



Sajeev John

University of Toronto

(Princeton University)

Localization of light

Hot topics

- Slow light
- Stop light
- Superprism
- Metamaterials (Negative refraction, invisible cloak)

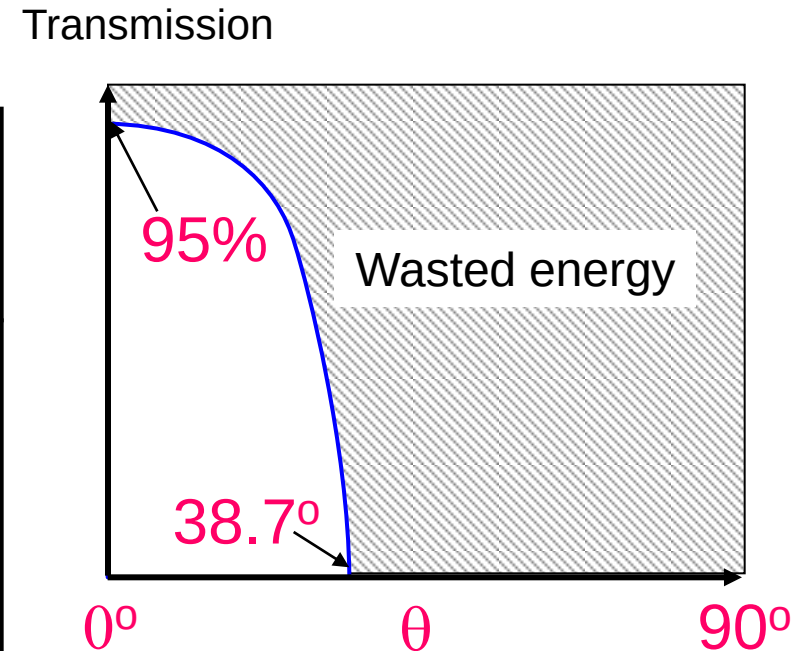
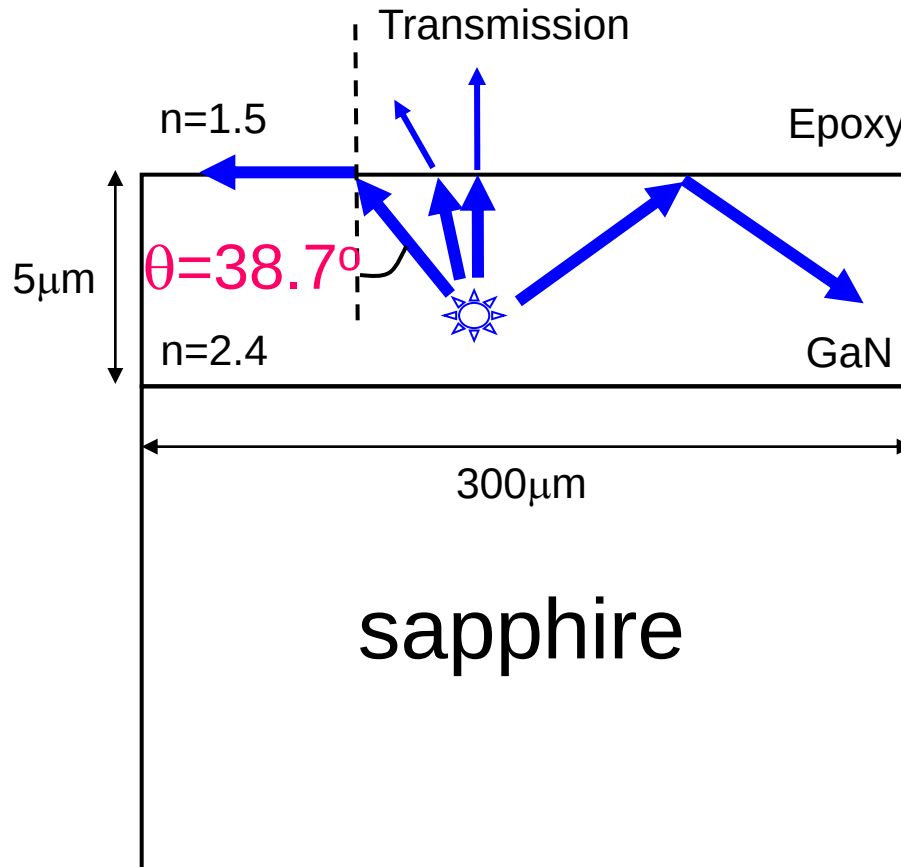
Main PC applications

- PC LED
- PC solar cell
- PC laser
- PC fiber
- Waveguides (All-optical integrated circuits)

Photonic crystal LED

- Extraction efficiency (surface roughness)
- Polarized light (backlight of LCD display)
- Directional emission

Fresnel reflection at GaN/Epoxy interface



Enhanced light extraction from GaN-based light-emitting diodes with holographically generated two-dimensional photonic crystal patterns

Dong-Ho Kim, Chi-O Cho, Yeong-Geun Roh, Heonsu Jeon,^{a)} and Yoon Soo Park
*School of Physics and Inter-university Semiconductor Research Center, Seoul National University,
 Seoul 151-747, Korea*

Jaehee Cho, Jin Seo Im, Cheolsoo Sone, and Yongjo Park
Photonics Program Team, Samsung Advanced Institute of Technology, P.O. Box 111, Suwon 440-600, Korea

Won Jun Choi and Q-Han Park
Department of Physics, Korea University, Seoul 136-701, Korea

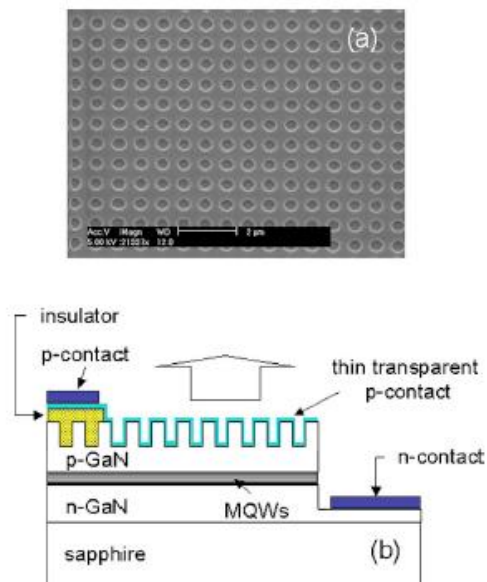


FIG. 1. (Color online) (a) Scanning electron microscope image for a PC-LED device surface. The square-lattice air-hole array pattern was generated by the holographic double-exposure method. The lattice period of this specific example is $\Lambda \sim 700$ nm. (b) Schematic view of the PC-LED, illustrating the vertical layer structure of the device.

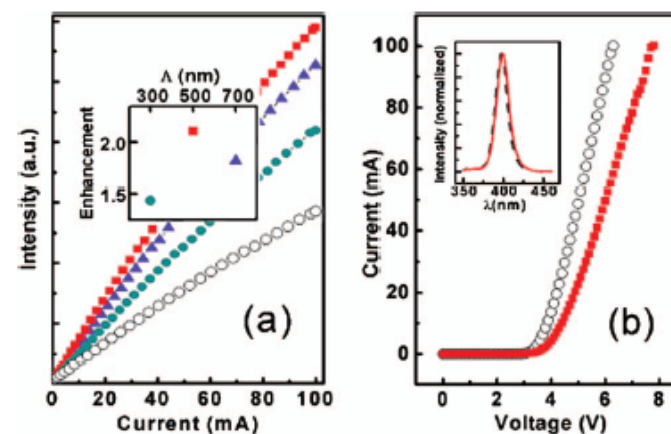
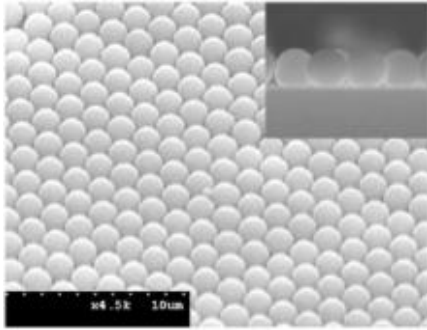


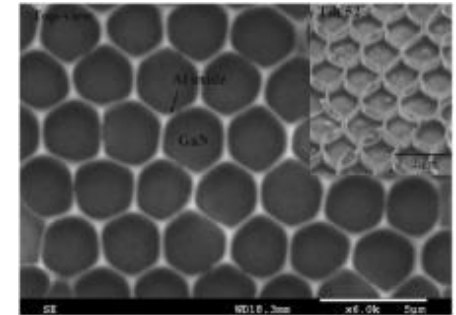
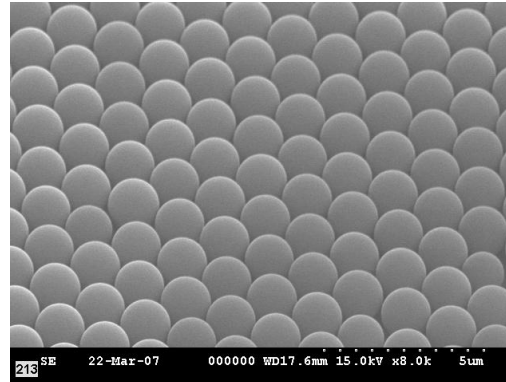
FIG. 2. (Color) (a) Light output vs injection current characteristics (L-I) for PC-LED chips with lattice constants of 300 nm (●), 500 nm (■), and 700 nm (▲), together with that from a planar reference device (○) for comparison. Shown in the inset is the electroluminescence enhancement factor of the PC-LEDs relative to the reference LED. (b) I-V characteristics for the $\Lambda=500$ nm PC-LED (■) and the reference (○). The inset displays emission spectra for the PC-LED (—) and the reference (---), with their peak intensities normalized for direct comparison of the spectral shapes.

Applications of microspheres



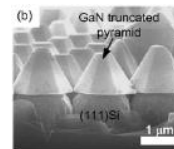
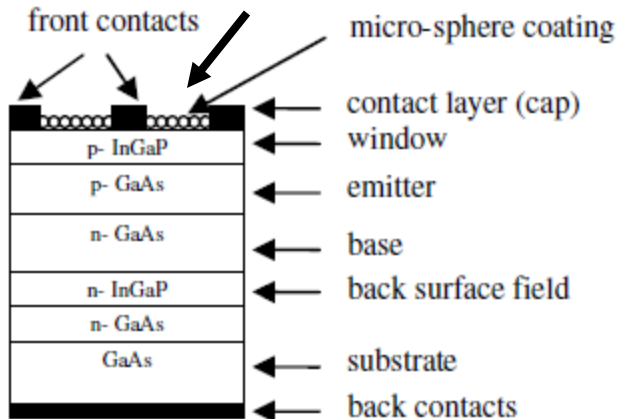
Surface patterning

Opt. Express. vol. 17, p. 6519, 2009



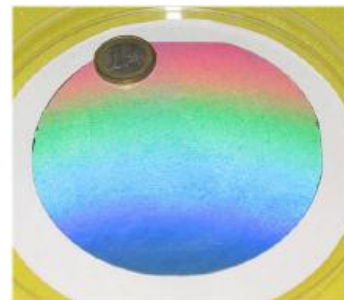
Surface patterning

Appl. Phys. Lett. 90, 242106, 2007



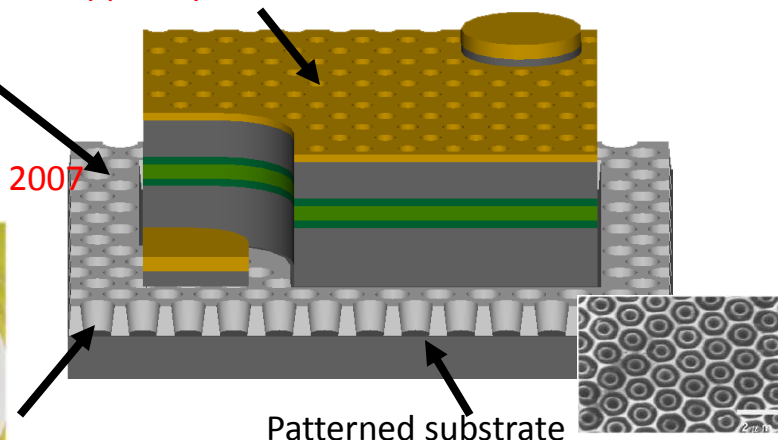
Patterned buffer layer

Appl. Phys. Lett. 91, 261910, 2007



Nano-patterned substrate

Appl. Phys. Lett. 95, 011110, 2009

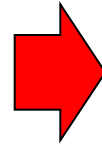
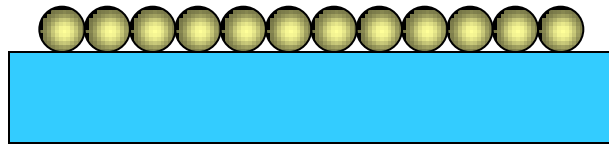


Patterned substrate

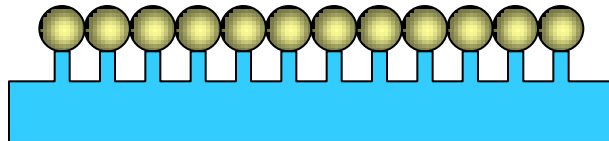
Jpn. J. Appl. Phys. 48, 020212, 2009

Applications of monolayer microspheres

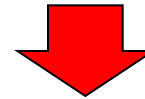
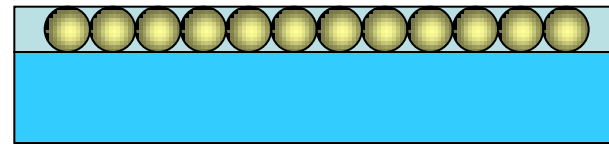
Deposition



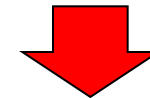
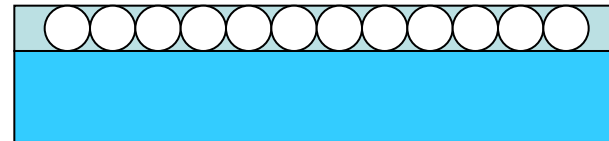
Etching



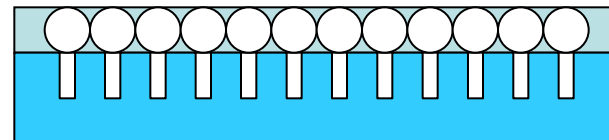
Infilling with dielectric materials
or metals or magnetic materials



Burning

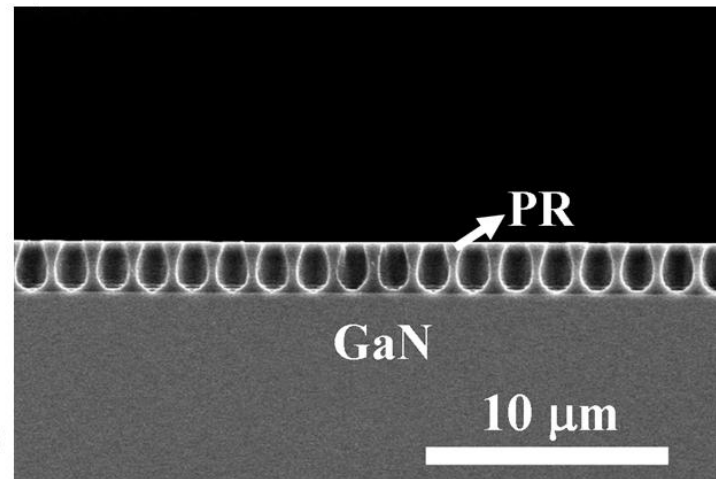
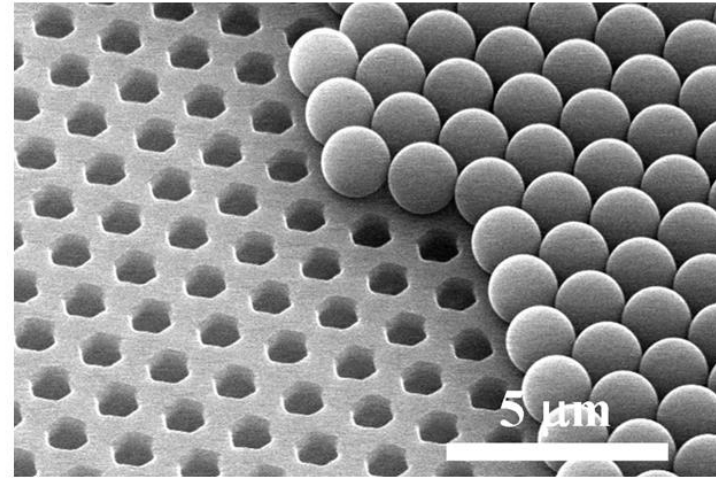
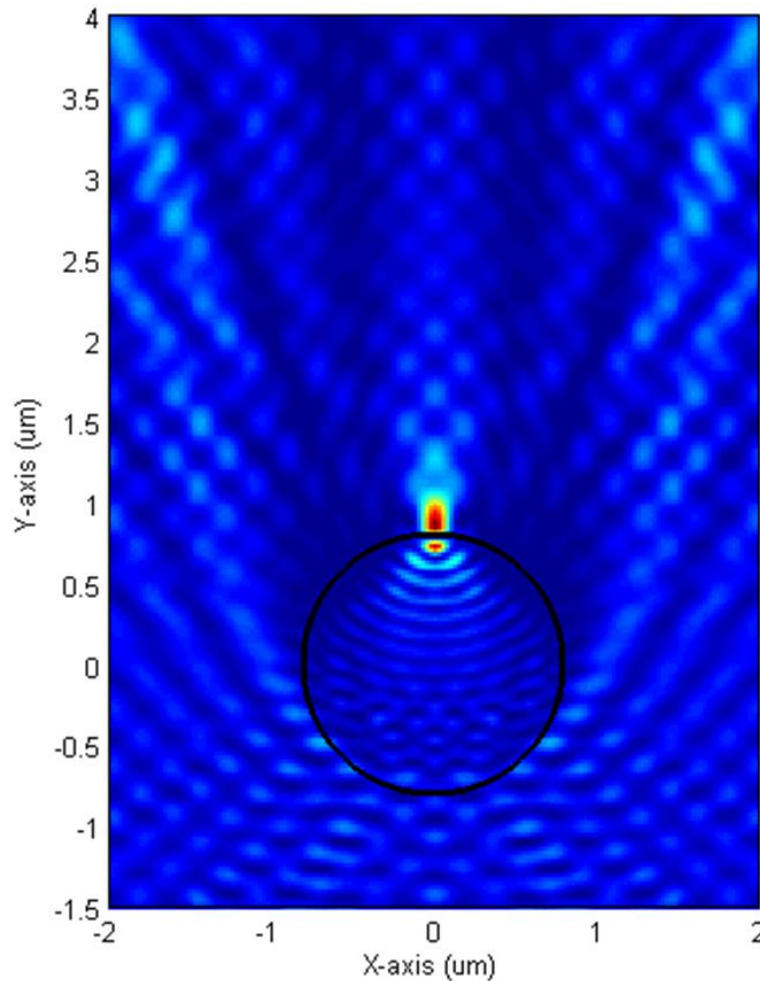


Etching



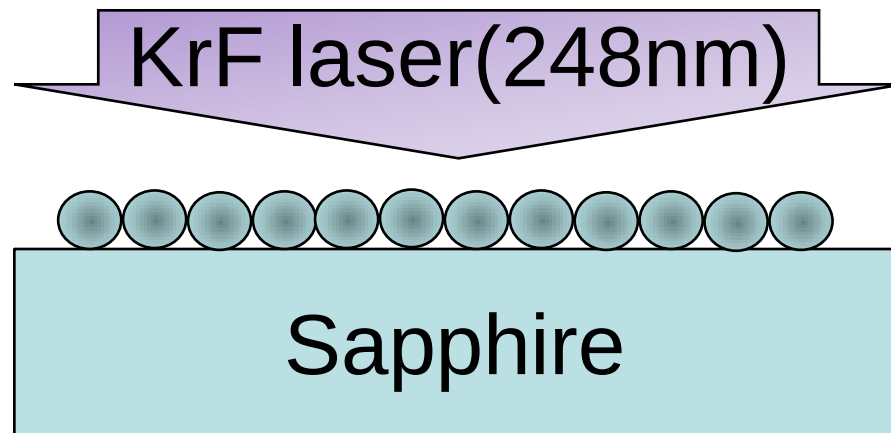
- Fabrication for nano-patterns
- gratings
- Periodical magnetic nano-structures

Patterned Substrates



KrF (248nm) laser ablation on Sapphire

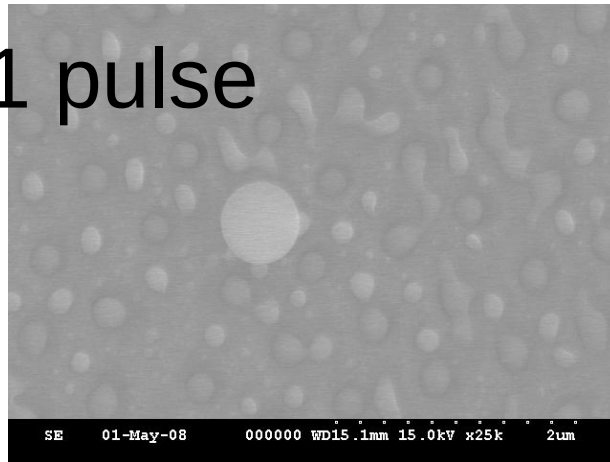
laser beam size $1.1 \times 1.1 (\text{mm}^2)$



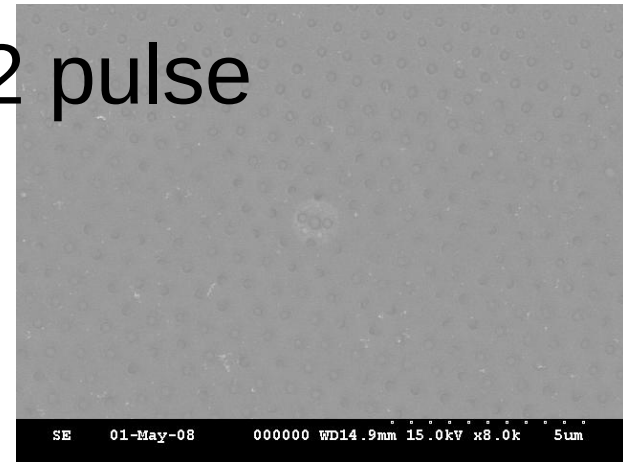
KrF laser at 16.1kV(800mW)

Substrate: sapphire

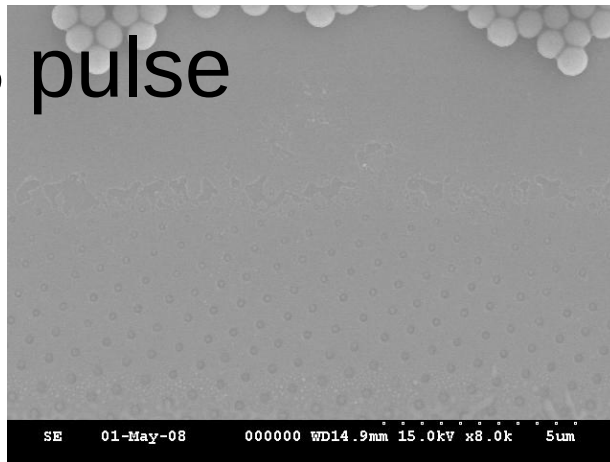
1 pulse



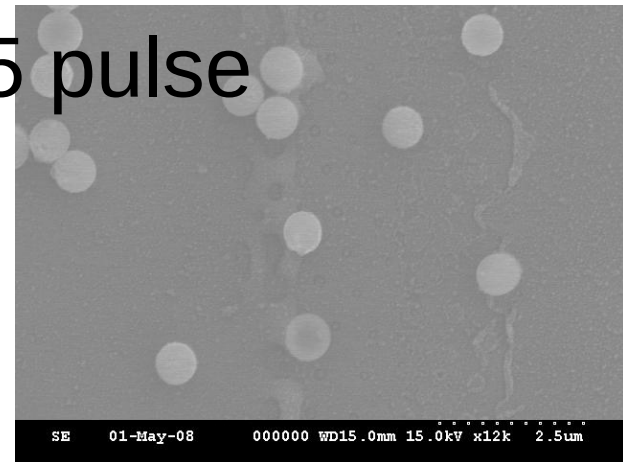
2 pulse



3 pulse



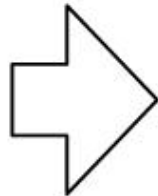
5 pulse



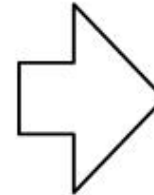
Miniaturization of electrical and optical components



1911



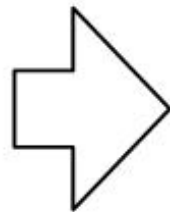
1950



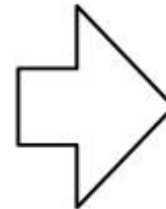
1958



13th century



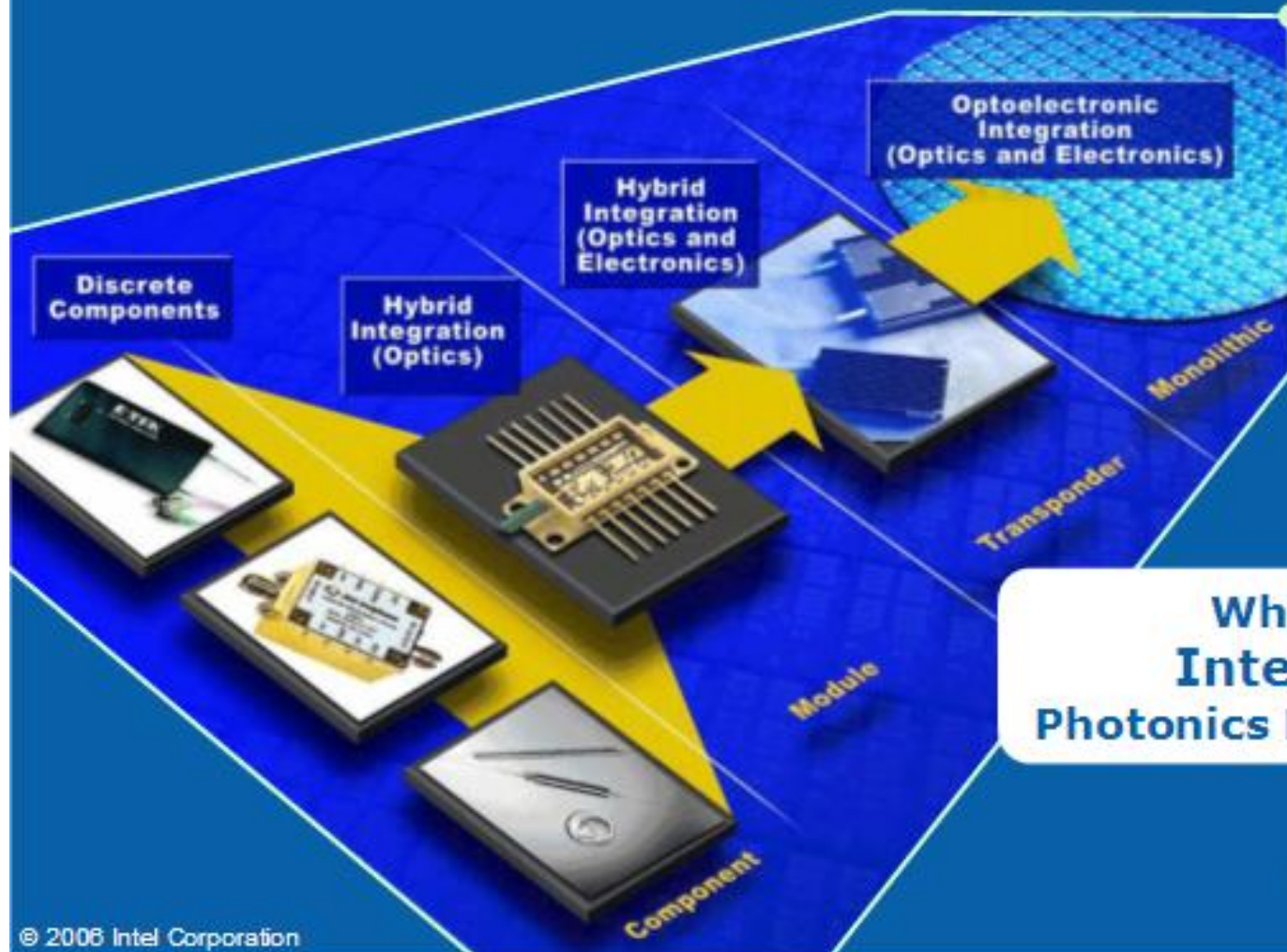
20th century



Now

Photonics Evolution

?



© 2006 Intel Corporation

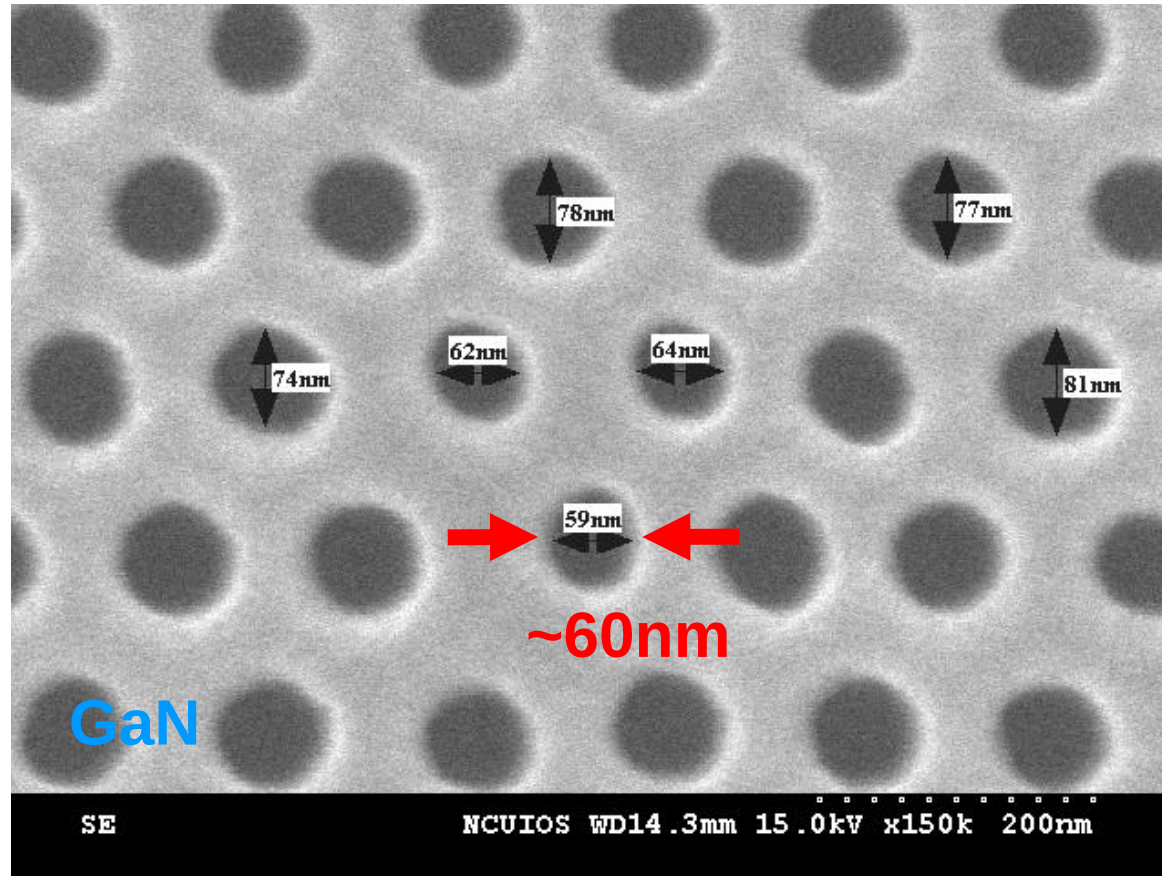


Necessary Devices

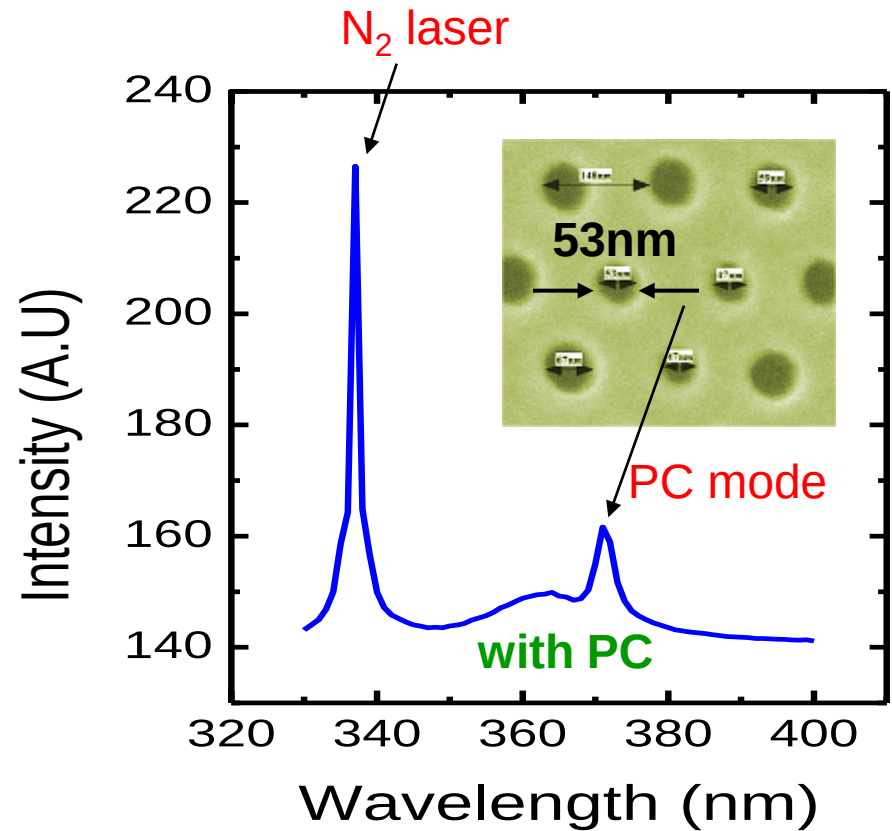
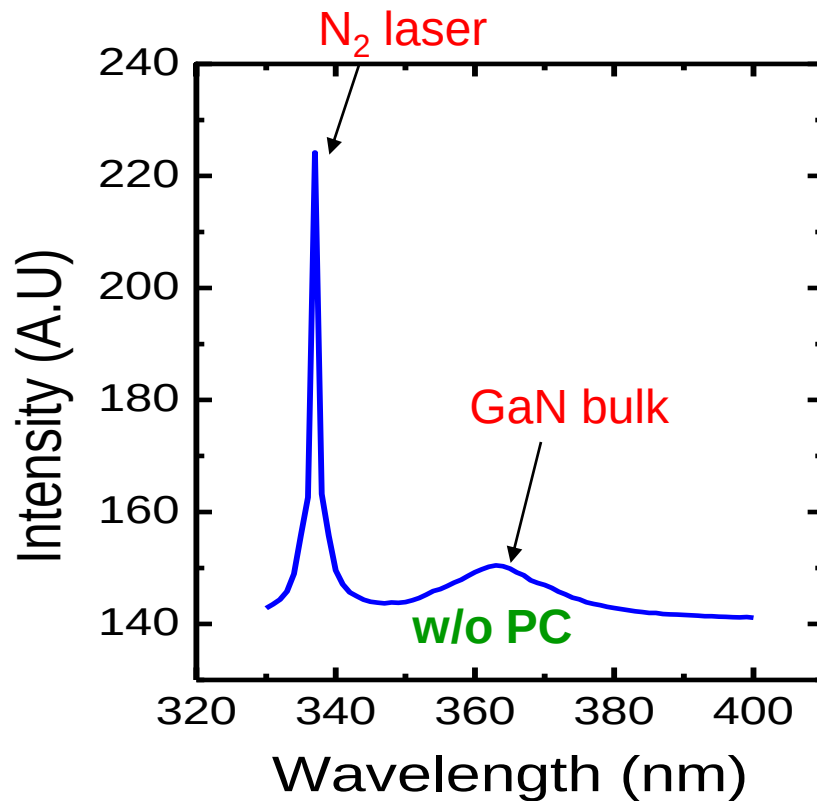
- Nano-light sources
- Nano-waveguides
- Nano-detectors
- Nano-switches
- Passive nano-devices(WDM, couplers, filters)
- Electrically modulated nano-devices
- Optically modulated nano-devices
- Integration of all devices

Photonic crystal light source

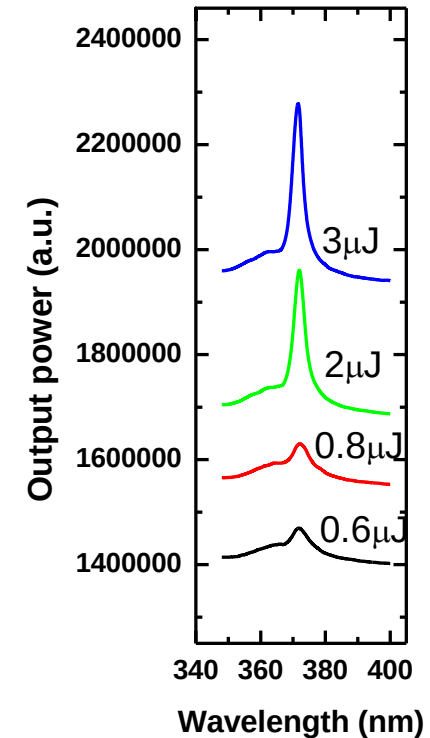
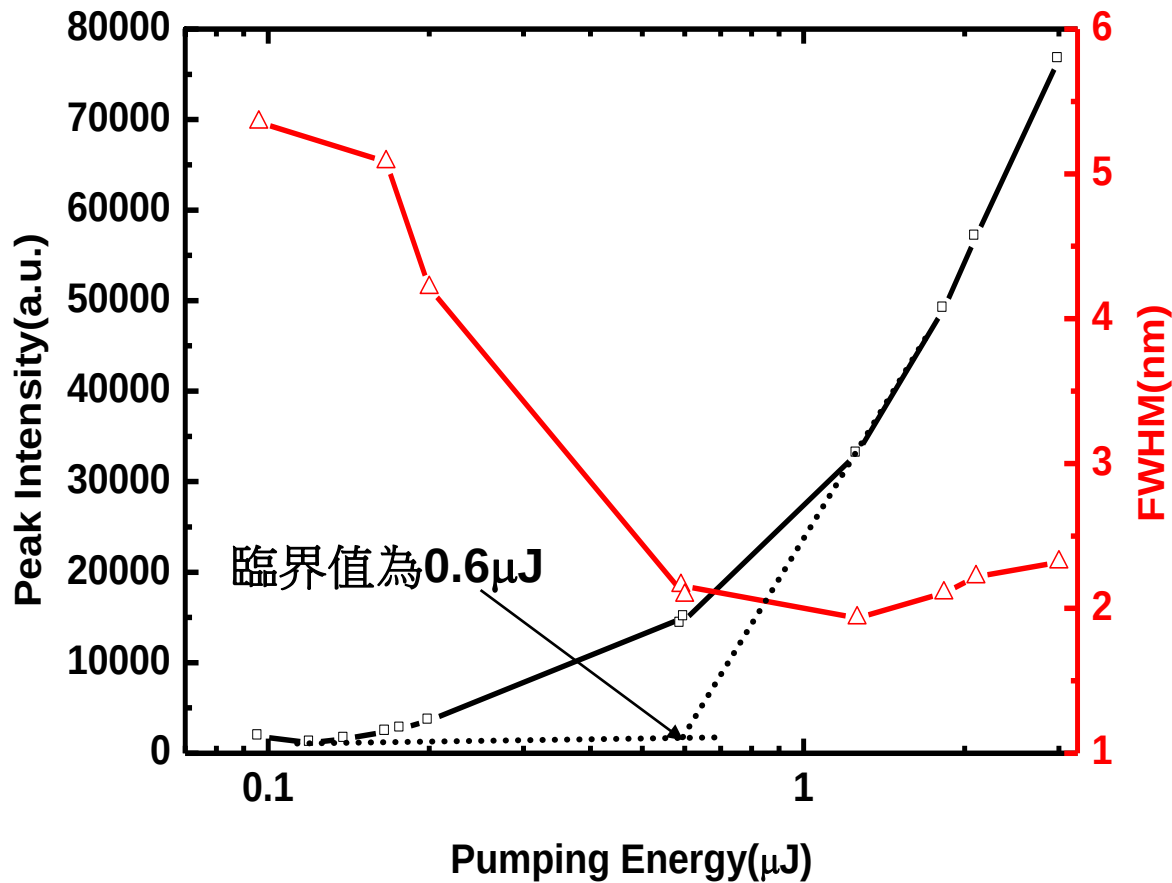
GaN photonic crystals



GaN photonic crystal mode

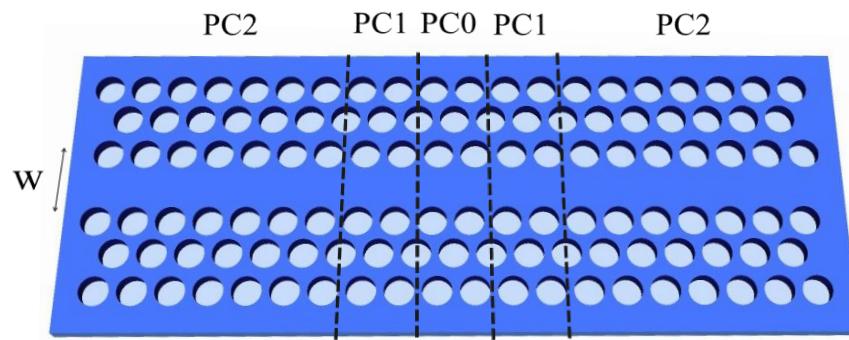


Pumping energy V.S. Peak intensity & FWHM

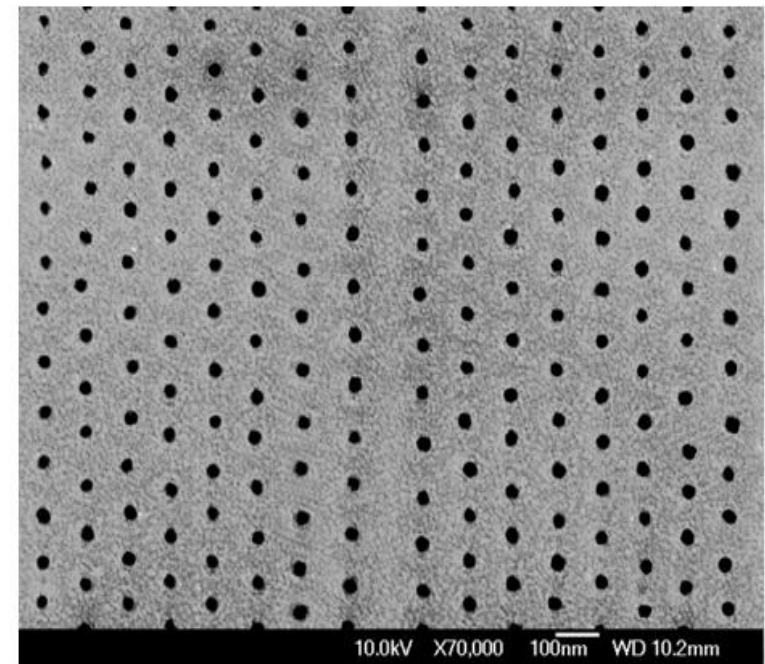


Appl. Phys. Lett. vol. 89, 071116, 2006.

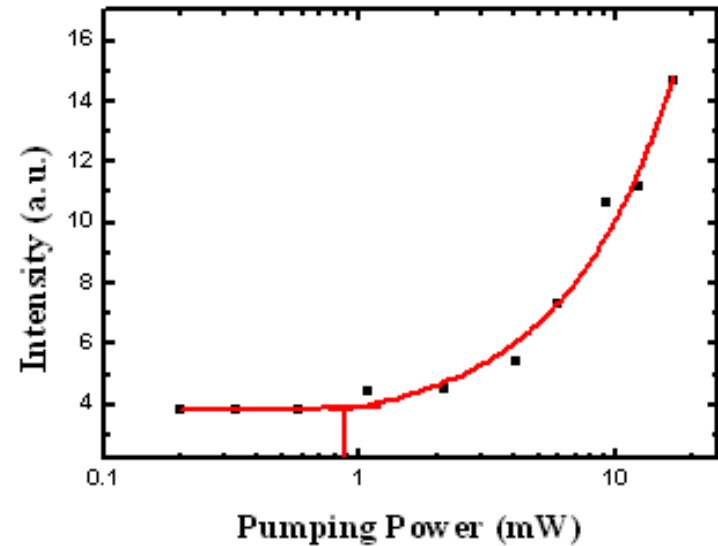
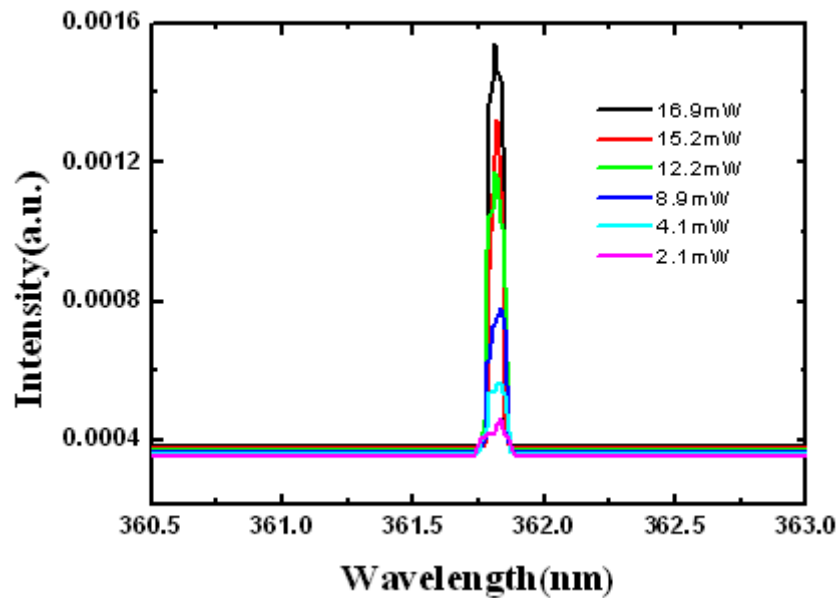
High-Q PC cavity



FDTD Simulation $Q=5 \times 10^9$

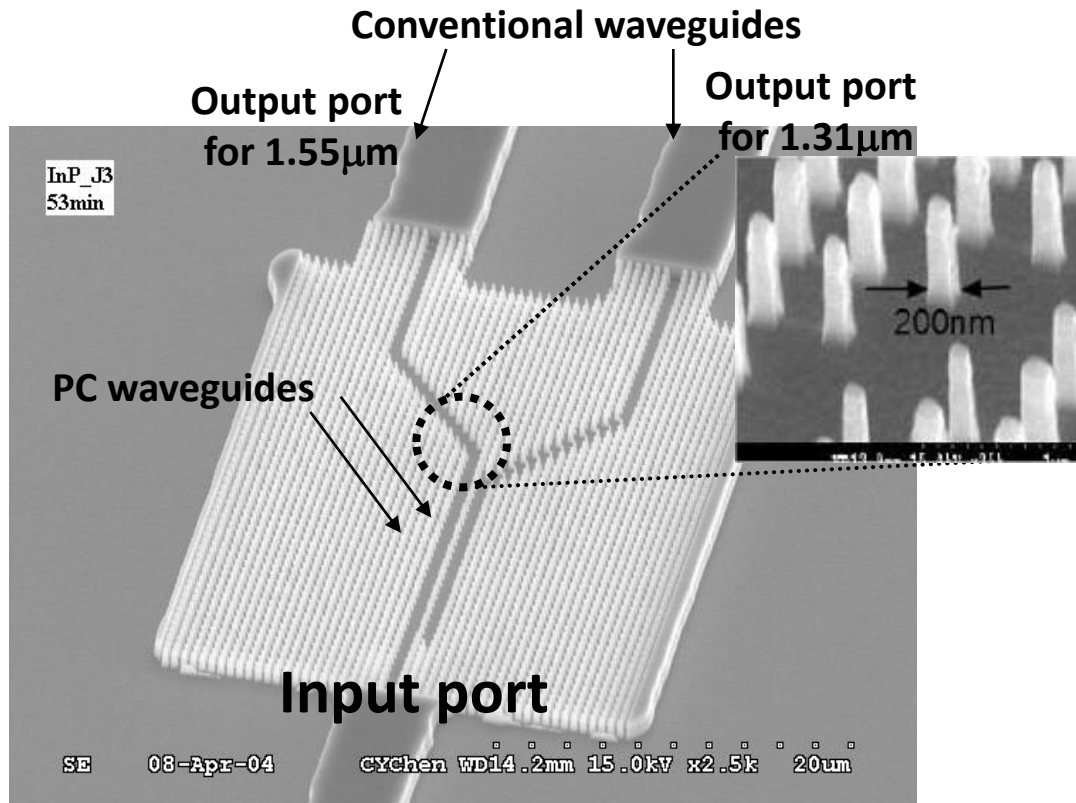


Experimental results



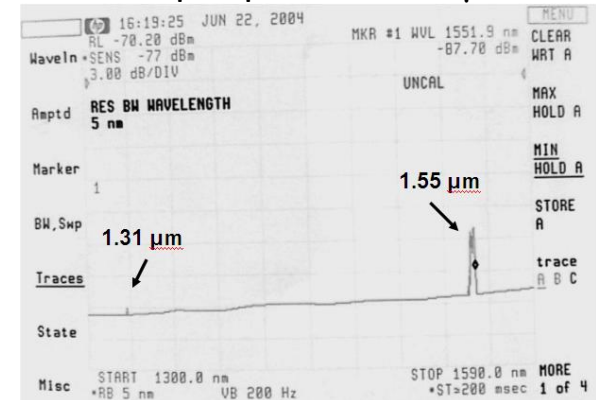
$Q=9095$

PC Directional Couplers

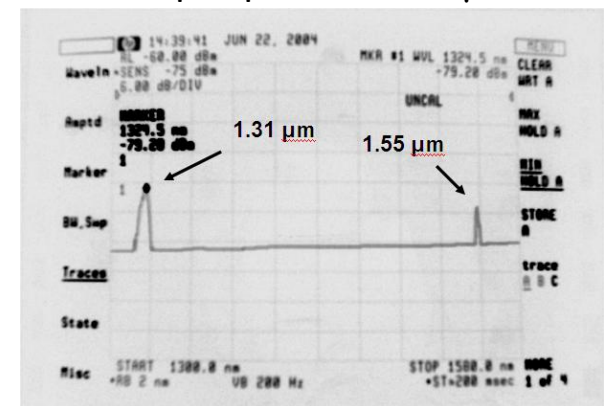


Tile 45 degree view

Output port for 1.55 μm



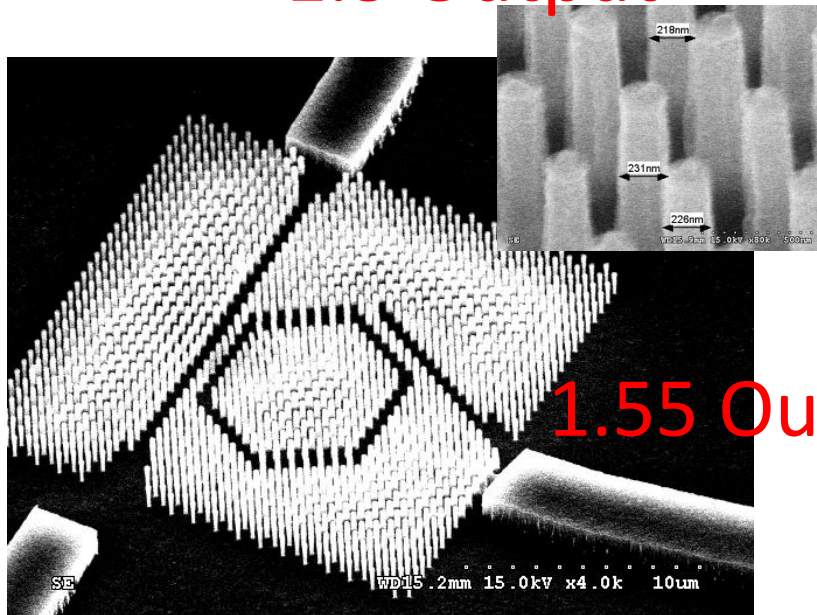
Output port for 1.31 μm



Optics Express, vol. 13, p.38, 2005

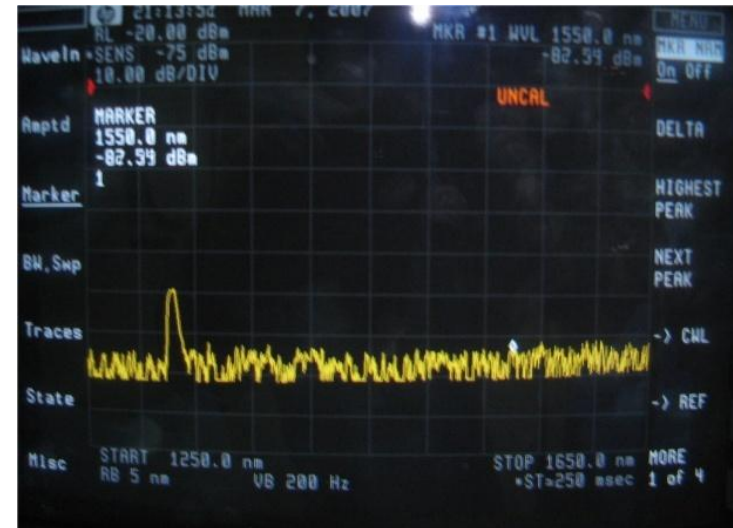
PC ring resonator (1.3/1.55 μm)

1.3 Output



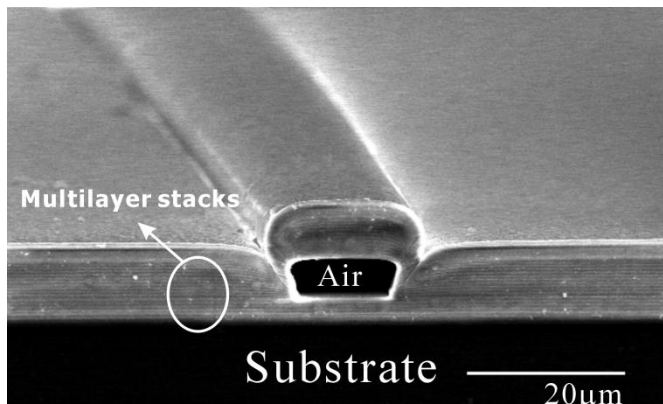
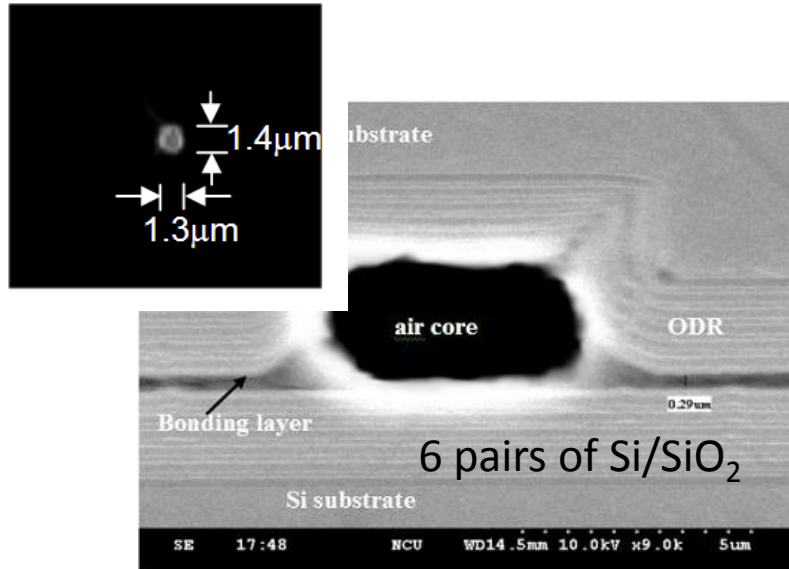
1.55 Output

Input



Opt. Express vol. 15, p. 15500, 2007

Semiconductor Hollow Waveguides



Propagation loss=1dB/cm for both TE and TM modes

Optics Express, vol. 12, 6589, 2004

IEEE Photon. Technol. Letters, vol.17, 2592, 2005

IEEE J. MEMS vol. 15, 584, 2006

Optics Letters, vol. 32, 1803, 2007

JOSA B vol. 24, 1853, 2007

US patent: 7,239,786B2, 2007

J. Phys. D: Appl. Phys. Vol. 42, 195106, 2009

Large operation bandwidth: C+L band

Low propagation loss

Low polarization dependent loss

Low material dispersion

Low non-linearity

Low material absorption

Micro-fluidic channel

90° bending loss < 1dB

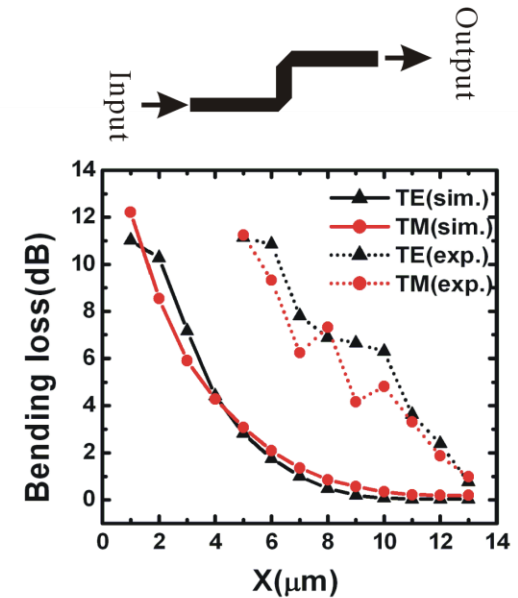
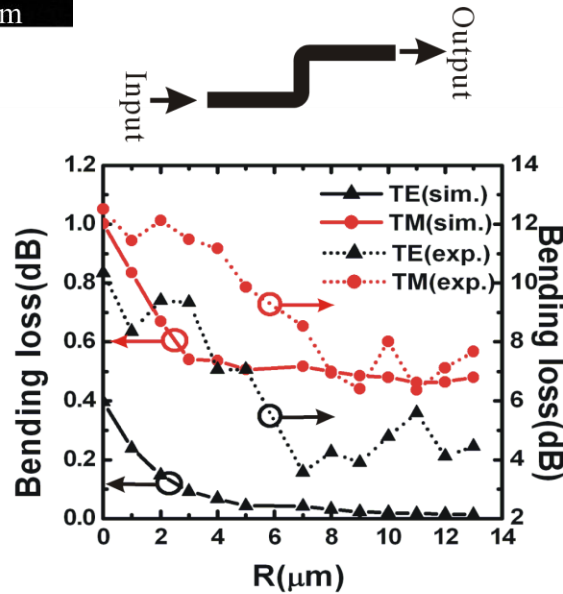
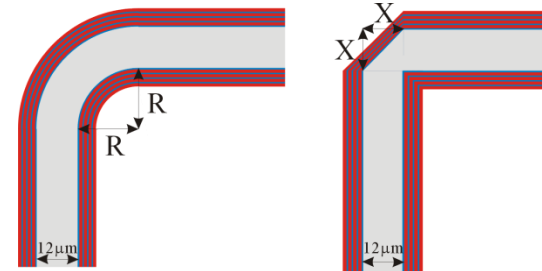
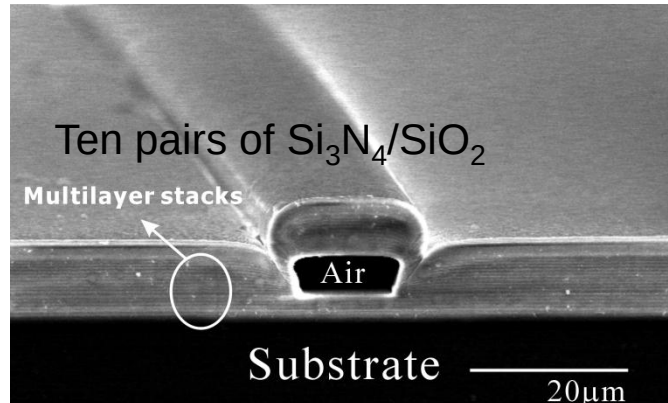
Optics Express vol. 16, 15069, 2008

Applied Optics vol. 50, 227, 2011



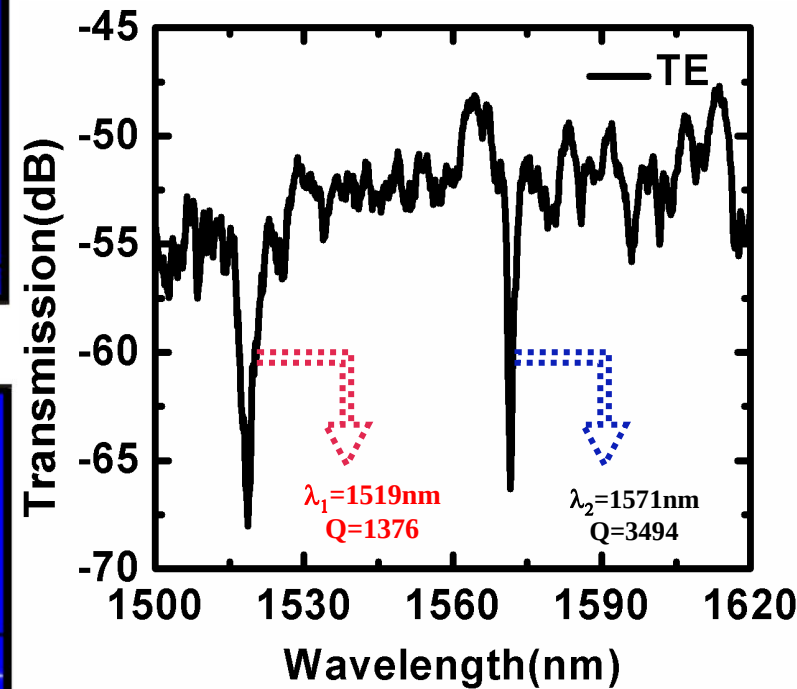
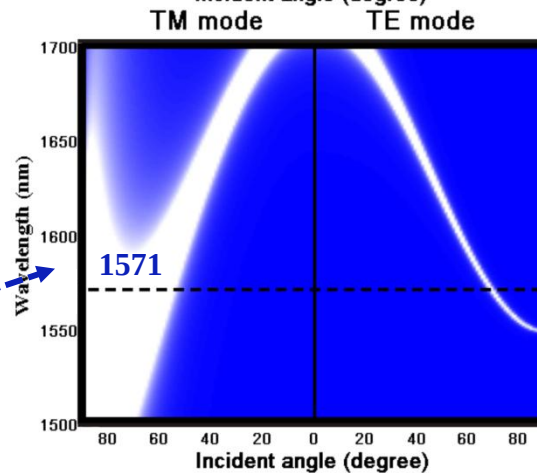
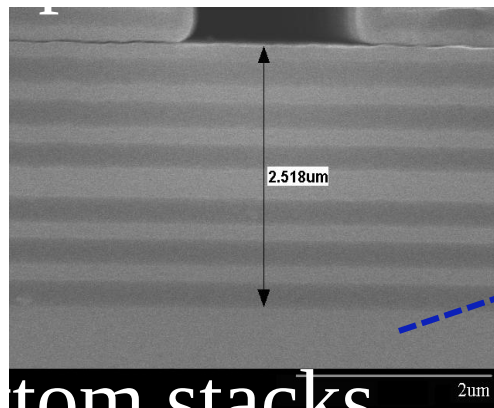
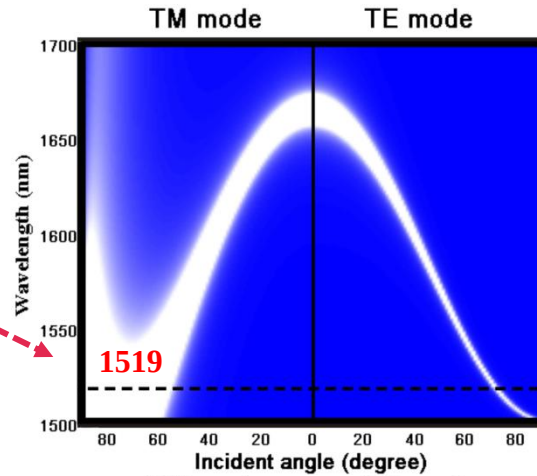
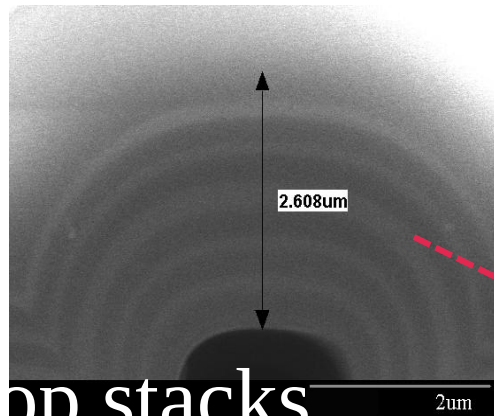
Applied Photonics Laboratory - NCU

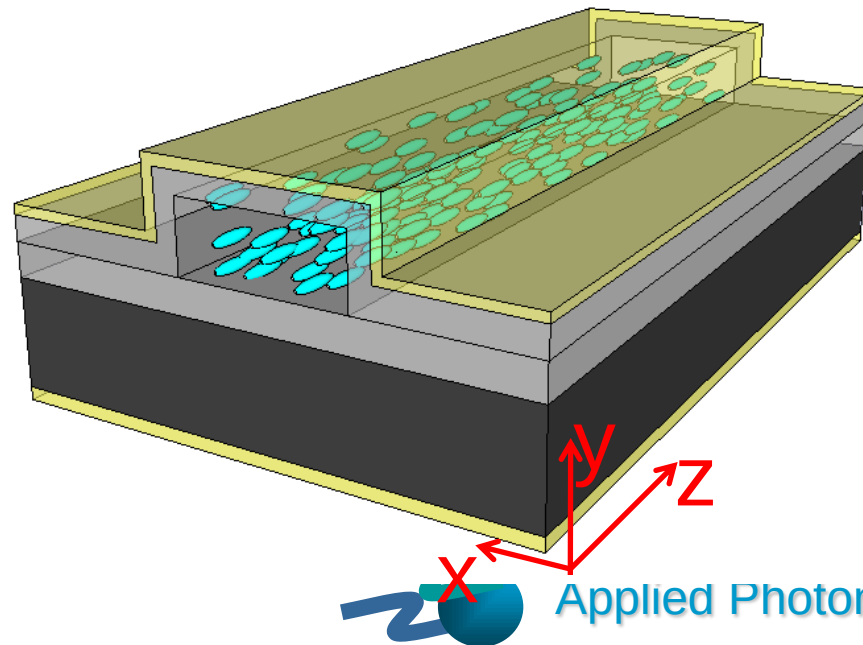
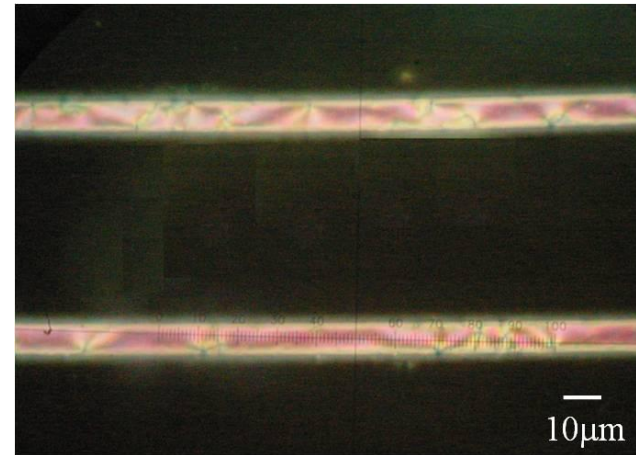
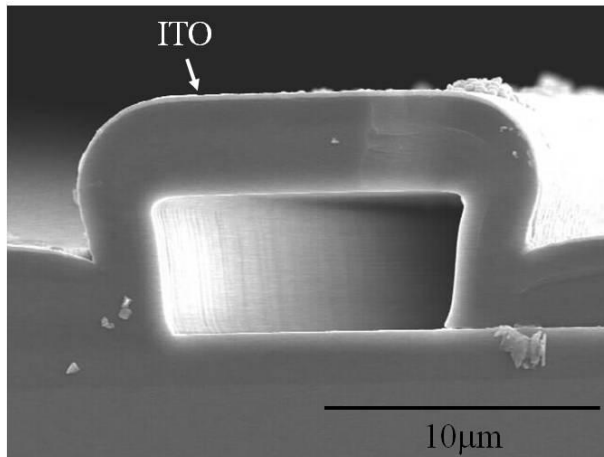
90° bent hollow waveguide



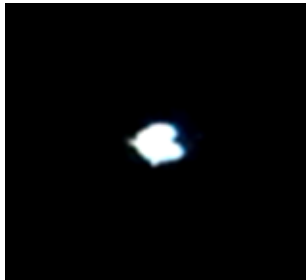
Optics Express 16.15069.2008

Discussion for measured results

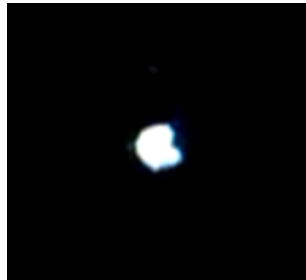


LC infiltrated hollow waveguide with Si/SiO₂

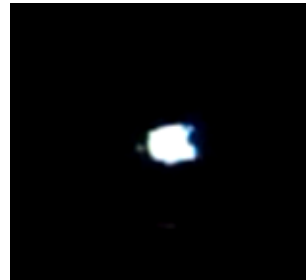
Output field images



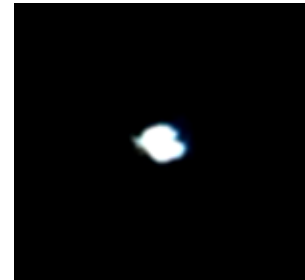
$0V_{PP}$



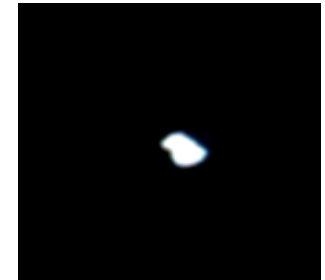
$0.5V_{PP}$



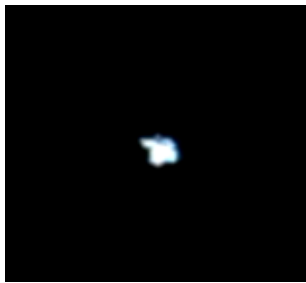
$1V_{PP}$



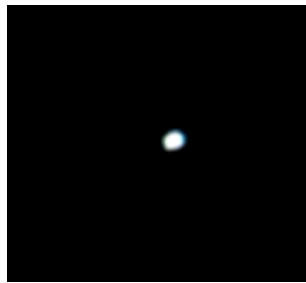
$1.5V_{PP}$



$2V_{PP}$



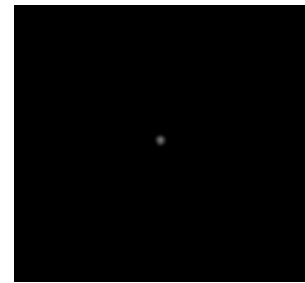
$2.5V_{PP}$



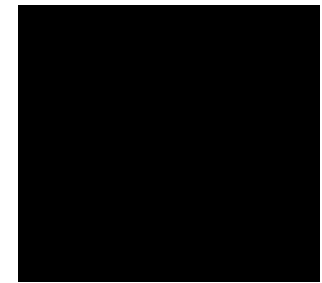
$3V_{PP}$



$3.5V_{PP}$

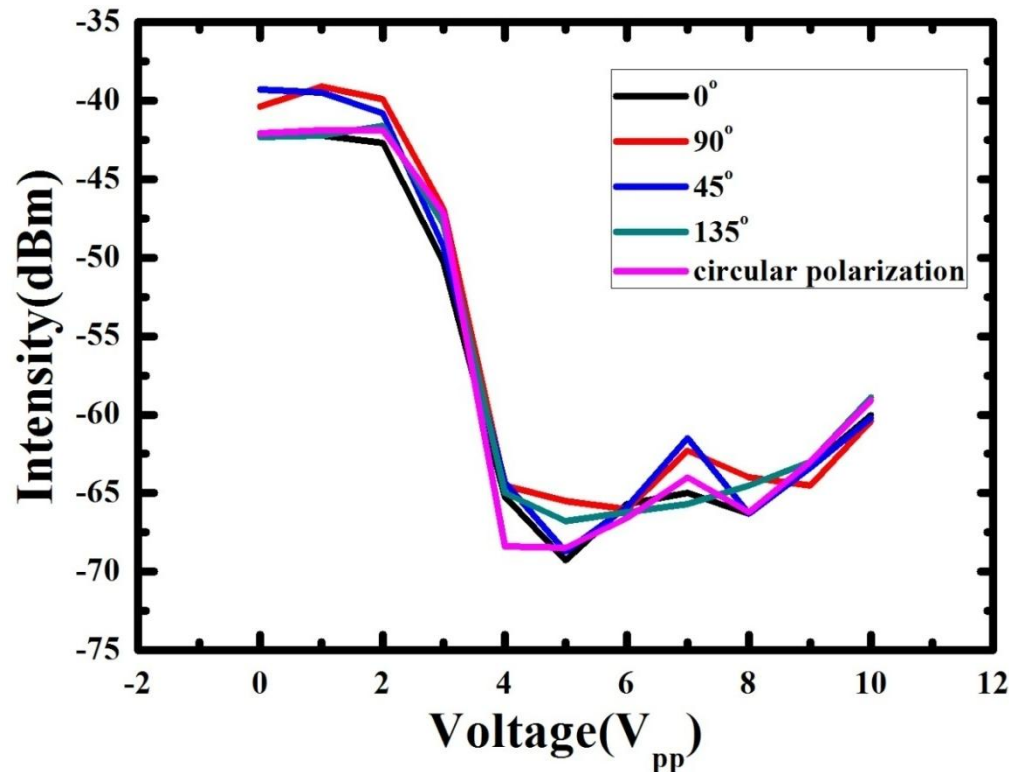


$3.8V_{PP}$



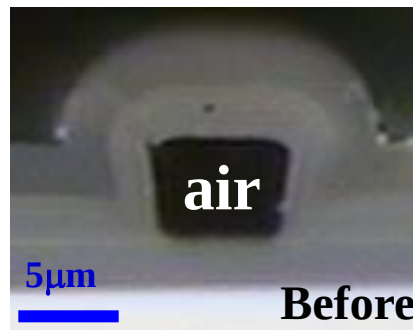
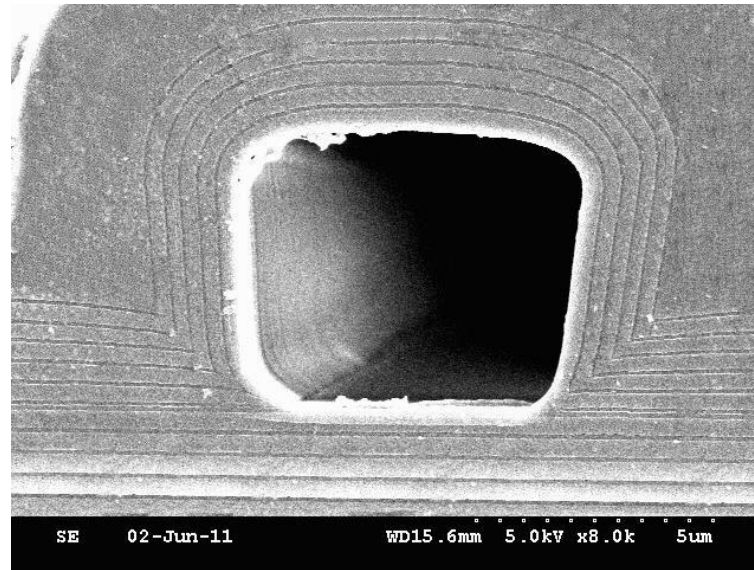
$4\sim 10V_{PP}$

Output Intensity

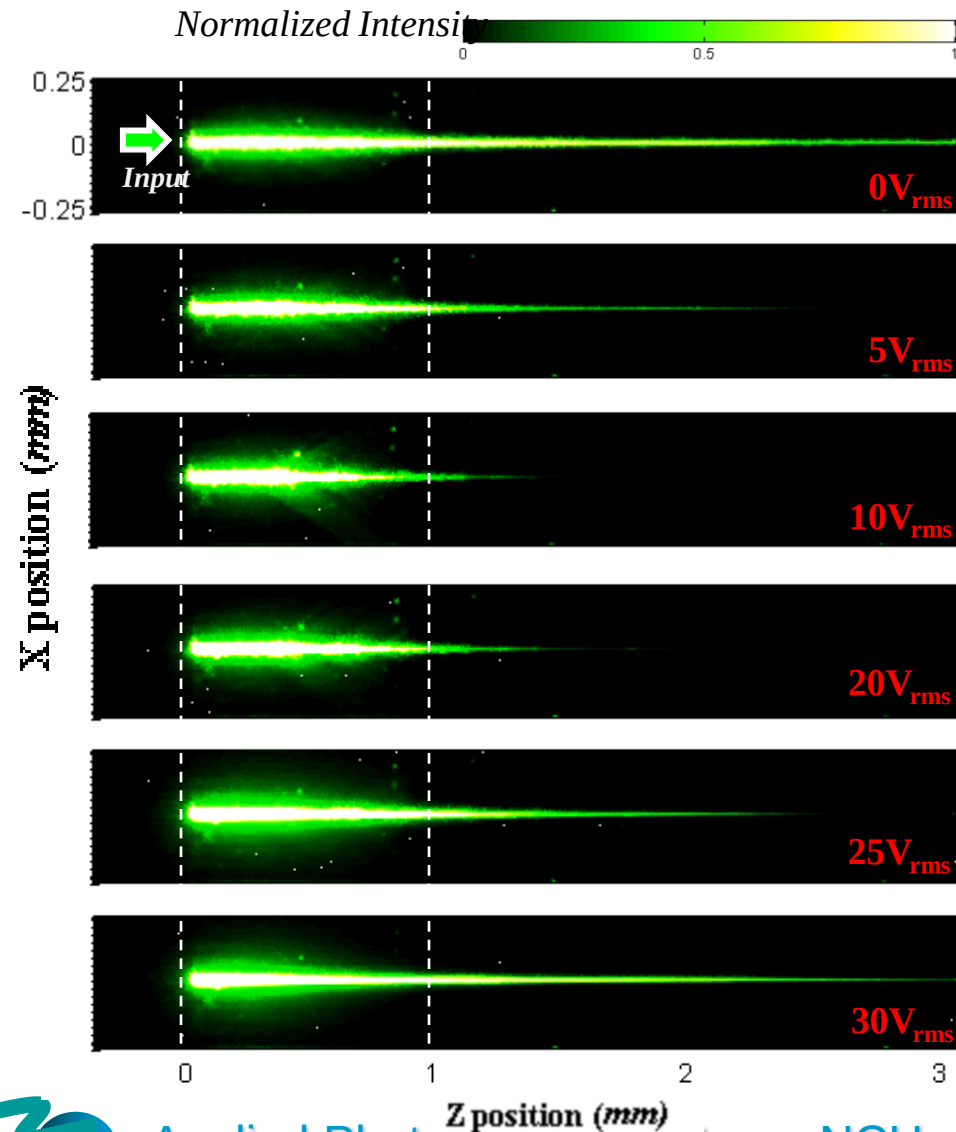
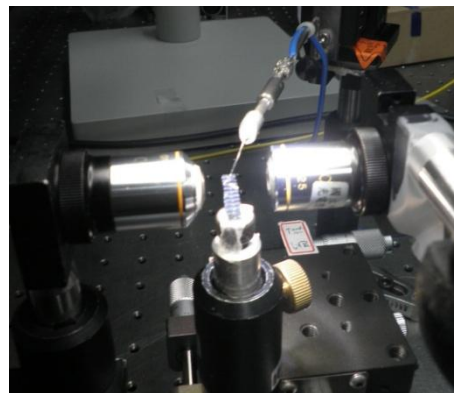
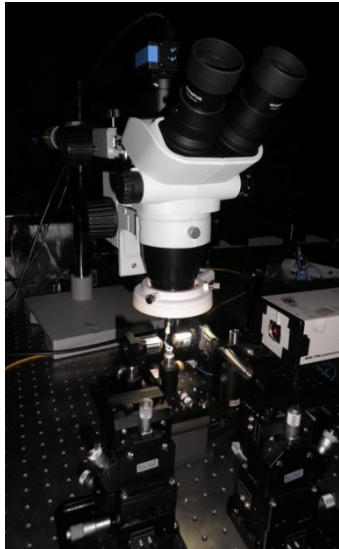


Optics Express vol. 19, p. 11890. 2011

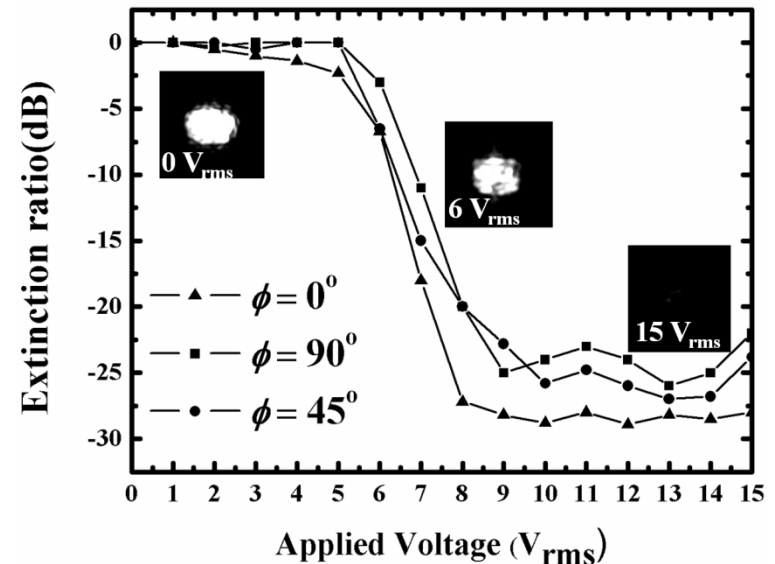
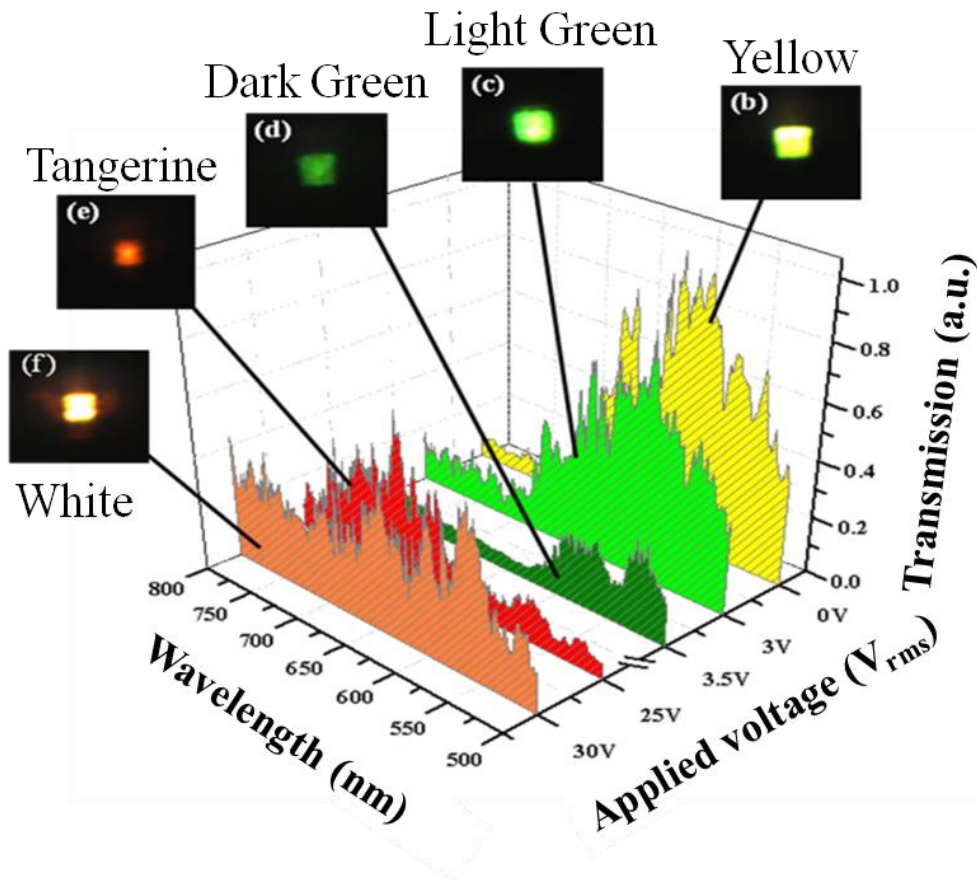
LC filled hollow waveguide with SiN/SiO₂



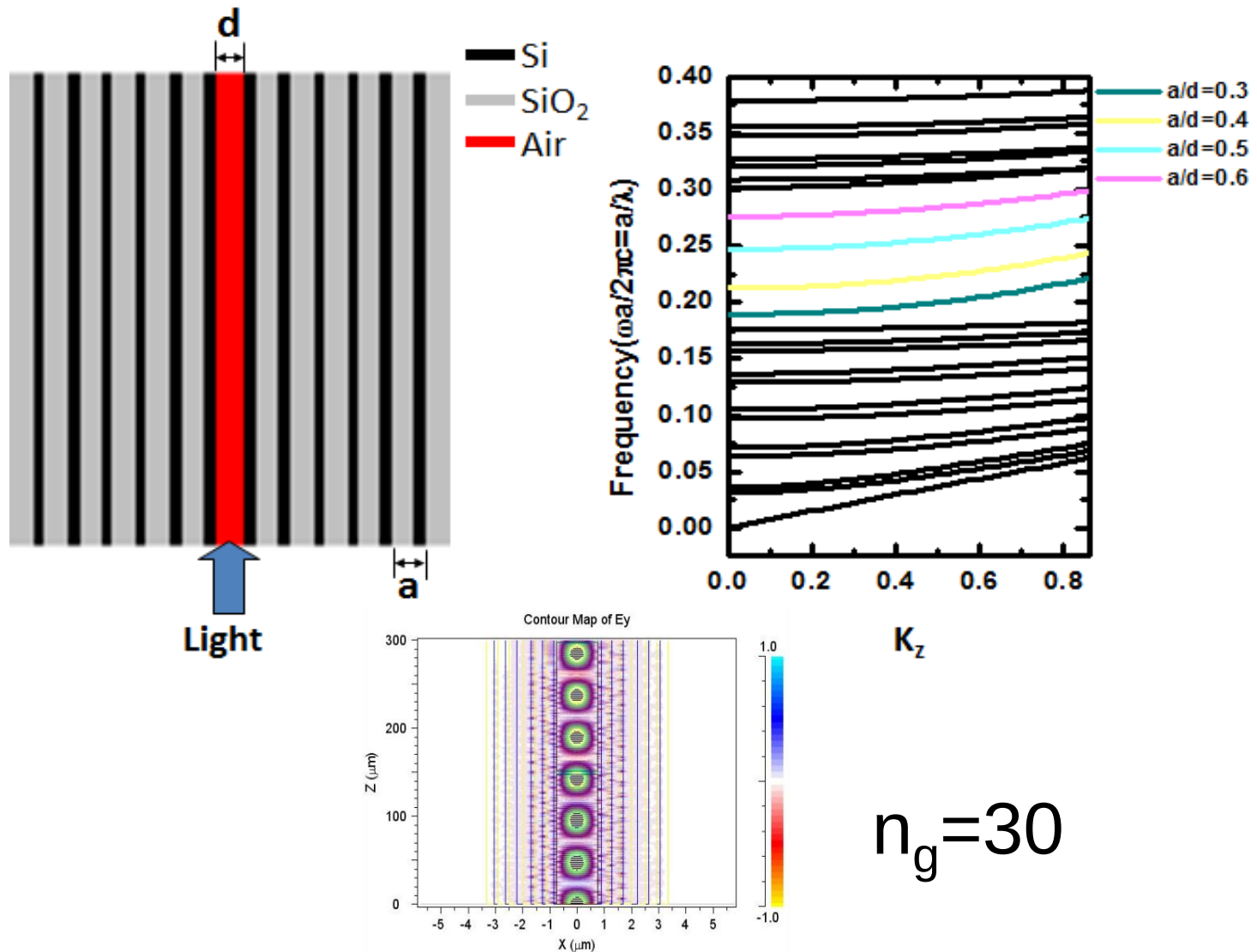
Top-view of waveguide



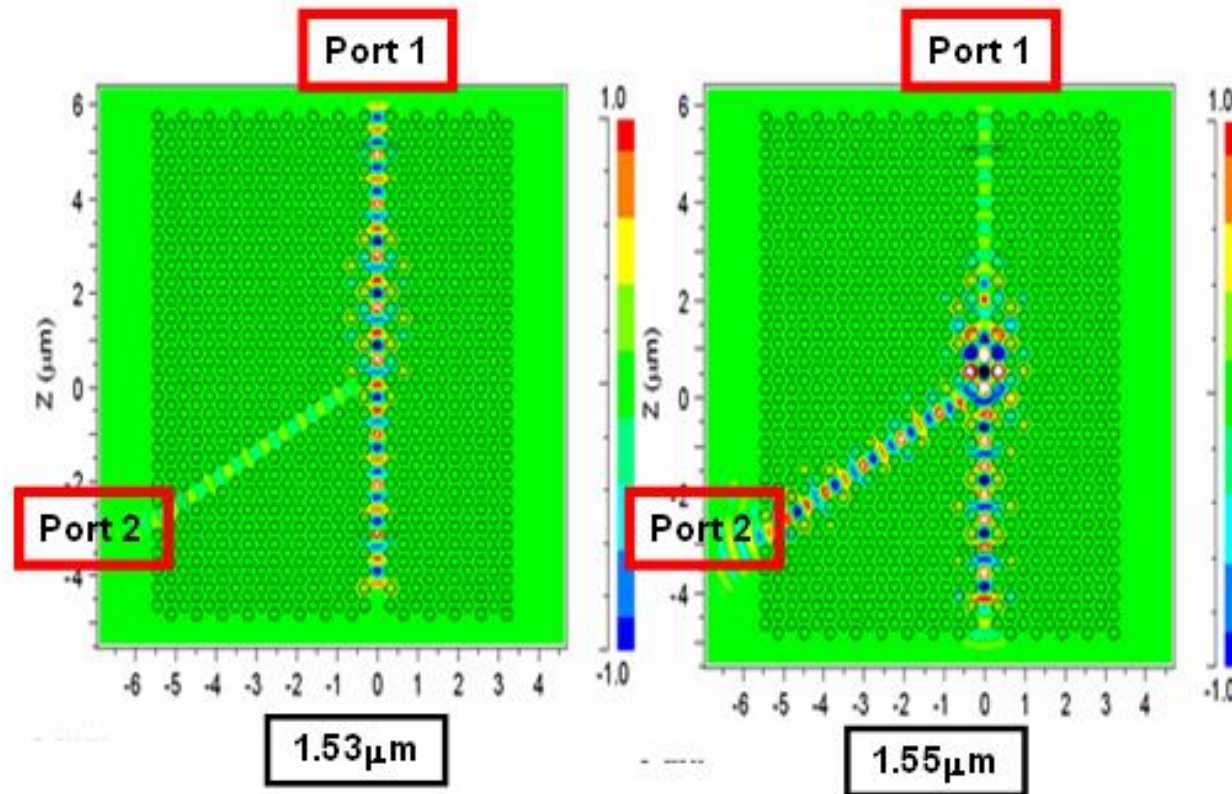
Tunable Color filter and intensity modulator



Slow light in hollow waveguide

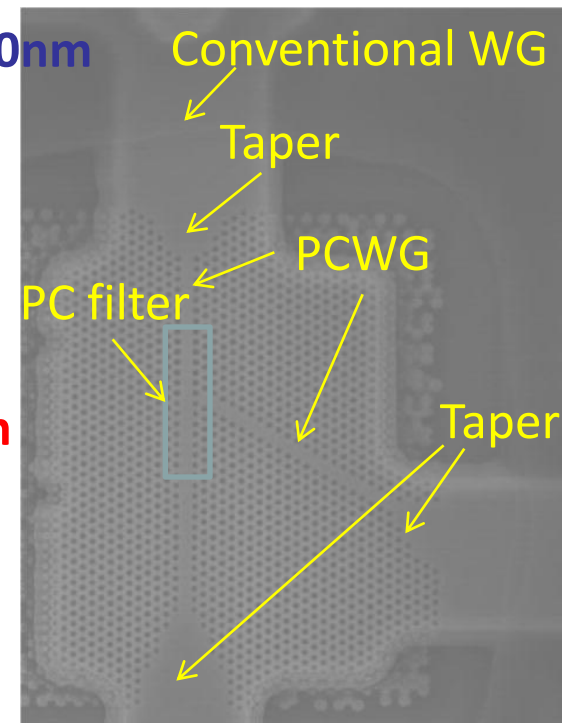
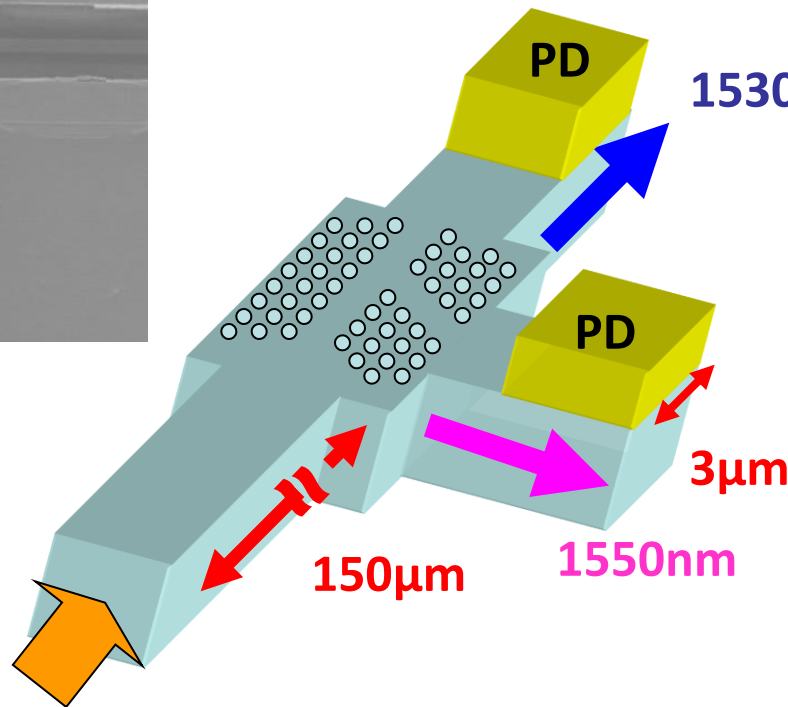
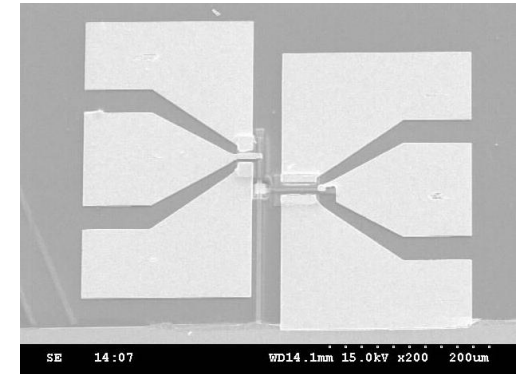
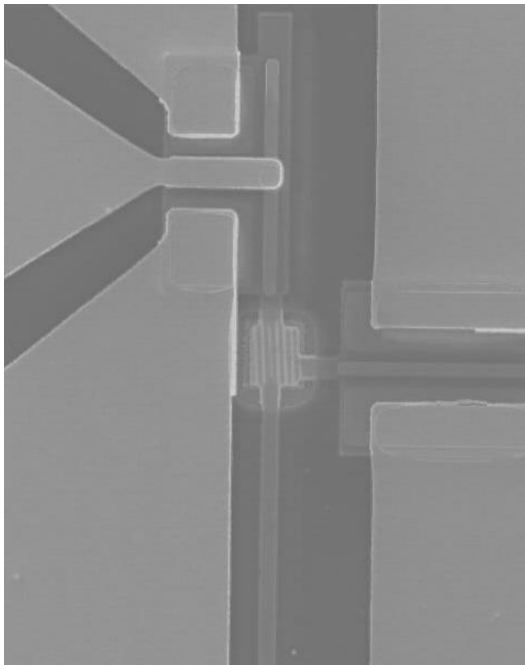


PC Channel Drop Filter



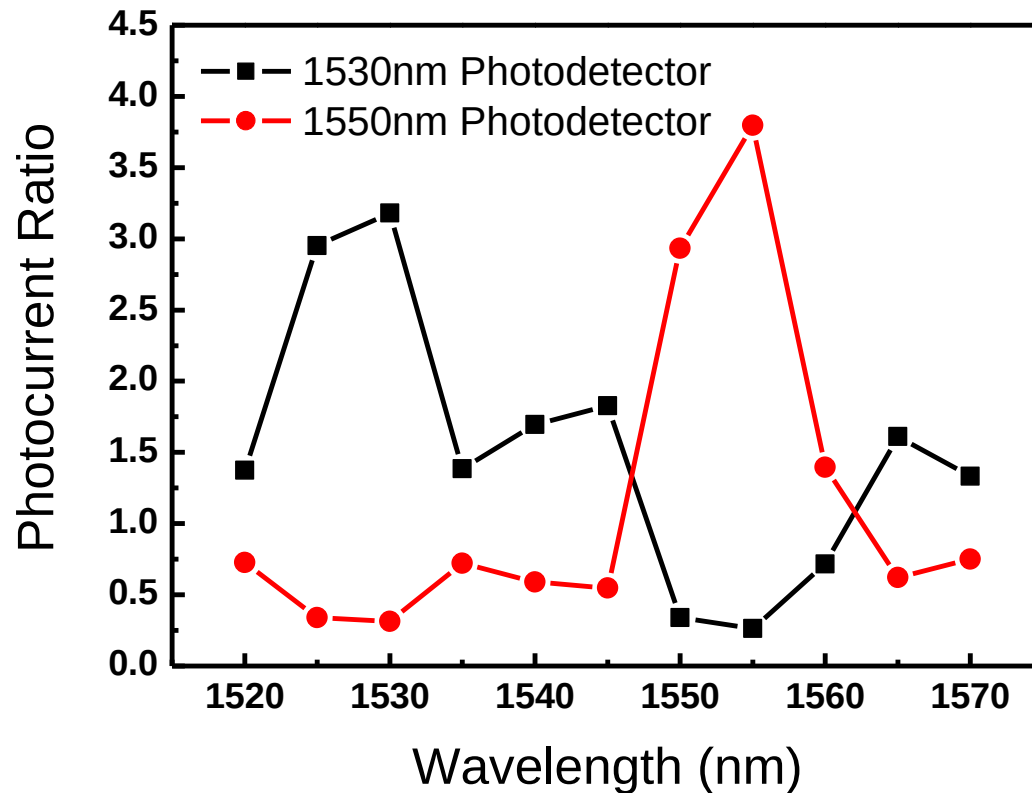
***M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi and I. Yokohana, *IEEE J. Quantum Electronics*, vol. 38, pp.736-742, Jul., 2002**

SEM images of devices



1530&1550nm

Photocurrent ratio of PC demultiplexers



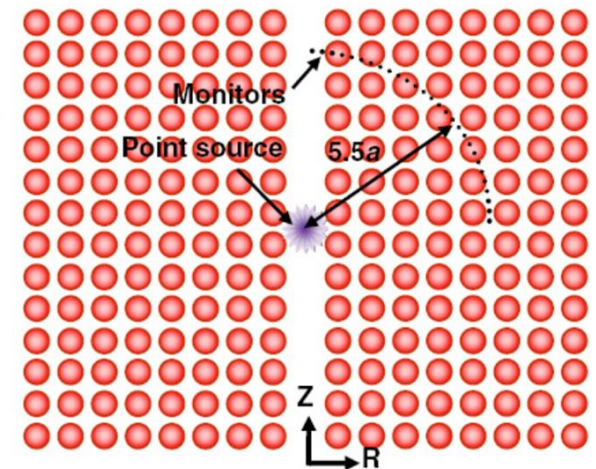
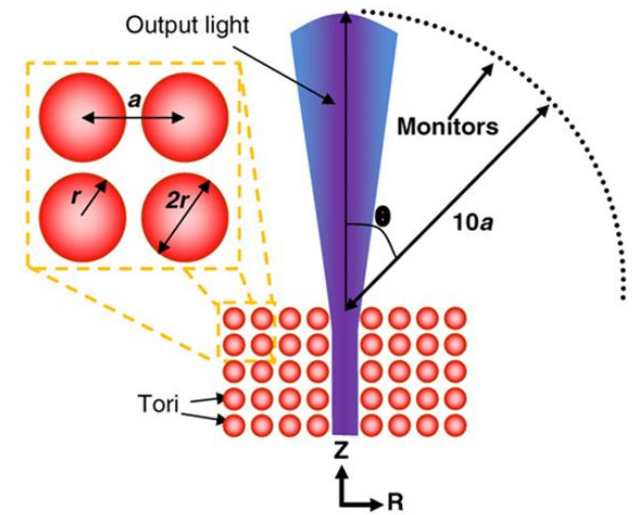
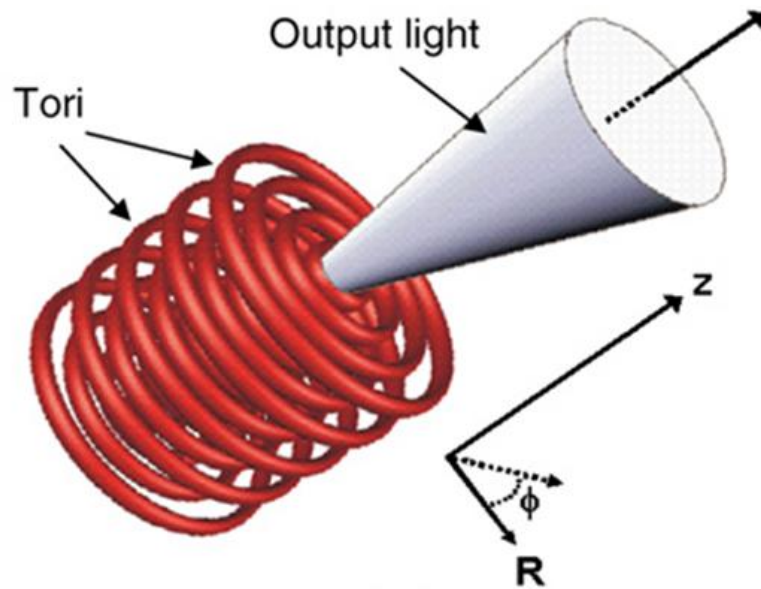
Optics Communications vol. 284, p. 4749, 2011



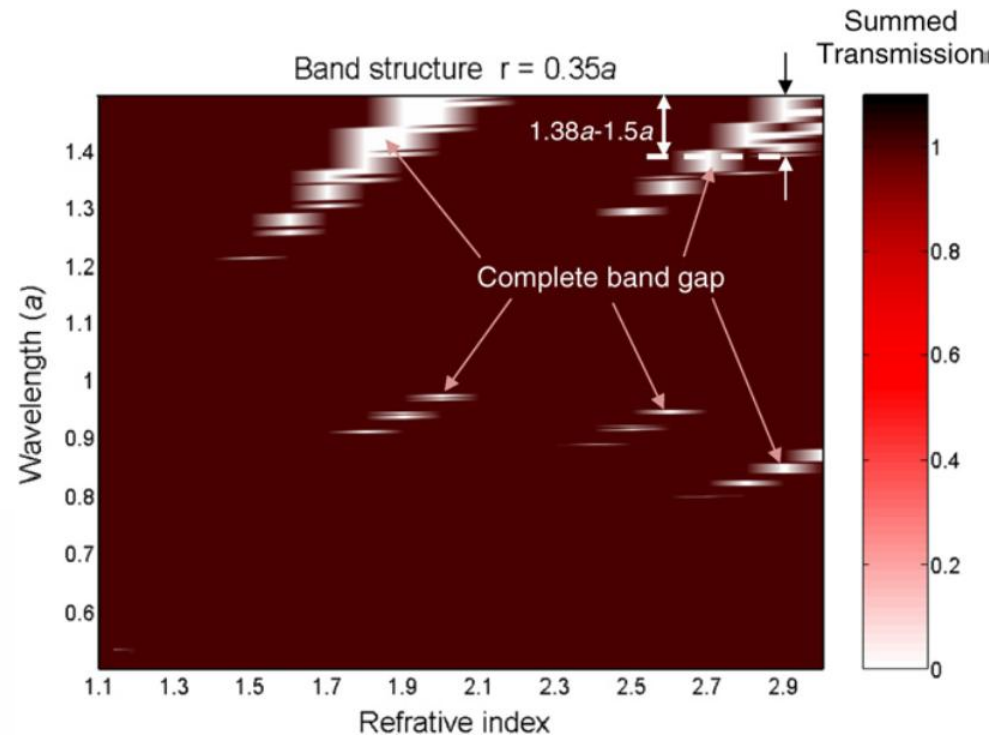
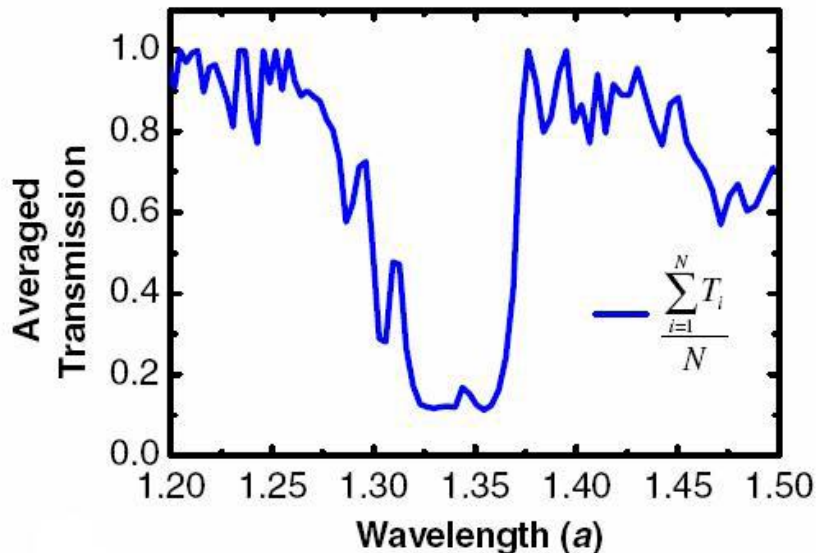
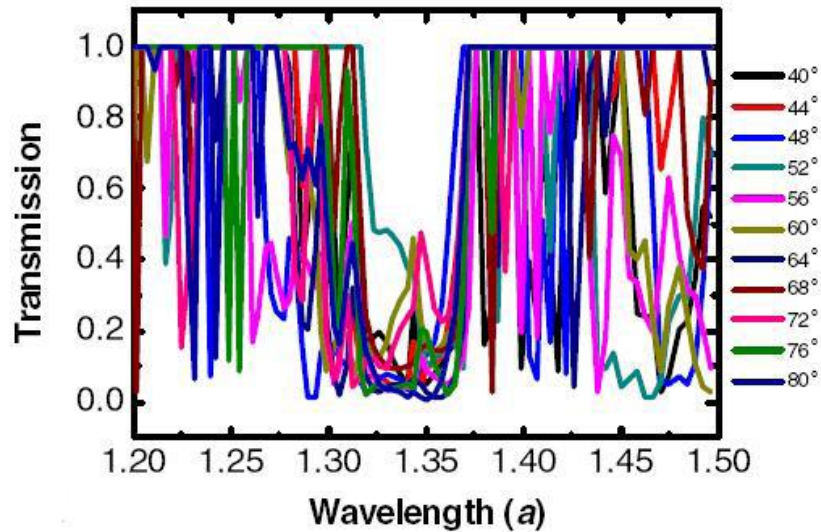
Donuts make confinement of EM waves



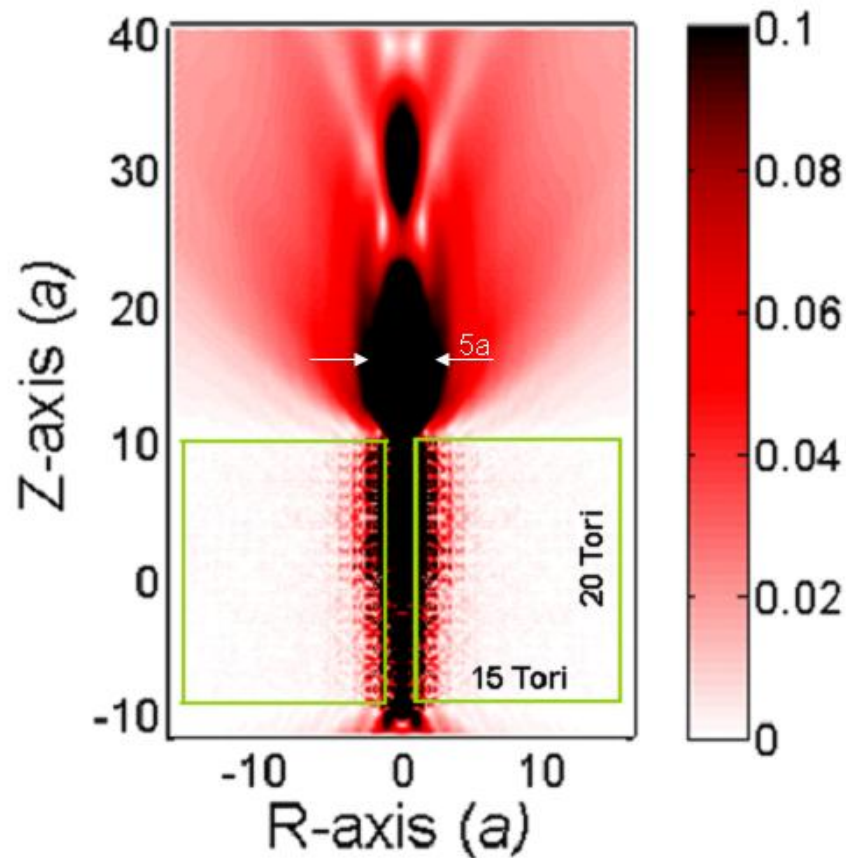
Concept of torus waveguide



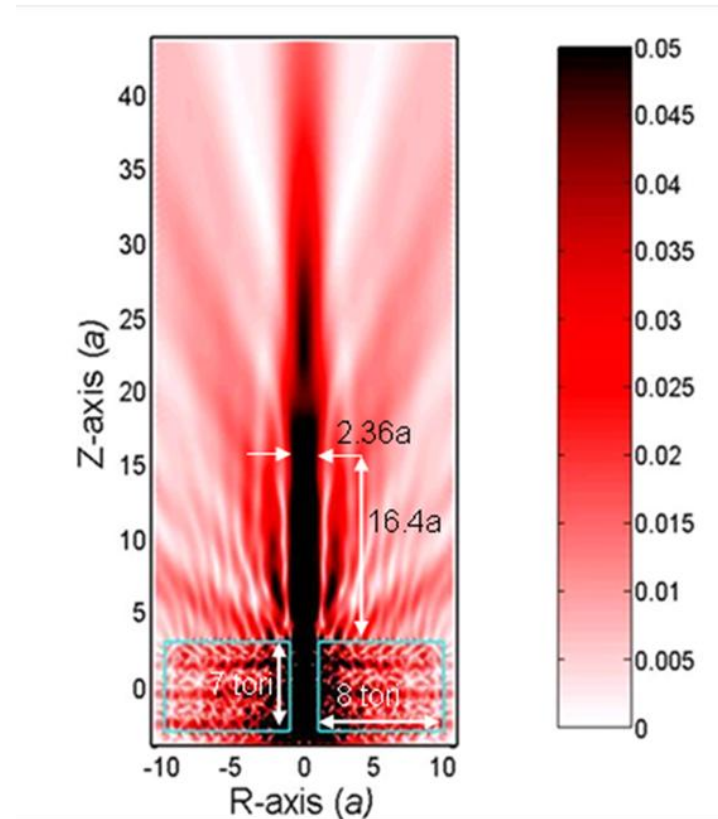
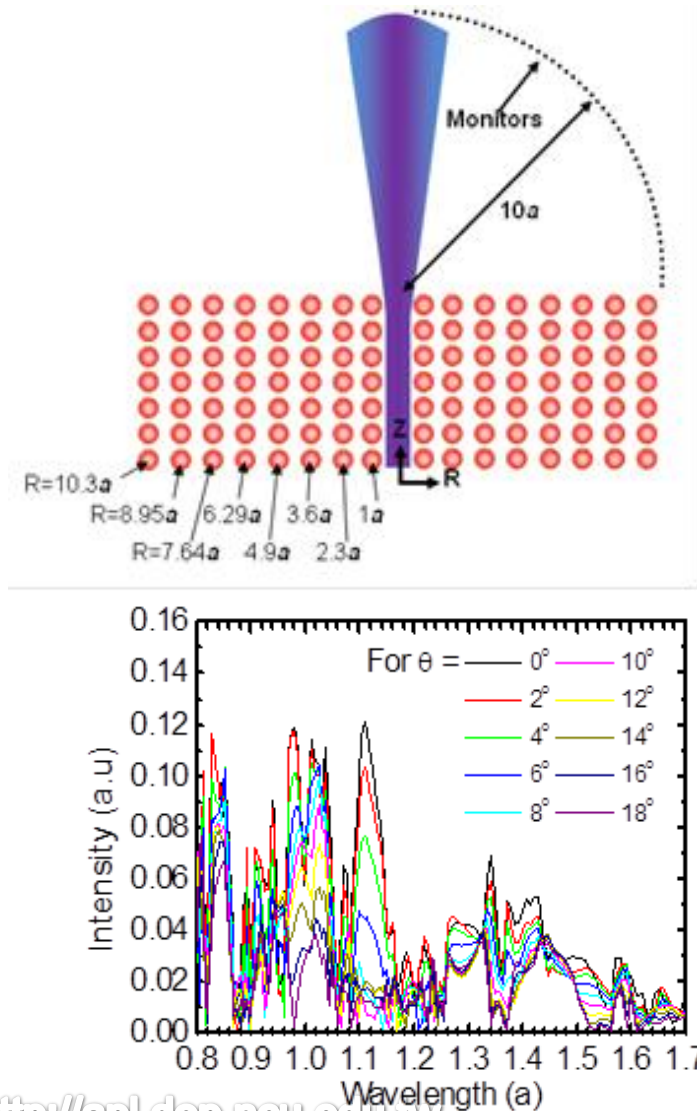
Transmission & Band structure



Energy confinement



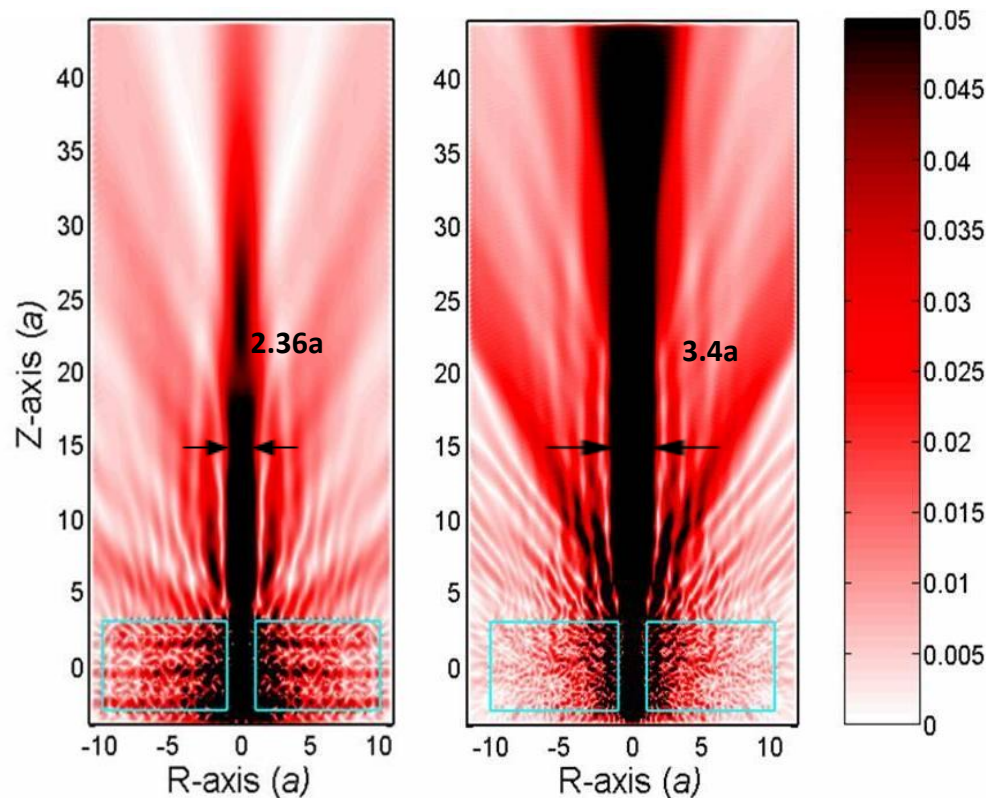
Diffractionless light beam



J. Phys. D: Appl. Phys. Vol. 43, p. 245103, 2010

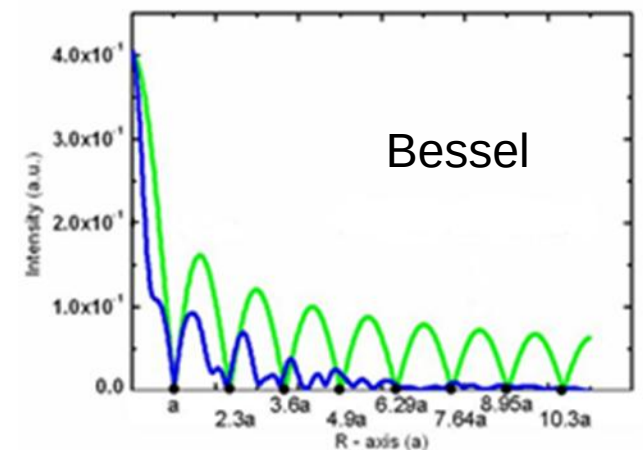
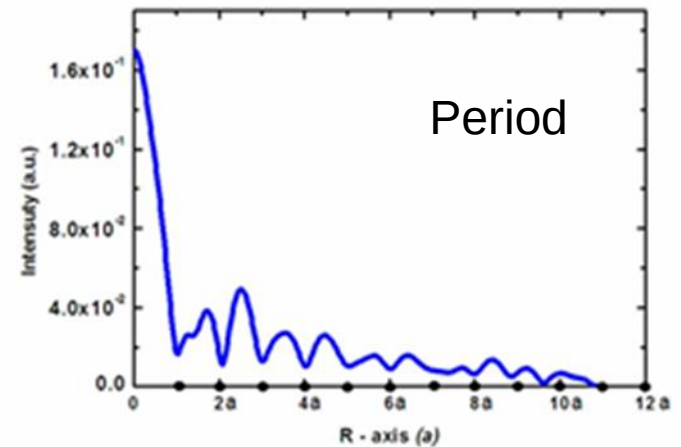


Periodic-type & Bessel-type

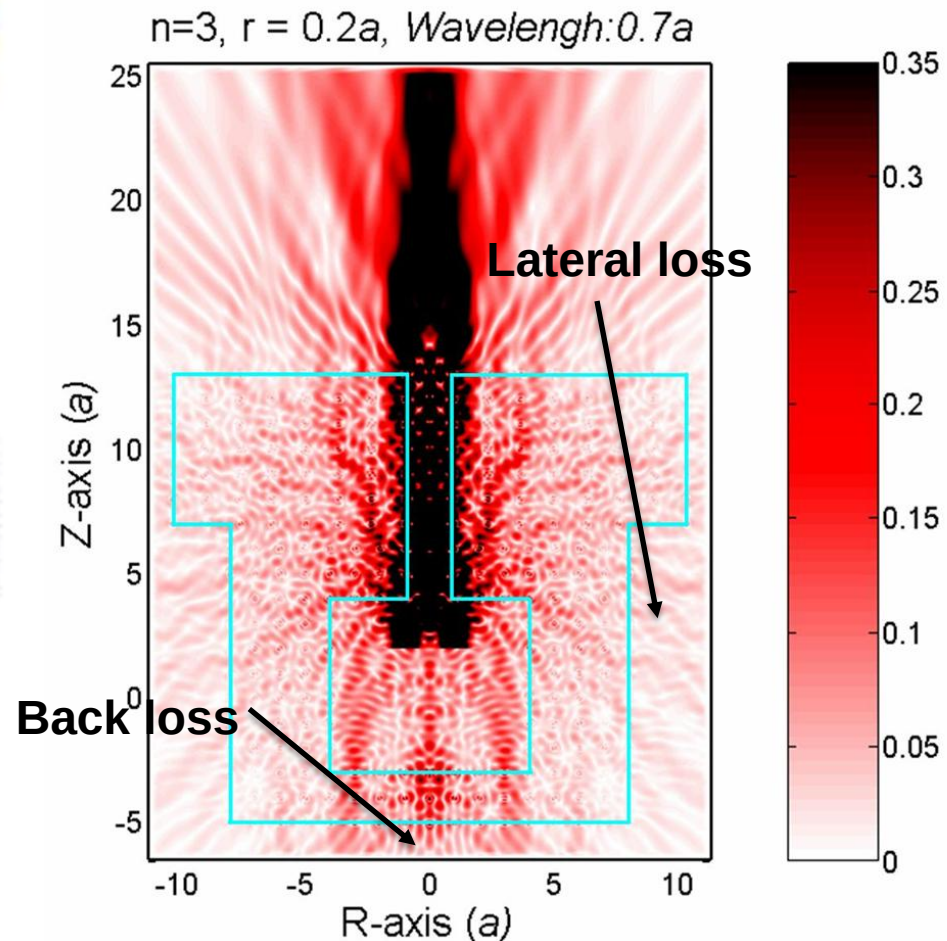
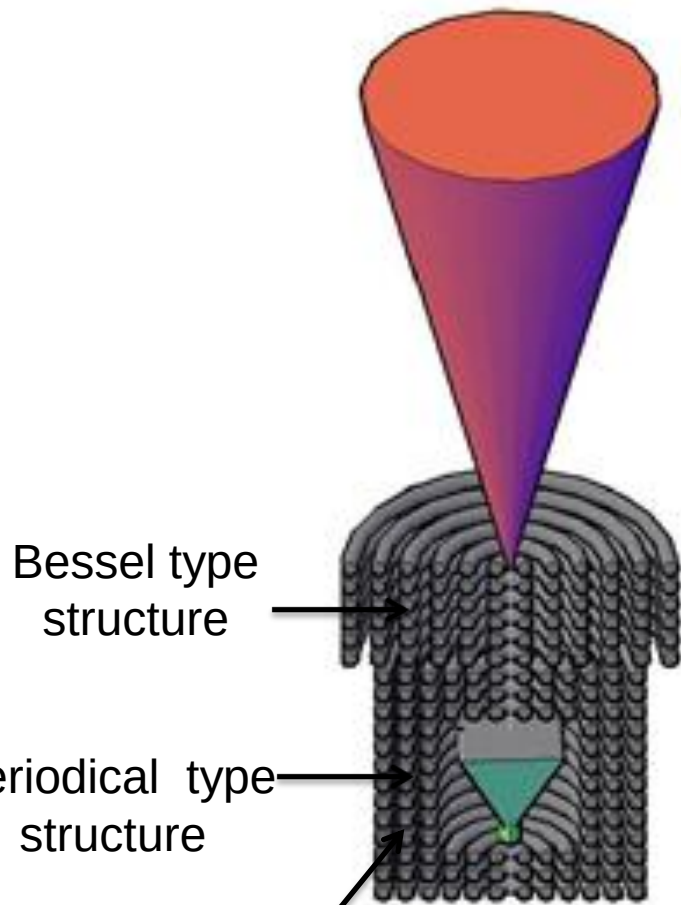


(a) periodic-type (b) Bessel-type
torus waveguides

accepted by Photonics and Nanostructures -
Fundamentals and Applications

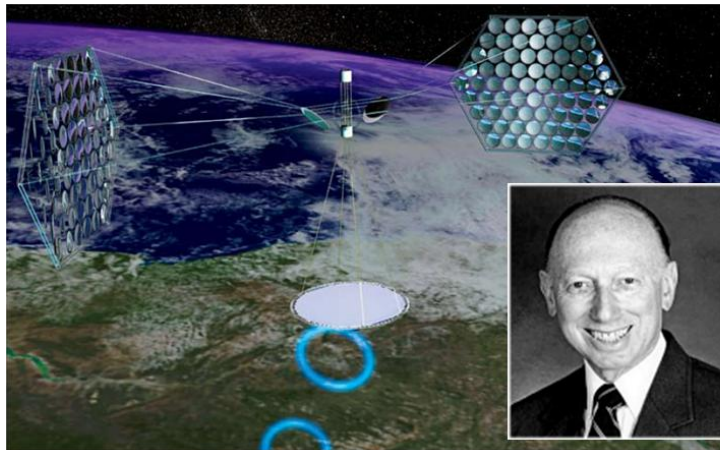


Application of Torus

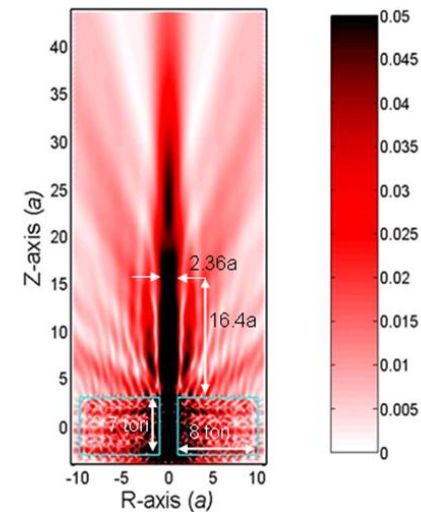
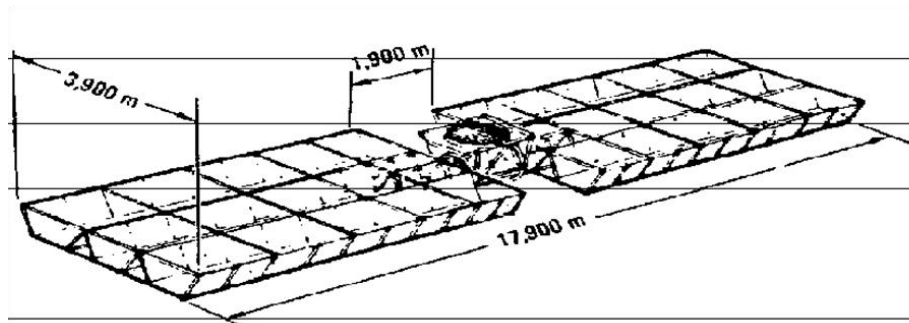
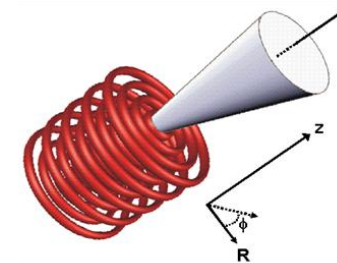


Application

1968 USA Little Inc. Dr. Glaser
Science **162**, p. 857 (1968)

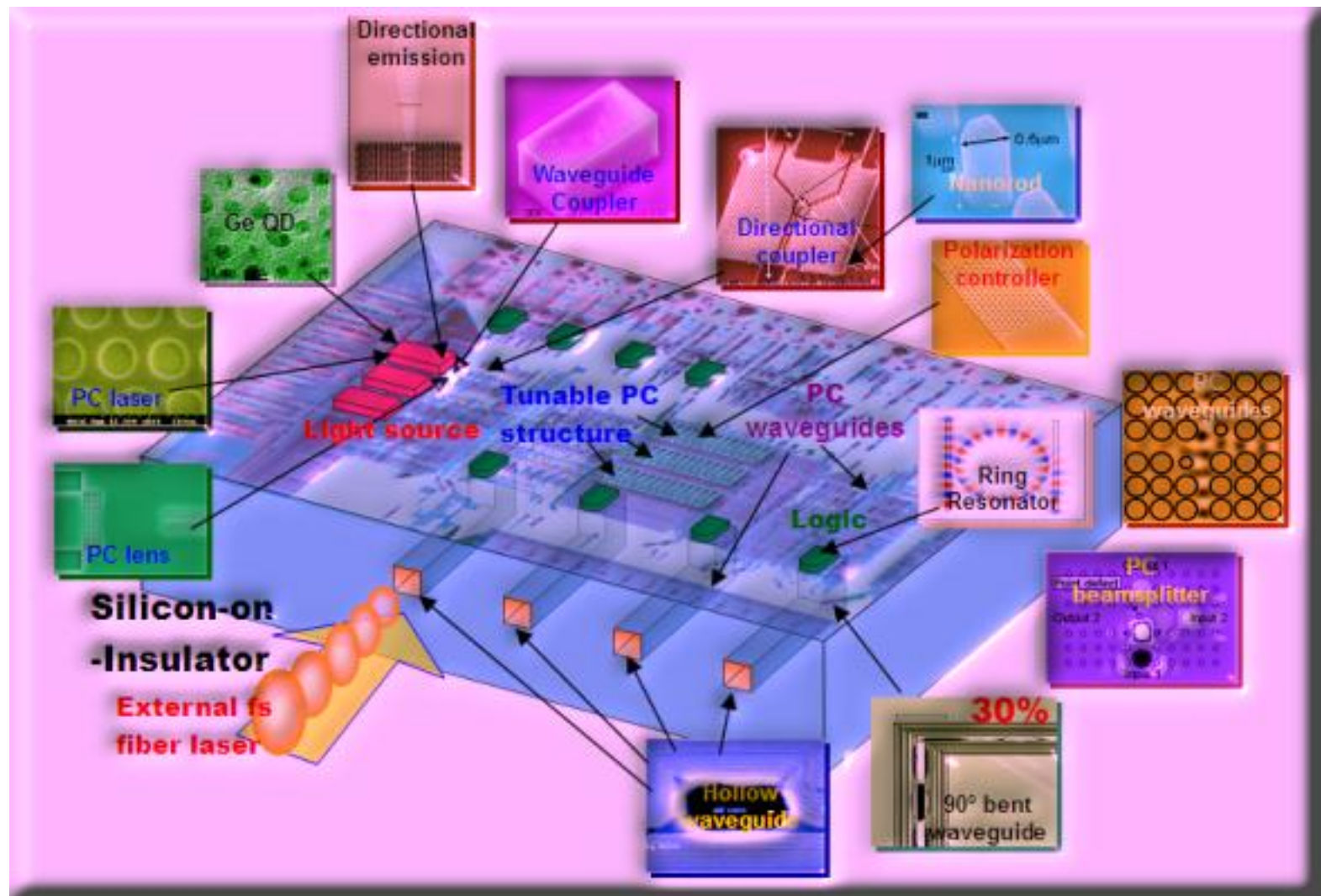


Torus waveguide



Chii-Chang Chen, Ya-Lun Tsai, Ching-Yi Chen, Jenq-Yang Chang, "Method of fabricating hollow waveguide having cyclic geometric structure," **US patent: 7,780,863 B2, Aug. 24, 2010**

All-optical PC integrated circuit



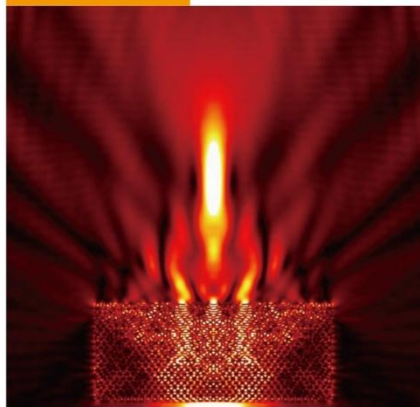
Book in chinese

光子晶體

從蝴蝶翅膀到奈米光子學

Photonic Crystals

樂丕綱 陳啓昌 著



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樂丕綱



陳啓昌



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Acknowledgement

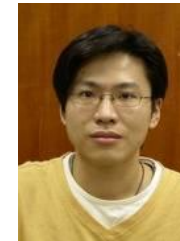
Assistant
researcher



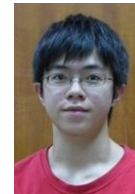
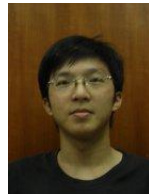
post-doc



Ph. D. students



Master students



Students from Univ. Paris 13



Chii-Chang Chen
trich@dop.ncu.edu.tw



Thanks for your attention

