2-Dimensional Whispering Gallery vs. 3-Dimensional Whispering Cave: PQR(Photonic Quantum Ring) Laser →Blue PQR Laser

O'Dae Kwon
Department of Electrical Engineering
Pohang University of Science and Technology
Pohang 790-784, Korea
odkwon@postech.ac.kr
http://www.postech.ac.kr/ee/light

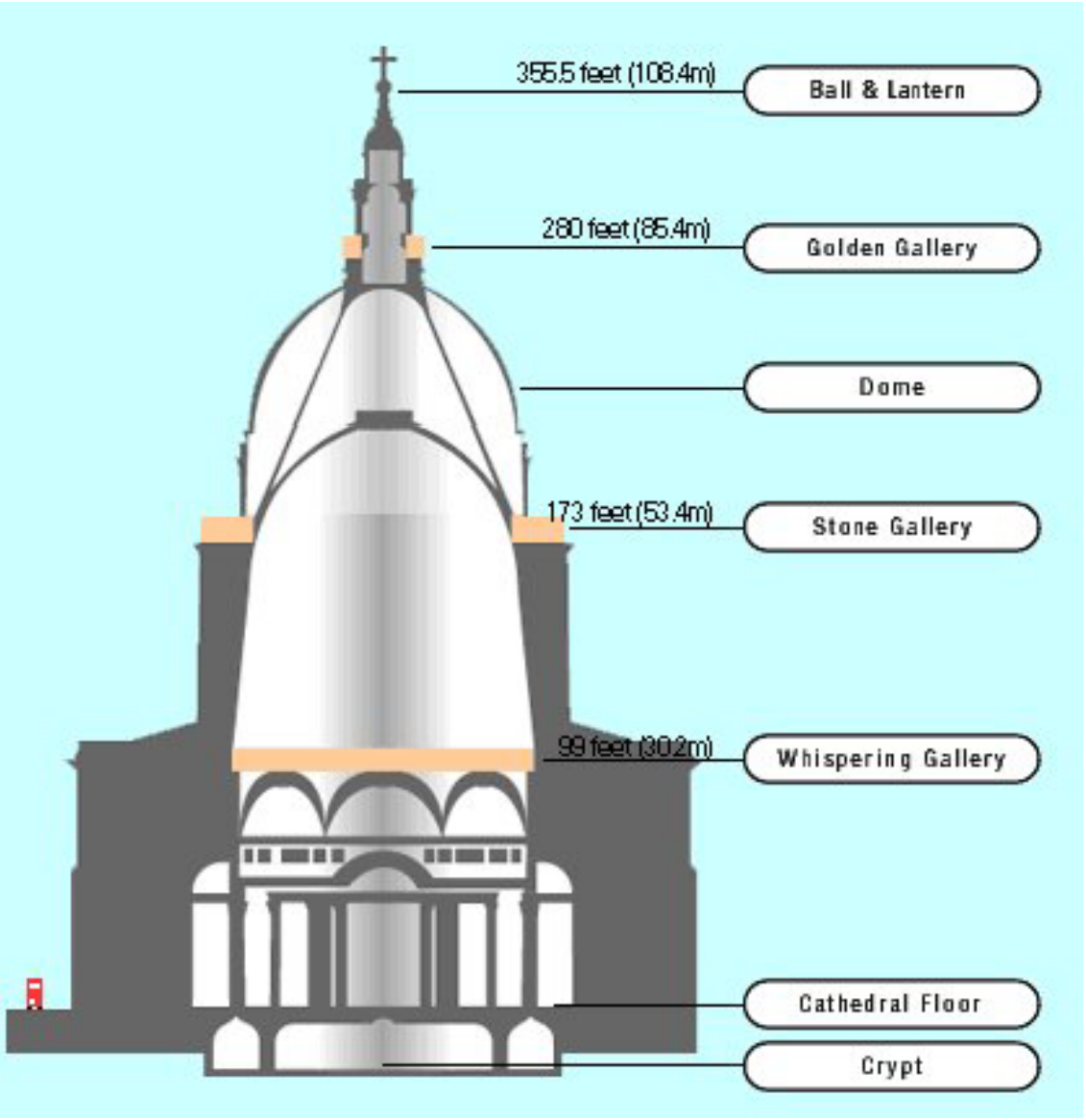
2-D Whispering Gallery vs. 3-D Whispering Cave

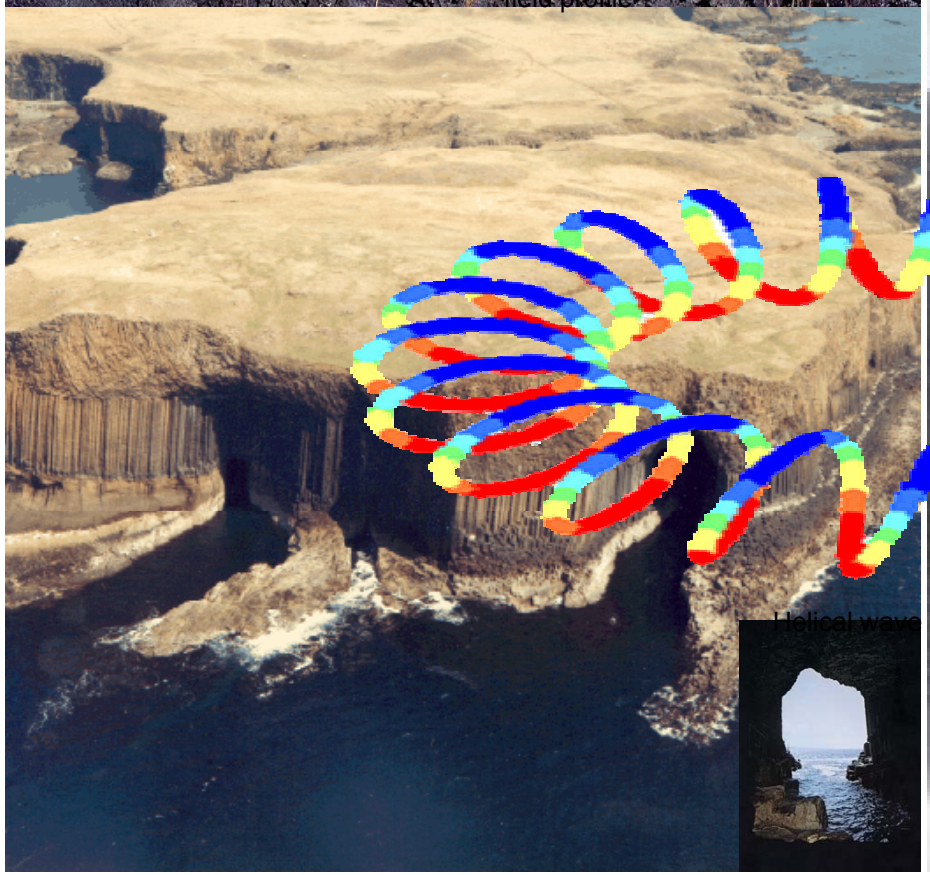
- →toroidal cavity 3D TIR → 3D WCM prop. of PQR
- →PQR from carrier-photon couple
- →IR PQR Laser →Single Mode
- →Red PQR Laser
- →Blue PQR Laser

St. Paul cathedral : Lord Rayleigh

concave Whispering Gallery – Bessel function

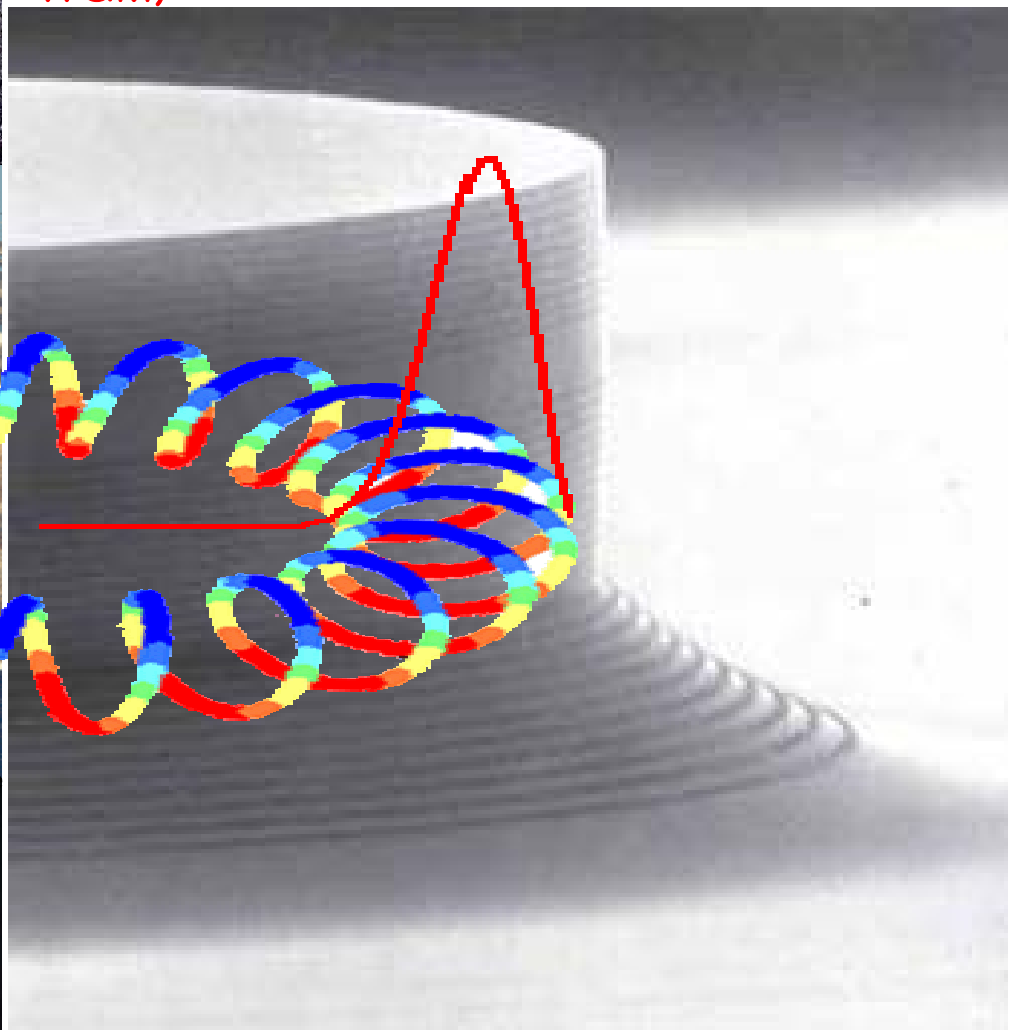
2D TIR (Total Intn'l. Reflec'n) – 2D symmetry



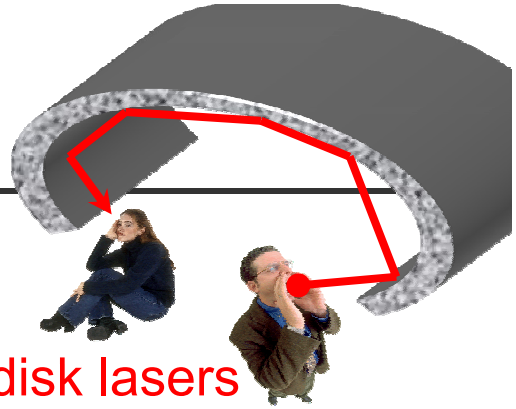


3D Whispering Cave Modes (3D WCM) : toroid of helix symmetry surface-normal dominant

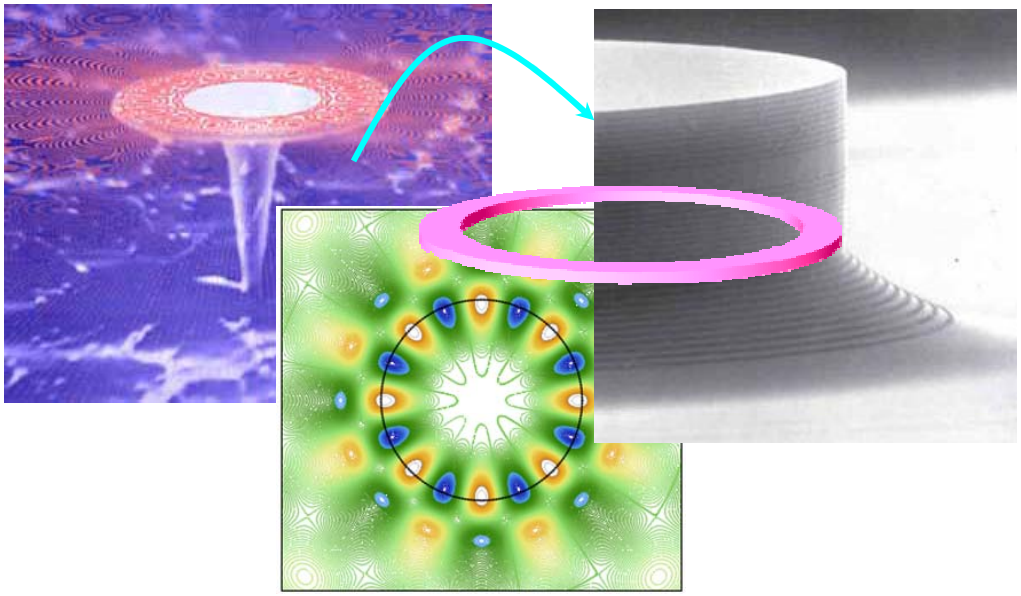
irreducible to a simple 2D symmetry (2D WGM)

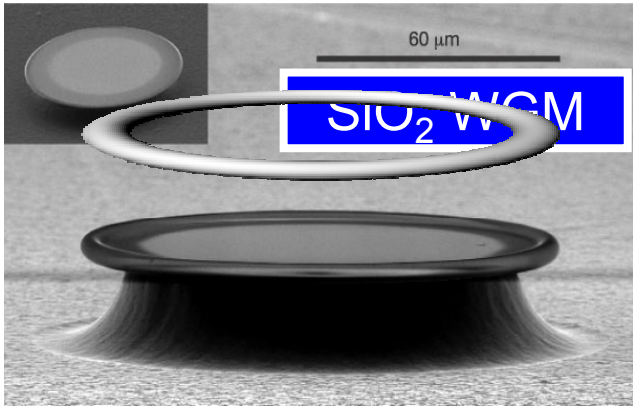


Micro Whispering Gallery Mode(WGM)



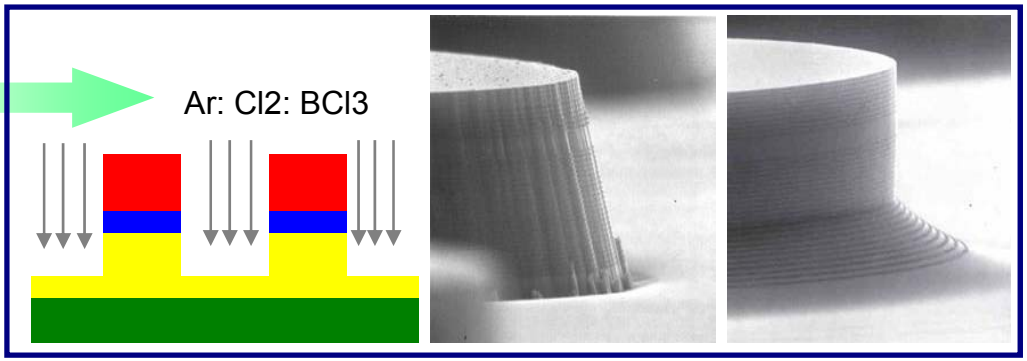
- 1910 Lord Rayleigh. WGM from concave surface
  Philosophical magazine, xx. 1001 (1910). 2D TIR
- 1992 A.F.J. Levi, R.E. Slusher et al. 2D WGM microdisk lasers (thumb-tack), Appl. Phys. Lett. **60,** 289 (1992). 2D TIR
- 1998 J.C. Ahn, et al., O'Dae Kwon. 3D WGM lasers by using naturally produced toroidal cavity in cylinders 3D TIR (whispering cave mode:WCM) Phys. Rev. Lett. **82,** 536 (1999); SPIE (1998)
- 2003 D.K. Armani et al & K.J. Vahala. WGM by using laser-baked toroid-shaped cavity Nature. **421**, 926 (2003). 3D TIR possible →WCM



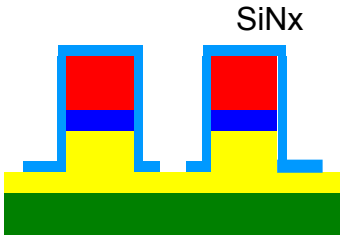


(3D WCM) PQR fabrication & structure

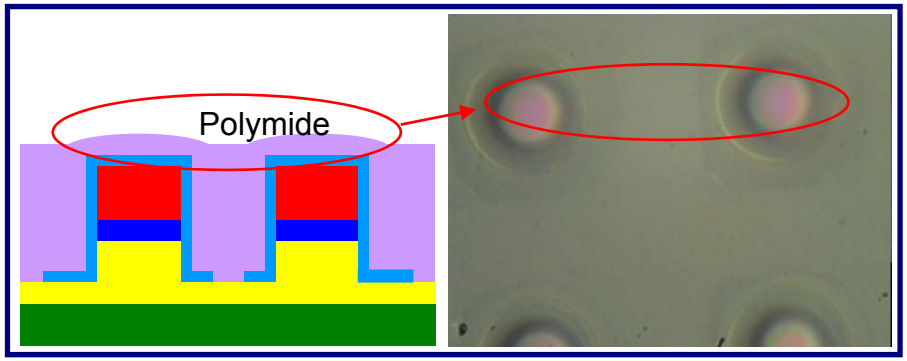
Epi structure



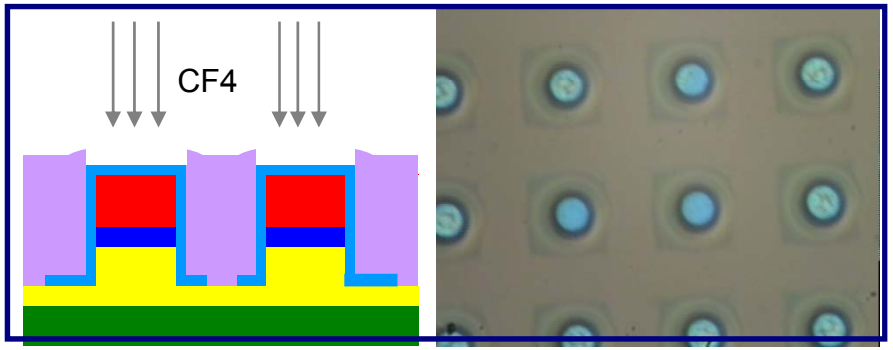
Vertical mesa using CAIBE



Silicon nitride coating

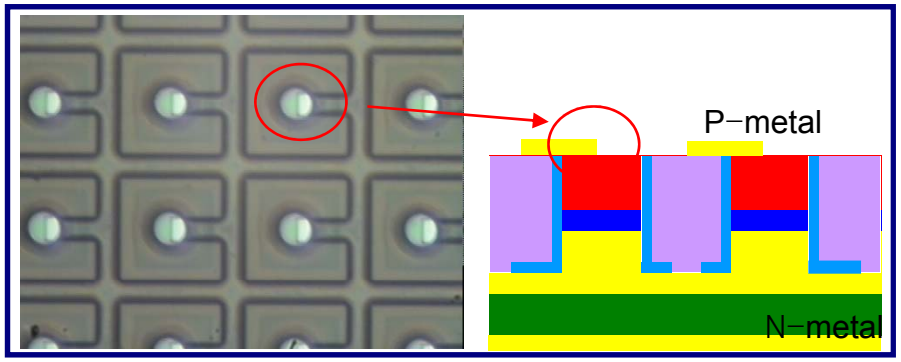


Planarization using polyimide



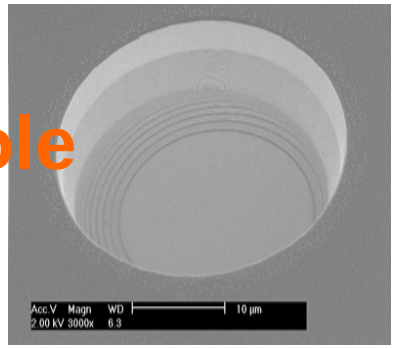
SiNx etching by RIE for metal contact

(3D WCM) PQR (concave) & PQR hole (convex)

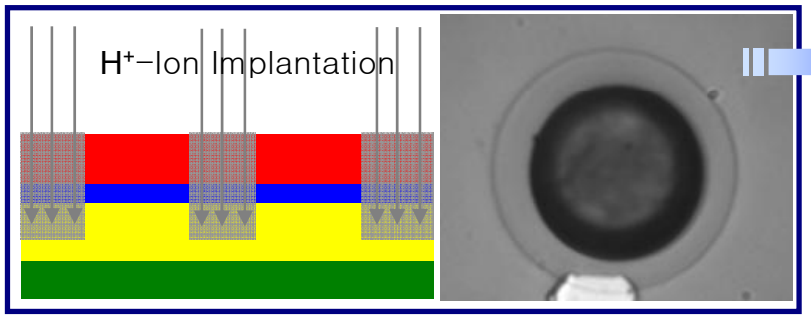


CMP-Metal-WireBond-Packaging

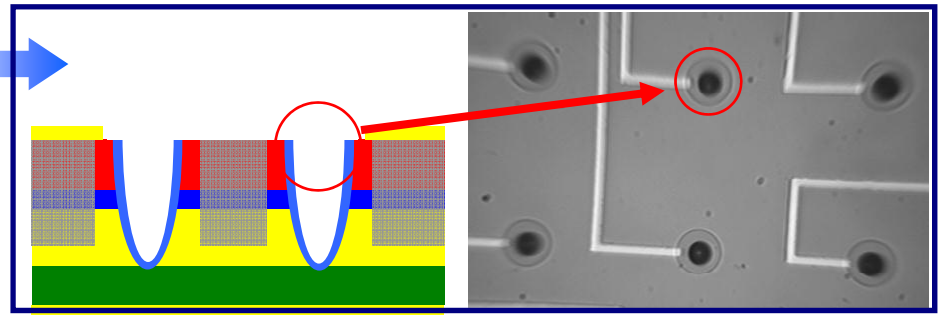
PQR hole



OPTO Paper # 6897-29 :Mega-pixel PQR hole chip : PC eff. isolations



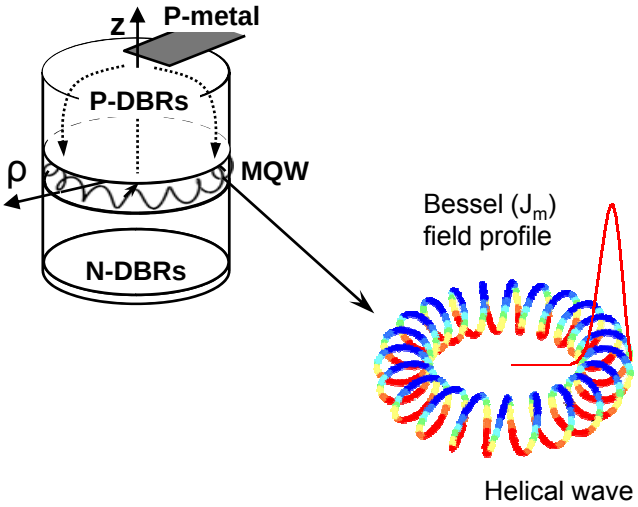
Ion implantation for hole isolation



Hole etching, passivation Metal contact

Photonic Quantum Ring

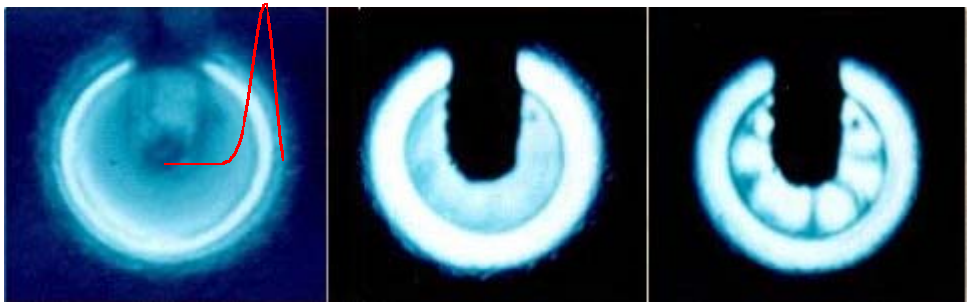
Ahn *et al.*, PRL, **82**, 536 (1999).



(*3D WCM-toroidal cavity*)

Bae *et al.* Optic. Lett., **28**, 1861 (2003).

- *Low threshold current (ϕ=15 μm)*

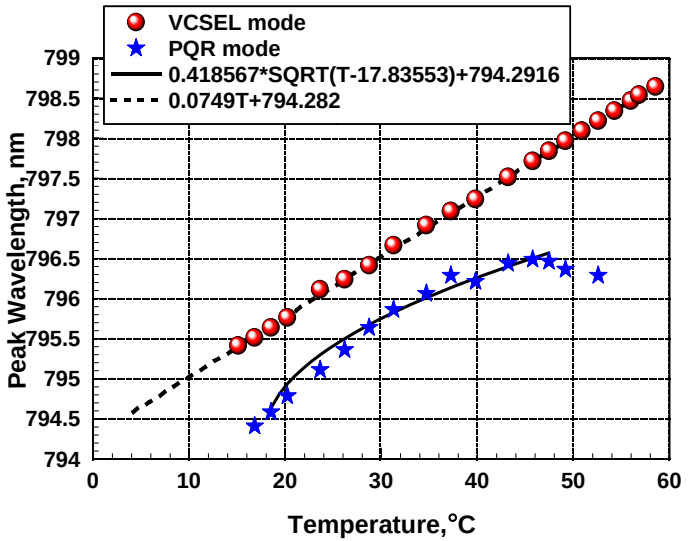


12μA, near the PQR threshold

11.5mA, below VCSEL threshold

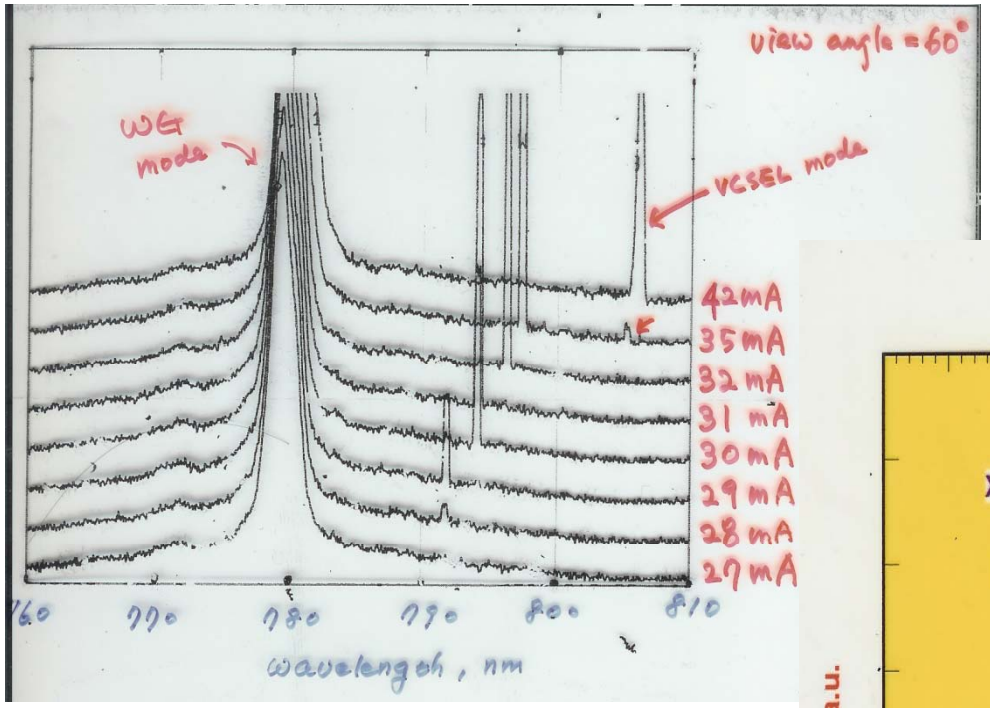
12.2 mA, above VCSEL threshold

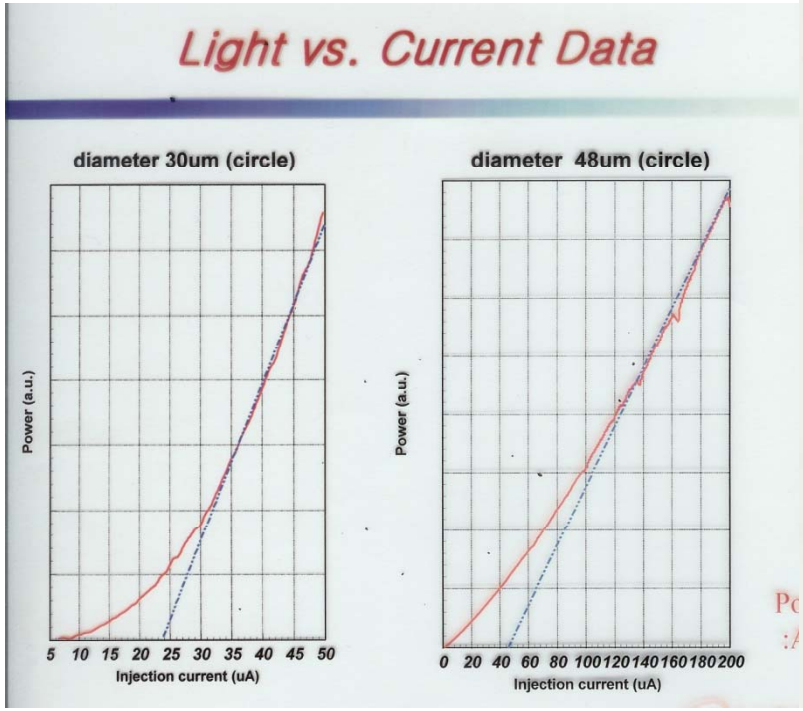
- *Temperature stability ($T^{1/2}$ dependent)*

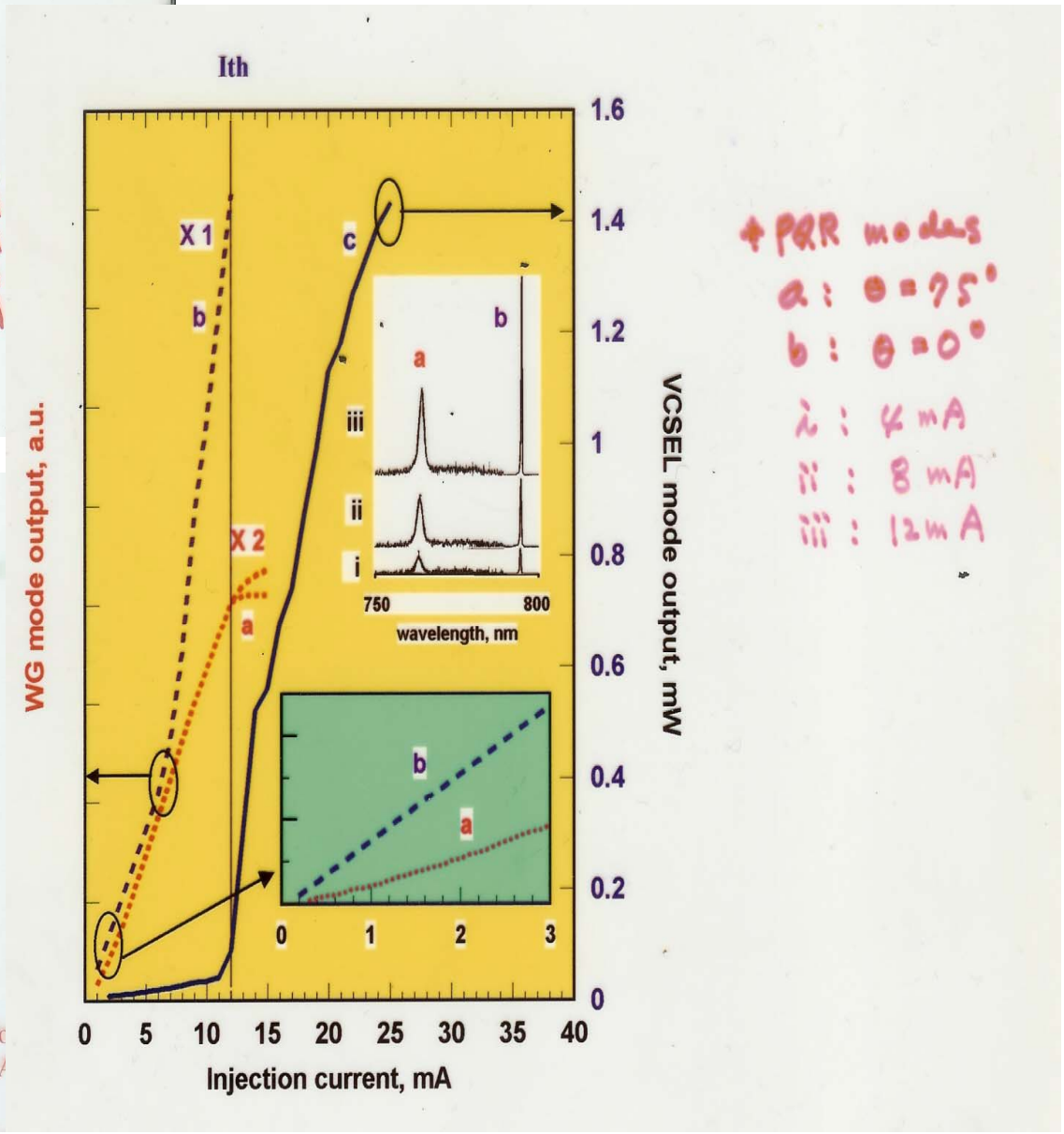


A. Yariv. APL, **53**, 12 (1988).

PQR : Early Raw Data



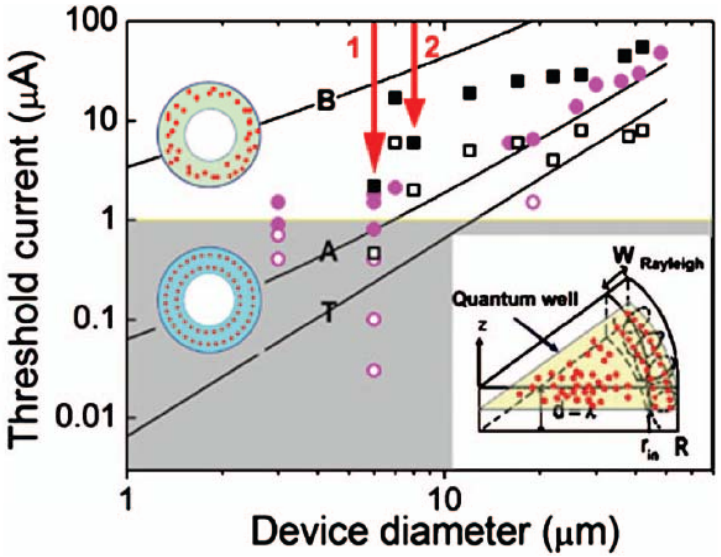




4 PQR modes
a : θ = 75°
b : θ = 0°
i : 4 mA
ii : 8 mA
iii : 12 mA

PQR Threshold I_{th}

Ahn *et al.*, PRL, **82**, 536 (1999).
Kwon *et al.*, APL, **89**, 11108 (2006).



PQR mesa: ● (threshold) ○ (transparency)

PQR hole: ■ (threshold) □(transparency)

$\phi[\mu m]$	$W_{Rayleigh}[\mu m]$	# of wires
10	0.314	3 (2.4)
20	0.629	5 (4.85)
30	0.943	7.2

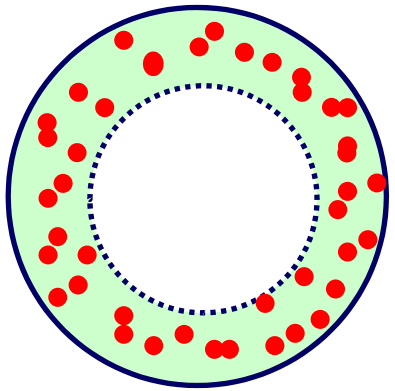
A. Yariv. APL, **53**, 12 (1988).

I. QW assumption

$$I_{th}^{QW} = I_{tr}^{QW} + I_{i}^{QW}$$

$$I_{tr}^{QW} = N_{tr}^{2D} \times \frac{\phi w}{2} \times \pi\phi \times \frac{e}{\eta\tau}$$

$$\left(W_{Rayleigh} = \frac{\phi w}{2}, w = 1 - \frac{n_{eff}}{n} \right)$$



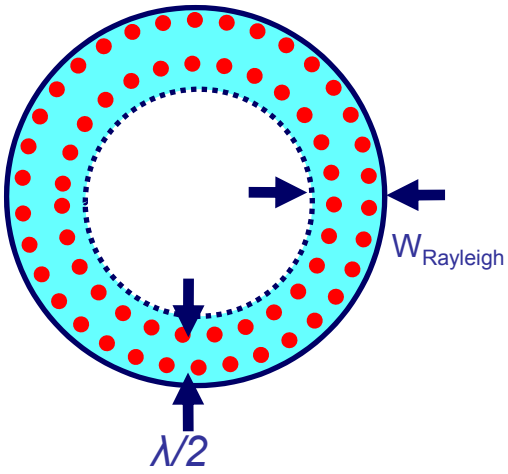
Chin-Chu-Ho,
JAP 75,3302(1994)

II. QWR assumption

$$I_{th}^{PQR} = I_{tr}^{PQR} + I_{i}^{PQR}$$

$$I_{tr}^{PQR} = \frac{W_{Rayleigh}}{\frac{\lambda_{PQR}}{2n_{eff}}} \times N_{tr}^{1D} \times \pi\phi \times \frac{e}{\eta\tau}$$

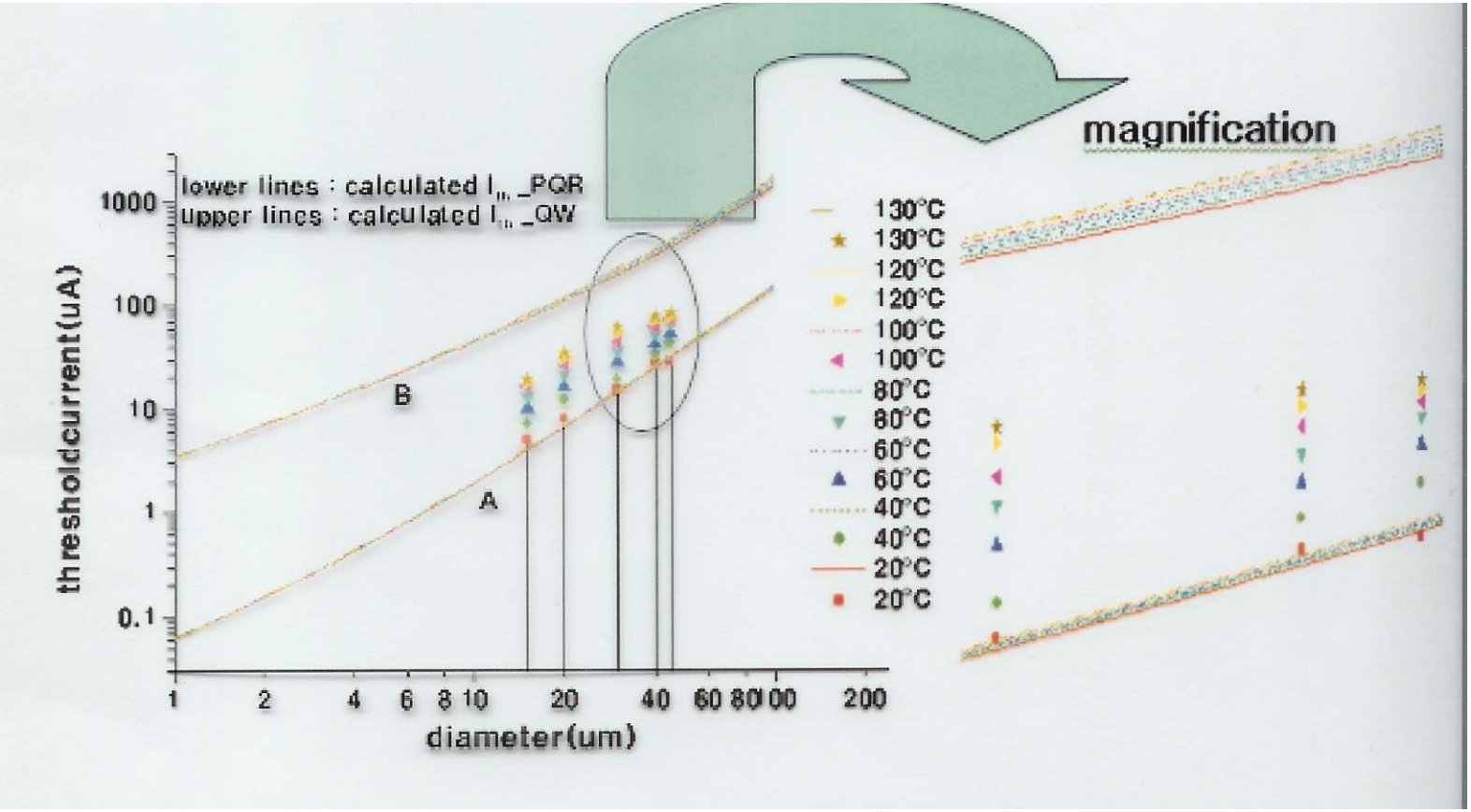
$$\equiv \chi$$



Park *et al.*, APL, **79**, 1593 (2001).

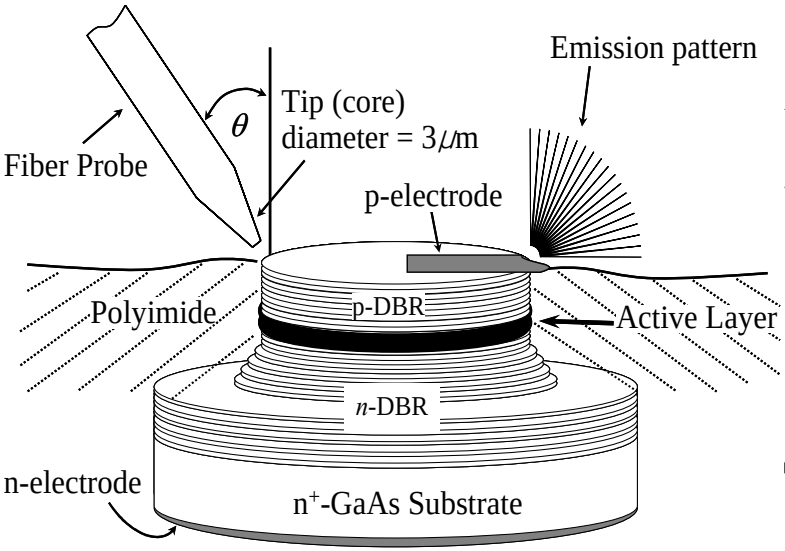
PQR : Early Raw Data

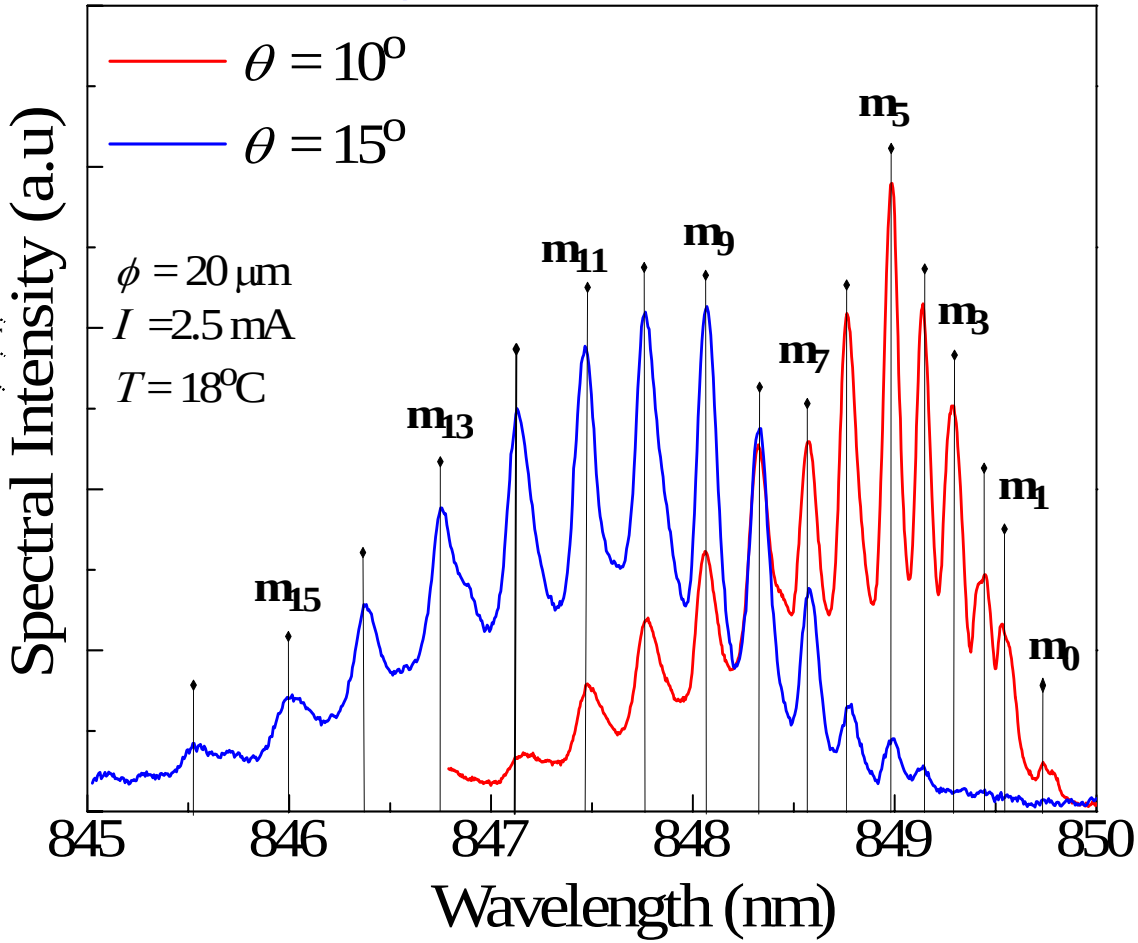
Operating Temperatures :20-130°C

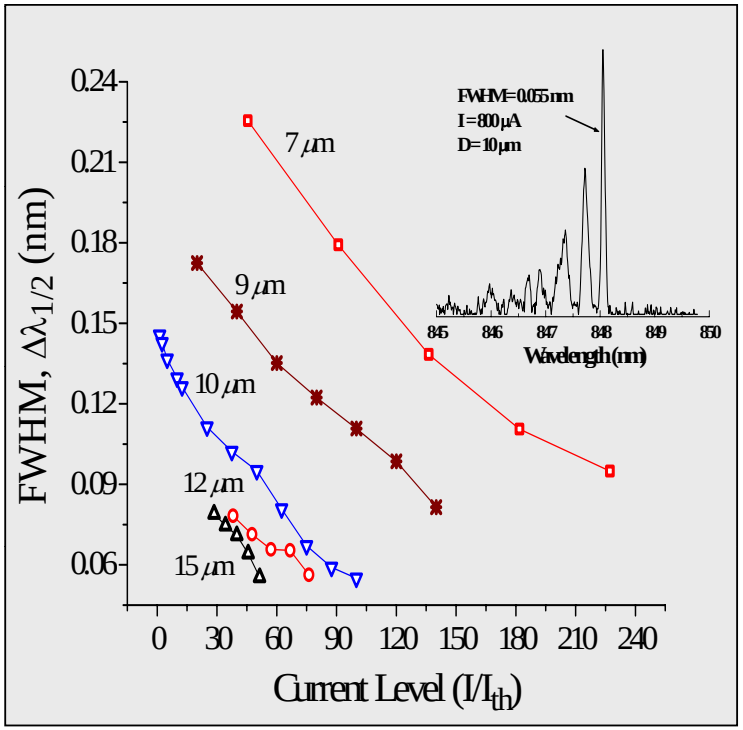


Spectral PQR Analy. of 3D WCM theoy

Opt. Lett. Vol. 28, 1861 (2003)





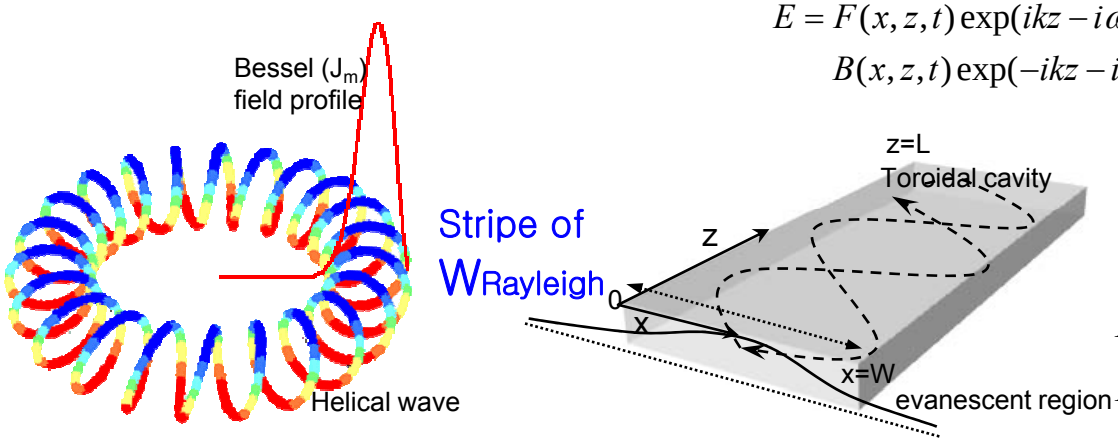


$$\theta_m = \sin^{-1}\left\{\frac{m\lambda_0}{2\pi R}\cdot\frac{n_m}{n_0}\left[1+\left(\frac{\lambda_0 m}{2\pi R n_0}\right)^2\right]^{-\frac{1}{2}}\right\}$$

PQR: carrier-photon dynamic model

Park *et al*., APL, **79**, 1593 (2001).

Dynamic filamentation and beam quality of quantum-dot lasers
E. Gehrig and O. Hess, APL, **84**, 1650 (2004).



$$E = F(x,z,t)\exp(ikz - i\omega t) + B(x,z,t)\exp(-ikz - i\omega t)$$

$$\nabla \cdot \overline{E} = -\frac{\partial \overline{B}}{\partial t} \qquad \nabla \cdot \overline{H} = \overline{J} + \frac{\partial \overline{D}}{\partial t}$$

$$\overline{D} = \varepsilon_0 \overline{E} + \overline{P} \qquad \overline{B} = \mu_0 \overline{H} \qquad \overline{J} = \sigma \overline{E}$$

$$\overline{P} = \varepsilon_0 \chi(N) \overline{E}$$

$$\frac{\partial F}{\partial t} + \frac{\partial F}{\partial z} = iD_P \frac{\partial^2 F}{\partial x^2} - i\Delta(x)F + \Gamma(x)[g(N) - i\alpha a N]F$$

$$\frac{\partial B}{\partial t} - \frac{\partial B}{\partial z} = iD_P \frac{\partial^2 B}{\partial x^2} - i\Delta(x)B + \Gamma(x)[g(N) - i\alpha a N]B$$

$$\frac{\partial N}{\partial t} = D_f \frac{\partial^2 N}{\partial x^2} + J(x) - \gamma N - \Gamma(x) g(N)(|F|^2 + |B|^2)$$

$$g(N) = a(N - N_0)$$

E. Gehrig *et al*., APL, 84, 1650 (2004).

F : *forward electric field*

B : *backward electric field*

N : *carrier density*

D_P : *Diffraction coefficient*

Δ : *transverse passive waveguiding factor*

Γ : *confinement factor*

g : *gain function*

α : *linewidth enhancement factor*

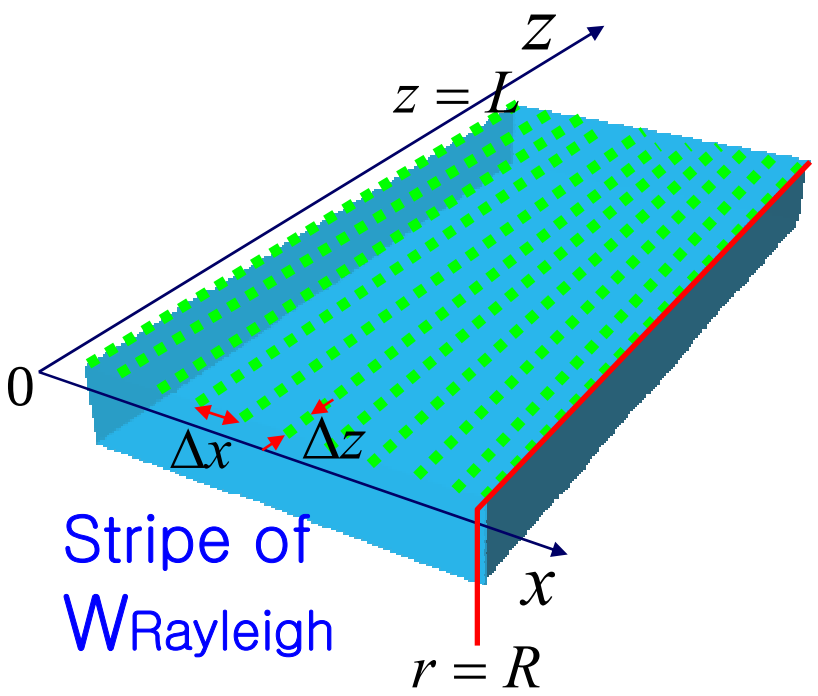
a : *gain coefficient*

D_f : *diffusion coefficient*

J : *carrier injection*

$\tau(=1/\gamma)$: *nonradiative recombination time*

FDM Simulation Parameters



$\phi[\mu m]$	$W_{Rayleigh}[\mu m]$	χ
10	0.314	3 (2.7)
20	0.629	5 (5.4)
30	0.943	8

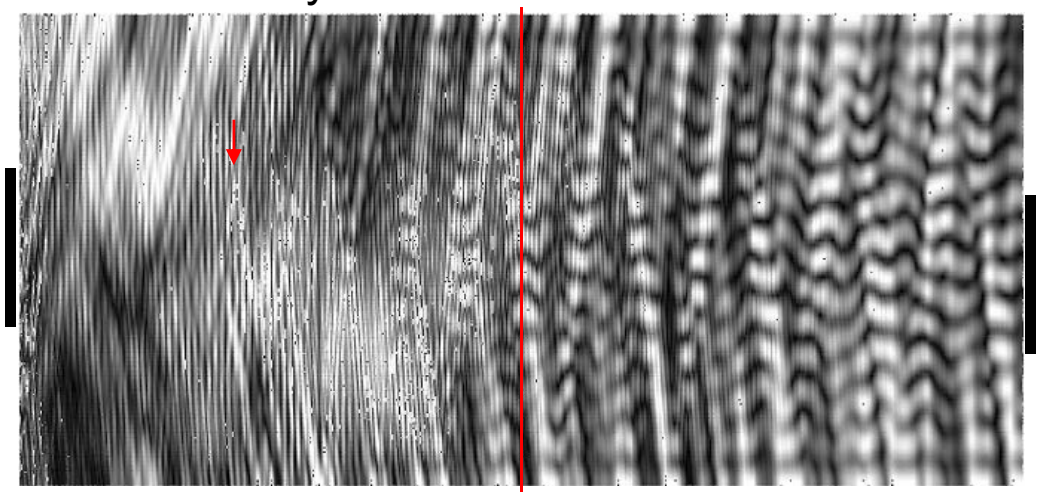
Parameter	Value
Lasing wavelength λ	850 nm
gain coefficient a	1.5×10^{-16} cm^2
Linewidth enhancement factor α	2
nonradiative recombination time τ	5 ns
diffusion coefficient D_f	30 cm^2/s
diffraction coefficient D_P	18×10^{-4} cm

$I = 1mA$ $N_0 = 0.67\times10^{18}$ $\Delta x = 30\,nm$ $\Delta t = 5\times10^{-15}$

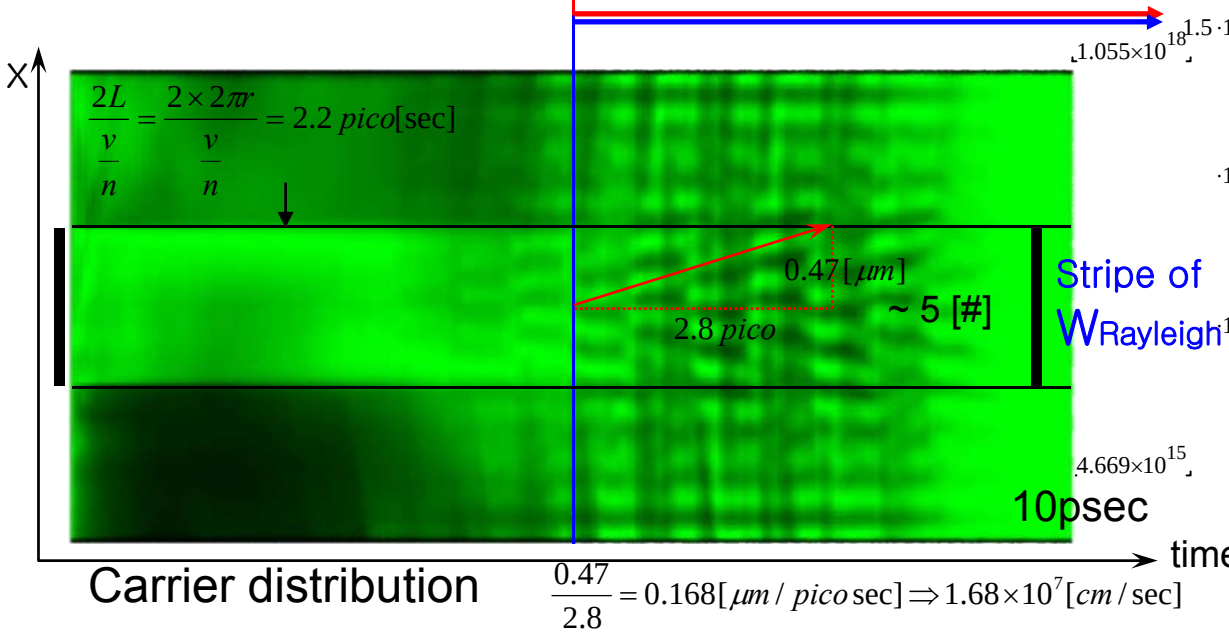
$W_{Rayleigh}$~1 μm, ϕ = 30 μm

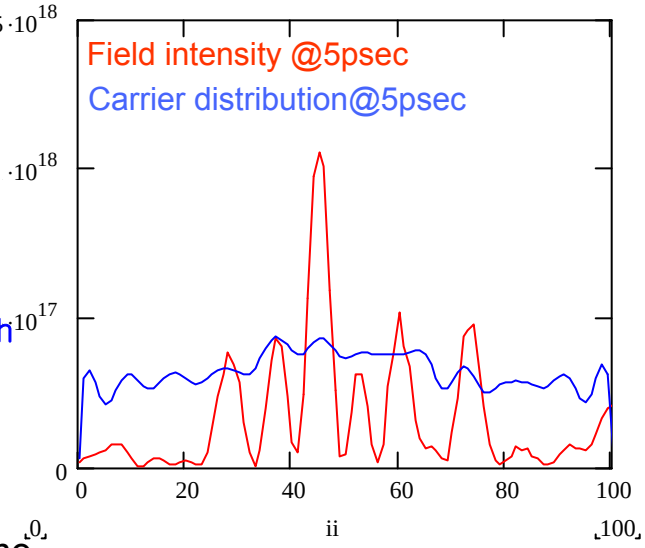
$\phi[\mu m]$	$W_{Rayleigh}[\mu m]$	χ
10	0.314	2.4
20	0.629	4.8
30	0.943	7.2

Field intensity



Stripe of $W_{Rayleigh}$



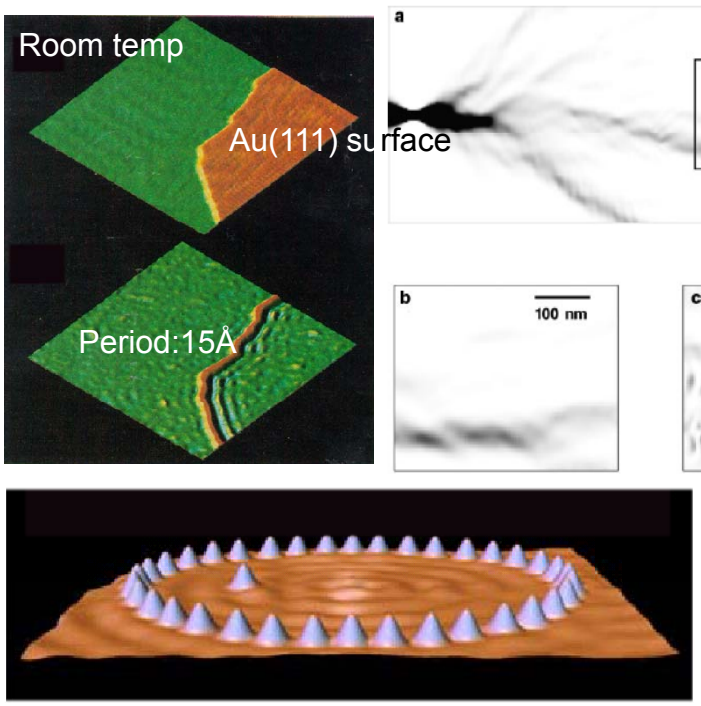


Carrier distribution

$$\frac{0.47}{2.8} = 0.168[\mu m / pico\sec] \Rightarrow 1.68\times10^{7}[cm/\sec]$$

Local density of states in 2DEG

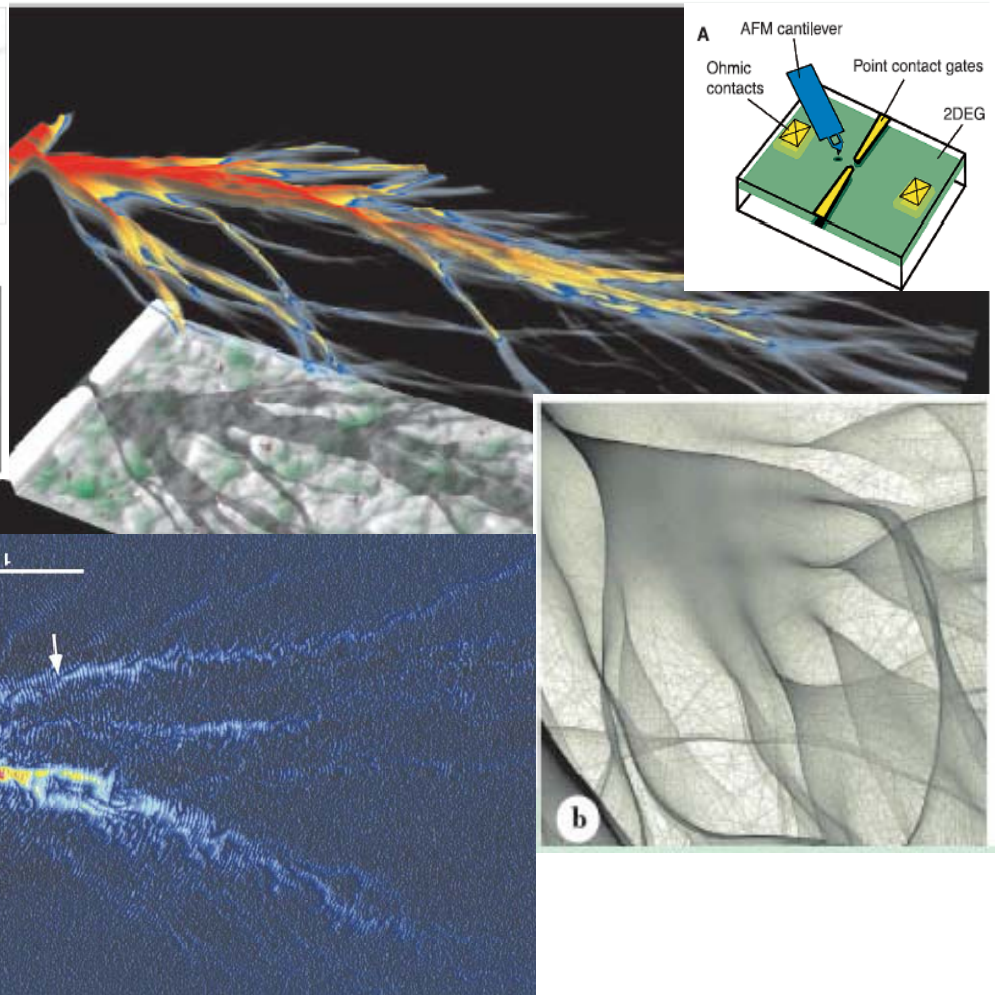
Electron standing waves in a 2DEGs



P. Avouris, Physics Today, **11**, 17 (1993).
M. F. Crommie, *et al*. Nature, **363**, 524 (1993).

Quantum corral of electrons

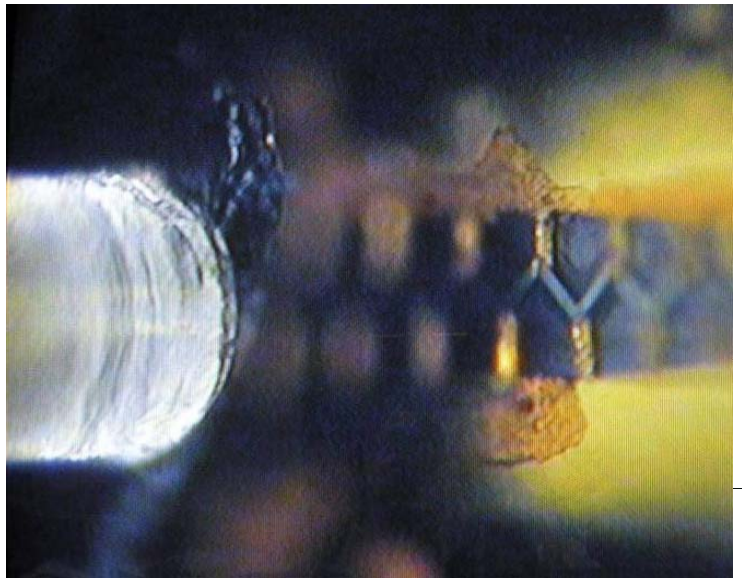
Coherent branched electron flow in a 2DEGs

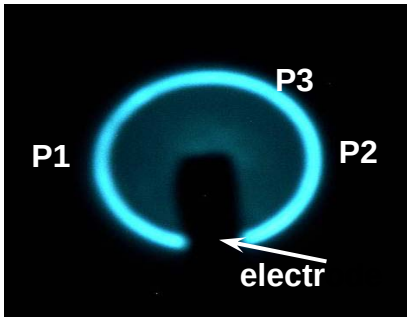


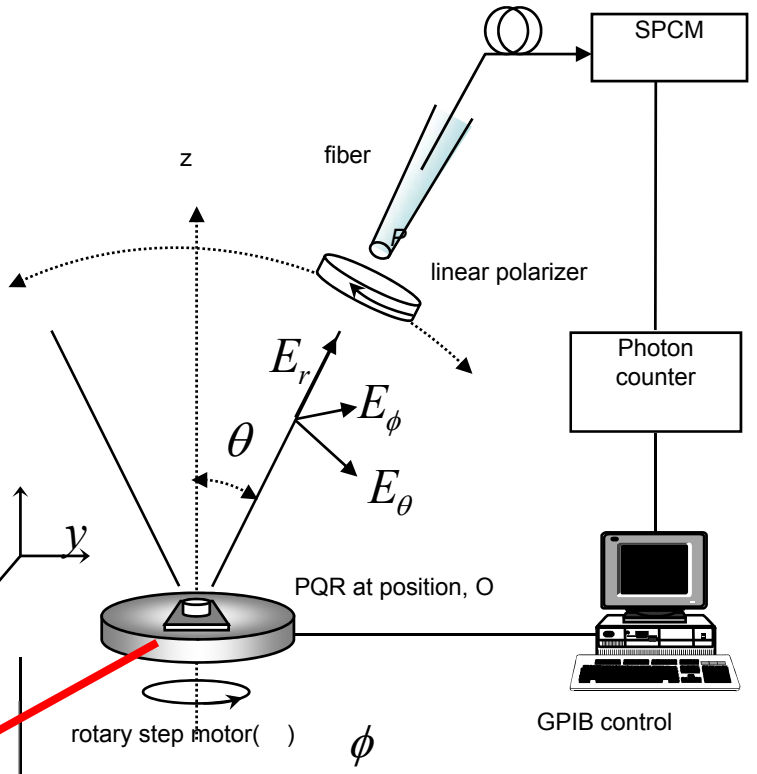
M.A. Topinka, R.M. Westervelt, E.J. Heller,
"Imaging Electron Flow", Physics Today **56**, 12 (2003).

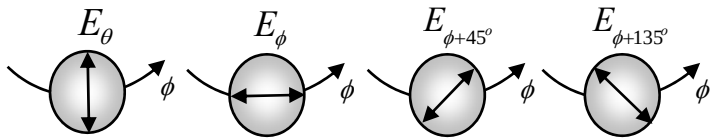
PQR Polarization Measurements

SAS(solid angle scanner)



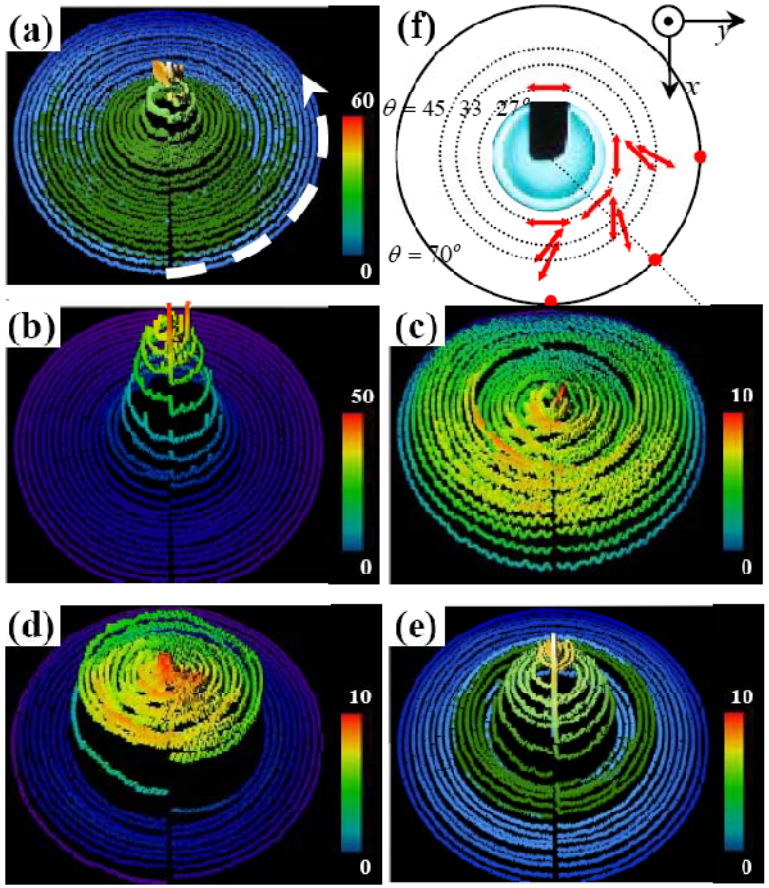






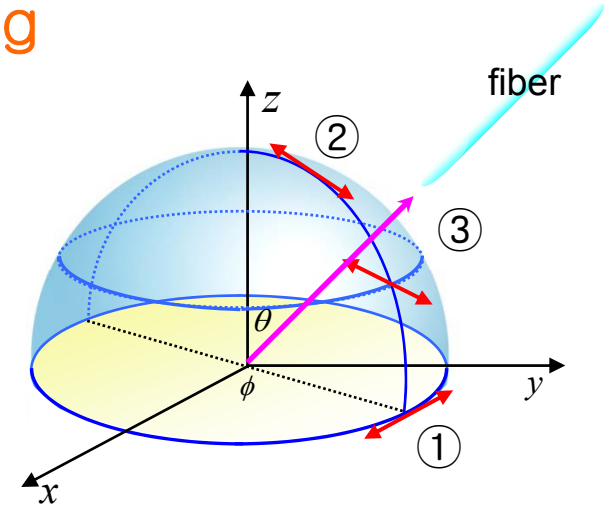
Polarization Vectors // PQR

Kim *et al.*, JAP, 102(5), xx (2007).



(a): without polarizer
(b): ϕ polarizer
(c): θ polarizer
(d): ϕ+45° polarizer
(e): ϕ+135° polarizer

Strong Carrier-Photon Coupling

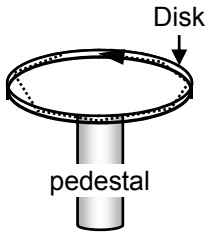


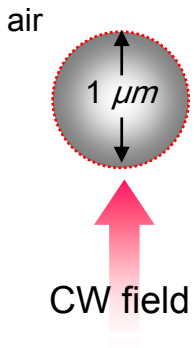
① : ϕ linear polarizer
② : θ linear polarizer
③ : ϕ +135°

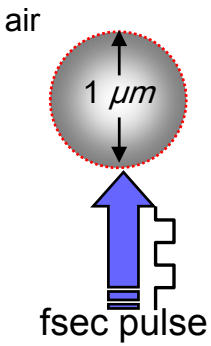
ϕ=15 μm, I=150 μA (10kHz)

NW-FDTD (ϕ = 1μm microdisk)

Via NWU FDTD – S. T. Ho group







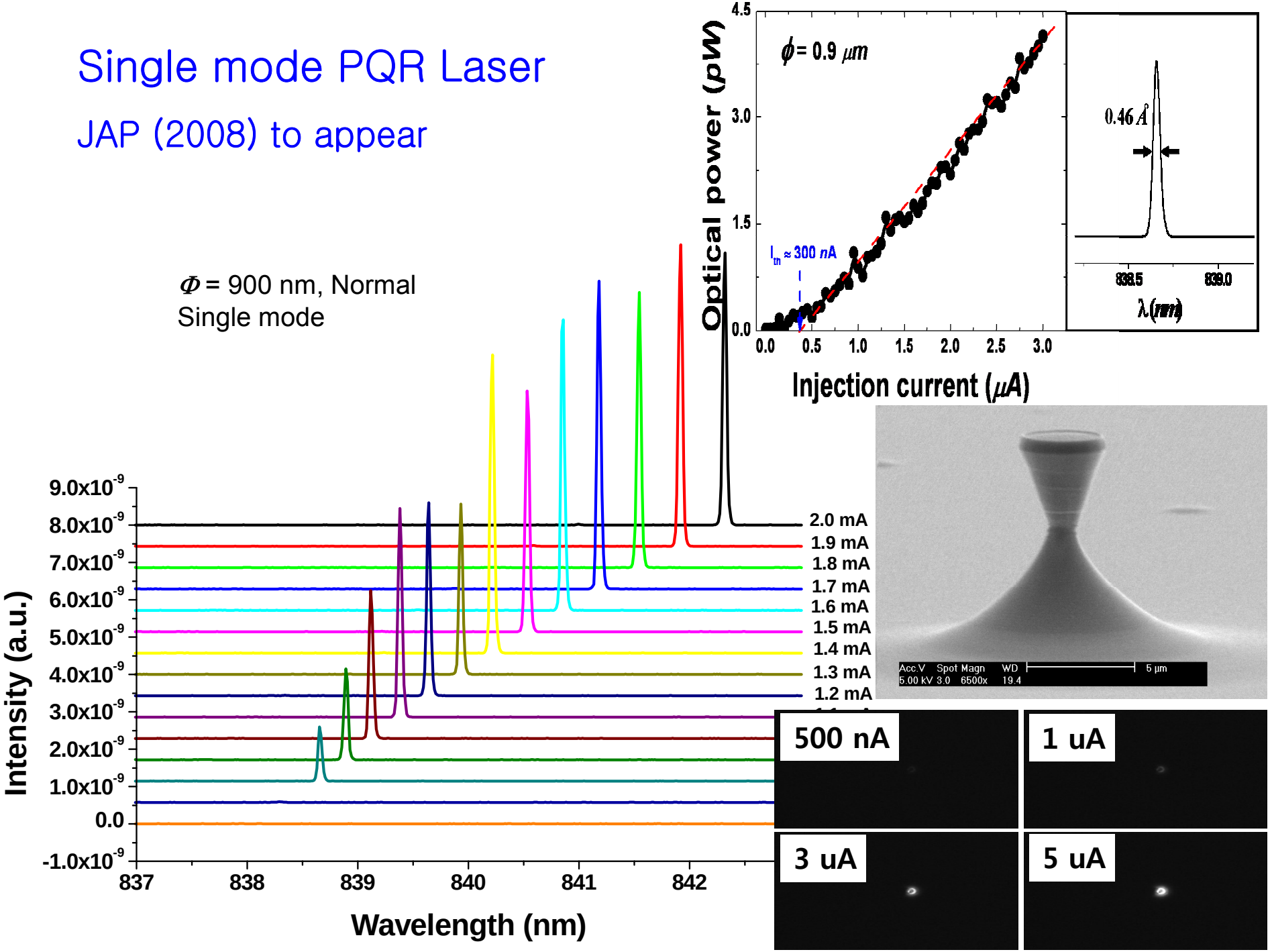
0.1psec, 0.2psec…0.8psec

0.01psec, 0.02psec…0.1psec

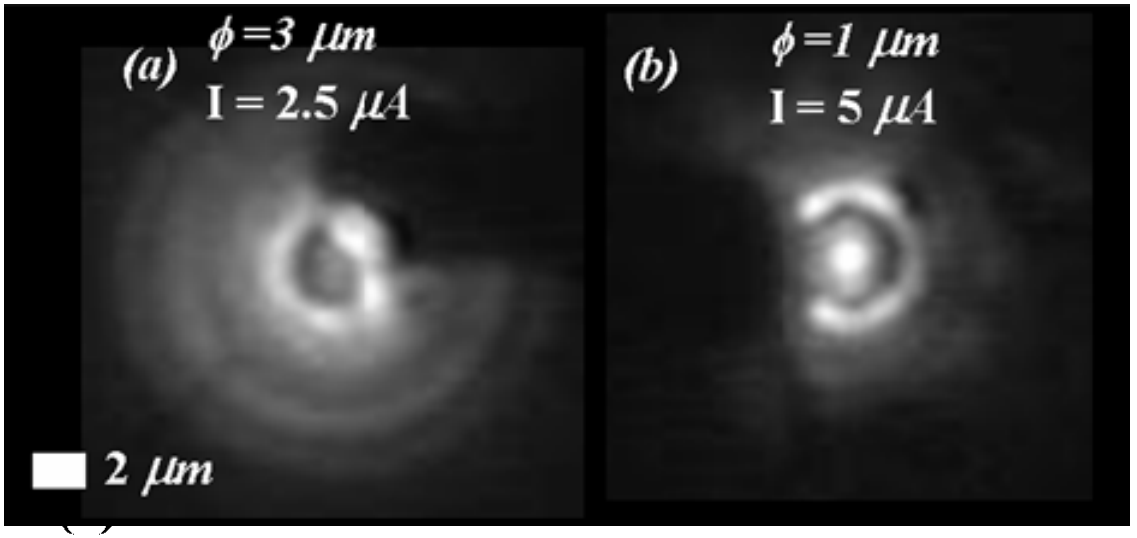
Single mode PQR Laser

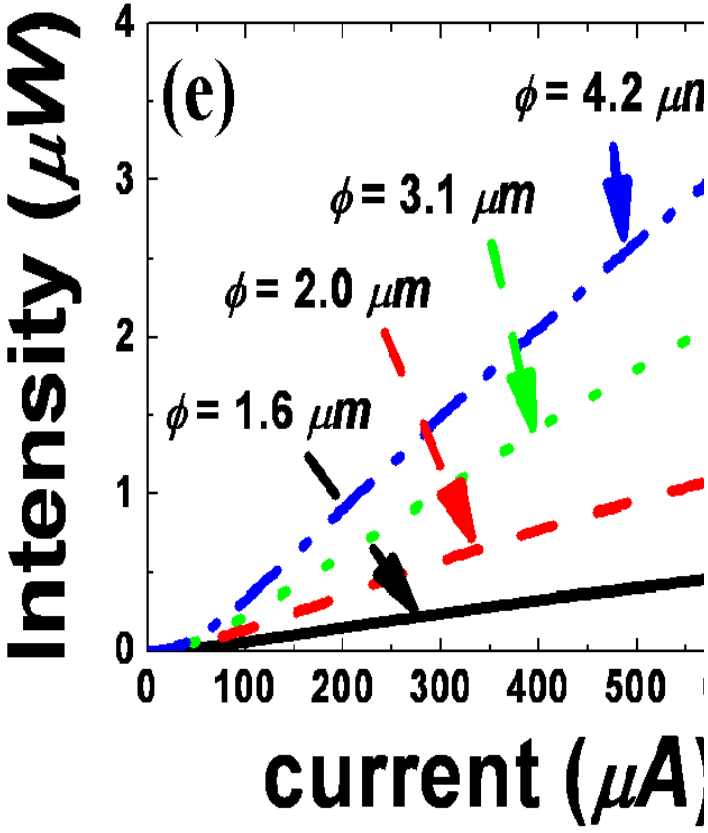
JAP (2008) to appear

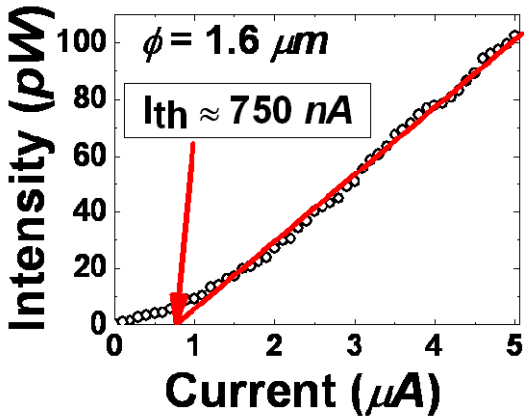
Φ = 900 nm, Normal
Single mode

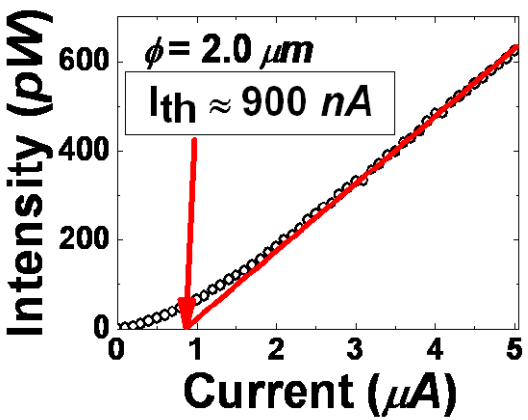


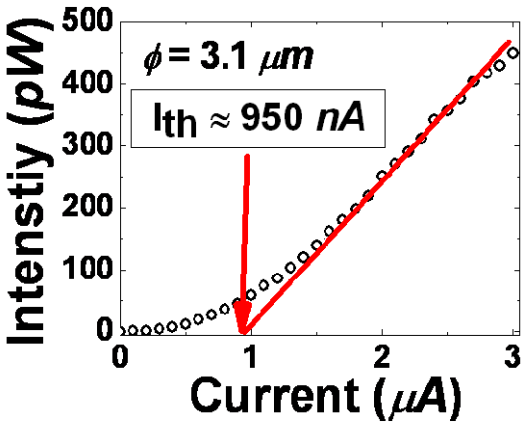
Near SM Laser L – I Curves

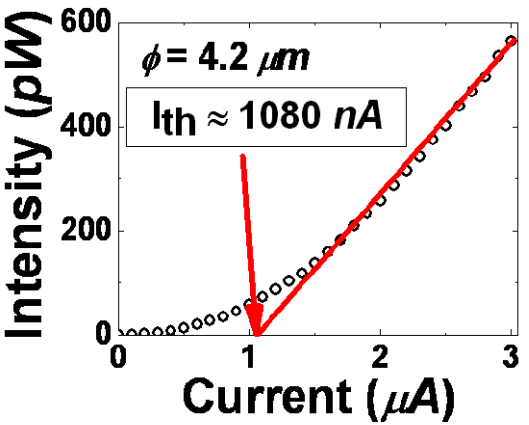




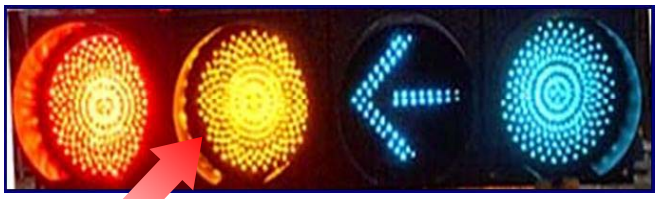


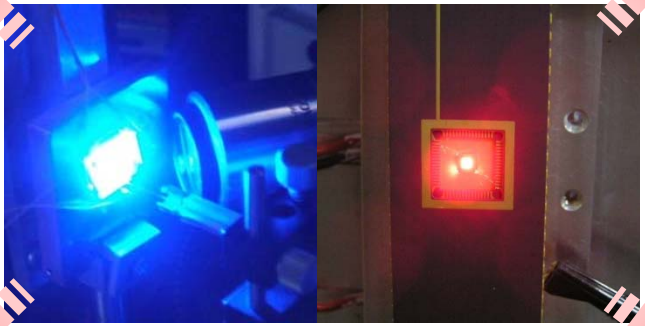


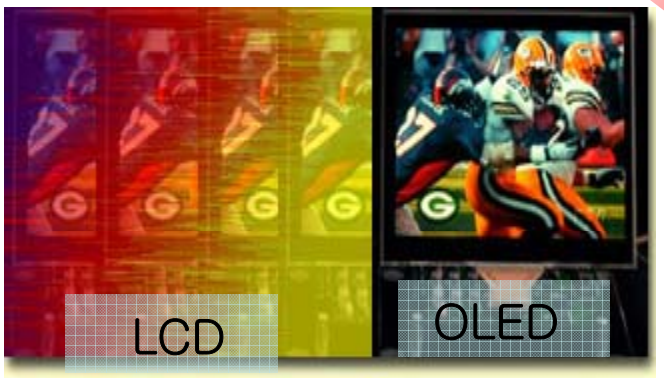


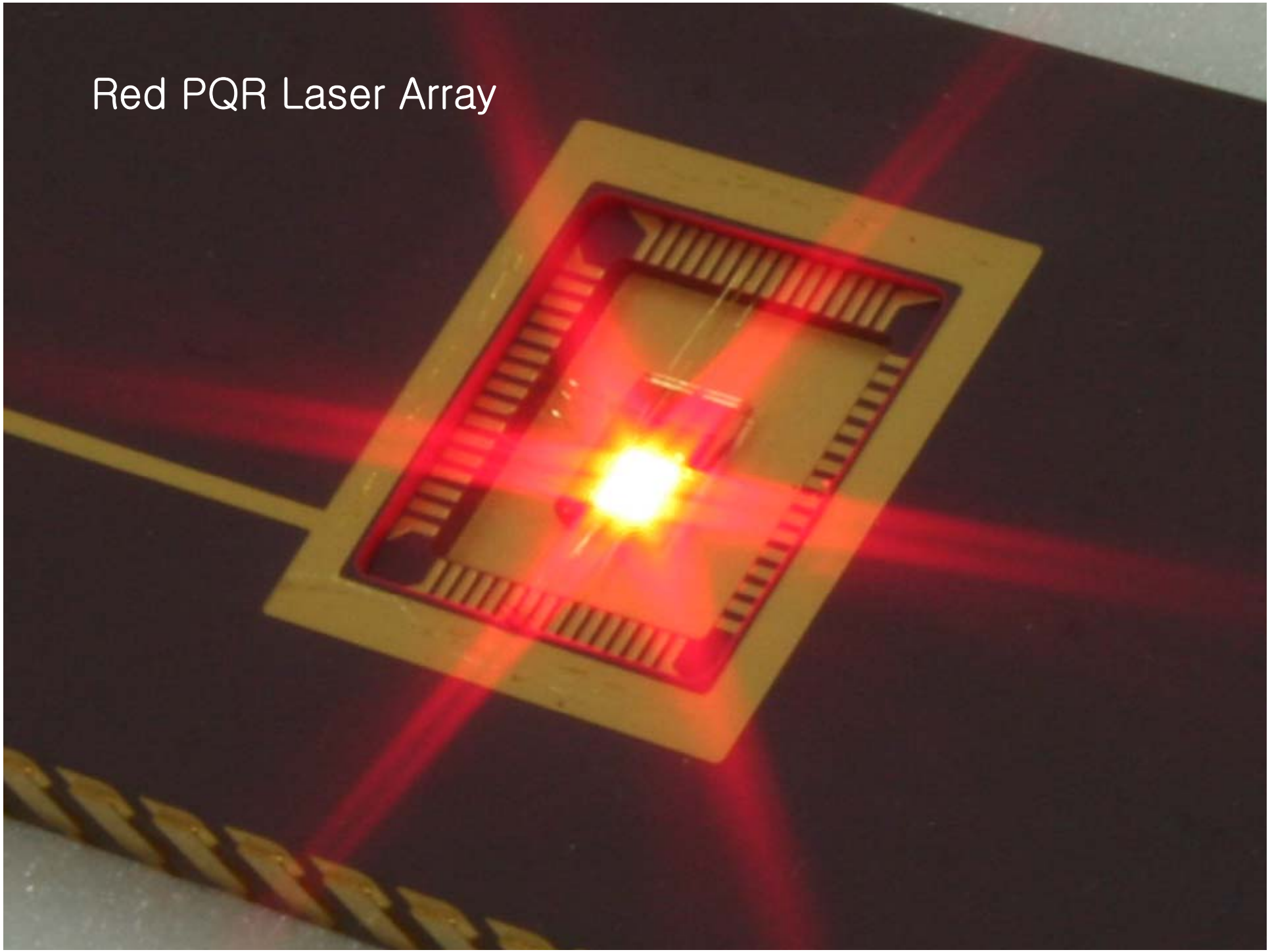


DISPLAY : from LED to PQR laser

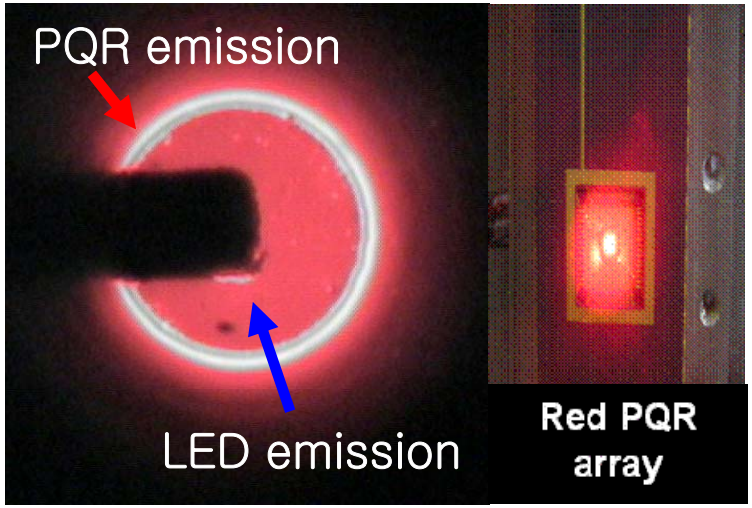


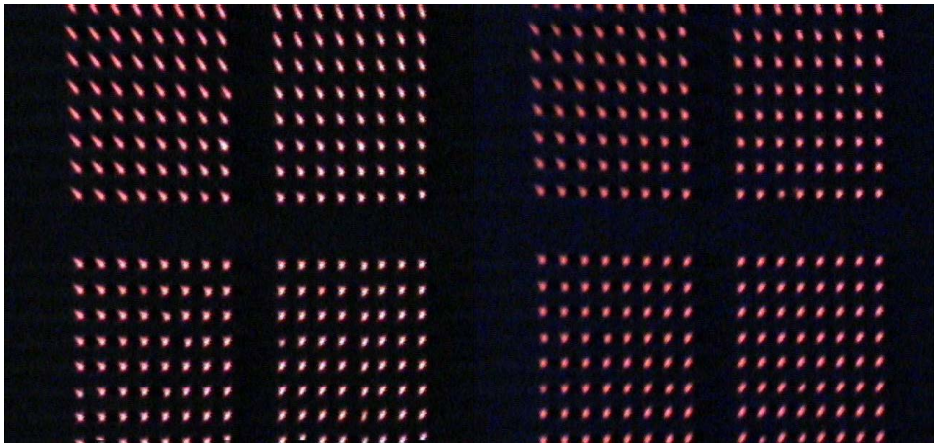





Red PQR Laser Array

Red PQR Laser Array





256 array (ϕ = 7 μm)
Spacing = 68 μm

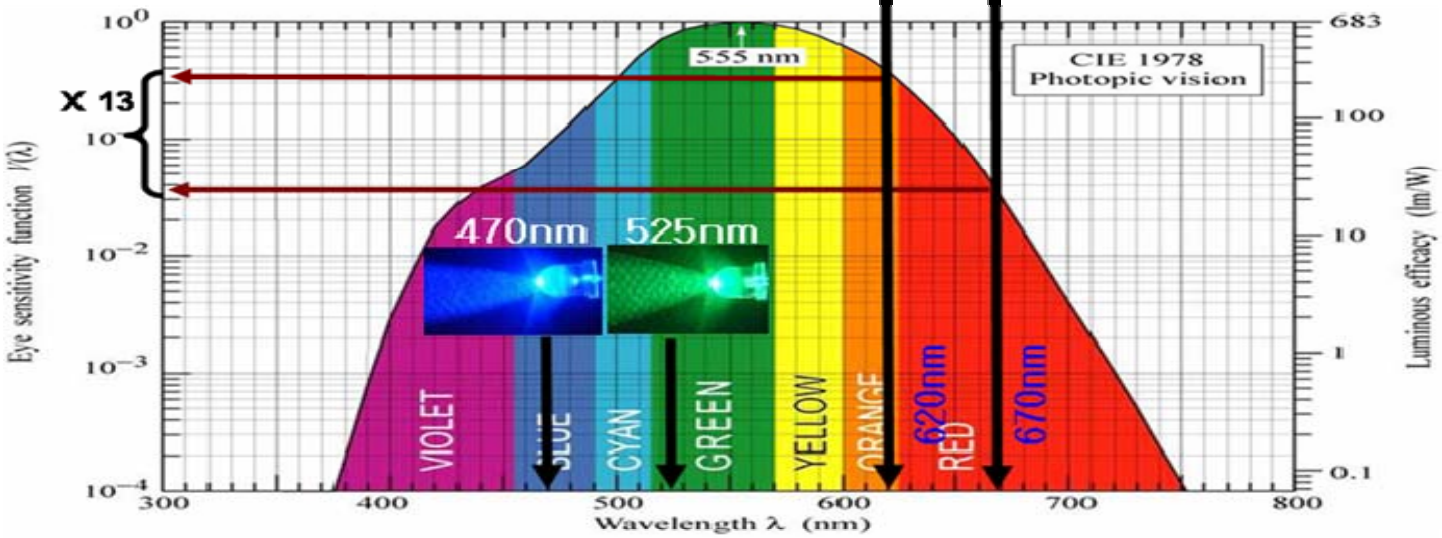
256 array (ϕ = 10 μm)
Spacing = 68 μm

I = 2 mA (7.8 μA/cell)

- The PQR lasing region is brighter than the LED emission region, which means very high emission efficiency of the PQR laser.

Luminous efficiency & intensity

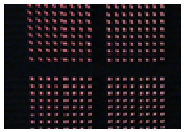
Conventional LED  256 PQR array



620 nm 

conventional LED
100mcd @ 20mA
Lumiled LED 44 lm/w

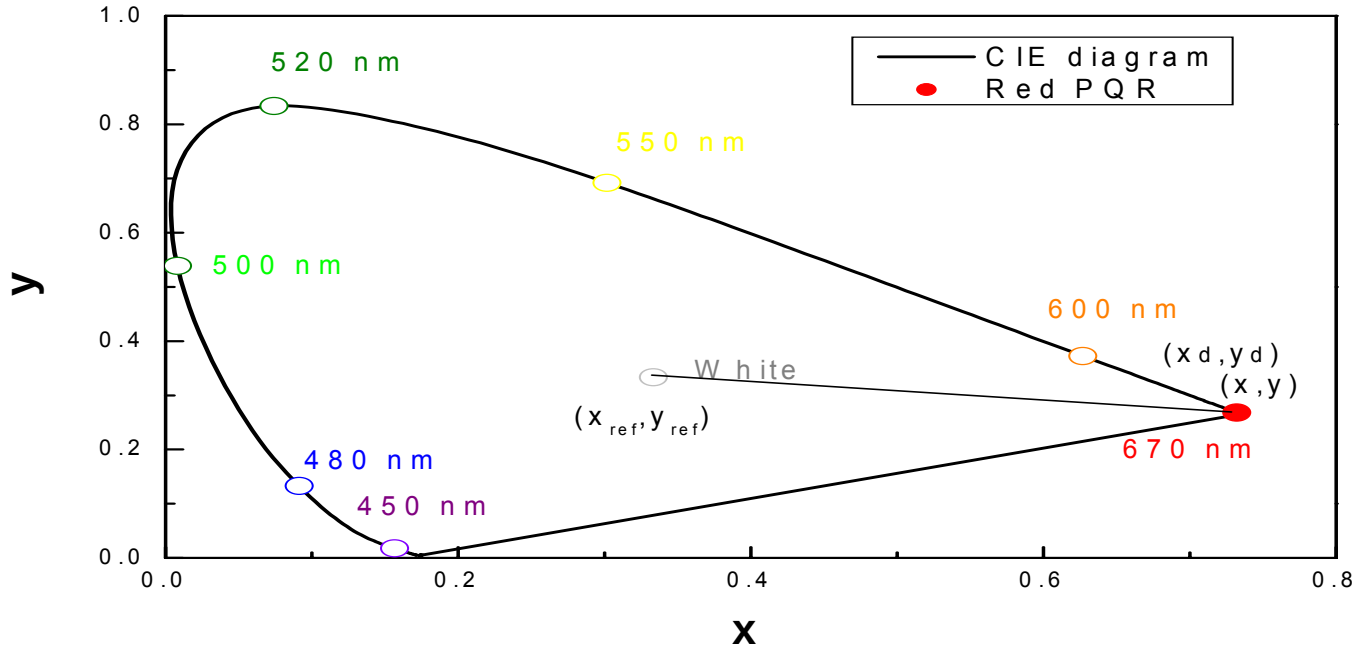
VS.

670 nm 

256 PQR laser
11.8 mcd @ 20mA
x 13 = 153 mcd
7.2 lm/w x 13 = 93.6 lm/w

PQR 93.6 >LED 44 @620nm on eye sensitivity diagram

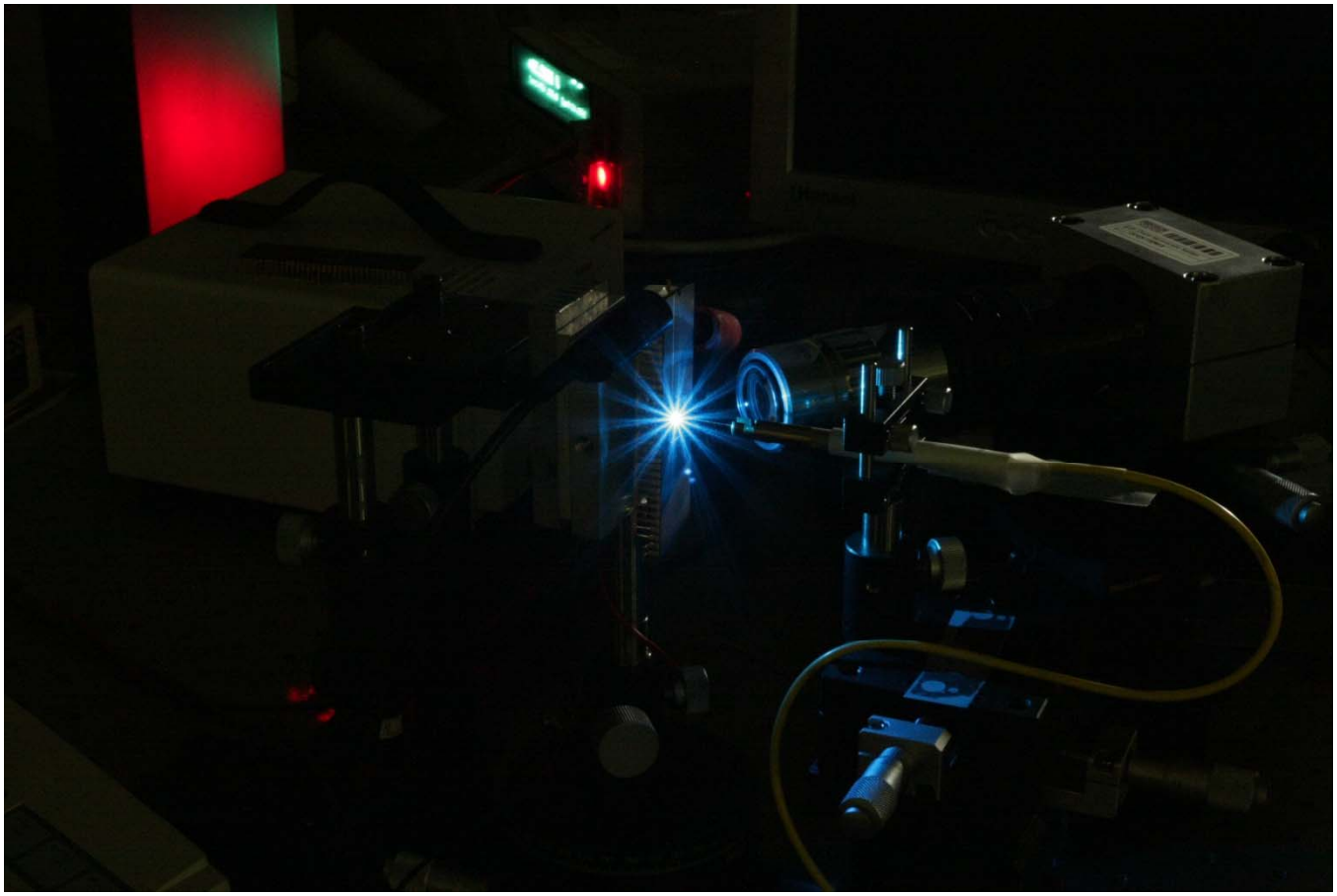
Color purity



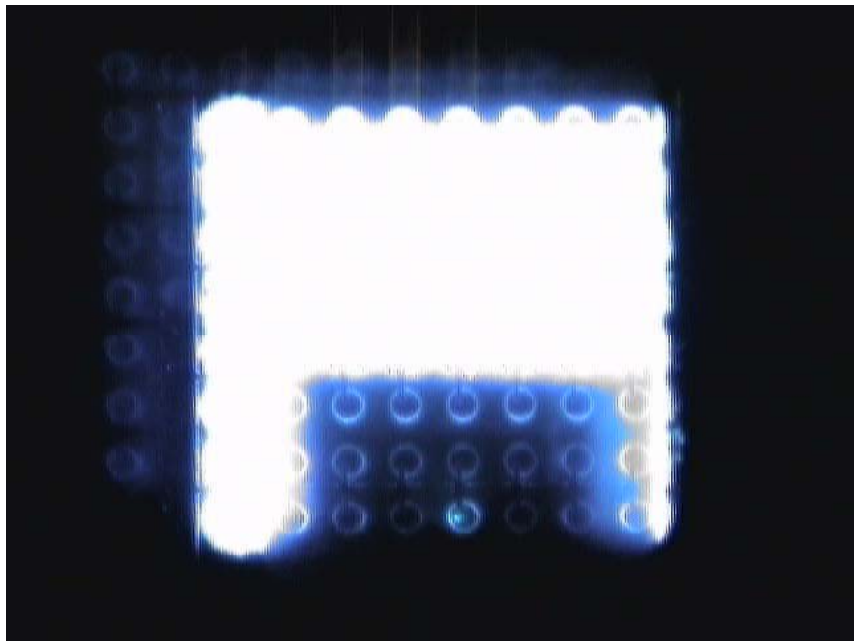
$$\frac{a}{a+b} = \frac{\sqrt{(x - x_{ref})^2 + (y - y_{ref})^2}}{\sqrt{(x_d - x_{ref})^2 + (y_d - y_{ref})^2}} \approx 1$$

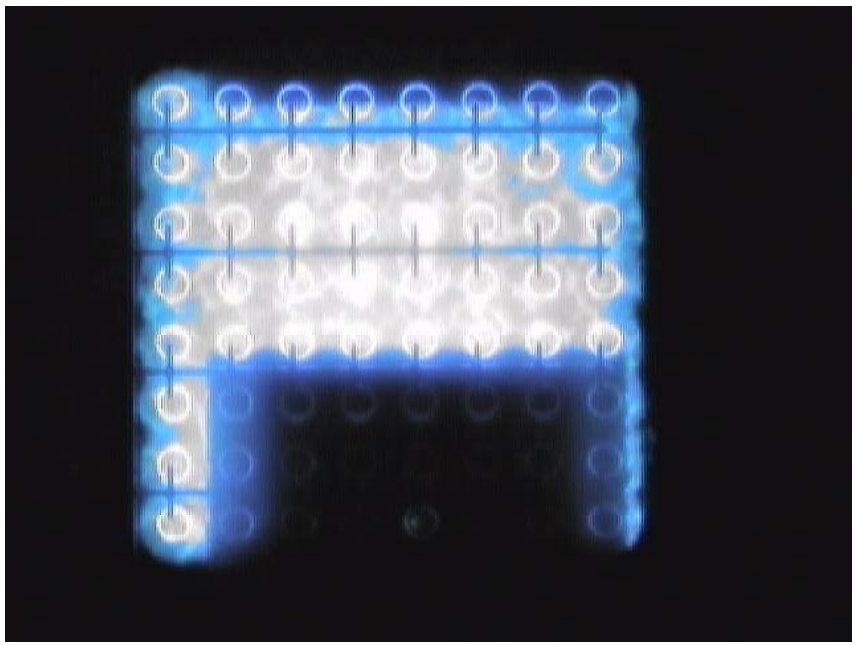
The PQR's color purity is about 1 which means high color rendering ability

Blue PQR laser at 480nm

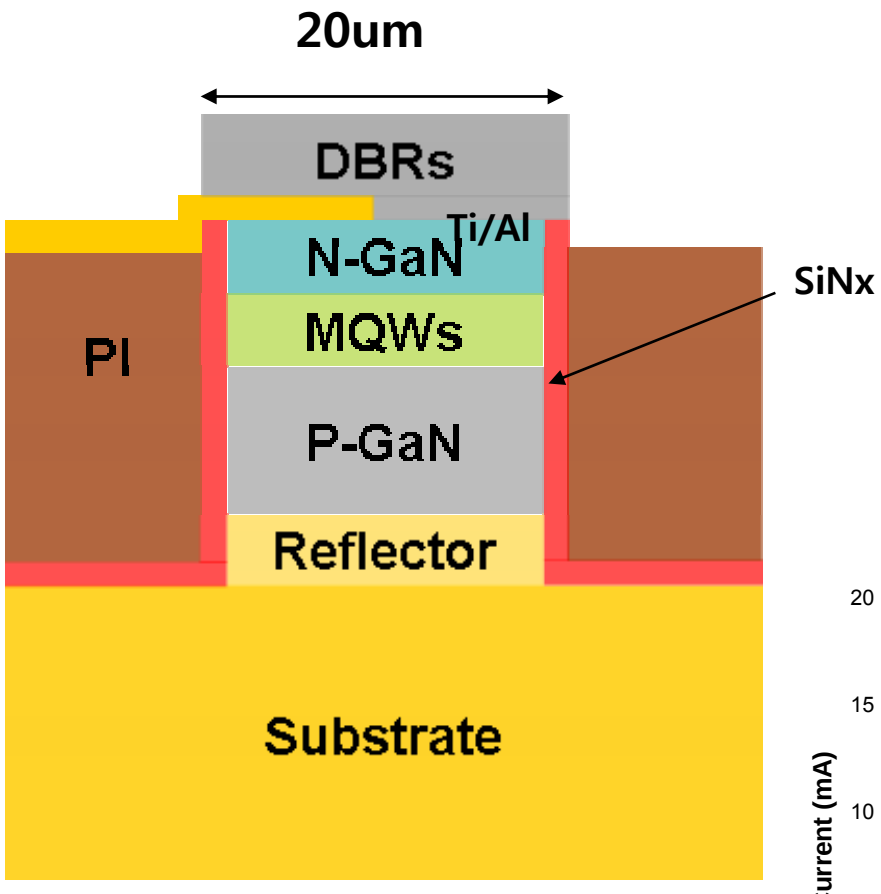


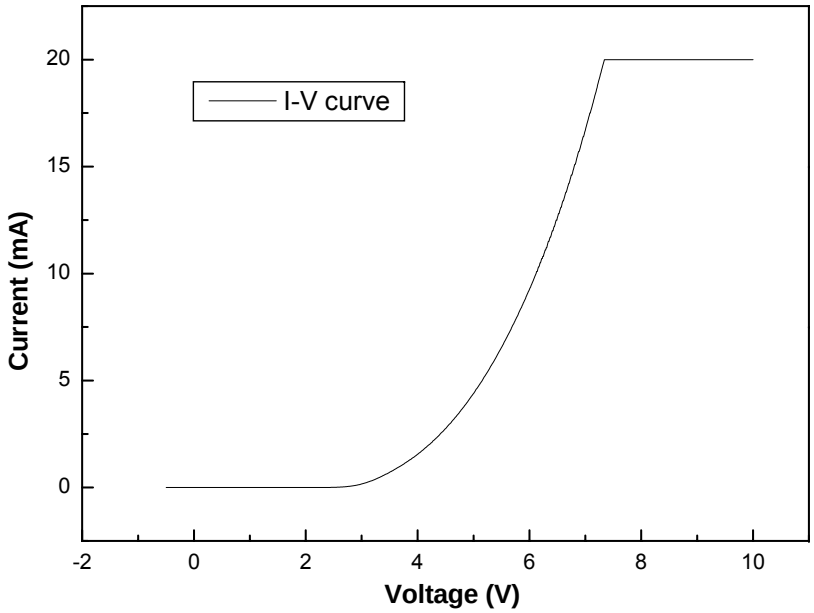
PQR array ($\phi[20\,\mu m]$, $35\mu m$ spacing)
CW/ room temp /at 60mA :
without & with an attenuation filter



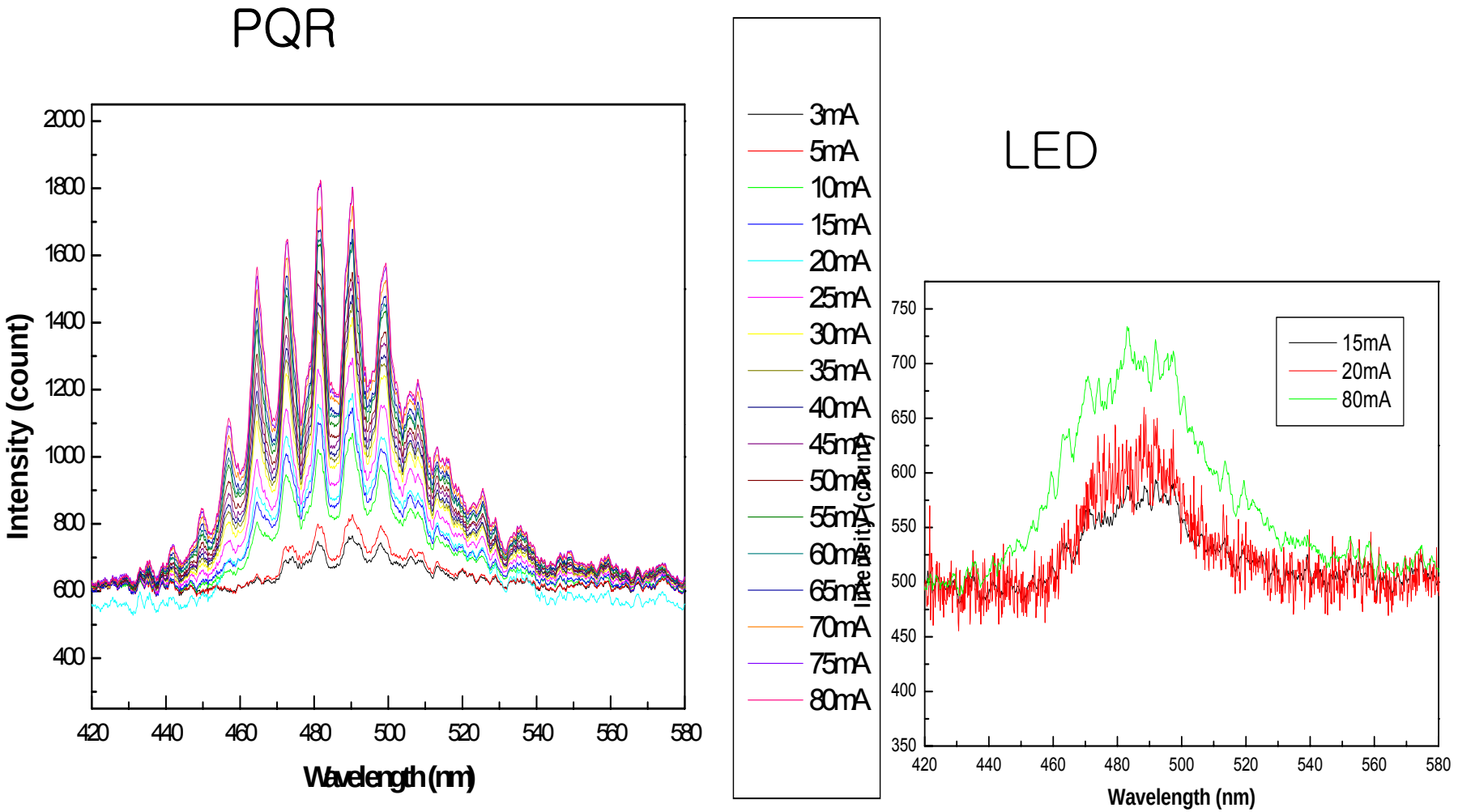


Blue PQR Laser Structure





Multimode PQR Lasing

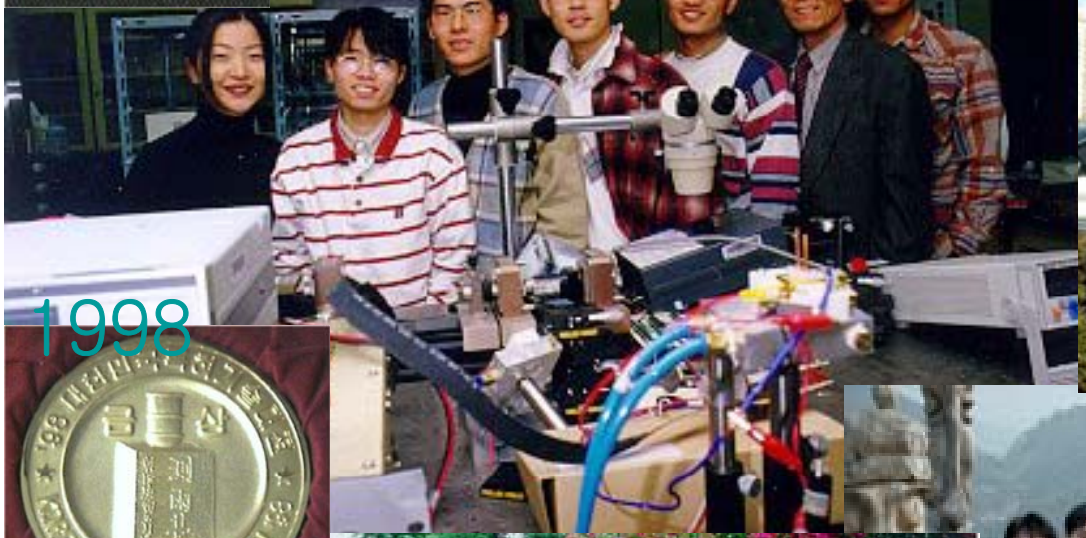


KR movie: Blue PQR Laser

US movie: Blue PQR Laser

Served for PQR

1997-8



2003-04

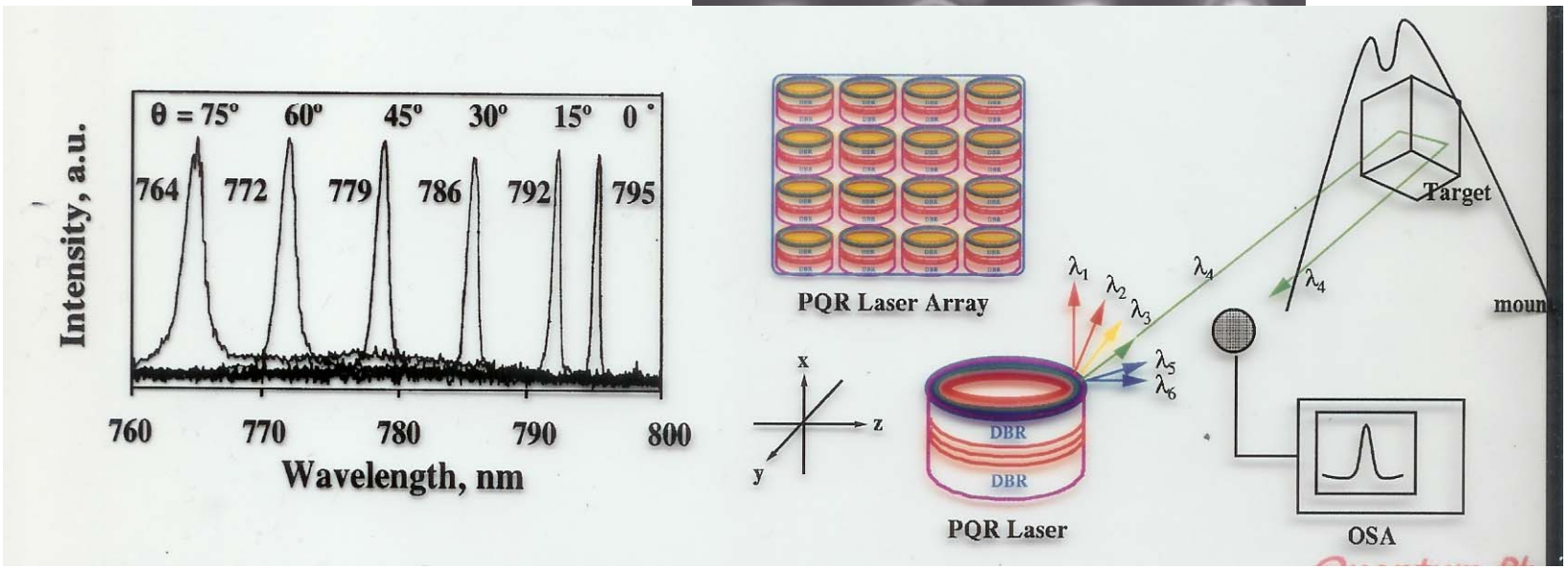
V. Minogin

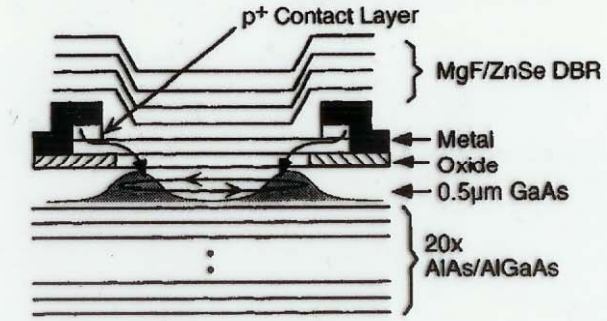
1998

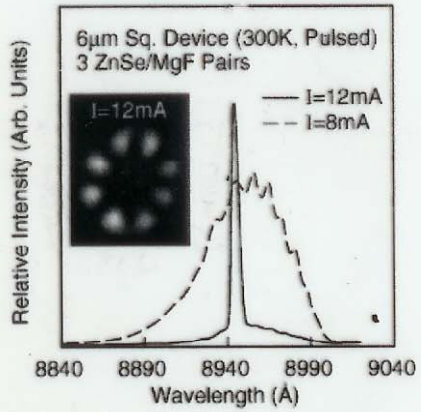
1997

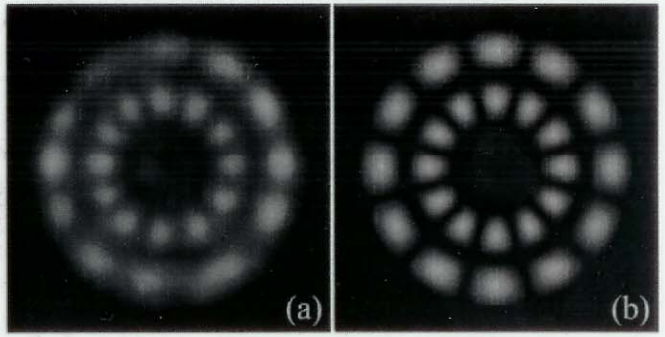
I. Prigogine & Mrs.

2002

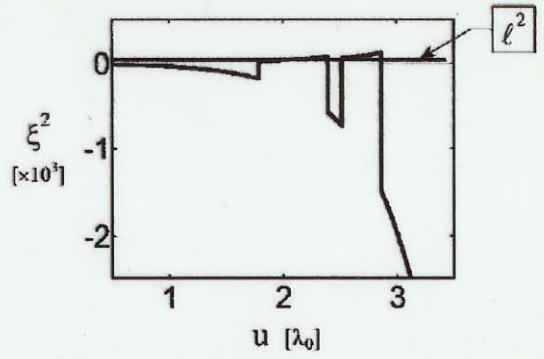

θ = 75°
60°
45°
30°
15°
0 °
764
772
779
786
792
795
Intensity, a.u.
760
770
780
790
800
Wavelength, nm
PQR Laser Array
x
z
y
DBR
DBR
PQR Laser
λ1
λ2
λ3
λ4
λ4
λ5
λ6
Target
OSA


p+ Contact Layer
MgF/ZnSe DBR
Metal
Oxide
0.5μm GaAs
20x
AlAs/AlGaAs


6μm Sq. Device (300K, Pulsed)
3 ZnSe/MgF Pairs
I=12mA
I=12mA
I=8mA
Relative Intensity (Arb. Units)
8840
8890
8940
8990
9040
Wavelength (Å)


(a)
(b)

20 [μm]


ℓ^2
0
-1
-2
ξ^2
[×10³]
1
2
3
u [λ₀]

InGaAs PQR : non-VCSEL type : Early Raw Data