ISLC

Sep. 12, 2016

Progress and Future Prospects of Photonic Crystal Lasers

SUSUMU NODA

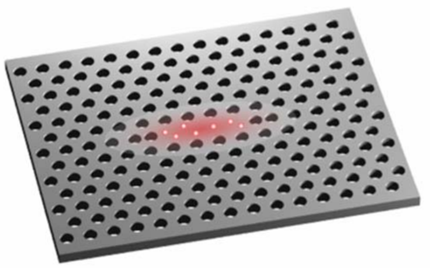
Department of Electronic Science and Engineering,

Kyoto University

Two-Types of Photonic Crystal Lasers

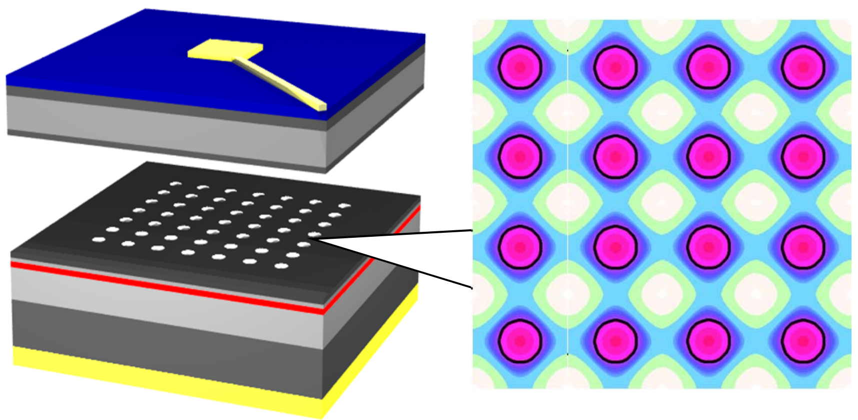
Photonic Crystal Nanolasers

(Photonic Crystal Nanocavities)



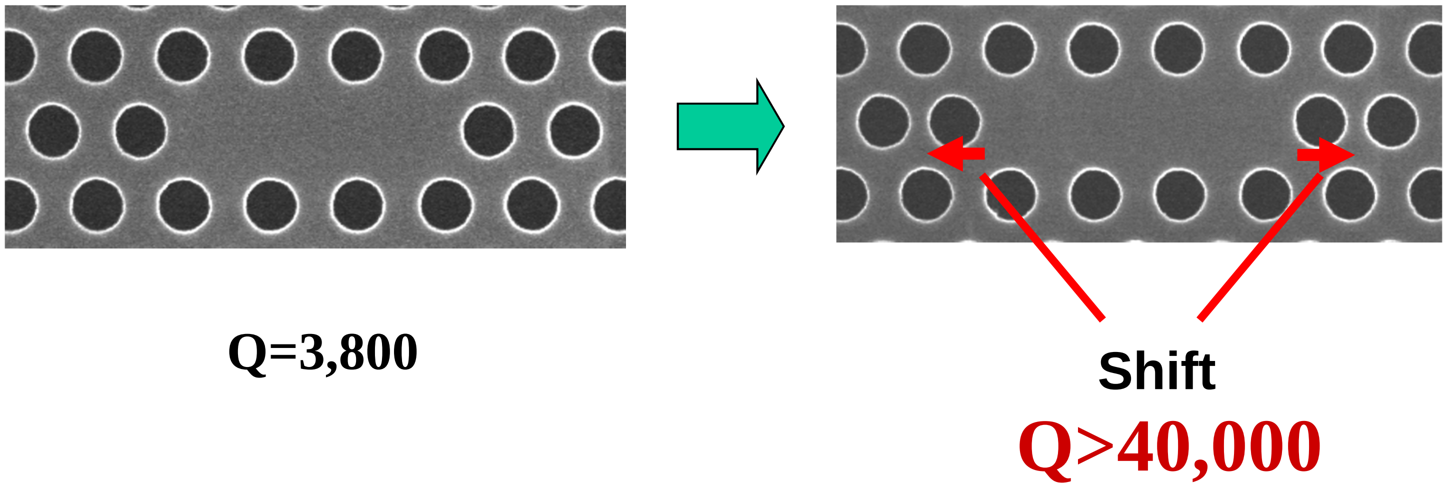
Photonic Crystal Broad-Area Lasers

(Photonic Band-edge Effects)



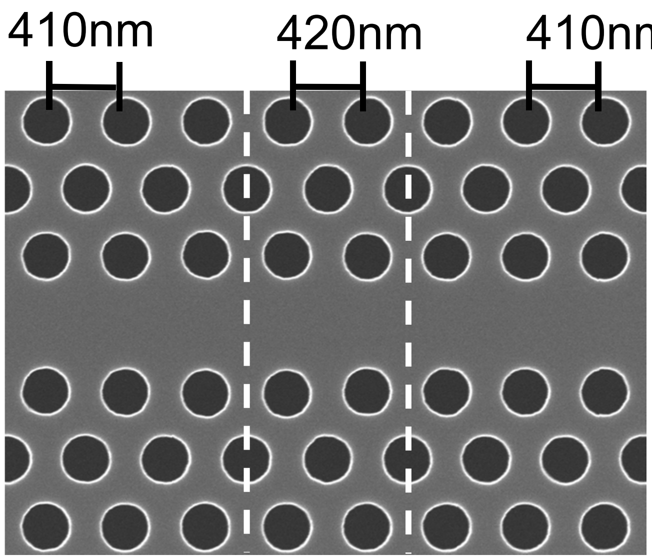
Progress in Nanolasers are based on:

Finding of Concept to Increase *Q* factor of Photonic Crystal Nanocavity



Akahane, Asano, Song, Noda, *Nature* (Oct., 2003)

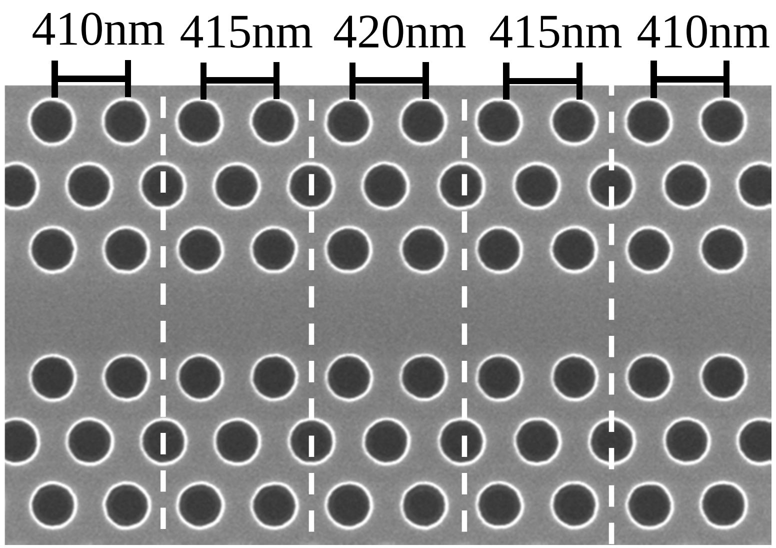
Key Point: Gentle Confinement (Ideally, Gaussian Confinement)



Double Heterostructure

Q=600,000

Song, Noda, et al, Nature Mat., 4 (2005) 207

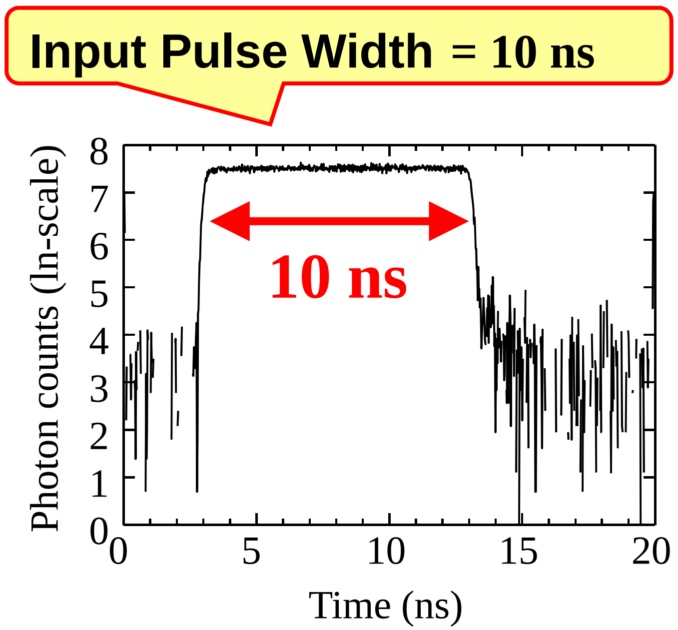


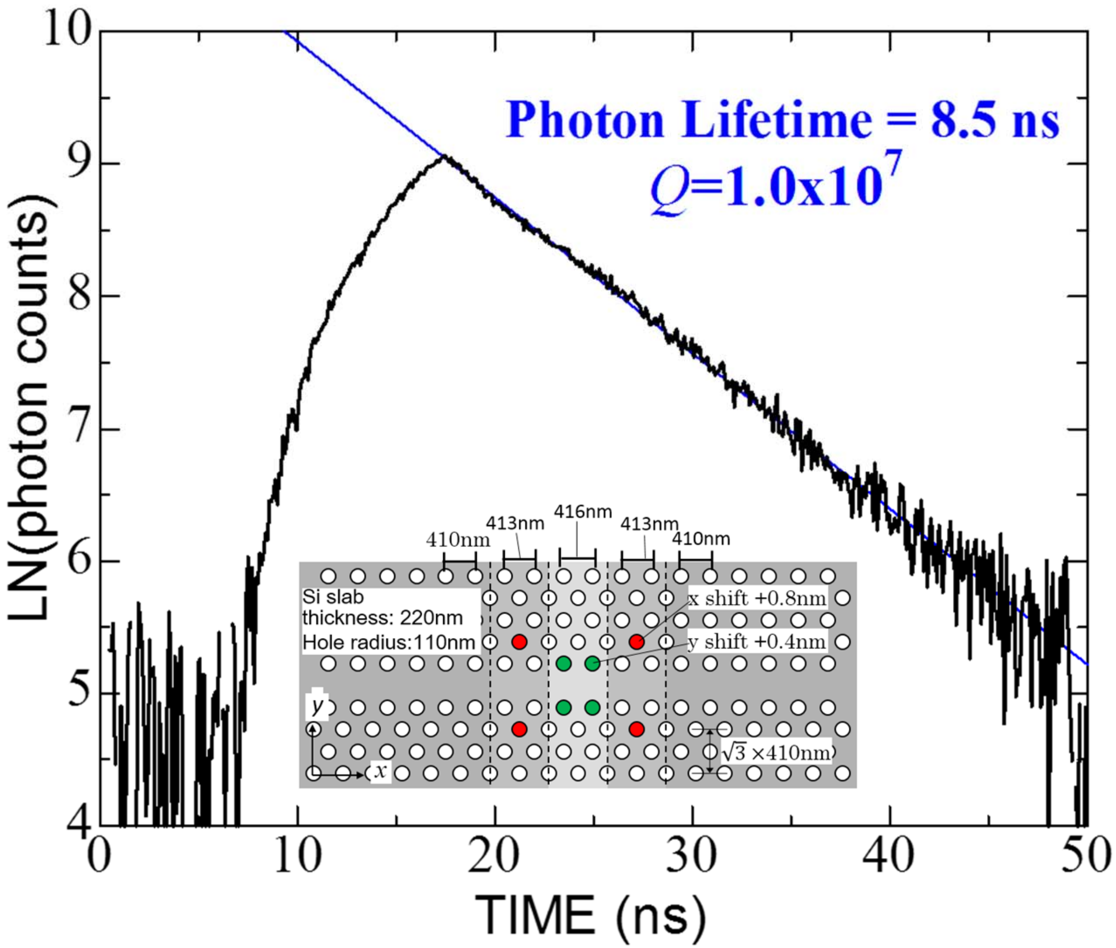
Multi-step Heterostructure

Q=2,500,000

Noda, et al, Nature Photonics, 1 (2007) 449

Latest Results

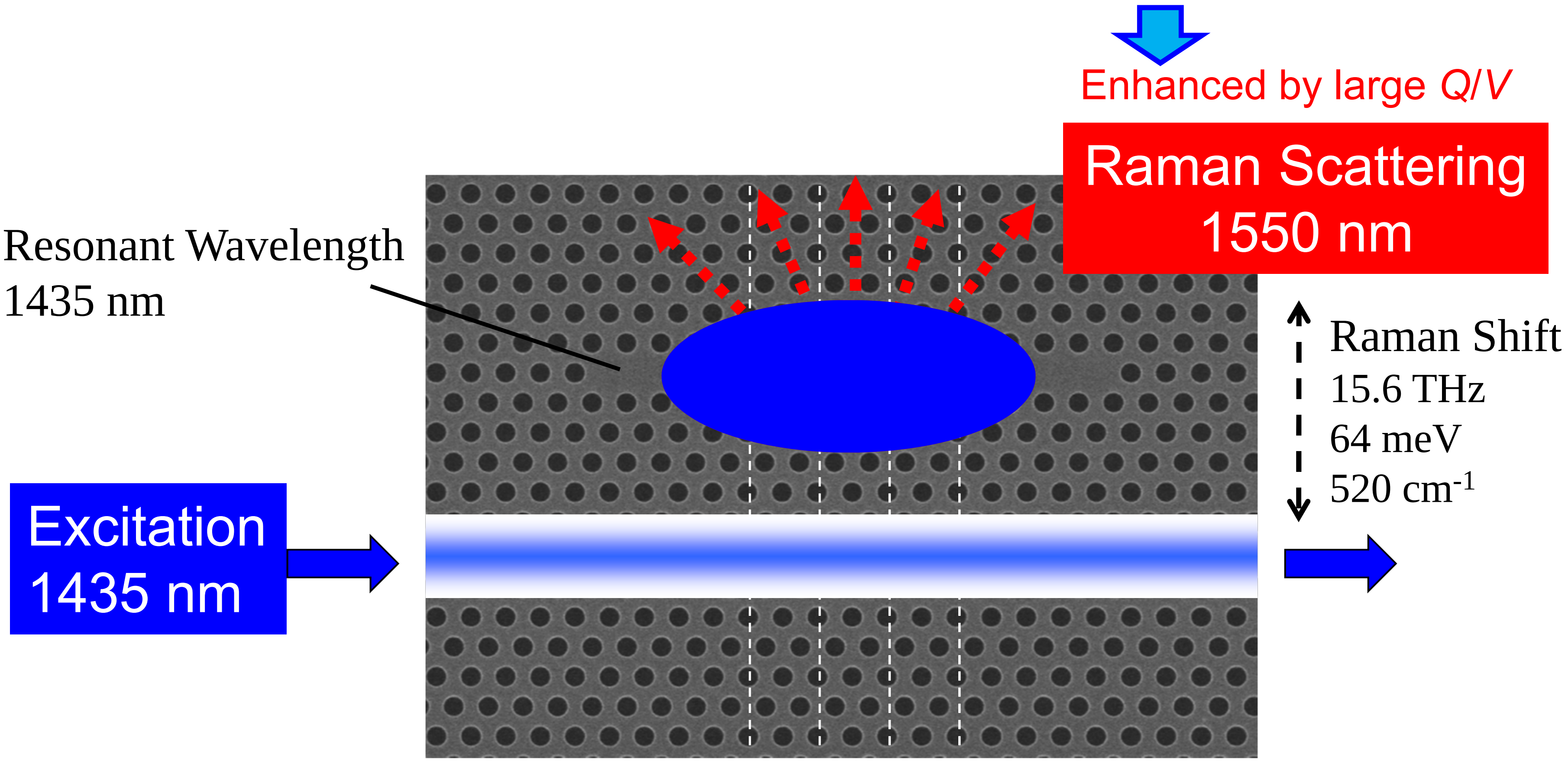


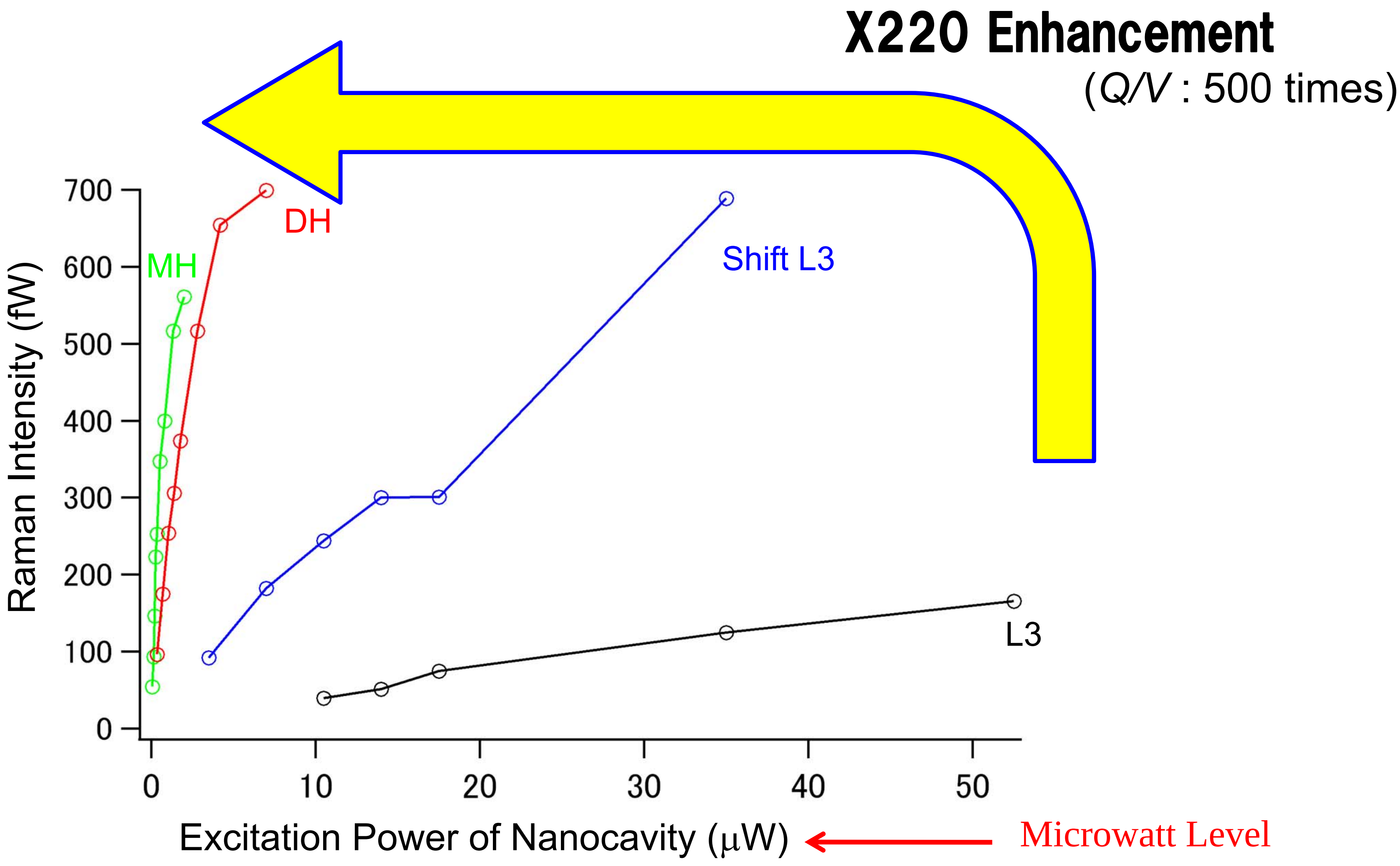


Q > 10,000,000 has been achieved

High-*Q* Photonic Crystal Nanocavity enables even Si Nano (Raman) Laser

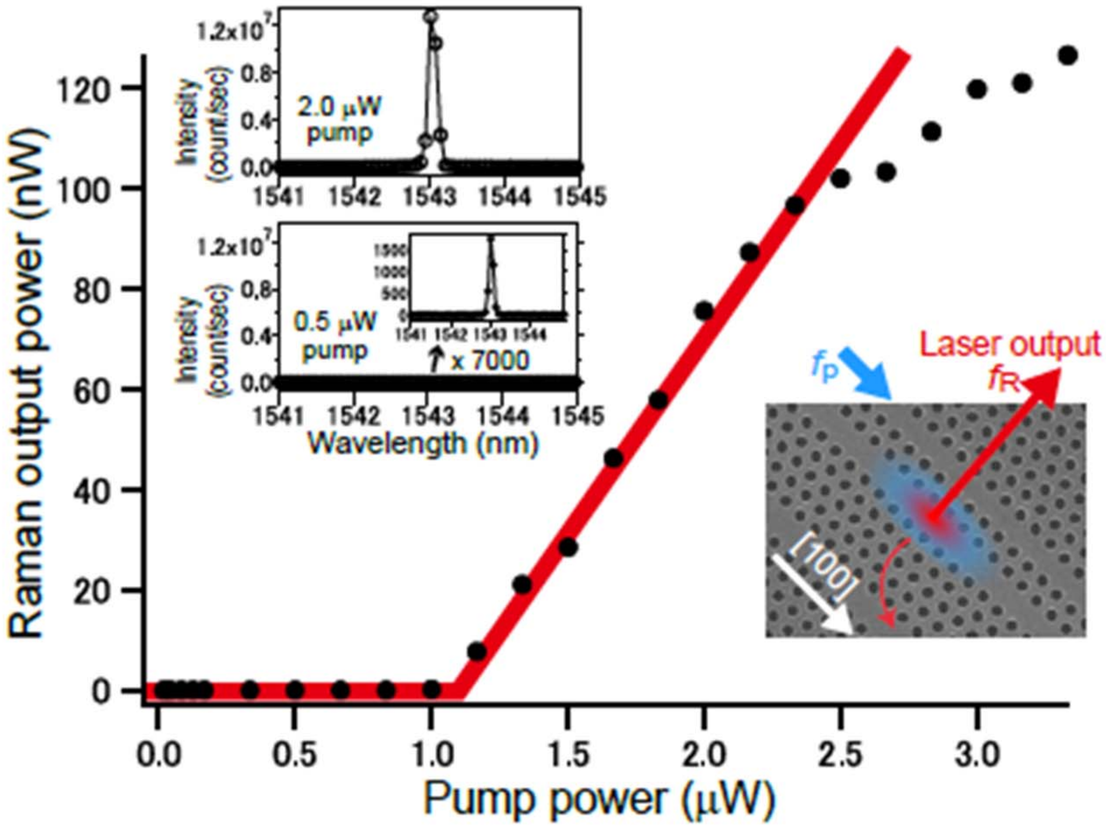
Raman Scattering is expected to be enhanced with increasing *Q*/*V*




X220 Enhancement
(Q/V : 500 times)
Raman Intensity (fW)
700
600
500
400
300
200
100
0
MH
DH
Shift L3
L3
0
10
20
30
40
50
Excitation Power of Nanocavity (μW)
Microwatt Level

Experimental Results

Micrometer-size and microwatt-threshold



RT operation and no PIN structure

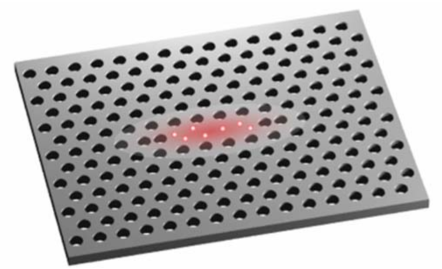
Nature (Takahashi, Inui, Asano, Noda, et al) (June 27, 2013)

Latest results: Threshold < 0.5μW, Efficiency > 19 %

Two-Types of Photonic Crystal Lasers

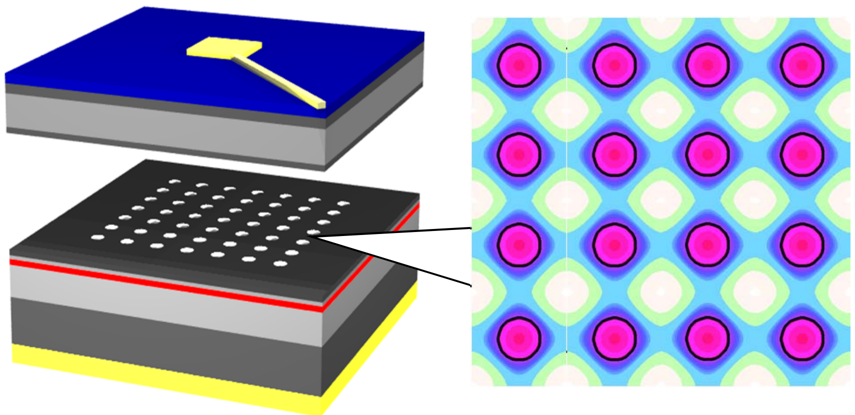
Photonic Crystal Nano-lasers

(Photonic Crystal Nanocavities)



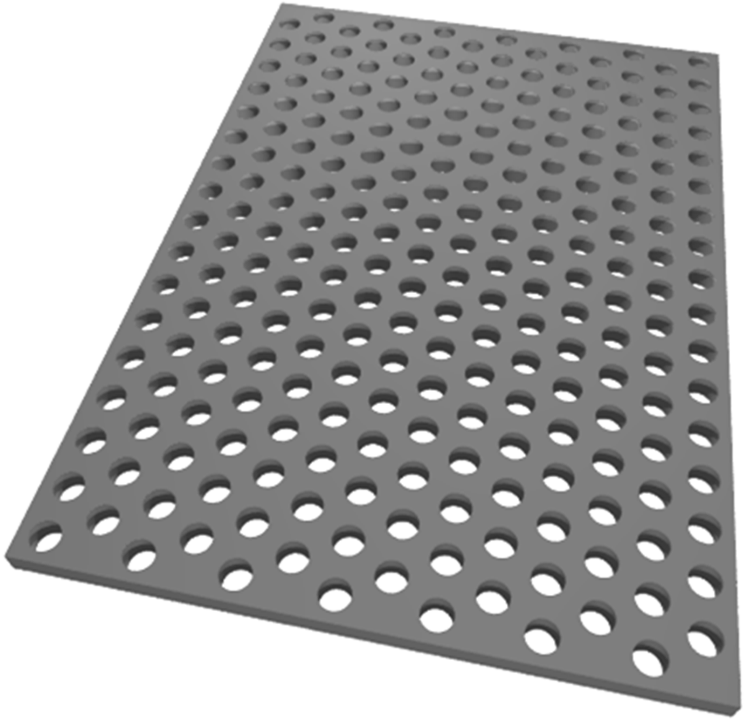
Photonic Crystal Broad-Area Lasers

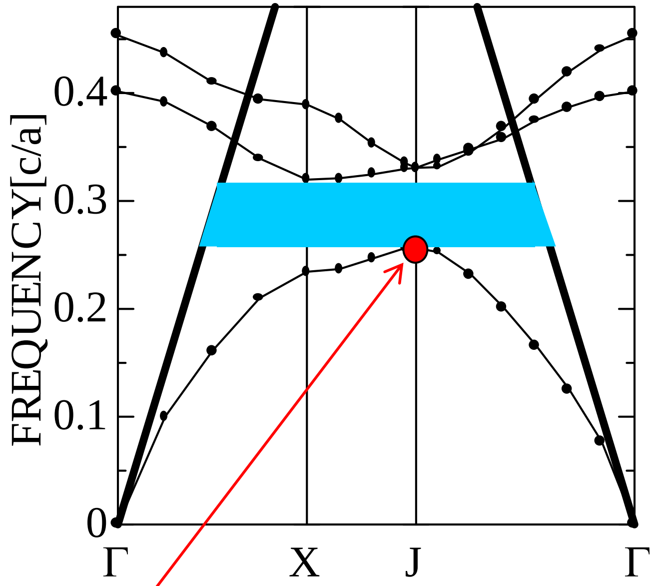
(Photonic Band-edge Effects)



Utilization of broad-area nature of 2D photonic crystal

No waveguide and no nanocavity



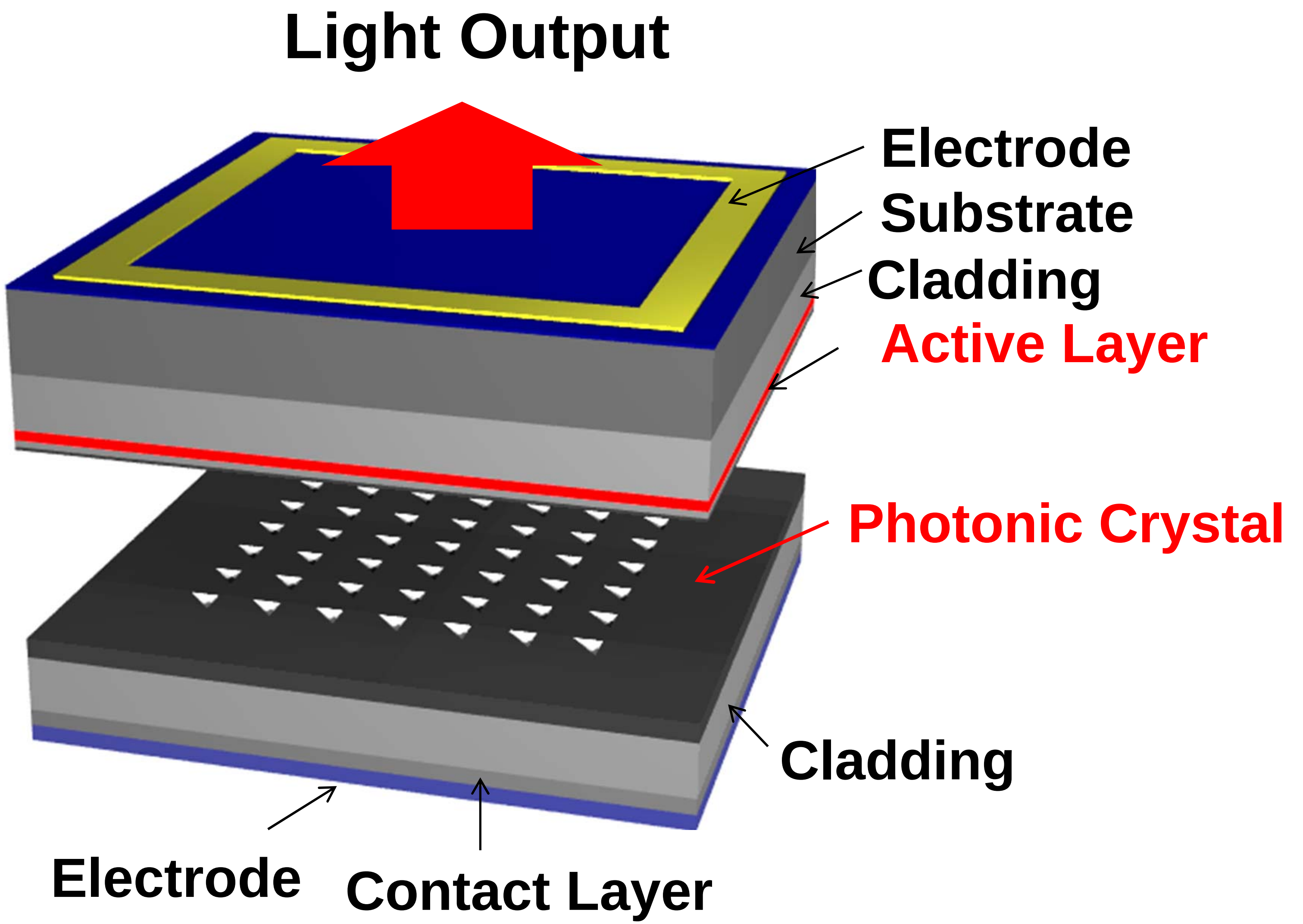


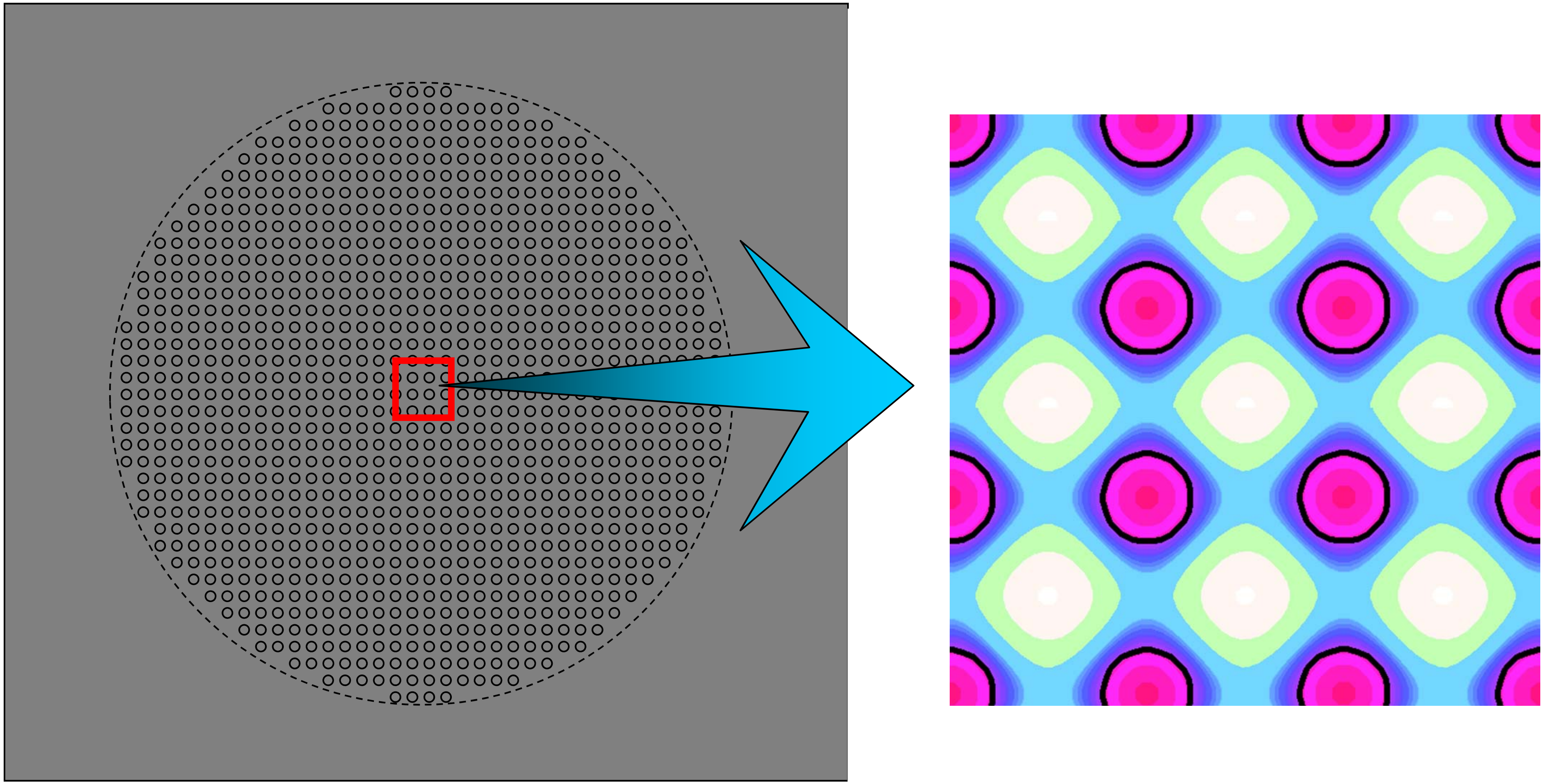
2D Bandgap

Utilization of photonic band-edge

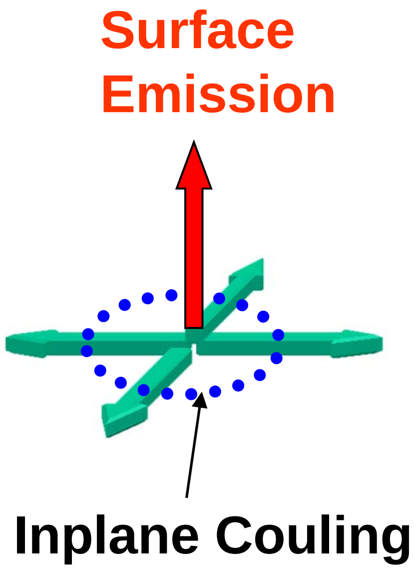
Bandedge-Based Photonic Crystal Lasers

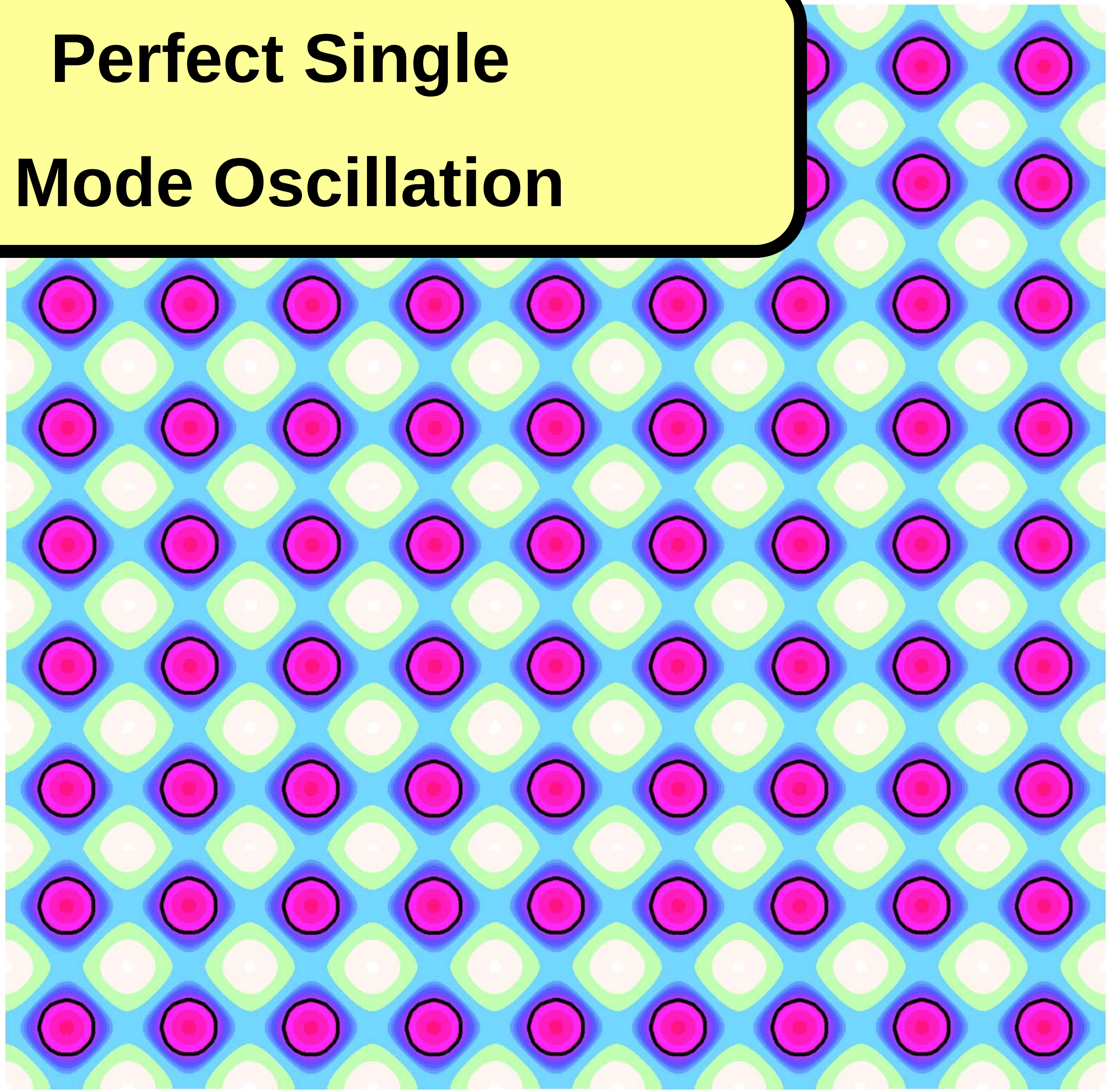
Distinctive feature: Broad-Area Coherent Oscillation



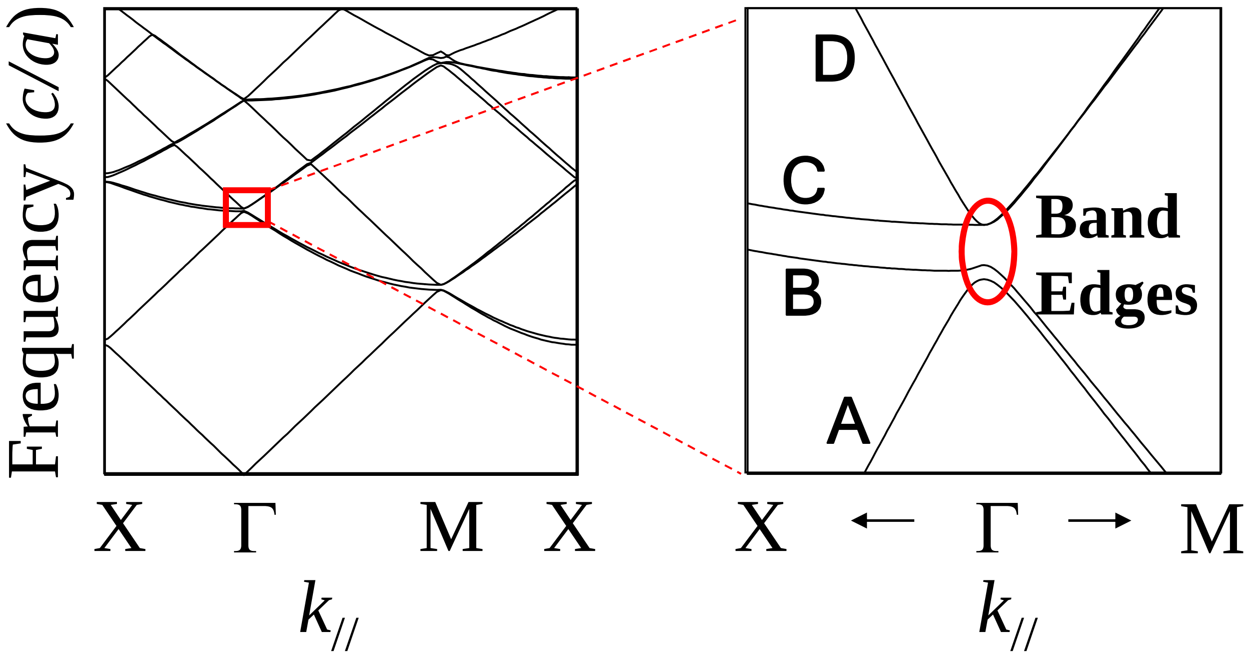


Perfect Single Mode Oscillation





Detailed Band Structure



Noda, et al, Science, 293, 1123 (2001)

Sakai, Noda, et al, *IEEE SAC* *(July 2005)*

Progress in Photonic Crystal Lasers

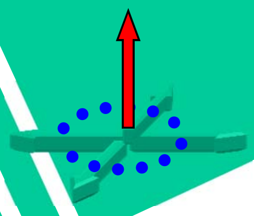
Commercially Available (0.2W class) (2014)

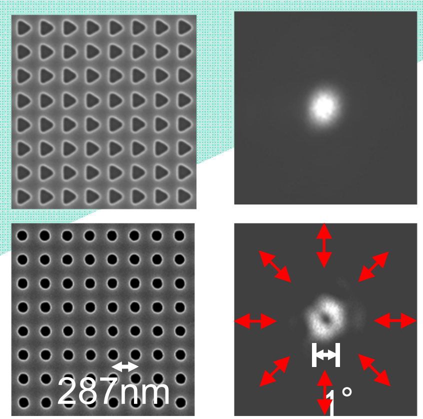
Realization of Beam Steering Function
Nat. Photon (2010)

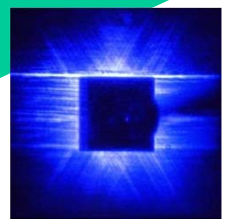
Expansion of Wavelength (Blue violet)
Science (2008)

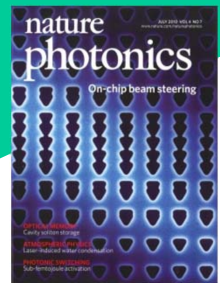
Control of Polarization and Beam Shape
Science (2001), Nature (2006)

Proposal and Demonstration of 2D Surface-Emitting Coherent Oscillation
APL (1999)



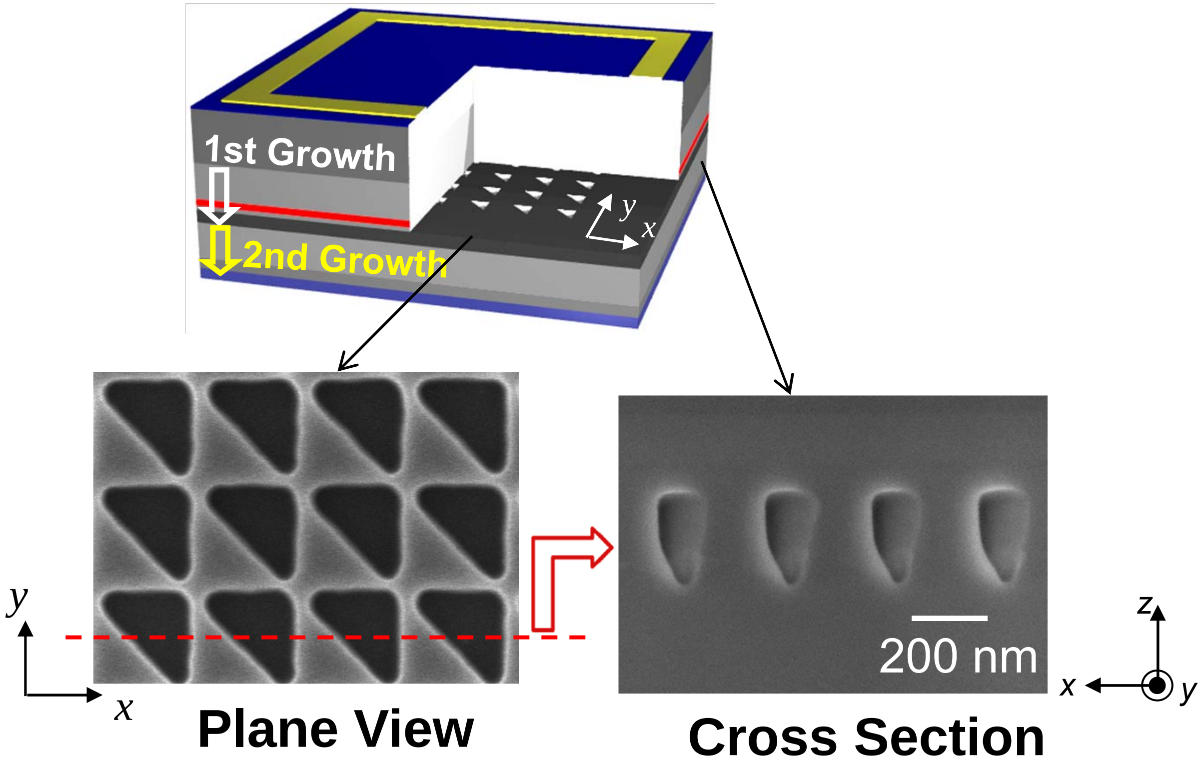






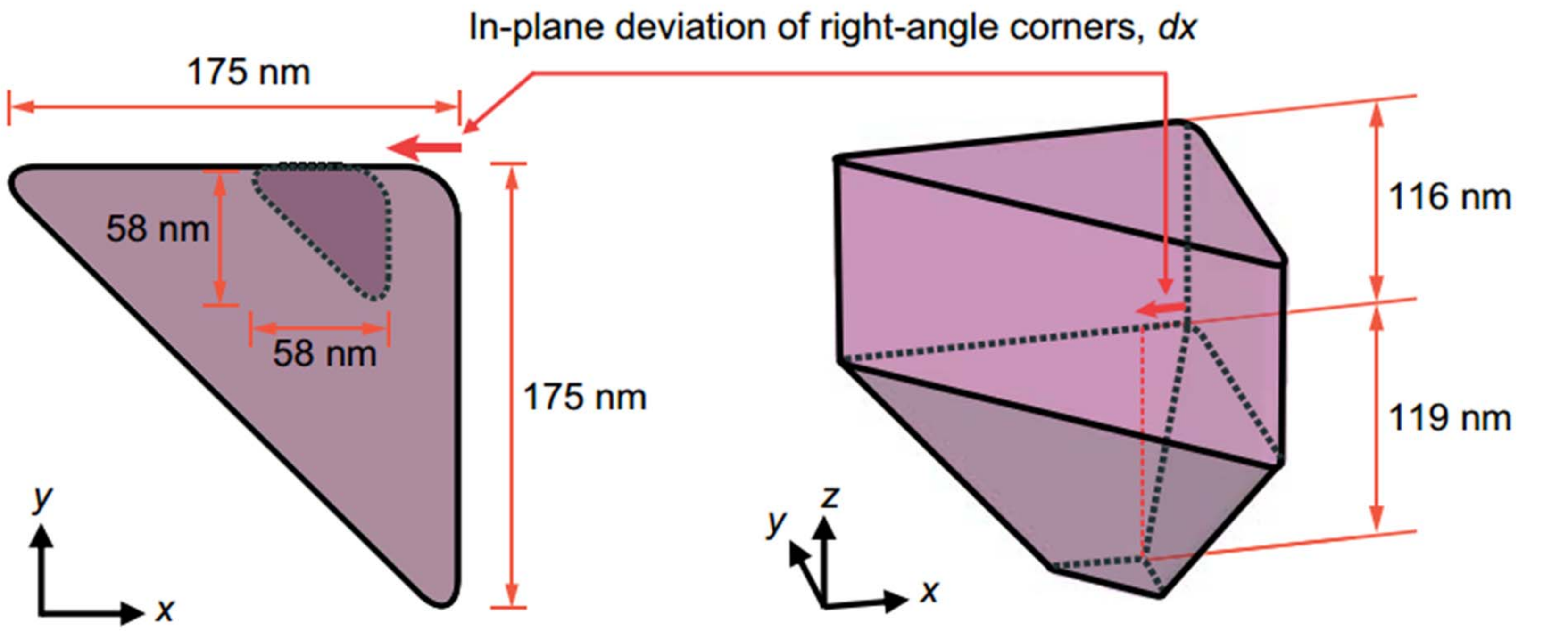
For CW Watt-Class High-Power Operation

Advanced MOCVD Growth of Photonic Crystals



Air holes have been well embedded

Embedded Air-hole Structure



Top View **Side View**

Air-hole structure is approximated by the combination of a triangular prism and a triangular pyramid

Analysis by 3D Coupled Wave Theory

Freq., Threshold Gain

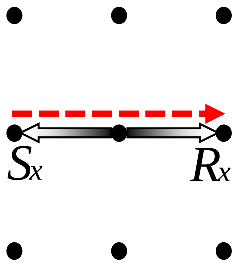
$$
\begin{cases}
(\delta+i\alpha)R_x=\kappa_{2,0}S_x-\dfrac{k_0^2}{2\beta_0}\displaystyle\int_{PC}\xi_{1,0}(z)\Delta E_y(z)\Theta_0^*(z)dz-\dfrac{k_0^2}{2\beta_0}\sum_{others}\int_{PC}\xi_{1-m',-n'}(z)E_{y,m',n'}(z)\Theta_0^*(z)dz+i\dfrac{\partial R_x}{\partial x}, \\
(\delta+i\alpha)S_x=\kappa_{-2,0}R_x-\dfrac{k_0^2}{2\beta_0}\displaystyle\int_{PC}\xi_{-1,0}(z)\Delta E_y(z)\Theta_0^*(z)dz-\dfrac{k_0^2}{2\beta_0}\sum_{others}\int_{PC}\xi_{-1-m',-n'}(z)E_{y,m',n'}(z)\Theta_0^*(z)dz-i\dfrac{\partial S_x}{\partial x}, \\
(\delta+i\alpha)R_y=\kappa_{0,2}S_y-\dfrac{k_0^2}{2\beta_0}\displaystyle\int_{PC}\xi_{0,1}(z)\Delta E_x(z)\Theta_0^*(z)dz-\dfrac{k_0^2}{2\beta_0}\sum_{others}\int_{PC}\xi_{-m',1-n'}(z)E_{x,m',n'}(z)\Theta_0^*(z)dz+i\dfrac{\partial R_y}{\partial x}, \\
(\delta+i\alpha)S_y=\kappa_{0,-2}R_y-\dfrac{k_0^2}{2\beta_0}\displaystyle\int_{PC}\xi_{0,-1}(z)\Delta E_x(z)\Theta_0^*(z)dz-\dfrac{k_0^2}{2\beta_0}\sum_{others}\int_{PC}\xi_{-m',-1-n'}(z)E_{x,m',n'}(z)\Theta_0^*(z)dz-i\dfrac{\partial S_y}{\partial x}.
\end{cases}
$$

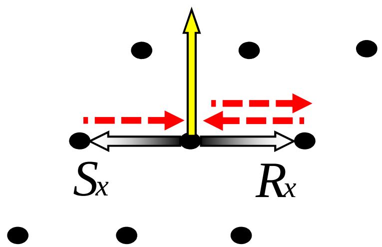
Coupling of Fundamental Waves

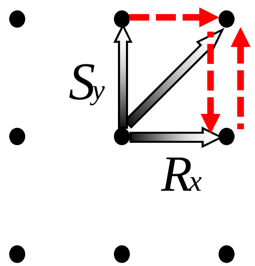
Vertical Radiation

Coupling with higher-order Modes

Finiteness Space Variation

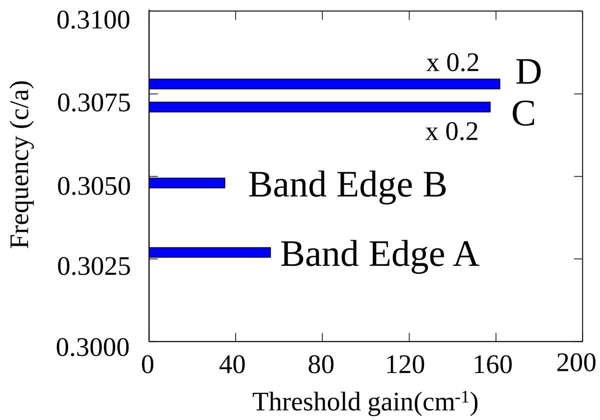






Calculated Results

▪**Threshold gains and frequencies.**



Lasing Band Edge: B,
(κ_3=1,400cm^{-1}, κ_1=570cm^{-1})

▪**Radiation Constant, Slope Efficiency**

$\alpha_{rad} = (\alpha_{up\text{-}rad}+\alpha_{down\text{-}rad}) = (16cm^{-1}+21cm^{-1}) = 37cm^{-1}$

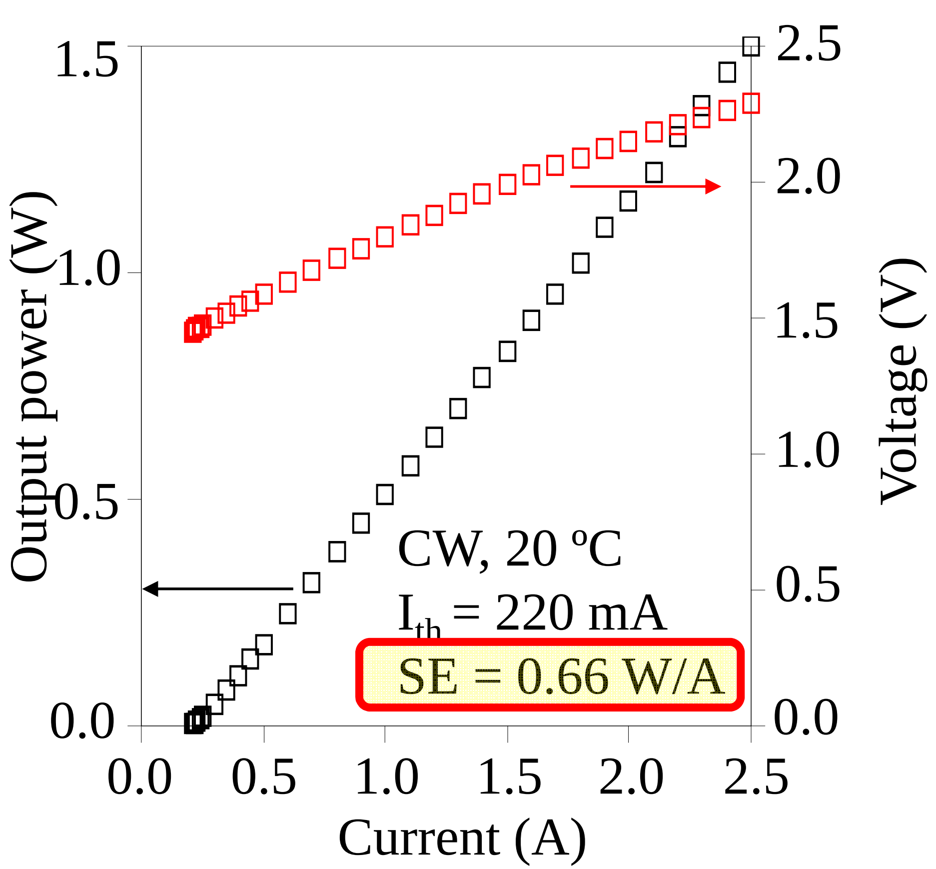
η=0.66 [W/A] (with electrode-reflectivity magnitude and phase of 0.8 and 120 degree, respectively)

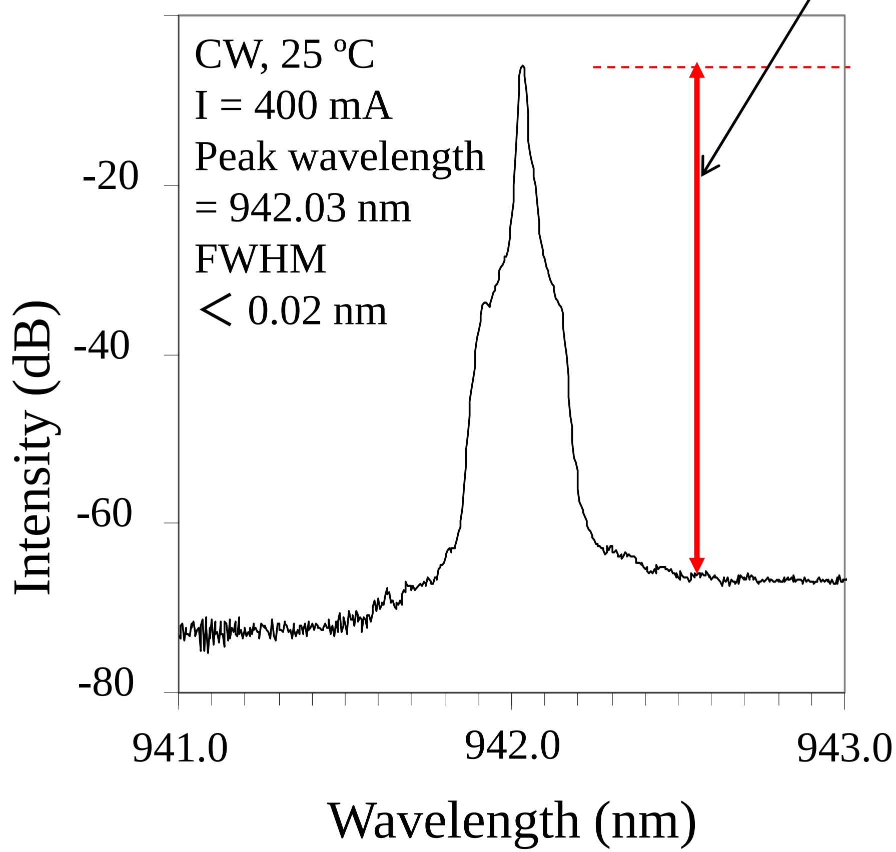
Experimental Characterization

Light Output Power Characteristics (200μmx200μm, RT CW)

Output of 1.5 W

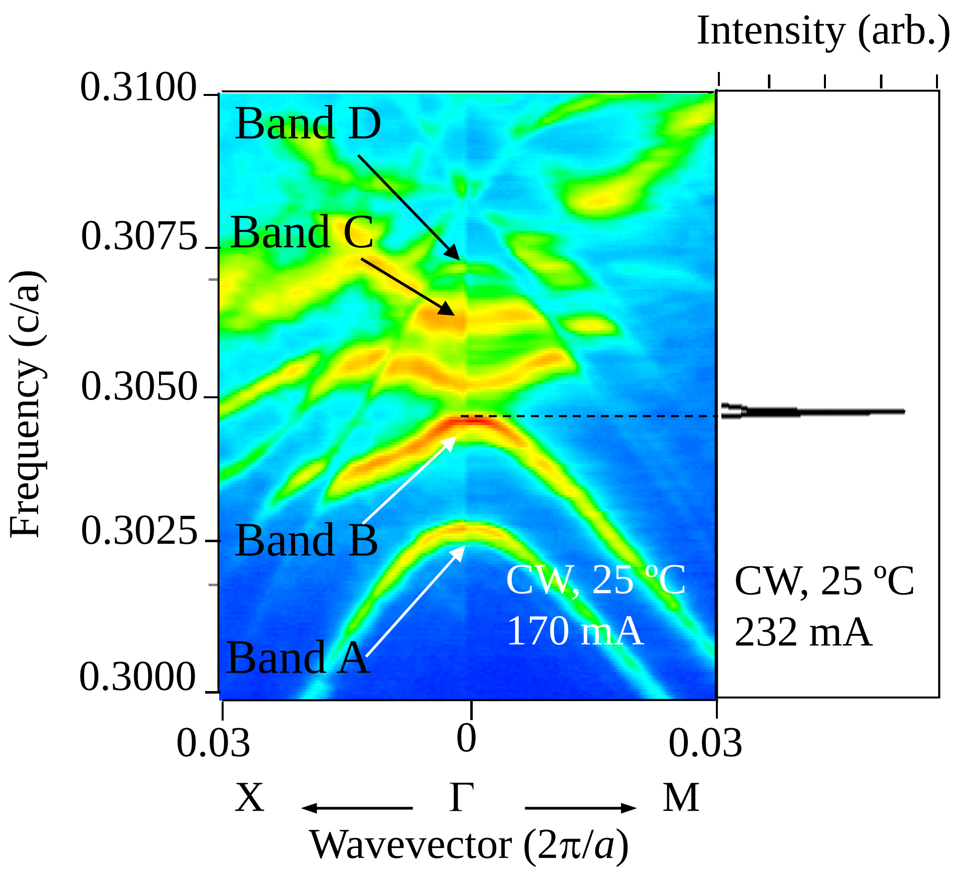
Side mode suppression＞60dB



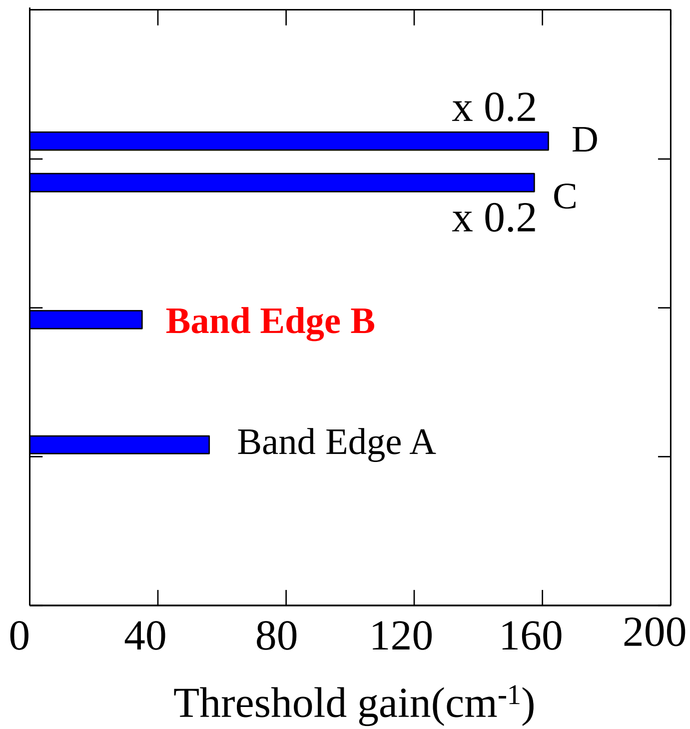


Lasing-Band Edge Identification

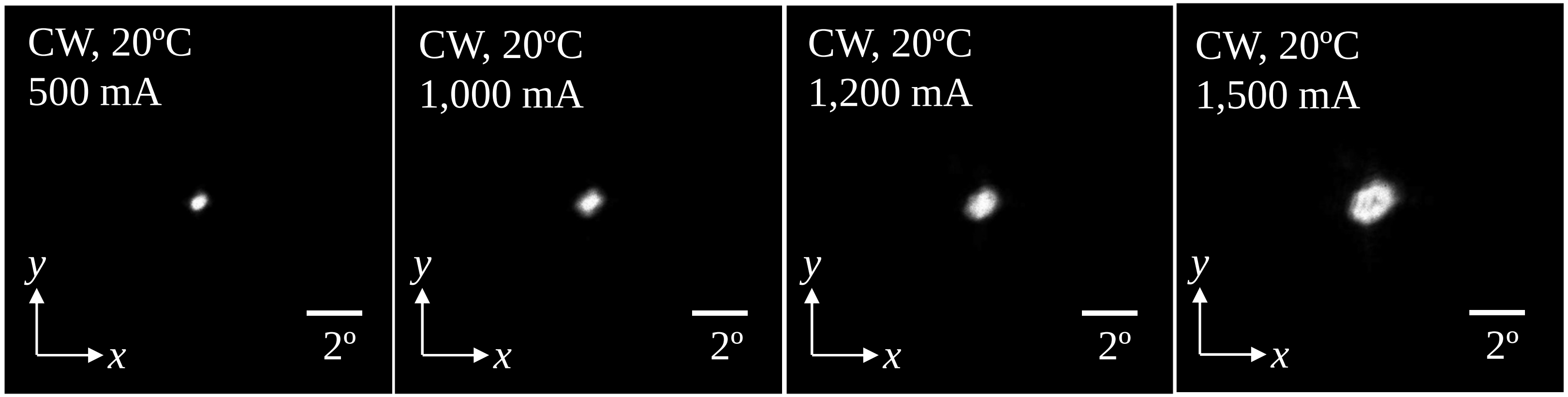
Experiment

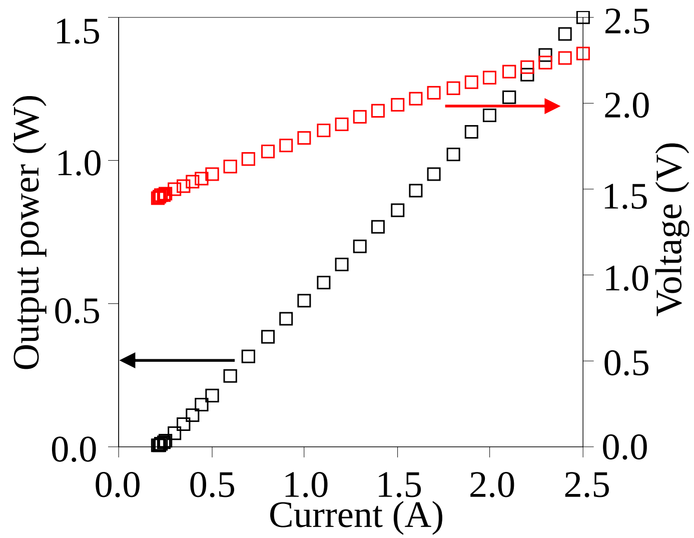


Theory



Far-Field Patterns

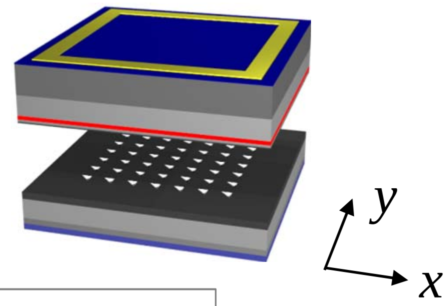


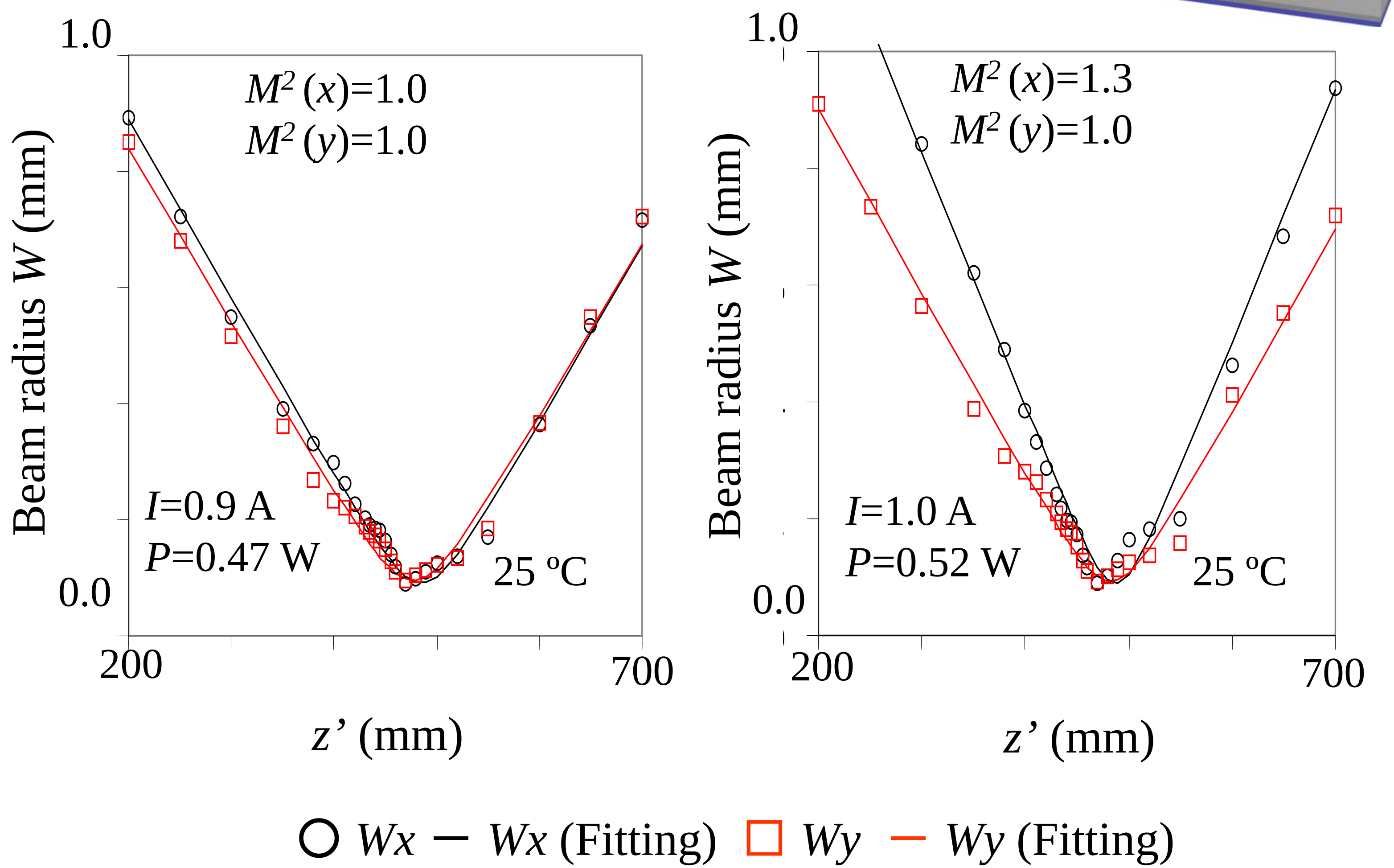


Beam Divergence Angle < 3 degree even at 1.5W

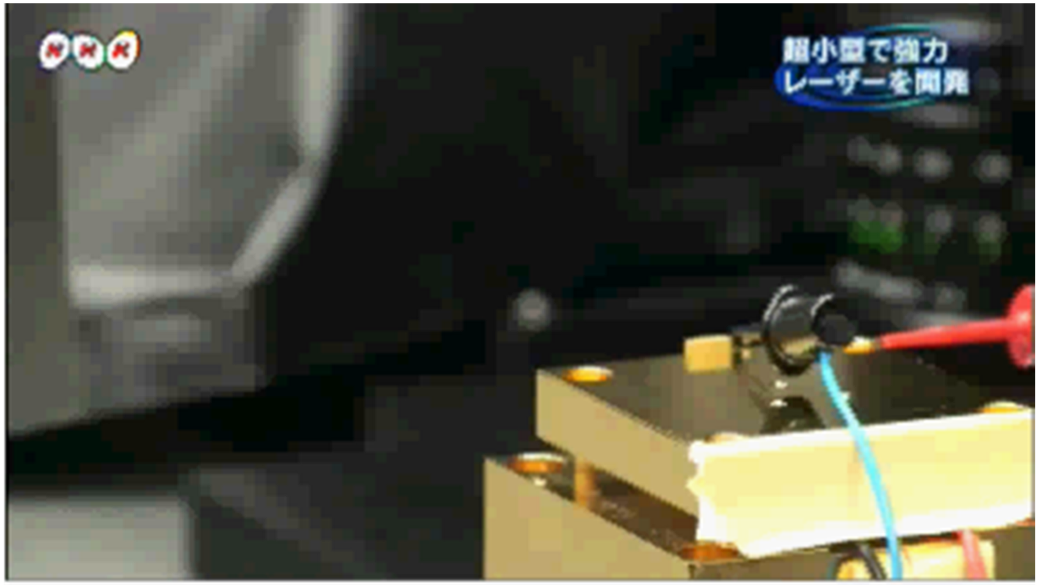
Evaluation of M^2 value

M^2~1.0 at Output power of 0.5W





Demonstration of Burning of a Piece of Paper without Lens

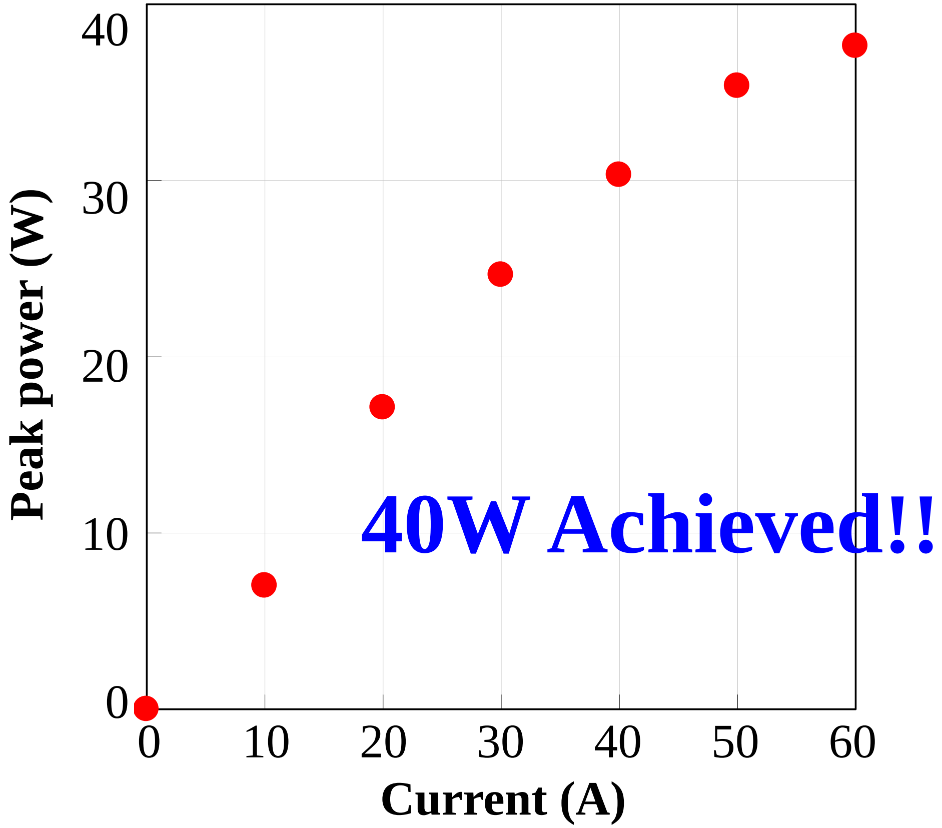


Hirose, Noda, et al, ***Nature Photonics*** *(April 2014)*

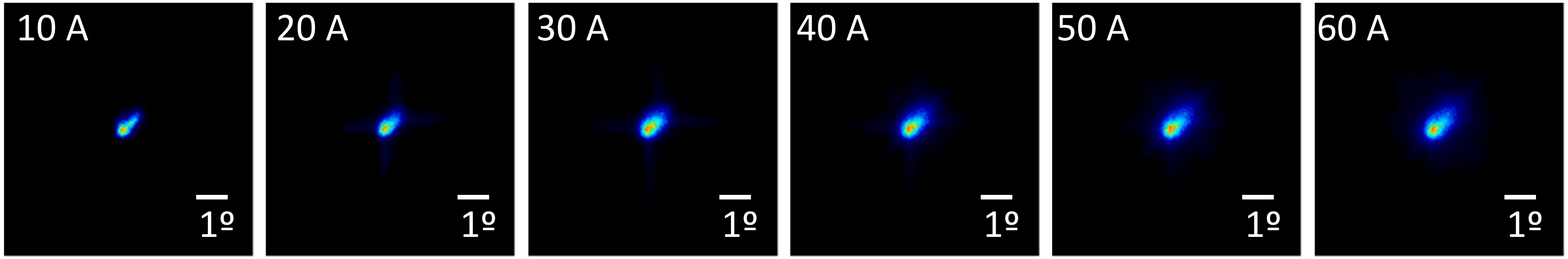
Pulse Operation

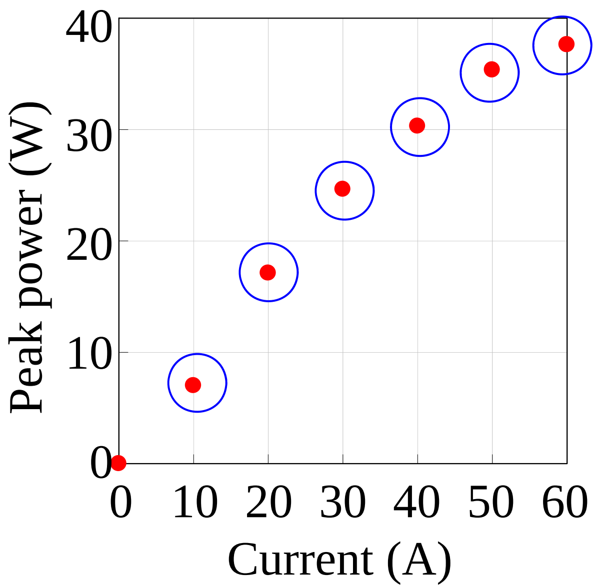
☆ PCSEL

- Pulse Width=100 ns
- Rate＝ 10 kHz
- Temp.＝20 °C
- Current＝60 A
- Output＝～40 W
- Ith=232 mA (@CW)
- Jth=0.58 kA/cm^2



Far-field Patterns



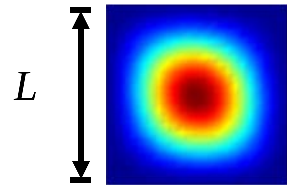


Beam Divergence <1º

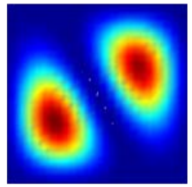
For Even Higher Power Operation

Device size should be increased

While keeping threshold gain difference between fundamental and higher-order modes

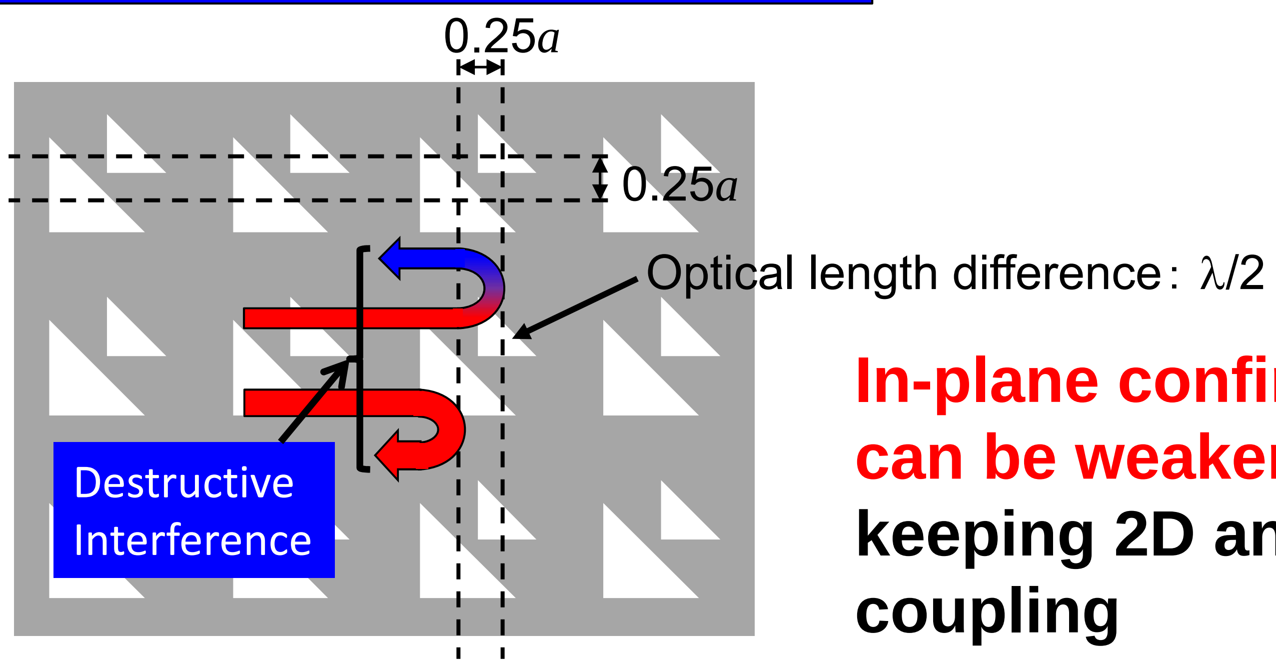


Fundamental Mode



Higher Mode

Double-Hole Structure



In-plane confinement can be weakened while keeping 2D and vertical coupling

The threshold gain of higher-order mode is increased more than that of the fundamental mode

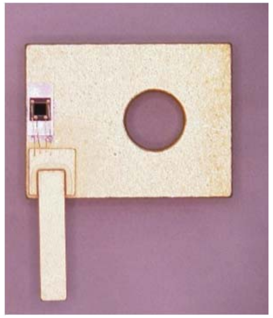
Breakthrough in Laser World for Material Processing

Big gas laser (or solid state laser) system can be miniaturized to one chip semiconductor laser

~ meter^3

<1/1,000,000

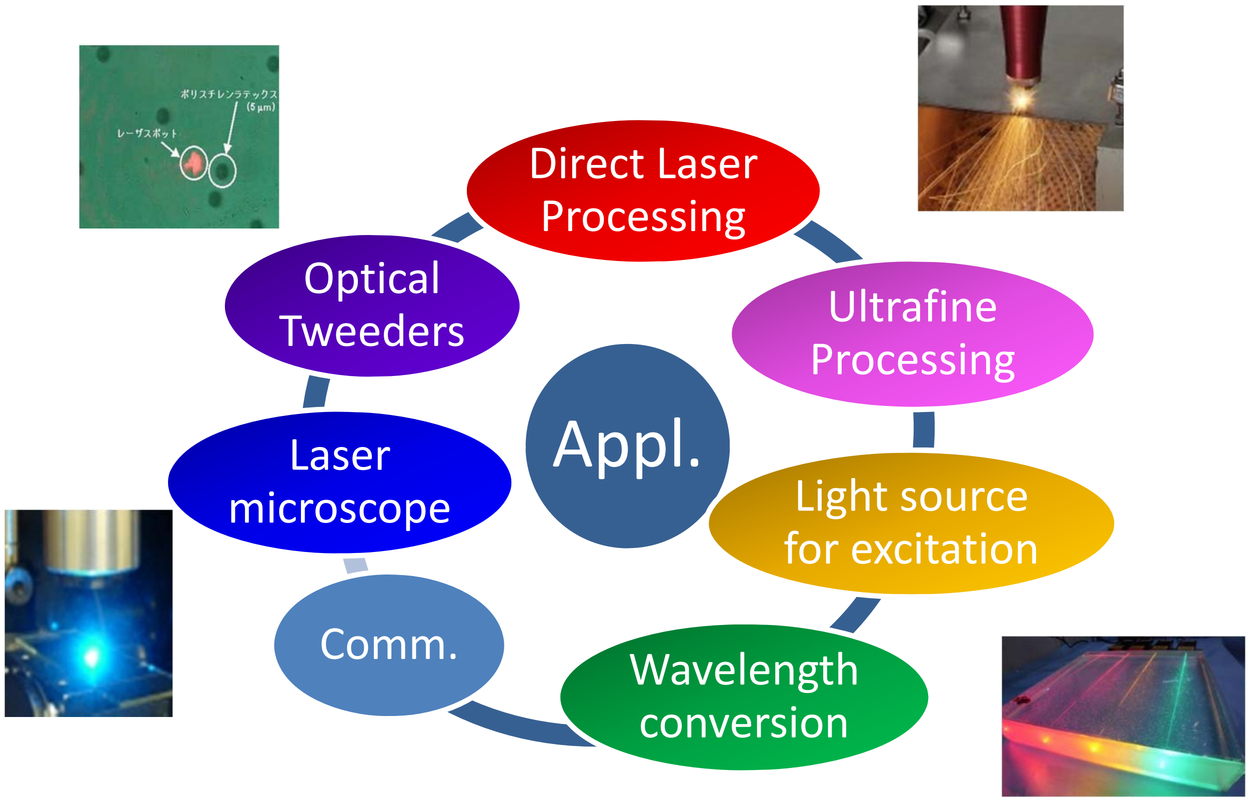
~ millimeter^3



CO_2 Laser System

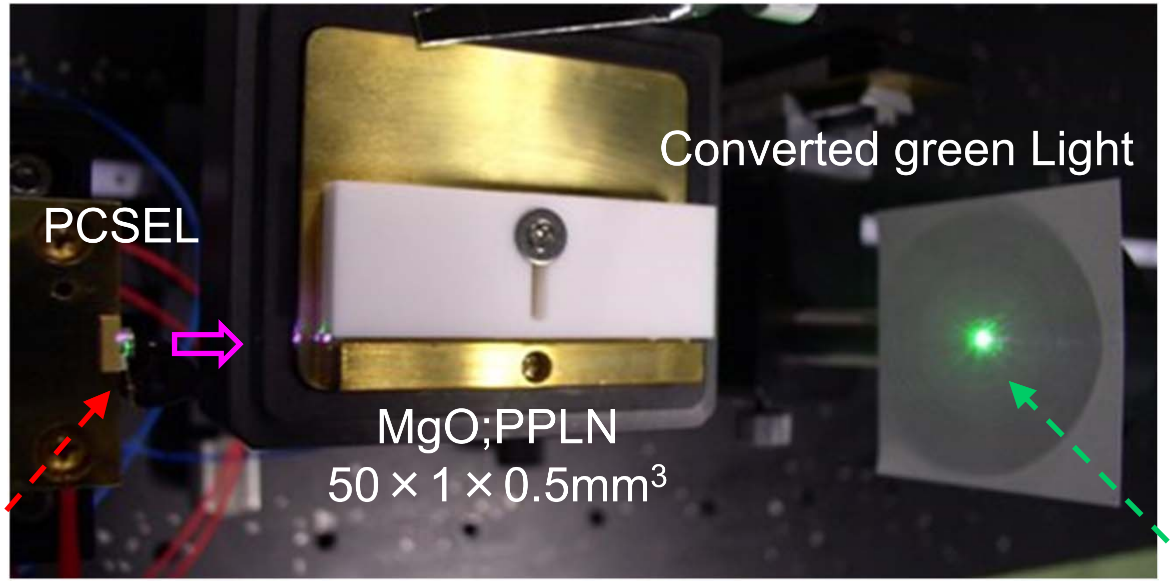
Photonic Crystal Laser

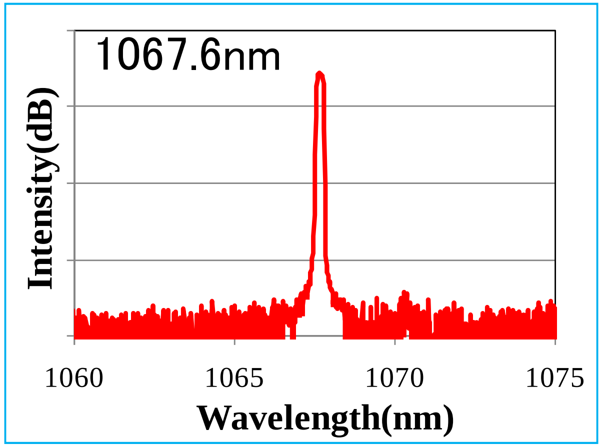
Examples of Various Applications

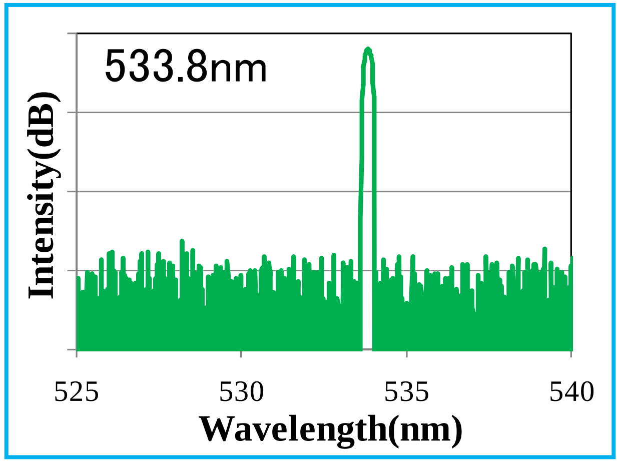


Wavelength Conversion

Lens-free Operation

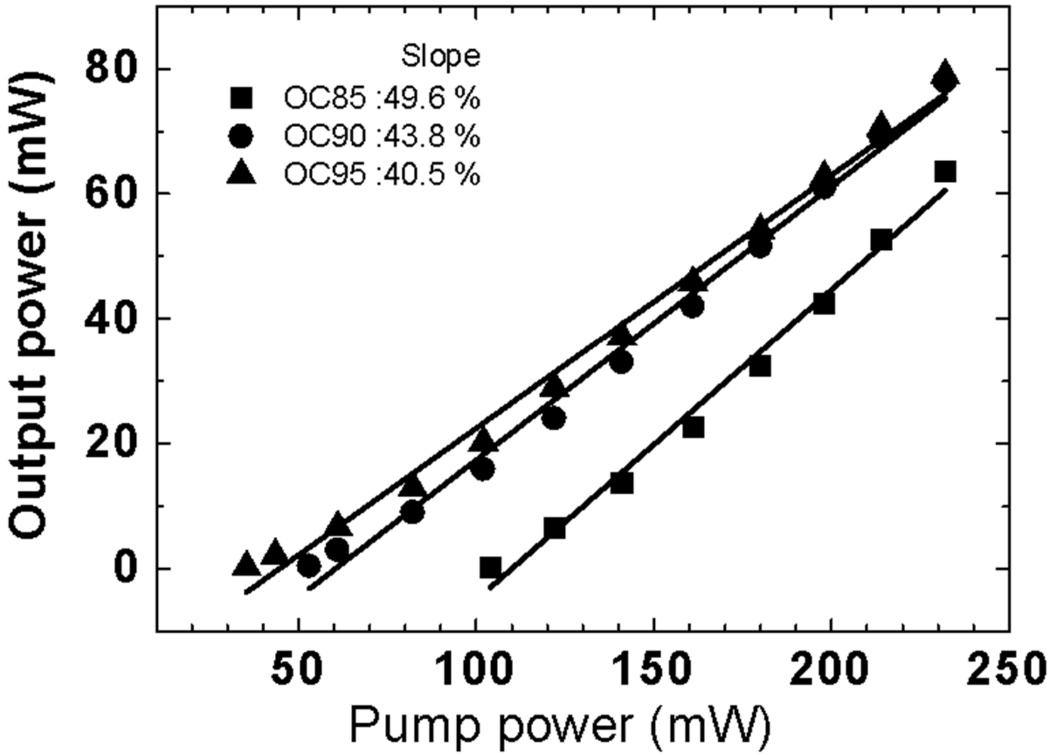


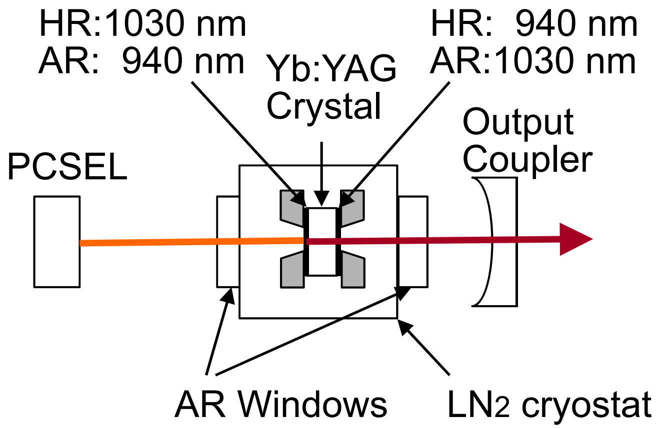




Light Source for Excitation
Yb:YAG Laser by PCSEL

Highly Efficient Lens-free Operation

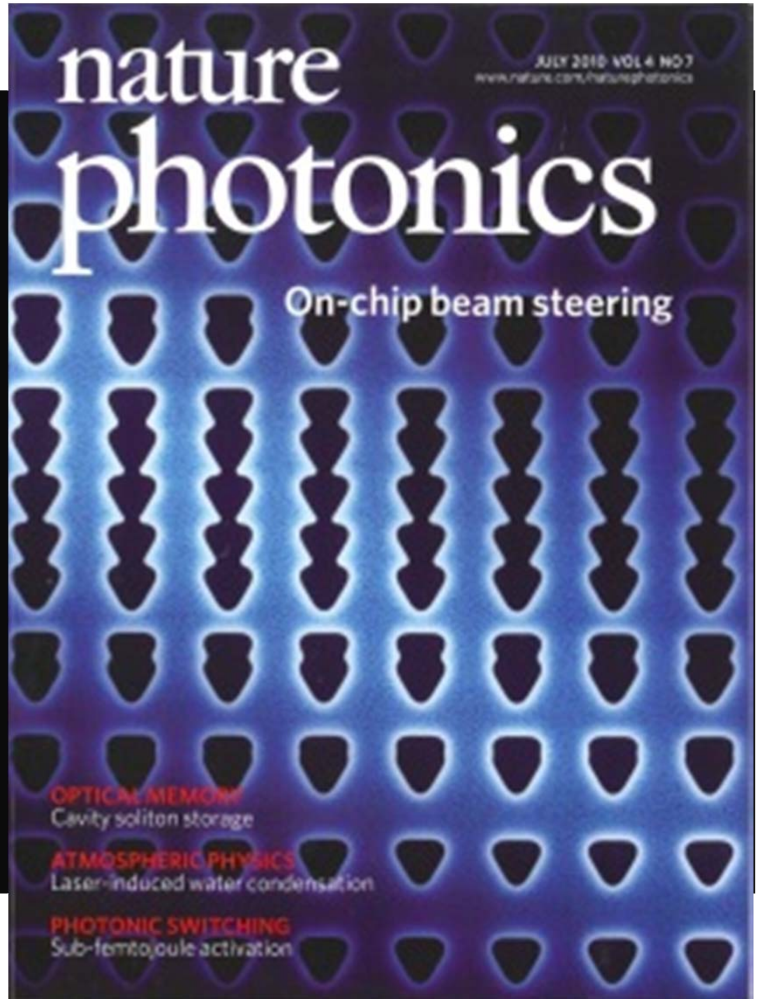




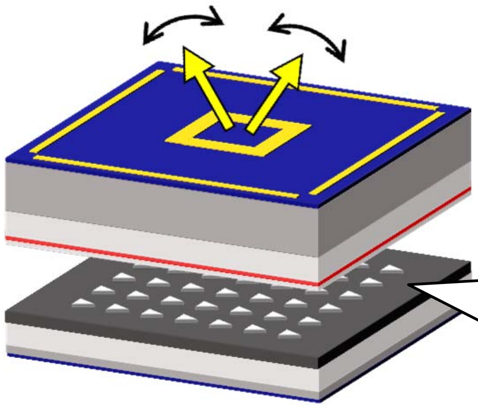
■Slope Efficiency
40-50 %

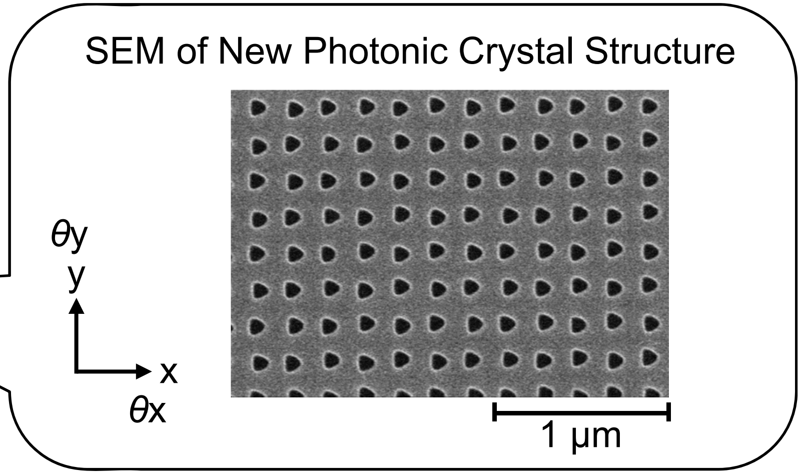
■Maximum Power : ~80 mW

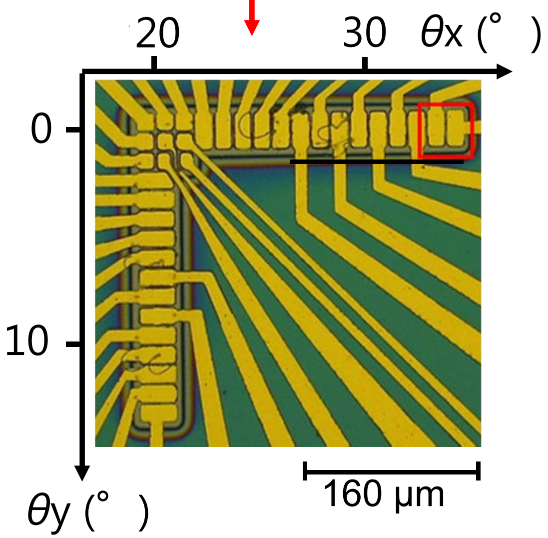
Beam Scanning Operation



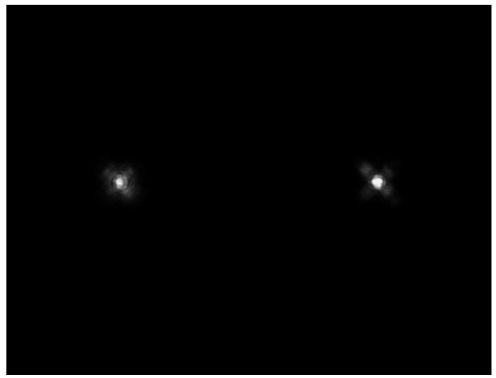
Even 2D Beam Scanning Operation







L-Shaped Arrayed Electrodes
for Beam Scanning



Details will be reported by Kitamura (Paper ThC6)

Summary and Perspectives

1.Nanocaviy-Based Lasers

/Highest Q factor > 10 million has been achieved

/All-Si Raman Lasing

2. Realization of High-Power, High-Beam Quality Lasers

/Watt-class CW Lasing Oscillation has been realized

/Even higher Power could be realized by Double Hole Devices

/Various New Functions and Applications including Wavelength conversion, 2D beam Steering Operations, etc.

Evolution of Semiconductor Laser World