

Near-field Scanning Optical

Microscopy of Photonic Crystal Laser

Koichi Okamoto

collaborated with

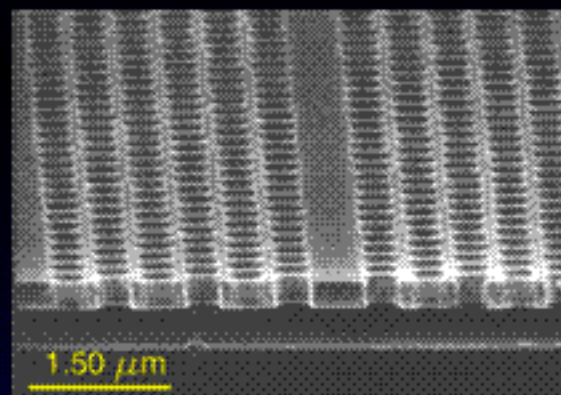
Marko Lončar¹

Tomoyuki Yoshie²

Axel Scherer

¹Present: Harvard University

²Present: Duke University

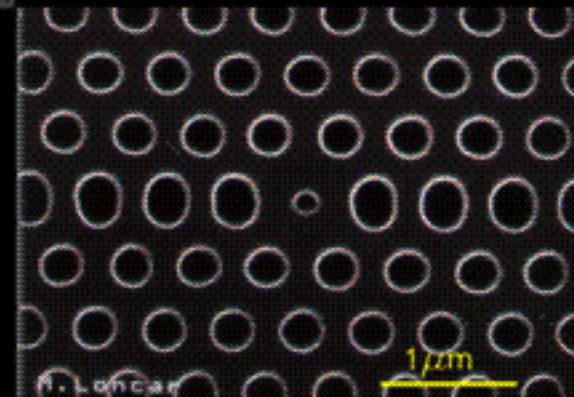


Caltech Nanofabrication Group



nanofab.caltech.edu

Photonic Crystals
Research

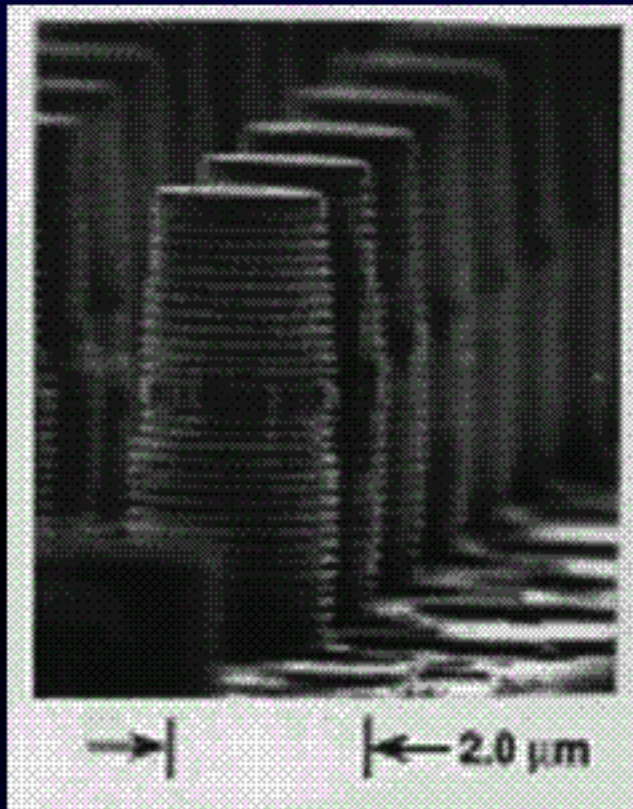




Photonic crystals

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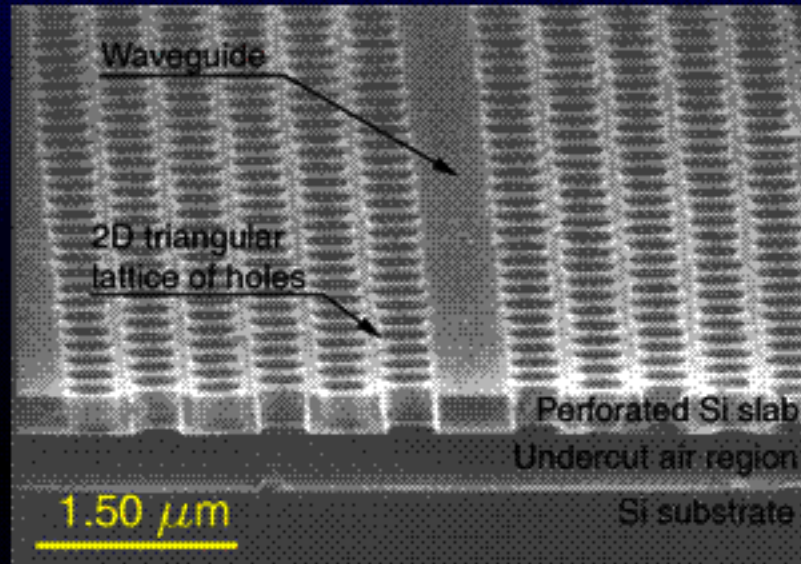
1D



A. Scherer (Bellcore)

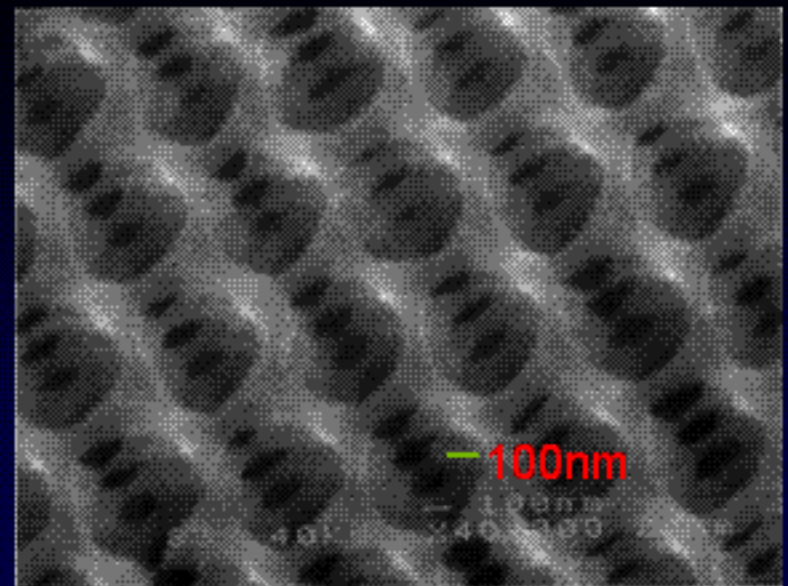
- High density integration
- Light confinement into small volumes

2D



M. Loncar (Caltech)

3D



C.C. Cheng (Caltech)

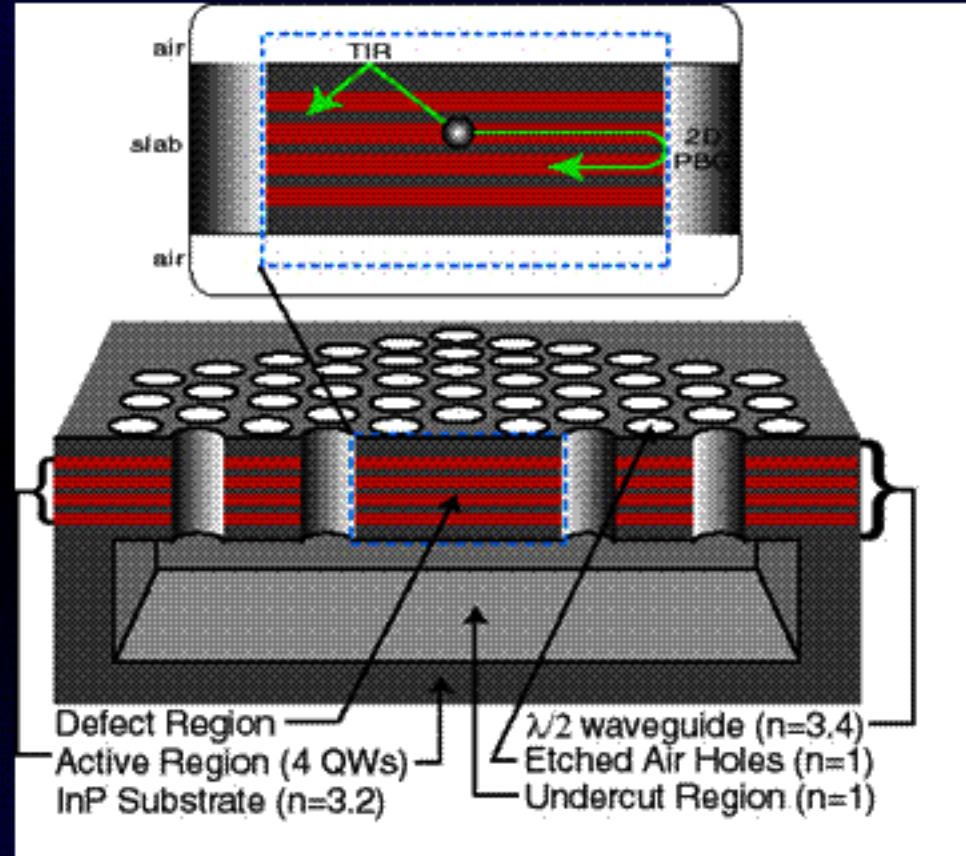
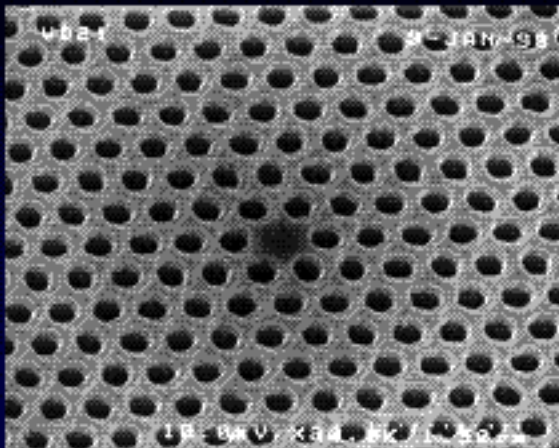


Motivation

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Photonic crystal cavities
can:

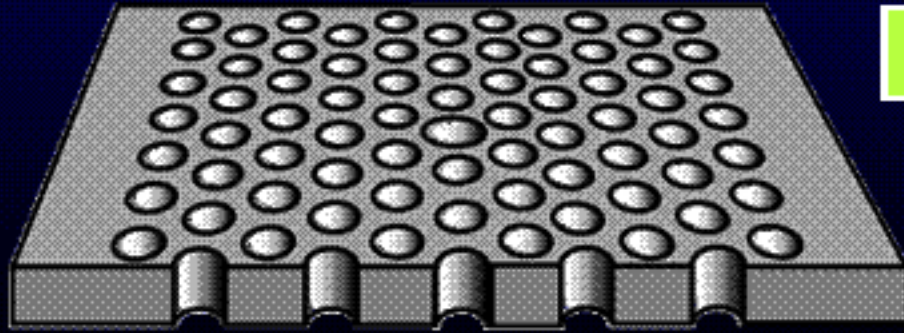
- store energy into the small volumes (V_{mode})
- contain energy efficiently (small "leaks") => big Quality factors (Q)



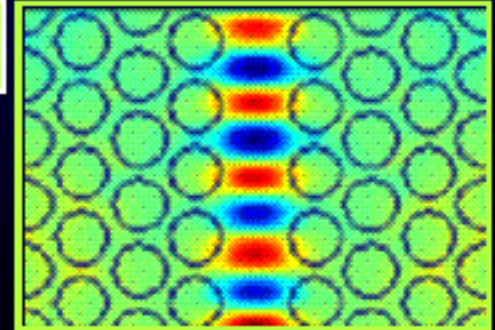


Nanophotonics Devices with PC

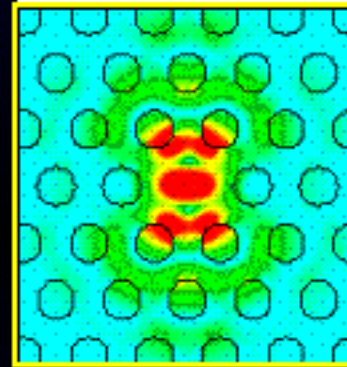
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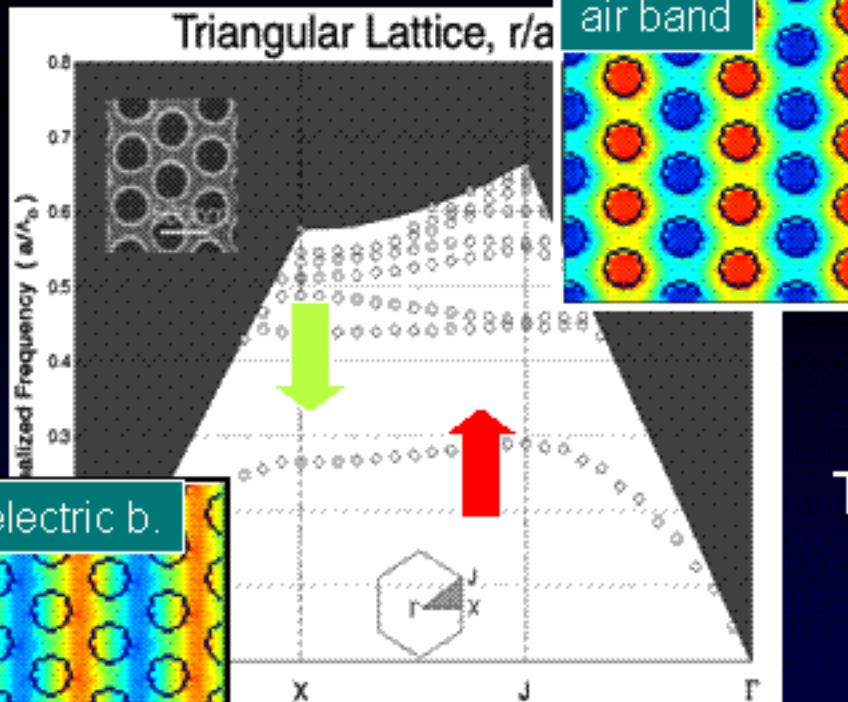
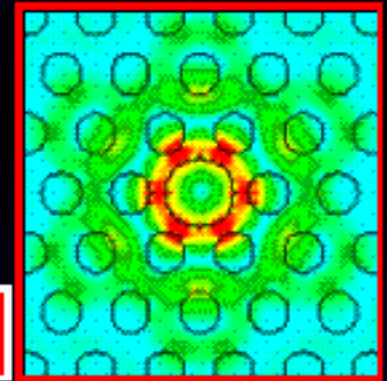
donor waveguide



donor cavity



acceptor cavity



Typical geometry for $\lambda=1.5\mu\text{m}$:

$a \approx 450\text{nm}$

$r \approx 130\text{nm}$

$d \approx 340\text{nm}$

periodicity

hole radius

slab thickness



Development of PC nano-cavity

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Photonic crystals Nanocavity

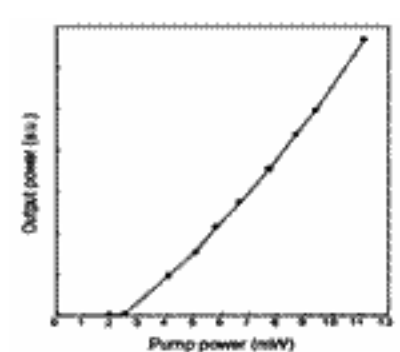
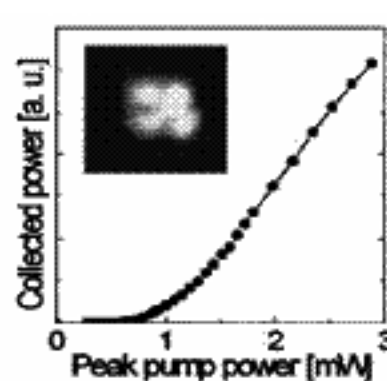
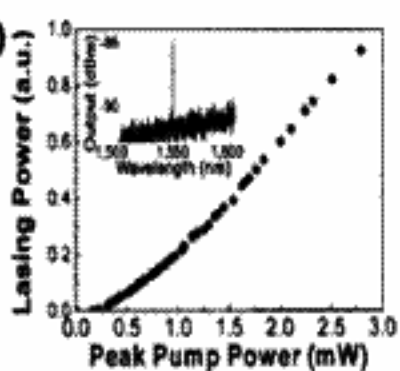
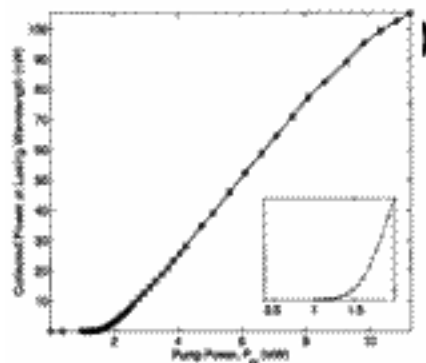
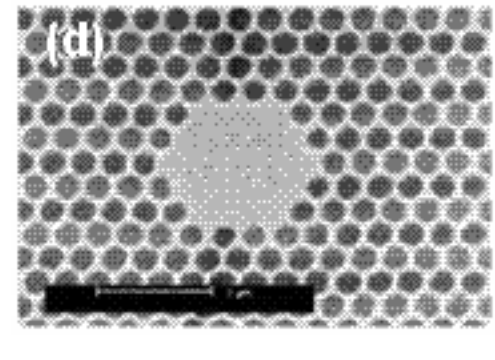
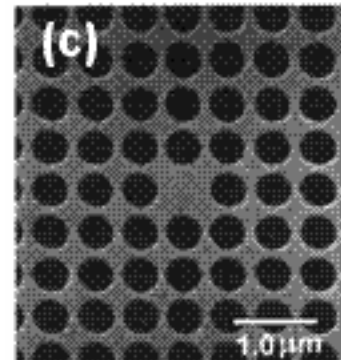
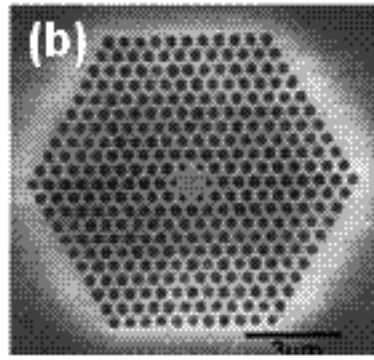
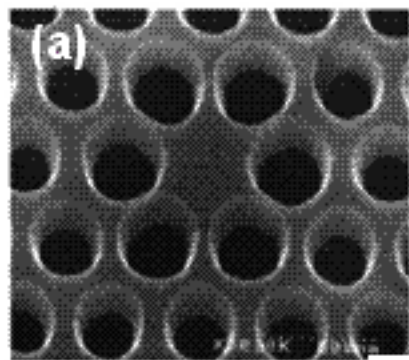
small volumes (V_{mode}), high quality factors (Q)

(a) O. Painter et al., *Science*, **284**, 1819 (1999).

(b) H. G. Park et al., *Appl. Phys. Lett.* **79**, 3032 (2001).

(c) H. Y. Ryu et al., *Appl. Phys. Lett.* **80**, 3883 (2002).

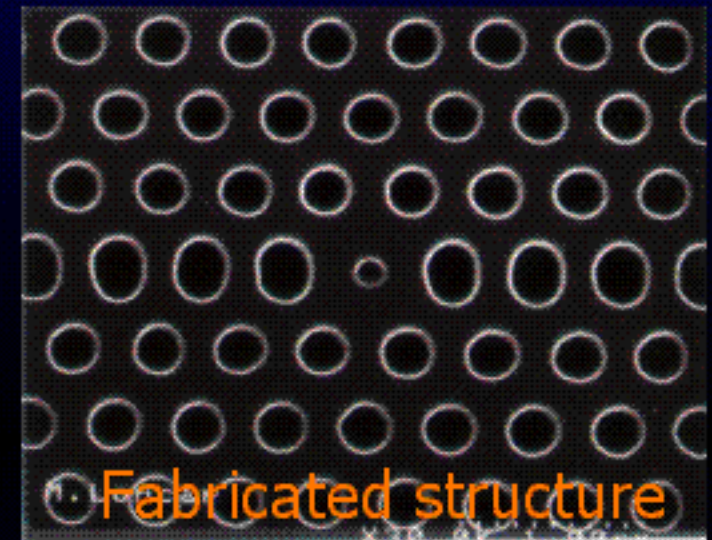
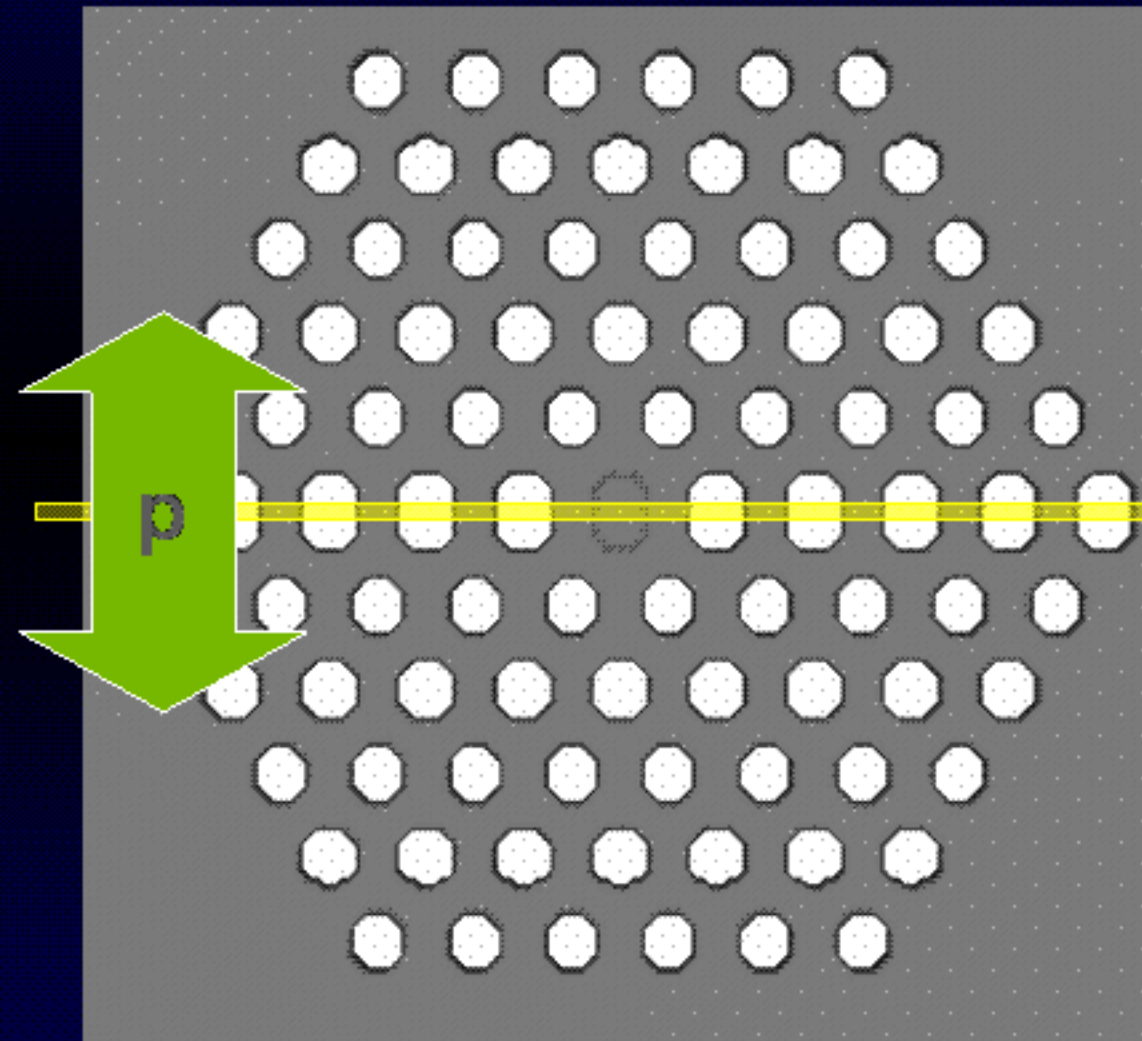
(d) P. T. Lee et al., *IEEE Photonics Technol. Lett.* **14**, 435 (2002).





High-Q Photonic crystal cavities

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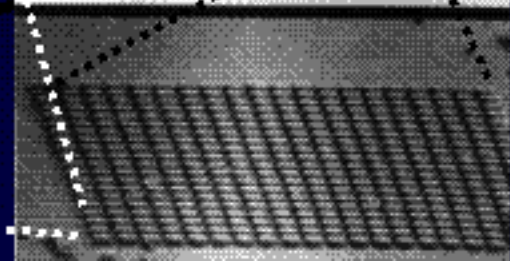
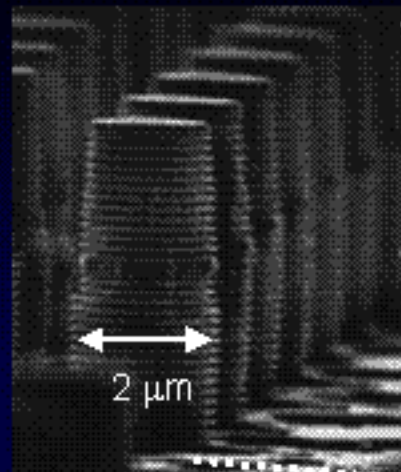
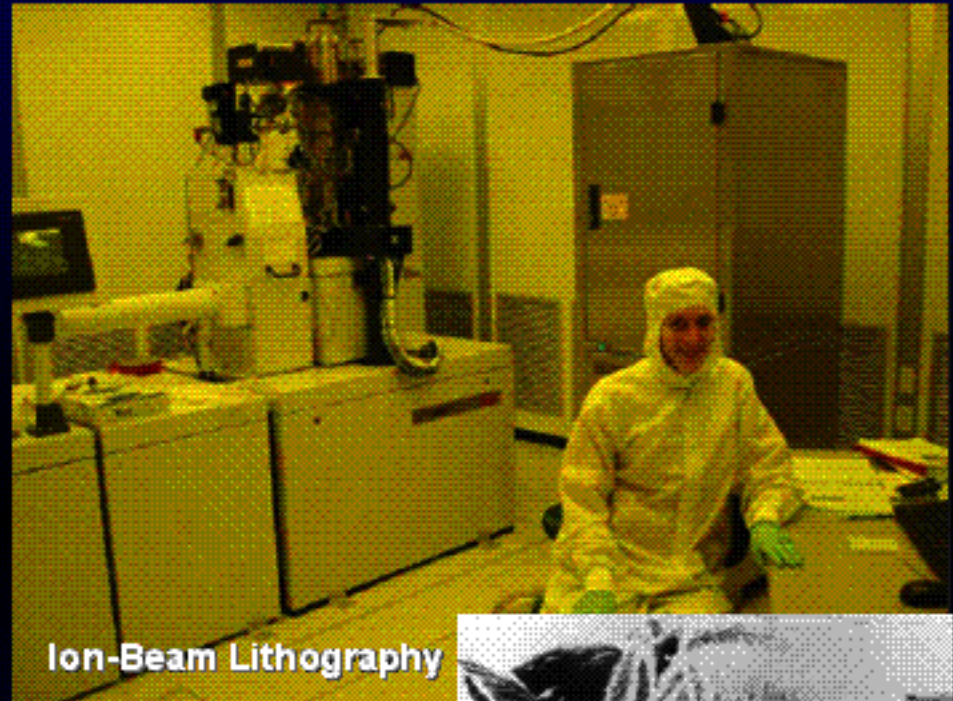
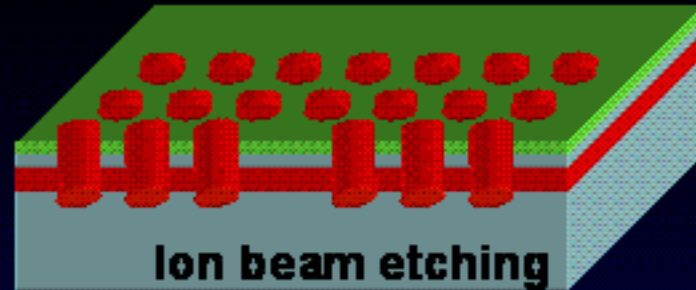


- J. Vučković et al.,
Phys. Rev. E, **65**, 016608, (2002).
M. Lončar et al.,
Appl. Phys. Lett., **81** 2680 (2002).
T. Yoshie et al.,
Appl. Phys. Lett. 79, 4289 (2001)



Fabrication Processes

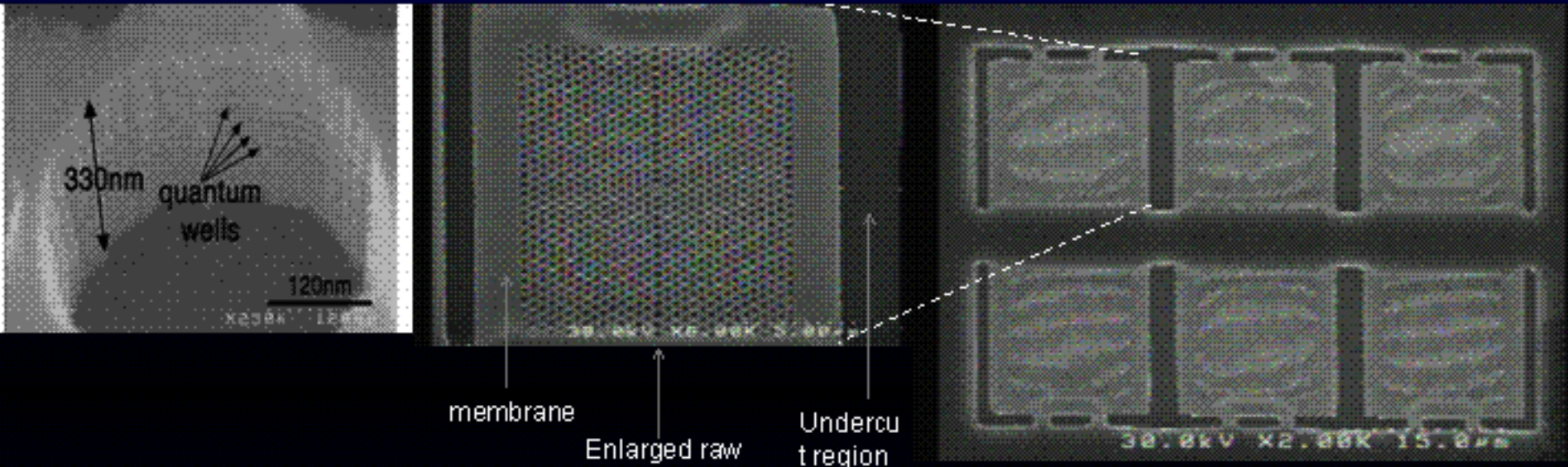
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Sample Structure

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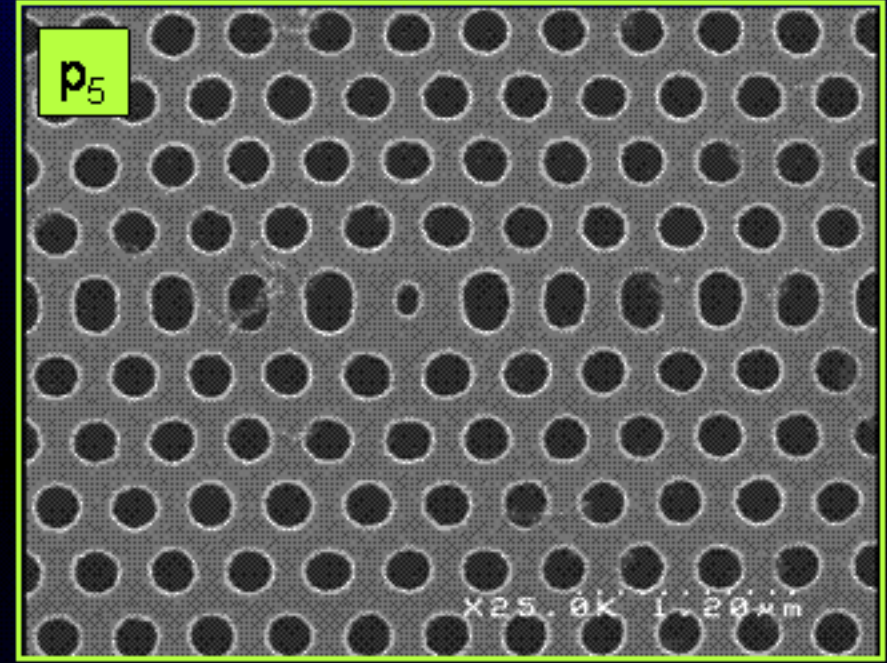
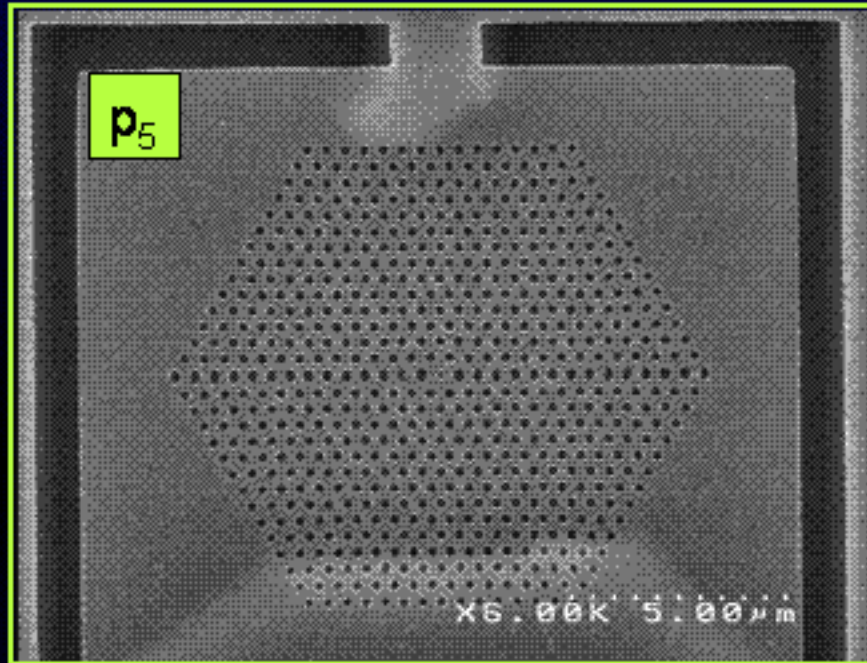
Fabrication

- 4 InGaAsP quantum wells embedded into InGaAsP slab. Designed to operate around 1550 nm.
- Fabrication mask: 150nm PMMA /50nm Au/ 100nm SiON
- Ion-beam milling used to transfer the mask into Au
- RIE using C_2F_6 used to transfer the mask into SiON
- ICP-RIE with Cl_2 used to make structures in InGaAsP
- undercut in $HCl:H_2O$ to make free-standing membrane



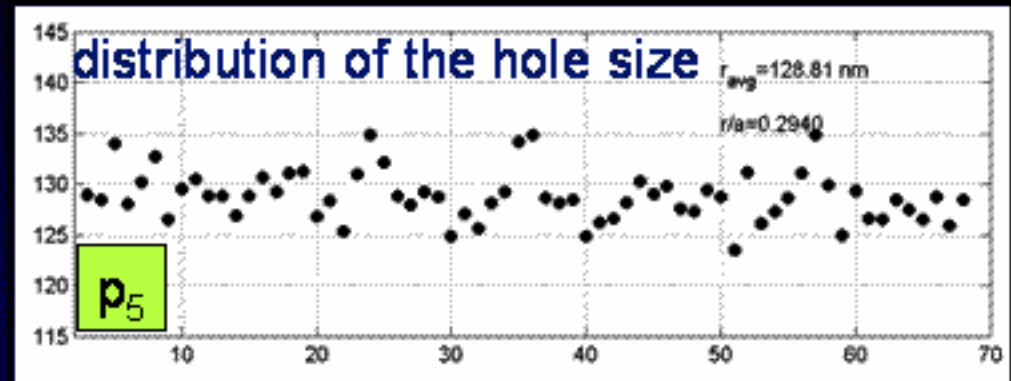
Fabricated Patterns

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$r_{avg} = 129nm$
 $r/a = 0.2940$

Fabrication tolerances: $\pm 4nm$





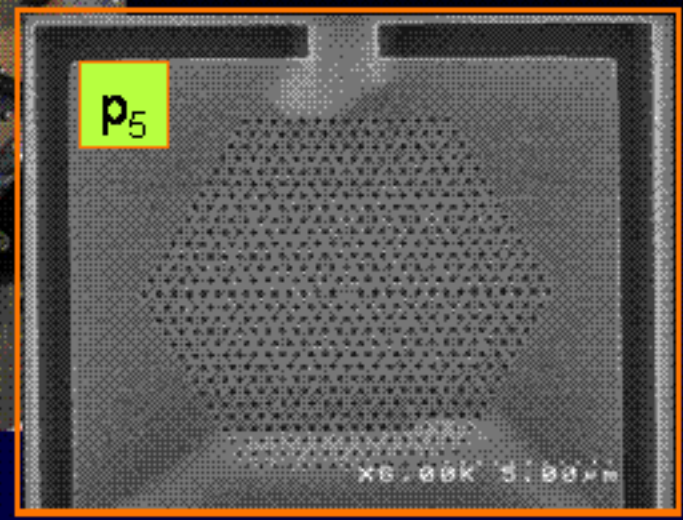
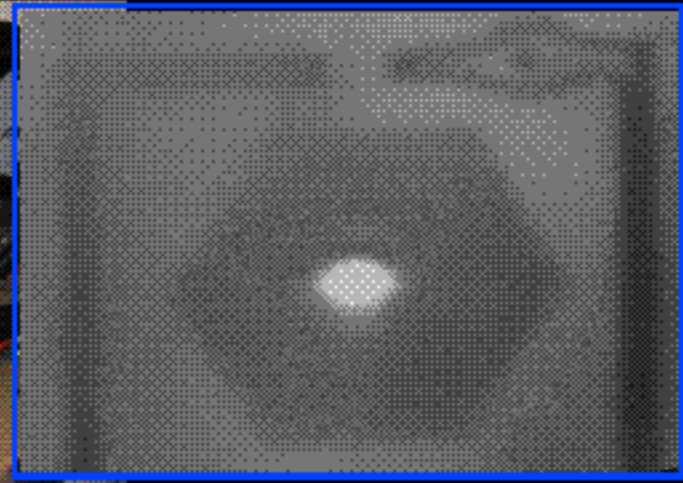
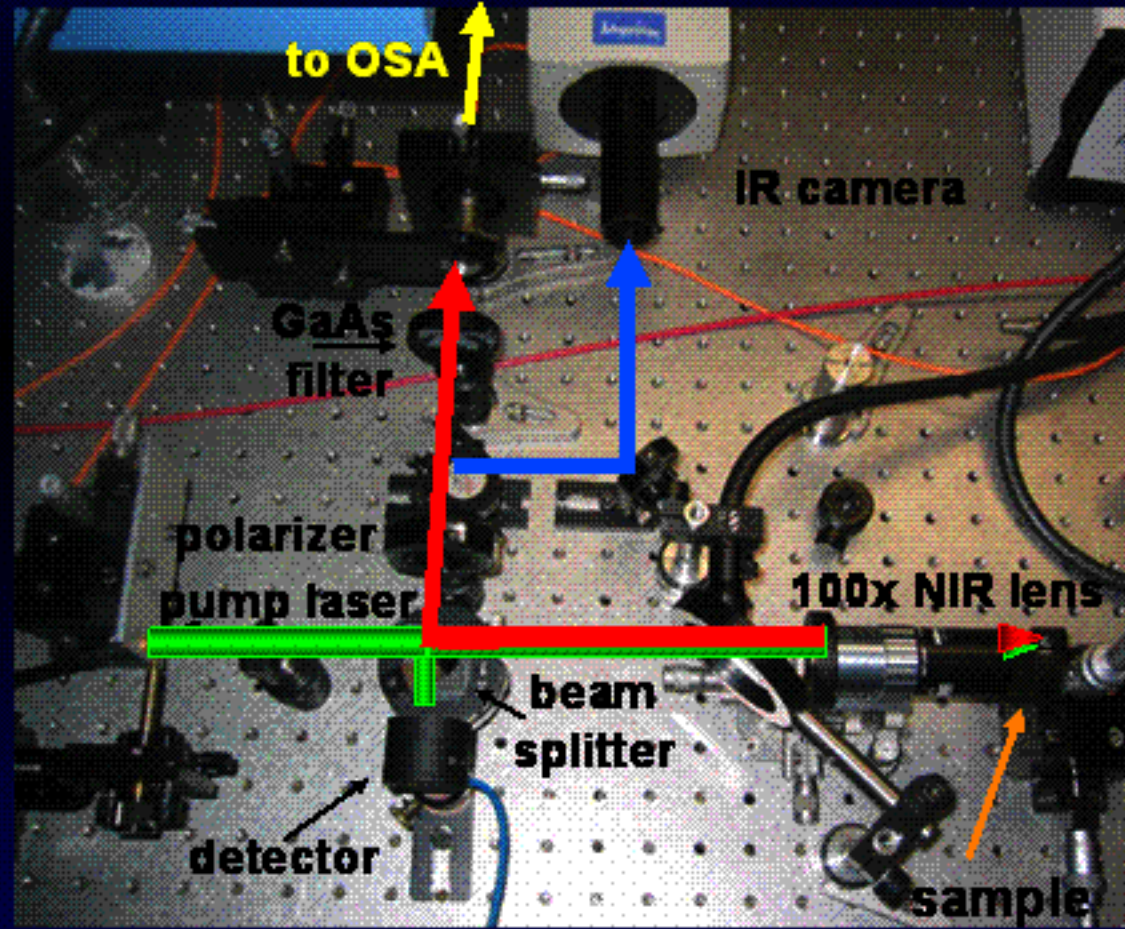
Photolumuminescence Setup

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 pump @ 830nm

 emission (1300, 1650) nm

- optical pumping
- room temperature
- 10ns - 30ns pulses (duty cycle 1% - 3%)



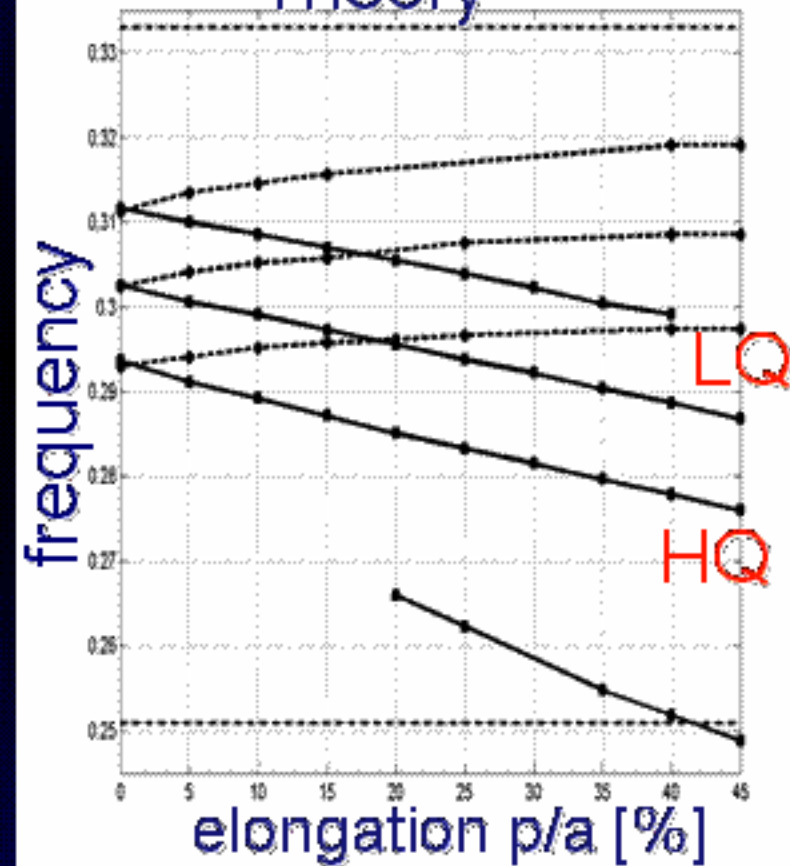


Experimental Results (PL)

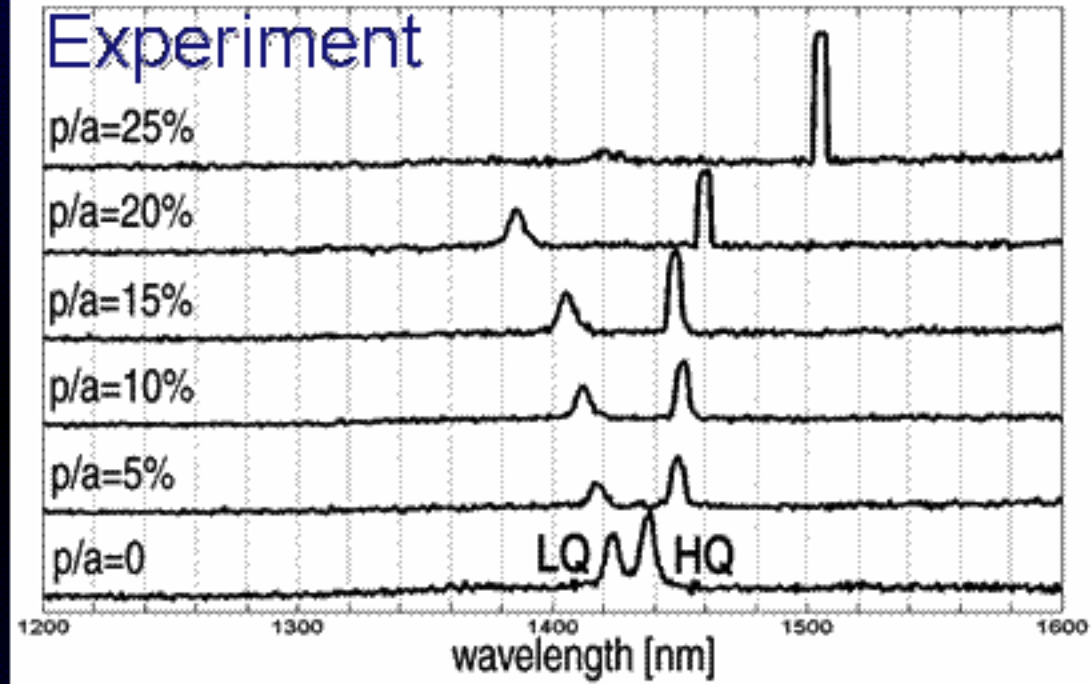
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M. Lončar et al., *Appl. Phys. Lett.*, 81 2680 (2002).

Theory



Experiment



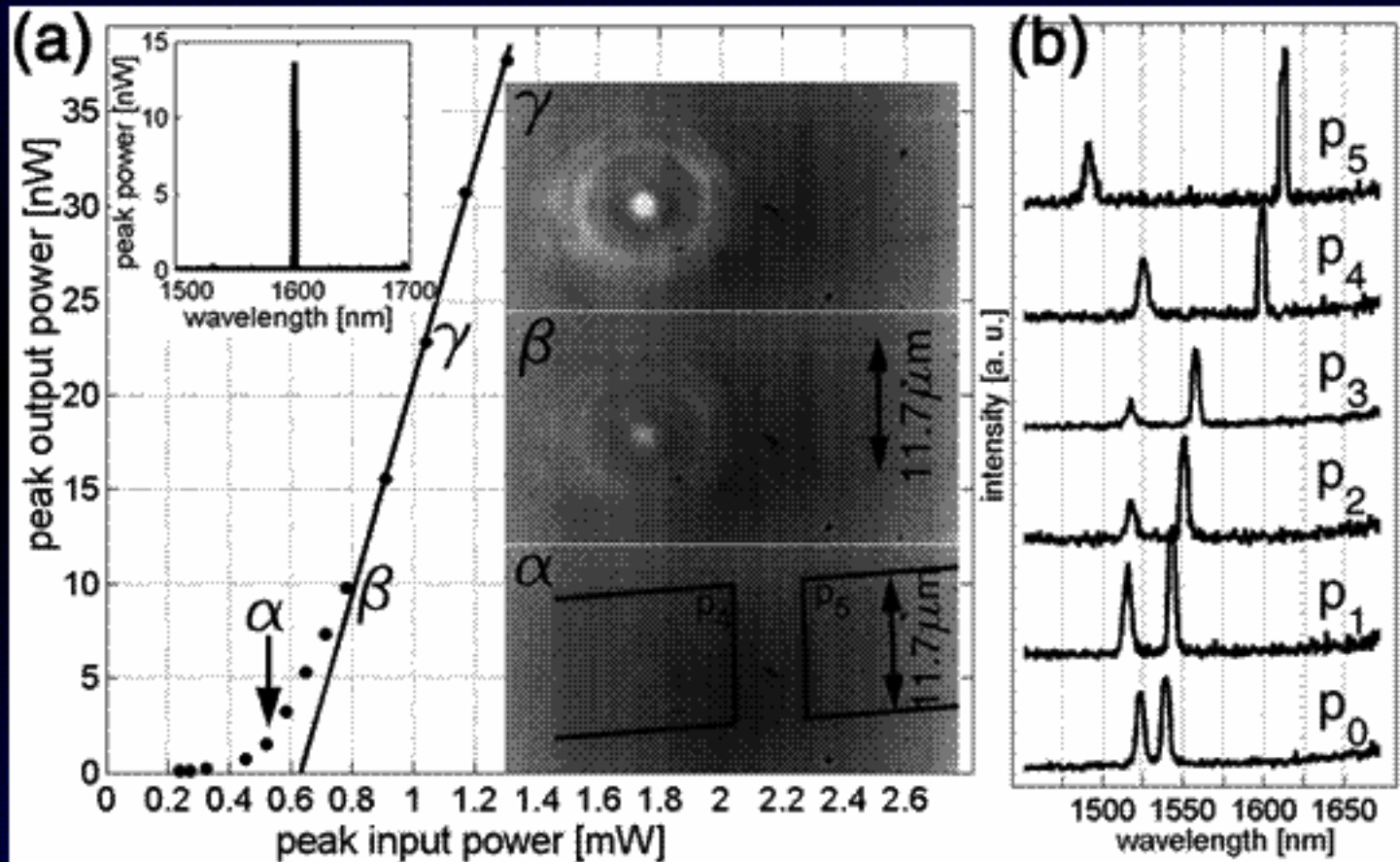
Peak positions as function of elongation parameter



Experimental Results (Lasing)

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M. Lončar et al., *Appl. Phys. Lett.*, 81 2680 (2002).



(a) L-L curve for p_4 cavity with smaller holes. (b) Tuning properties. Images of the lasing mode were obtained using IR camera and GaAs filter.

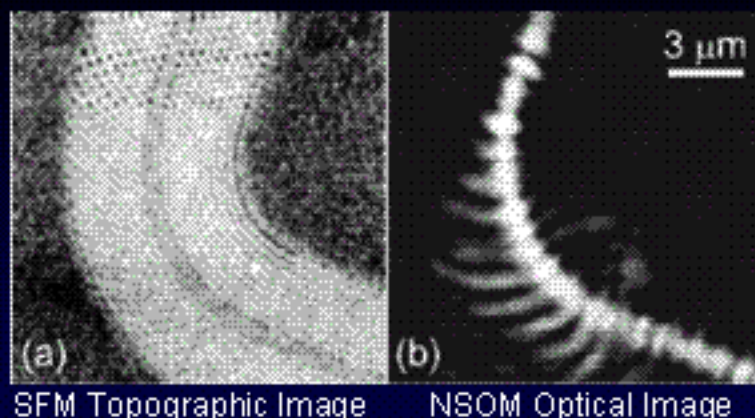
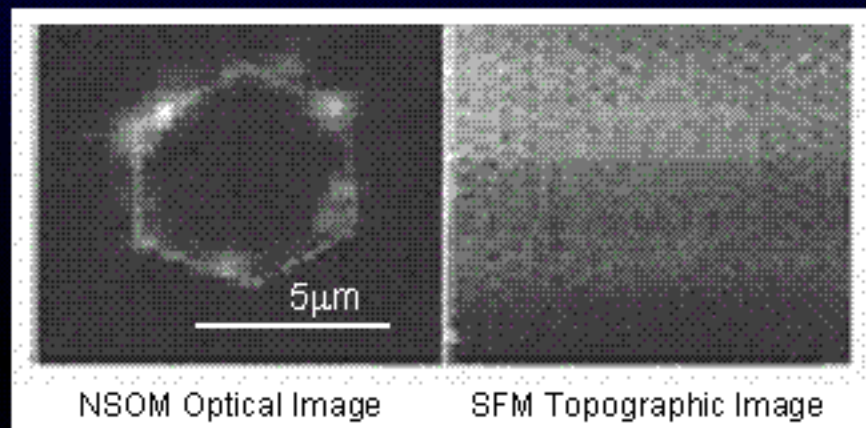
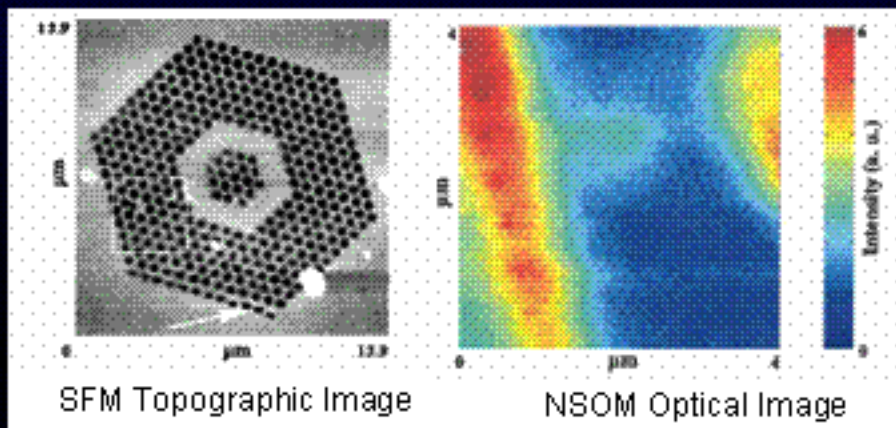


NSOM measurements for Photonic Crystal

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Near-field scanning optical microscopy (NSOM or SNOM)

↓ NSOM studies of photonic crystal (PC) cavities



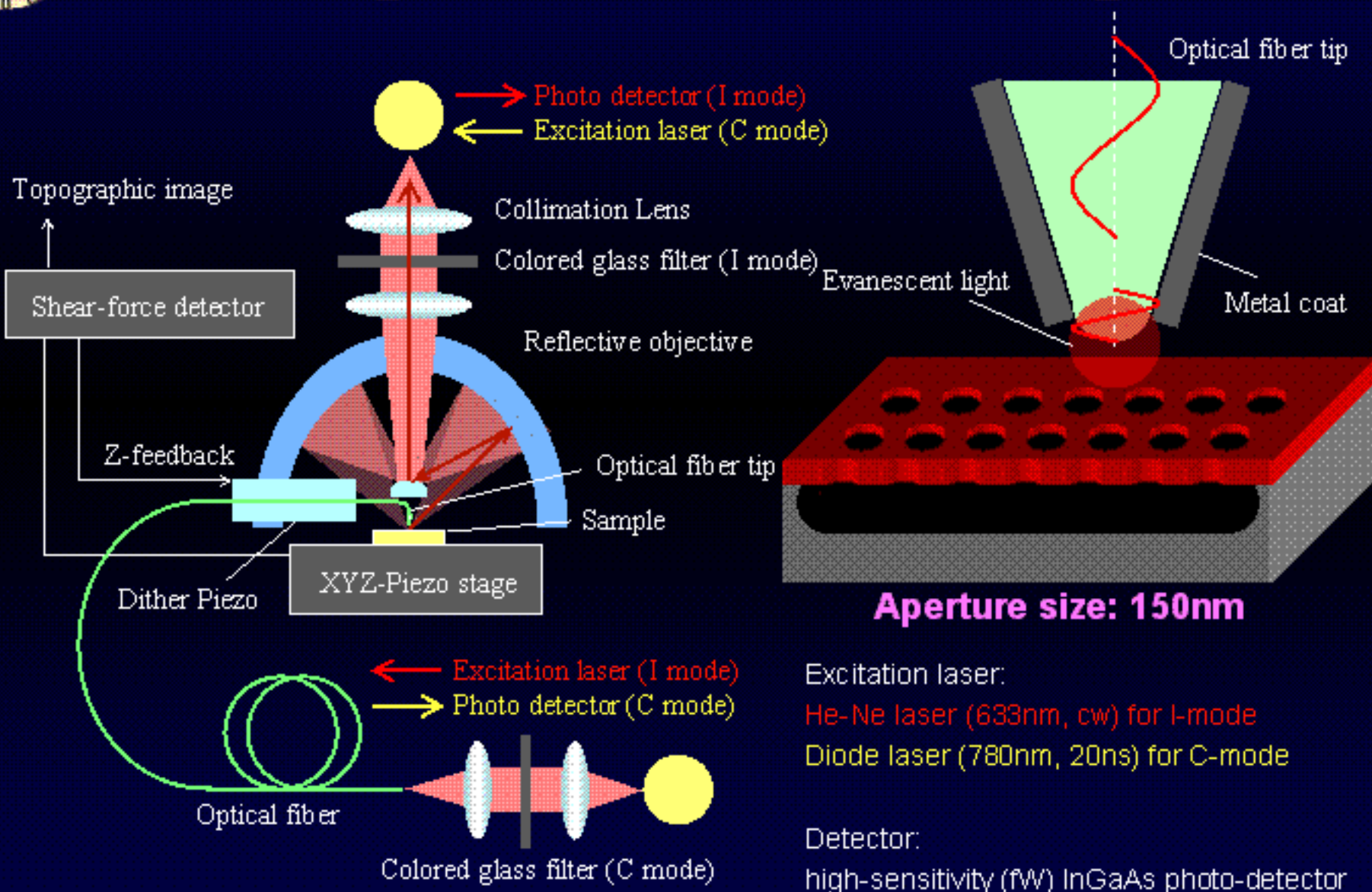
← NSOM studies of PC wave guide

Here we report much higher resolved NSOM images of PC nanocavities



Experimental Setup

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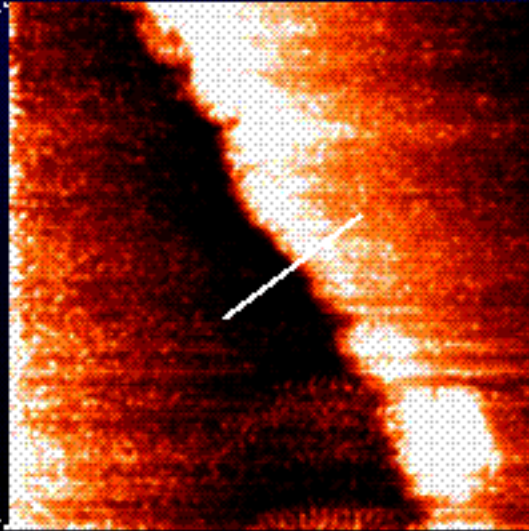
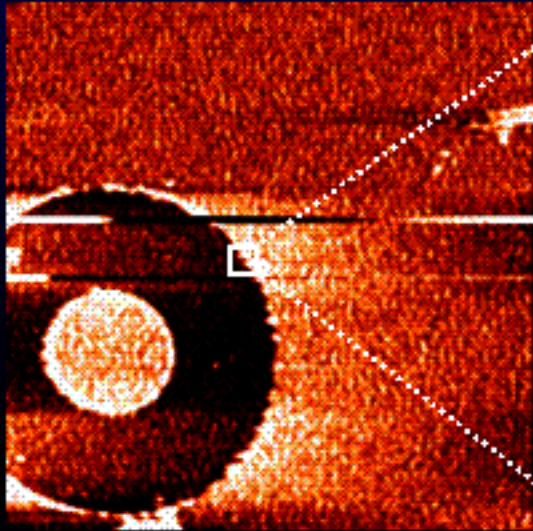




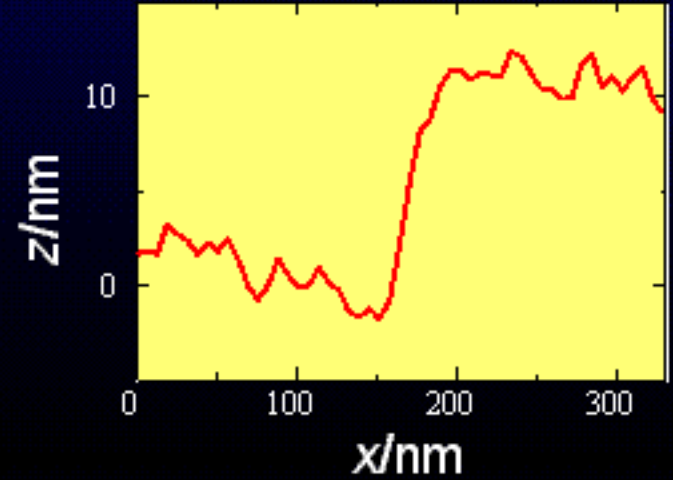
Spatial resolution of our setup

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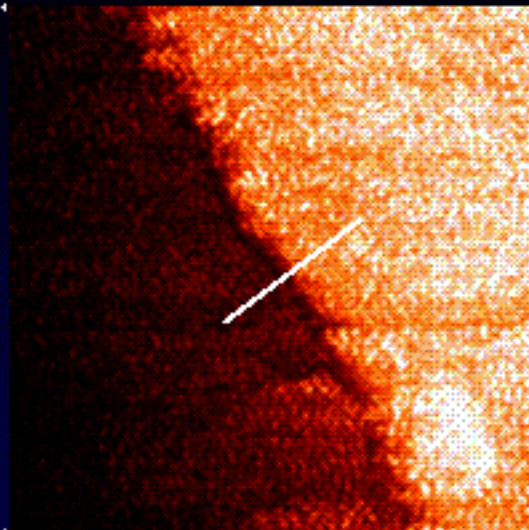
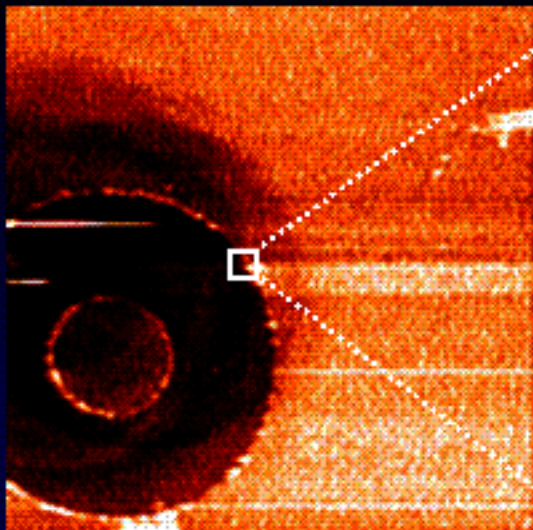
Topographic image



Spatial resolution is around 50 nm

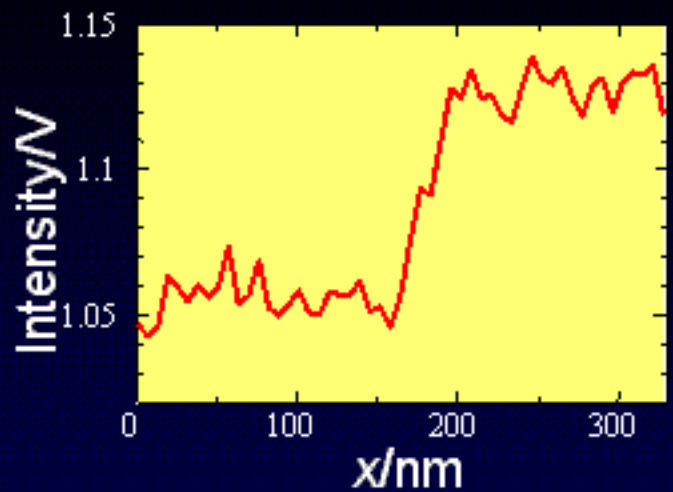


NSOM image



20X20 μm

1X1 μm





High-Q Nanocavity Design

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↔ Elongated

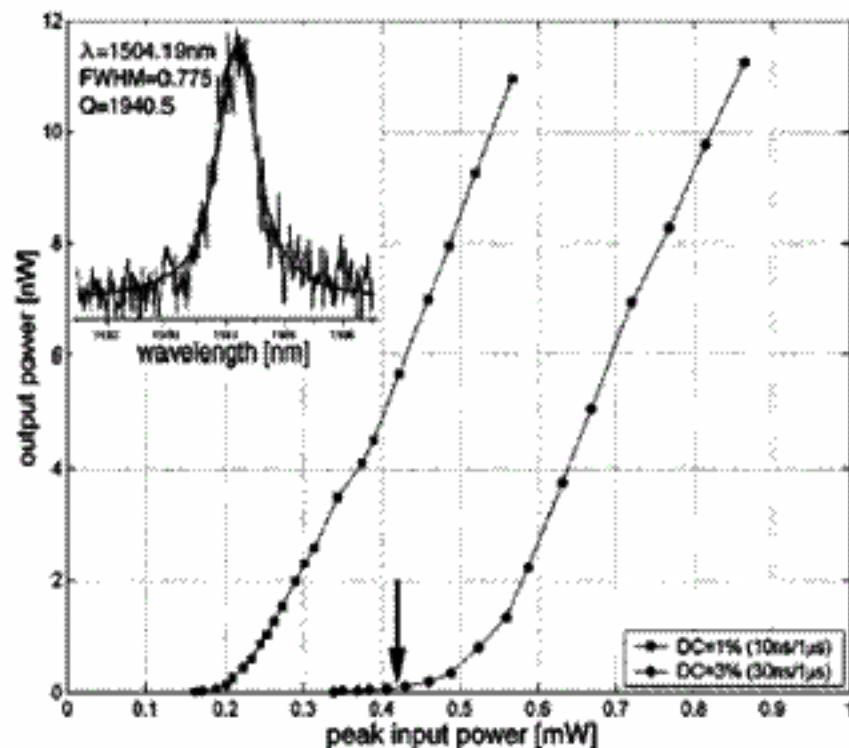
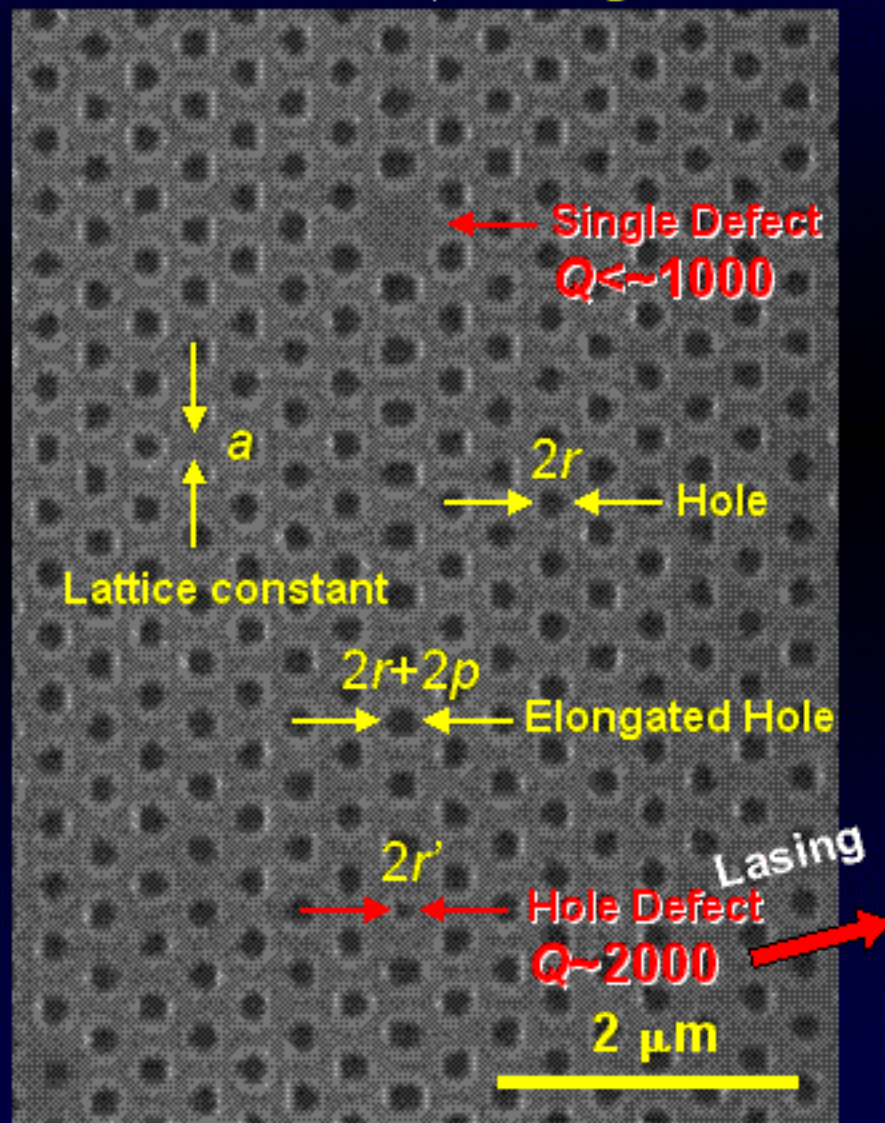


FIG. 5. L - L curve for p_5 cavity for two different DCs. The pulse periodicity was $1 \mu\text{s}$ in both cases. Spectrum taken below threshold (arrow) is shown in the inset.

M. Lončar et al., *Appl. Phys. Lett.*, 81 2680 (2002).

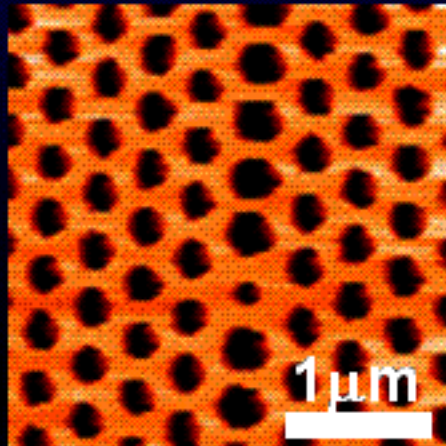


Dielectric band modes

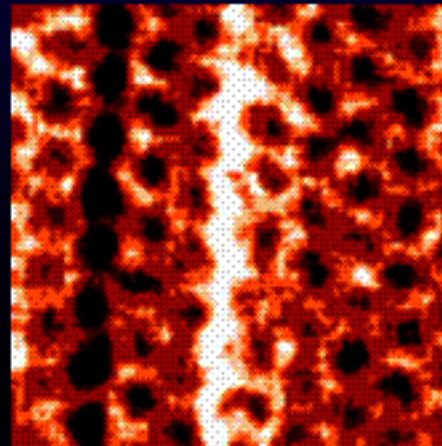
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C-mode operation of NSOM

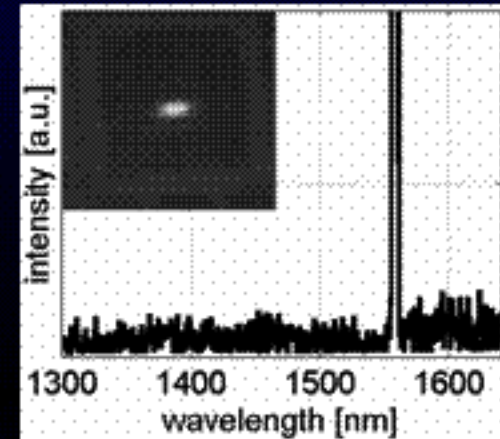
PC structure with bigger holes ($p/a = 25\%$)



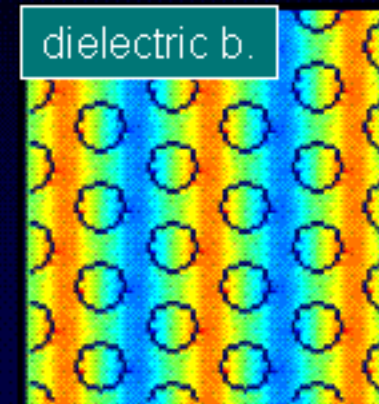
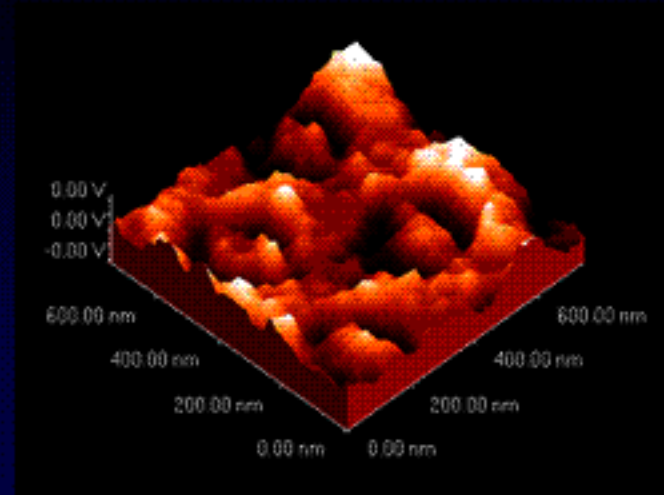
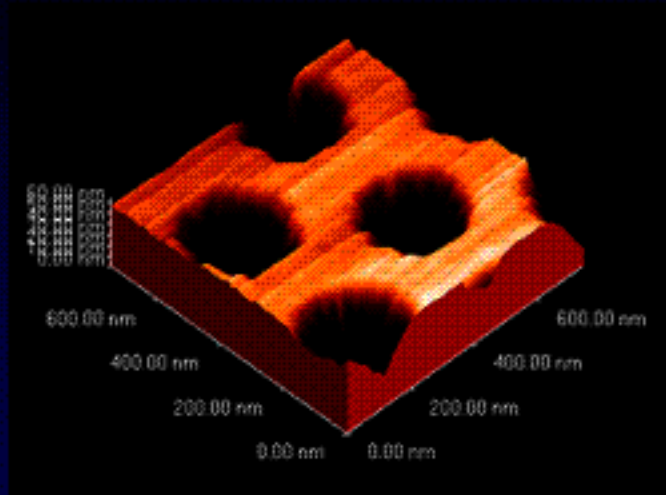
SFM Image



NSOM PL Image



PL Spectrum



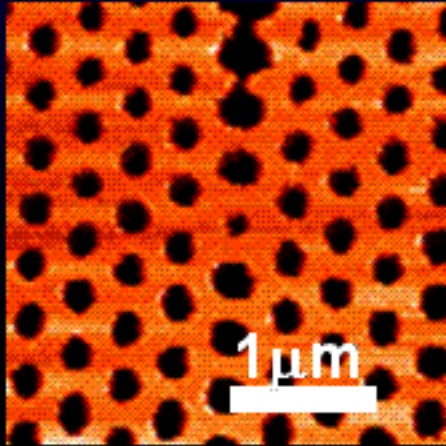


Air band modes

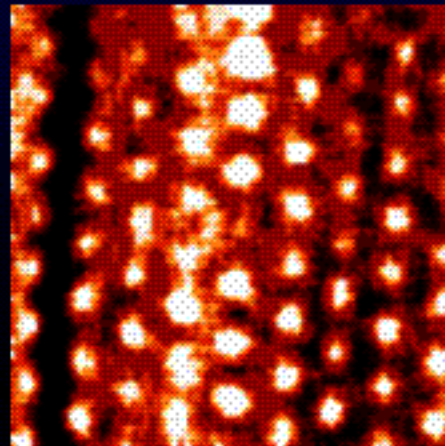
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C-mode operation of NSOM

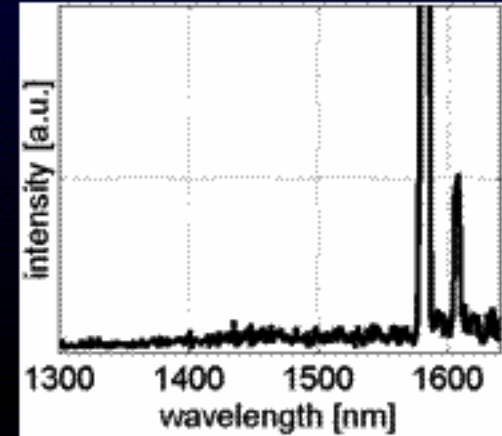
PC structure with bigger holes ($p/a = 25\%$)



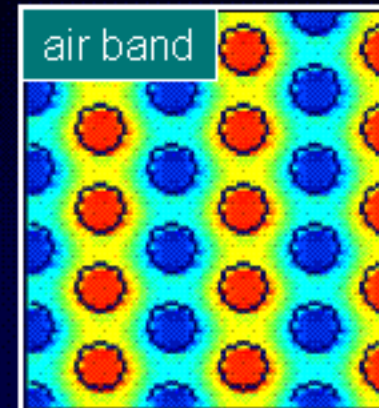
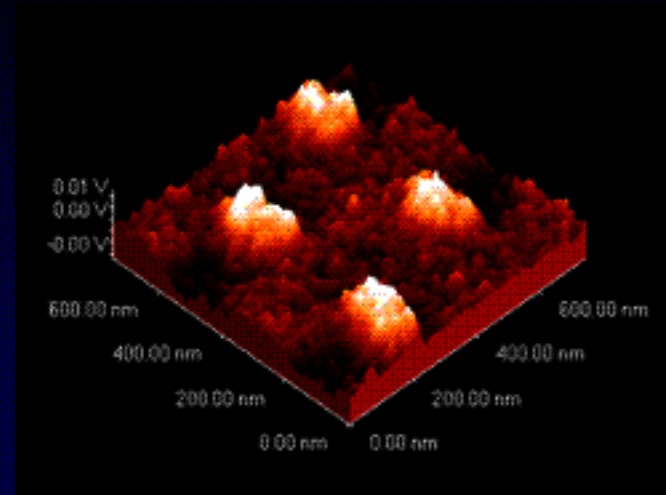
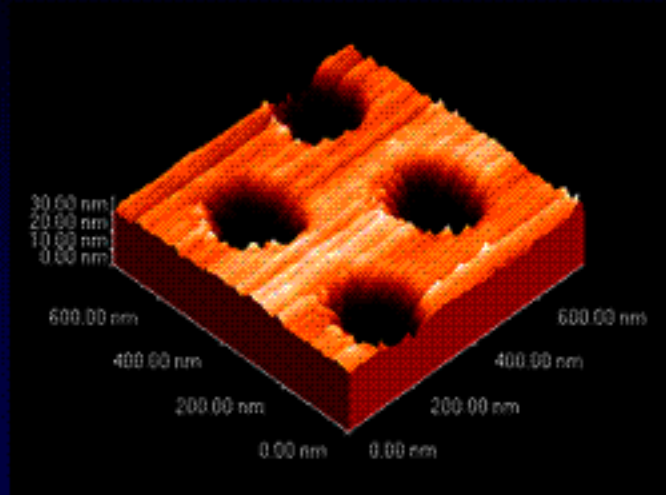
SFM Image



NSOM PL Image



PL Spectrum



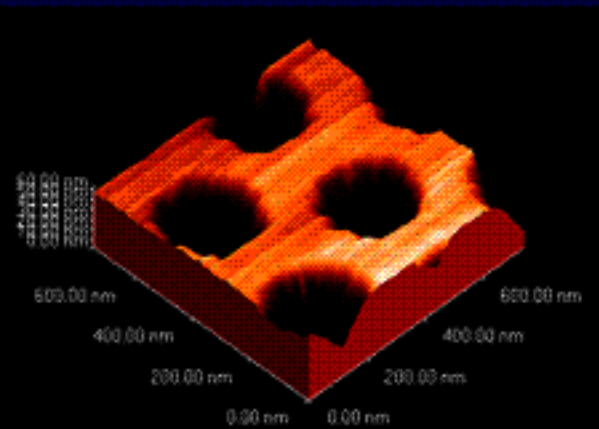


Dielectric band and air band mode

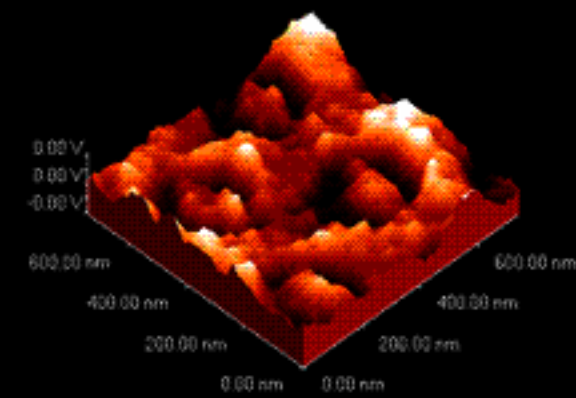
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C-mode operation

→ Air band

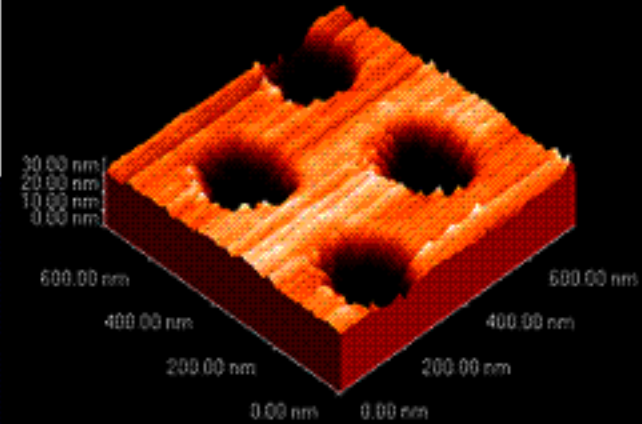
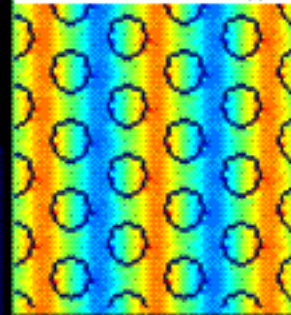
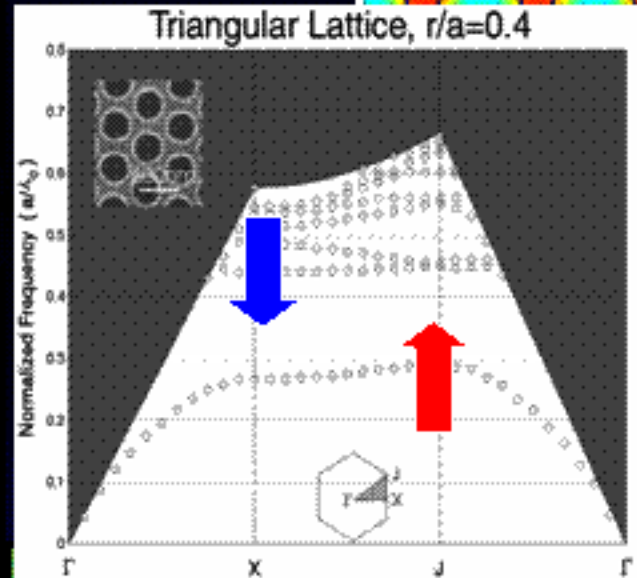
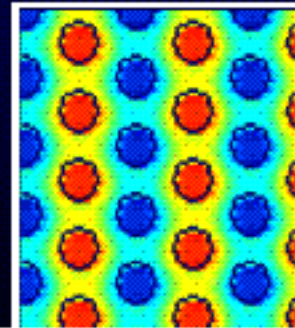


SFM Topographic Image

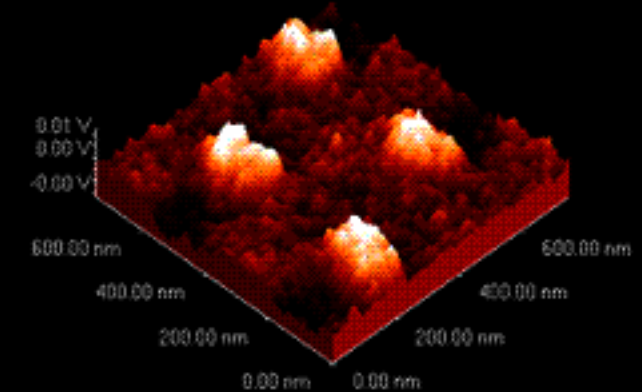


NSOM PL Image

Dielectric band ←



SFM Topographic Image



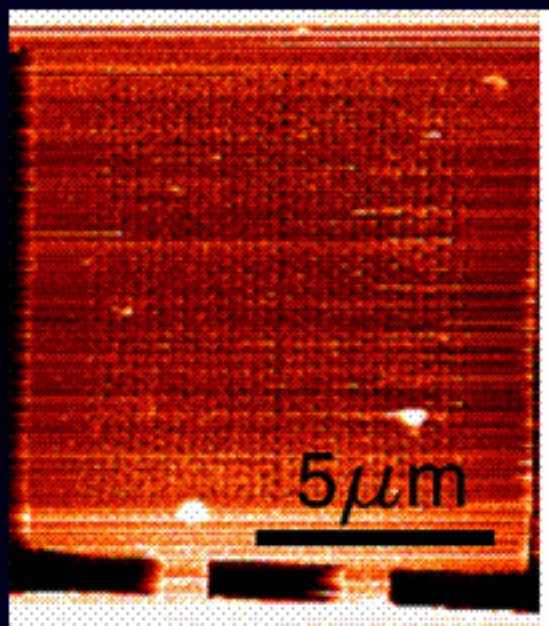
NSOM PL Image



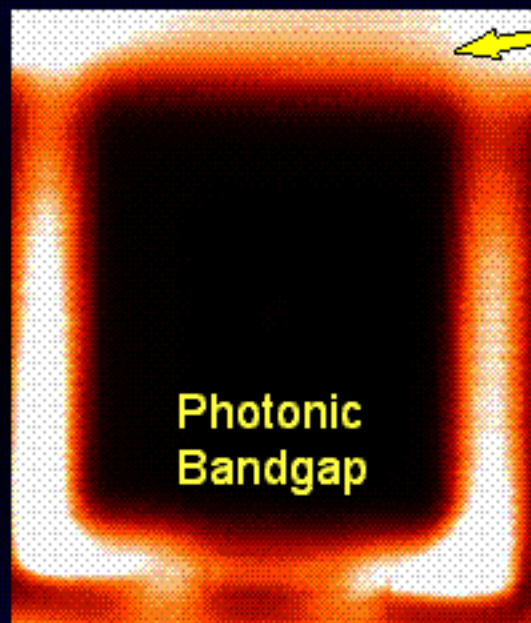
Fabry-Perot mode and Photonic Bandgap

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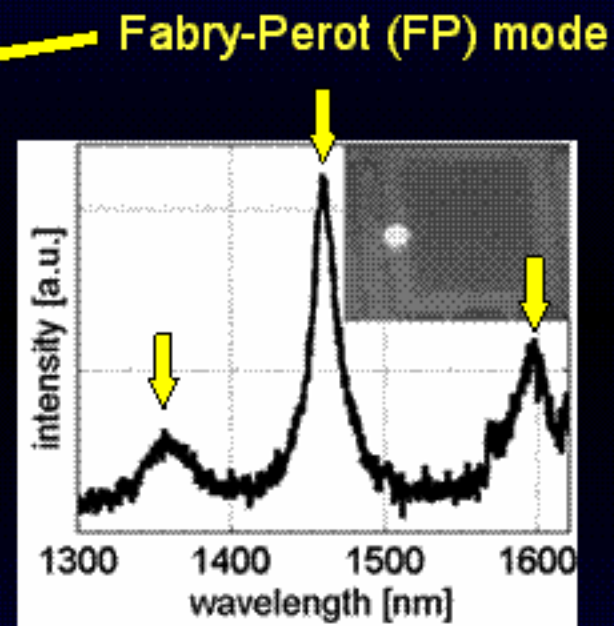
I-mode operation



shear-force microscopy (SFM) Topographic Image



Near-field scanning microscopy (NSOM) Optical Image



Photoluminescence (PL) spectrum

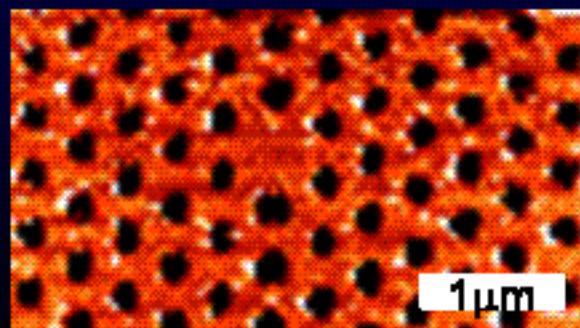


Reflection and PL Emission images

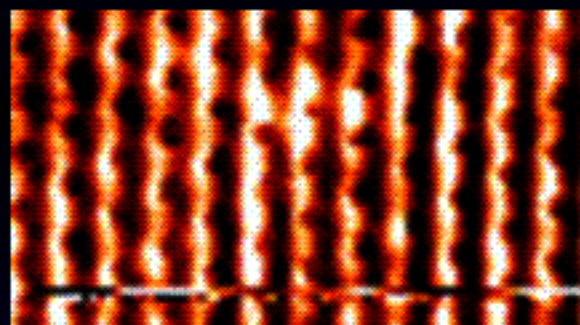
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I-mode operation

SEM image
 $p/a=20\%$



NSOM image
without
colored glass filter.

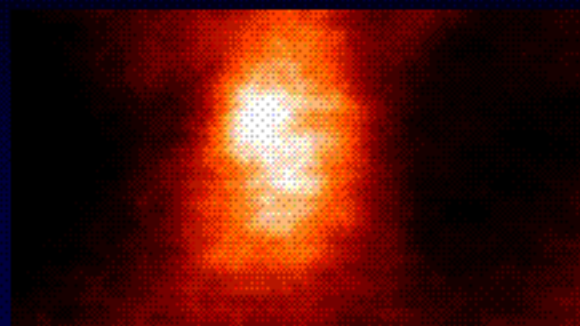


interference pattern was observed



reflection of the pump He-Ne laser light
from the sample surface

NSOM image with
colored glass filter.



localized defect modes was observed



emission from the quantum wells
modified by the presence of nanocavity

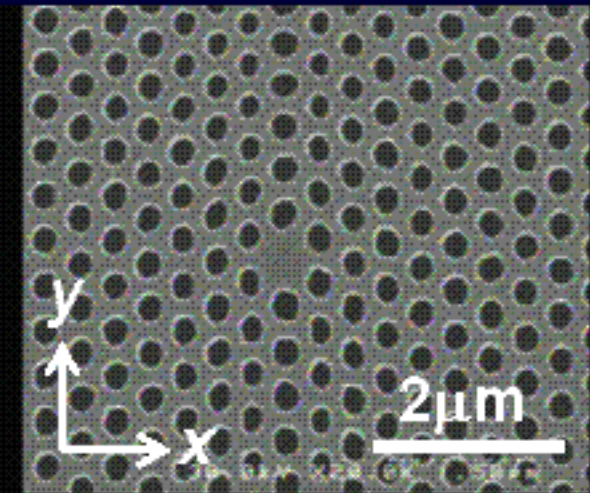


localized cavity modes

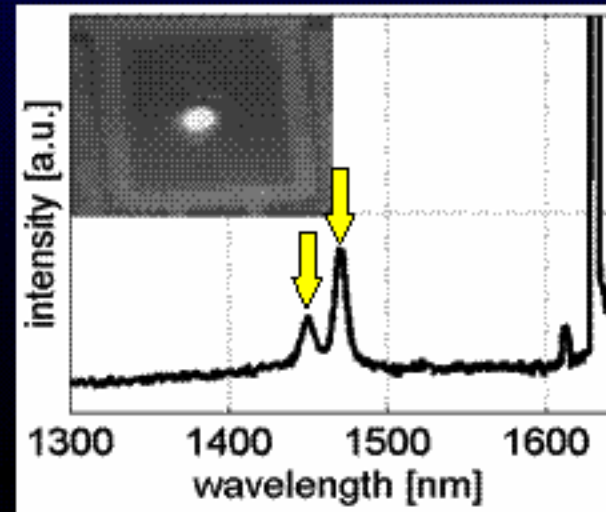
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$a=420$ nm, $r=135$ nm, $r/a=0.32$, $p/a=15\%$, $Q>\sim 1000$

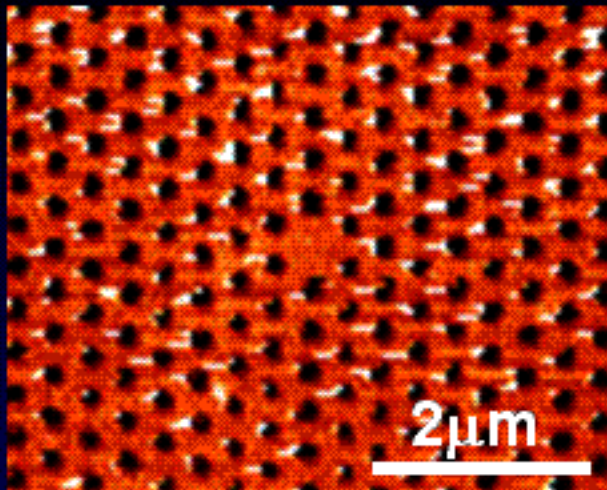
I-mode operation



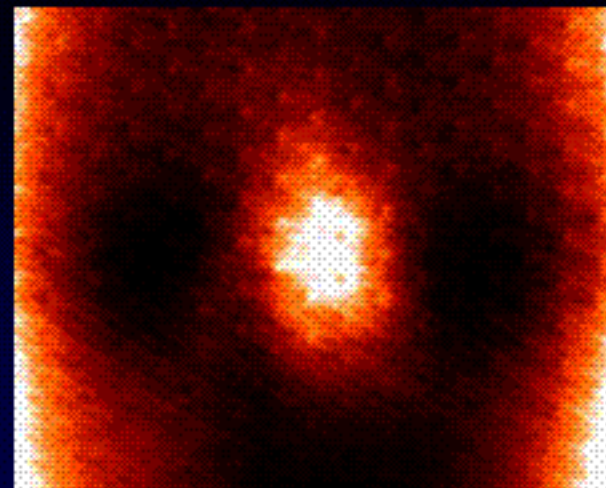
SEM Image



PL Spectrum



SFM Topographic Image

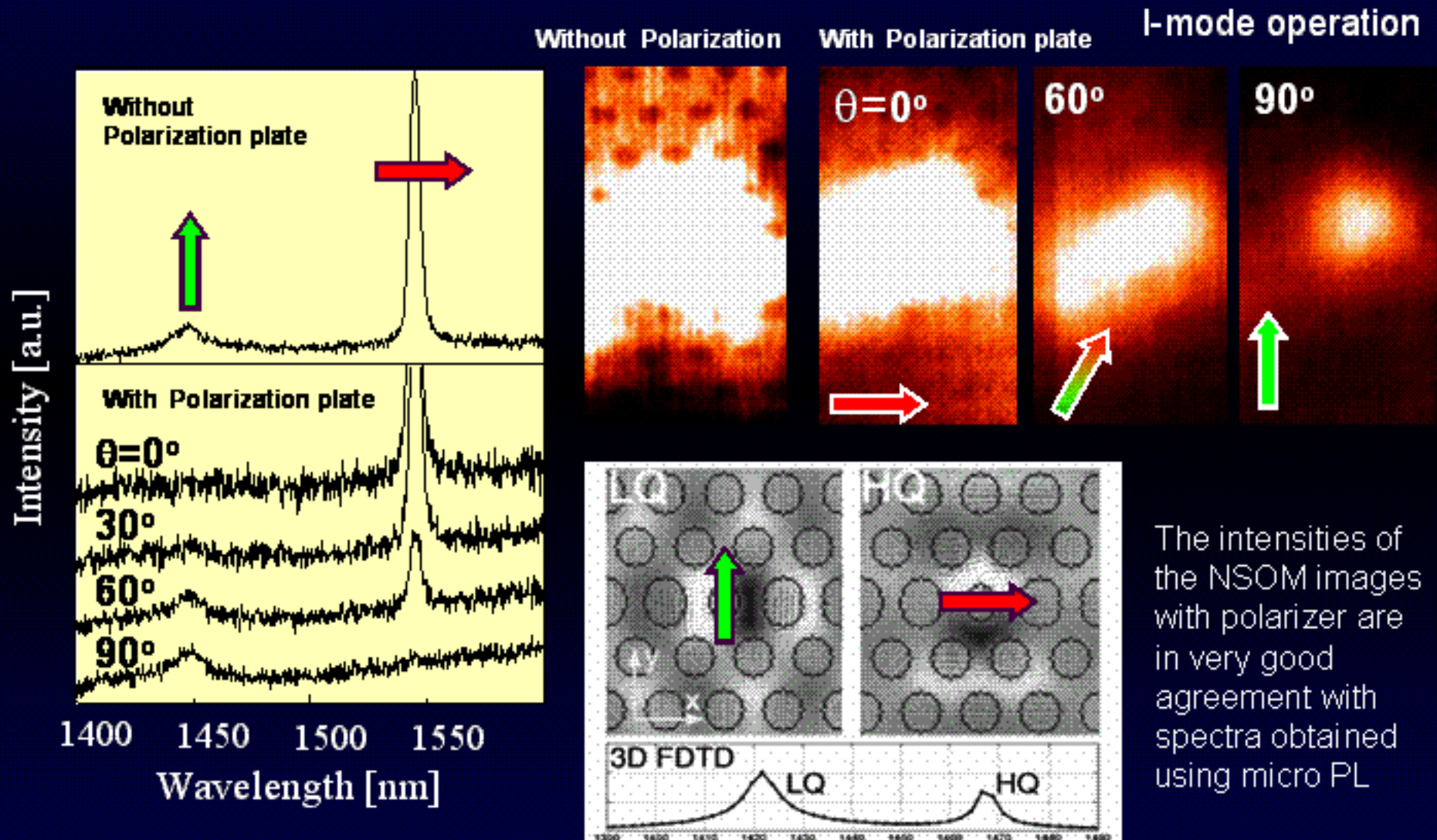


NSOM PL Image



Polarization dependence

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Mode profiles (Bz component) and polarization (E field) of the LQ and HQ modes, the result of 3D FDTD analysis. M. Lončar et al., *Appl. Phys. Lett.*, **81** 2680 (2002).

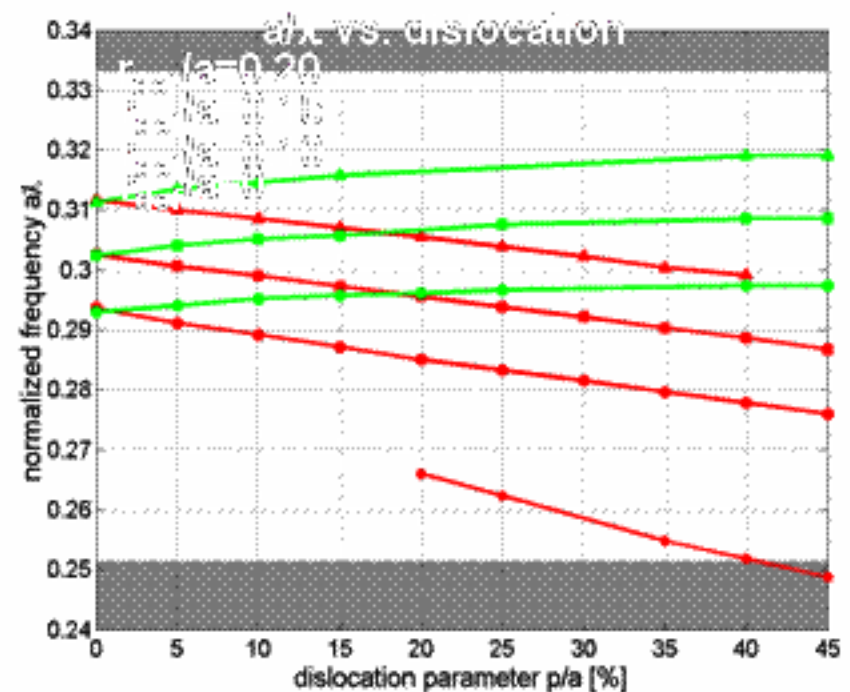
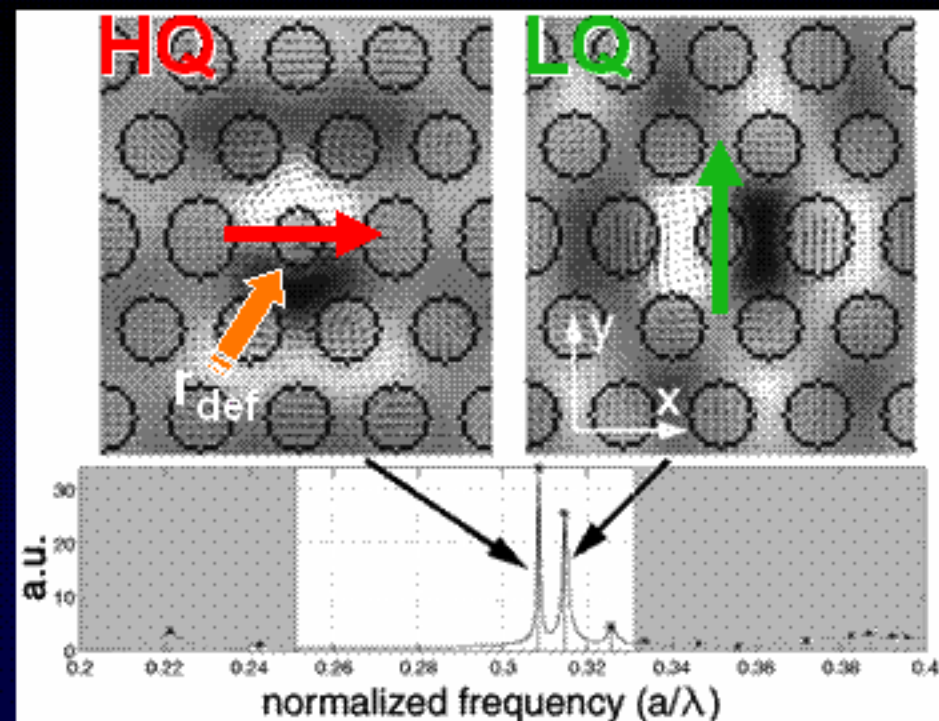


3D FDTD Analysis

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M. Lončar et al., *Appl. Phys. Lett.*, 81 2680 (2002).

- Cavity based on Fractional Edge Dislocations supports two dipole modes.
- The **HQ** mode, positioned at lower frequencies, is polarized along x-axis (E field), while the **LQ** mode, is polarized along y-axis.
- **HQ** mode is the high-Q mode ($Q > 5,000$). Q factors of **LQ** are $< 1,000$.
- Eigenfrequencies of **HQ** and **LQ** modes strongly depend on amount of dislocation (p) and central defect hole size (r_{def}).





Elongation $p/a(\%)$ dependence

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$a=420$ nm, $r=135$ nm, $r/a=0.32$, $p/a=0\sim 25\%$

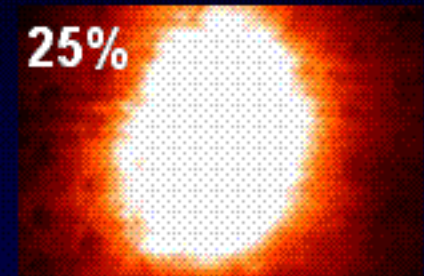
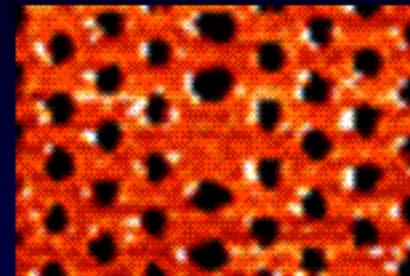
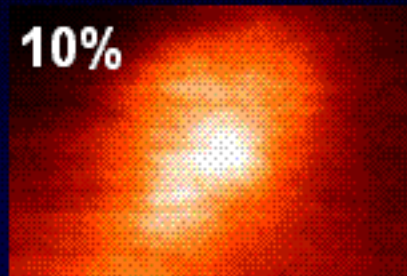
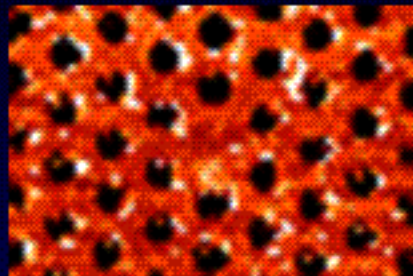
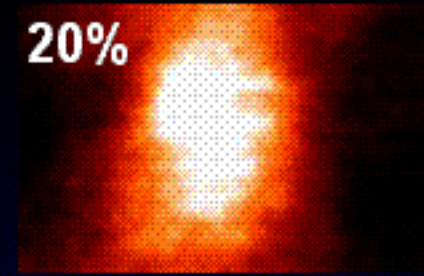
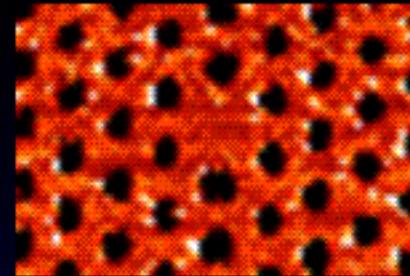
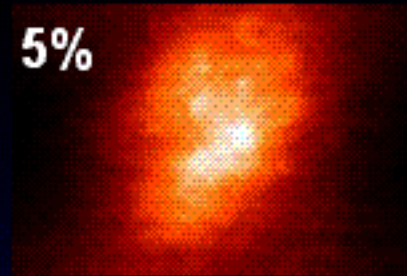
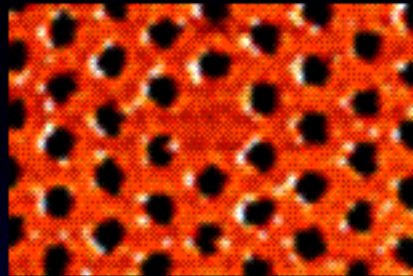
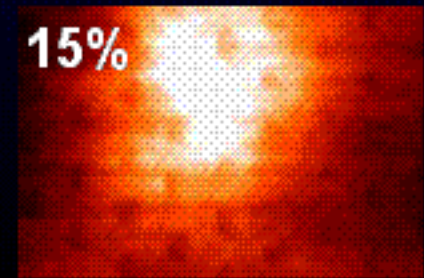
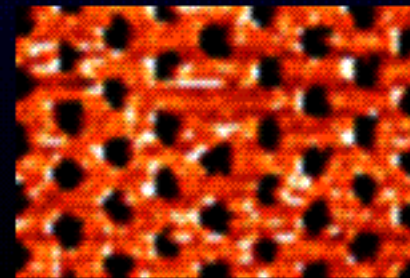
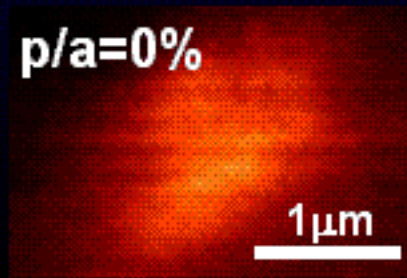
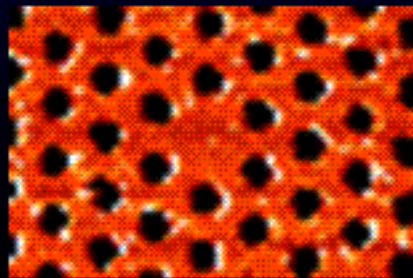
I-mode operation

SFM Image

NSOM PL Image

SFM Image

NSOM PL Image



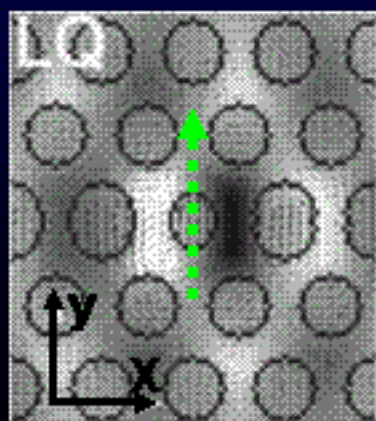
↔
Elongated



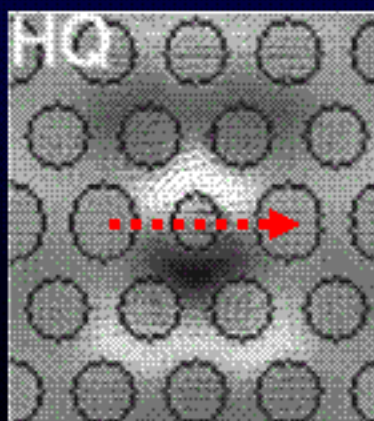
$p/a(\%)$ dependence of FWHM and Intensity

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↑
↓
Elongated

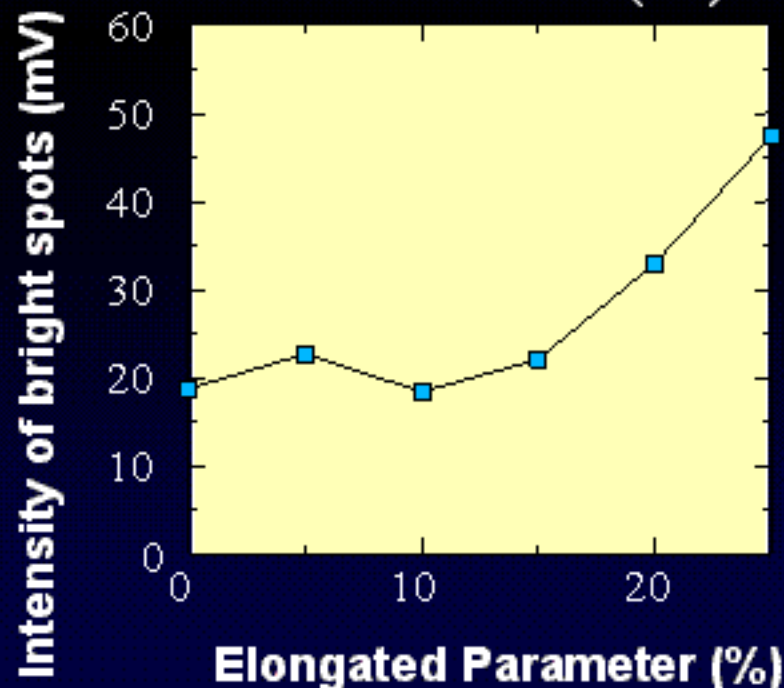
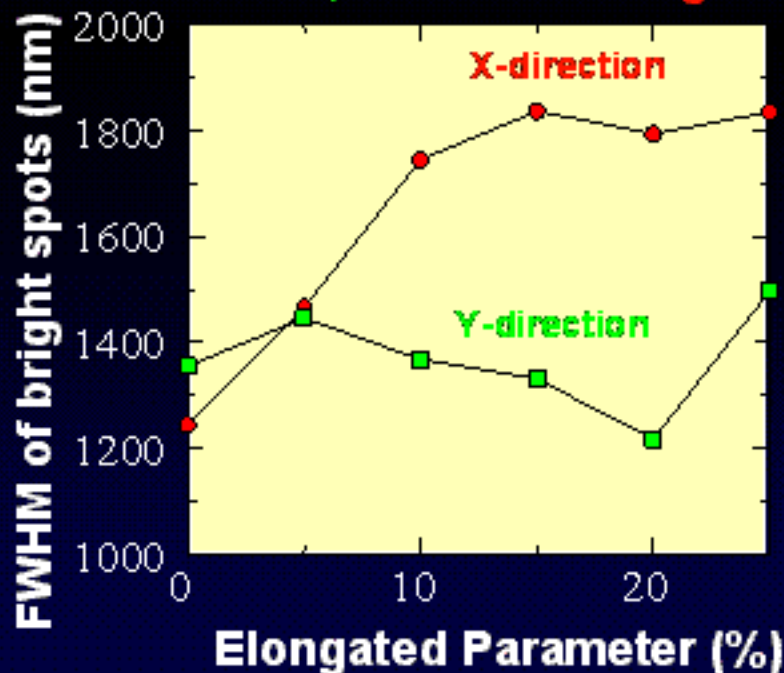
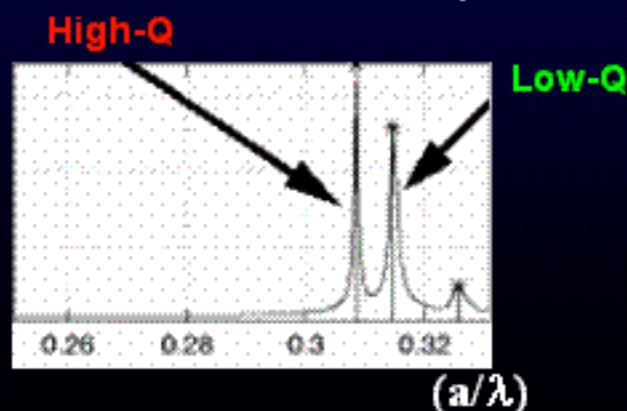


Low-Q mode



High-Q mode

I-mode operation



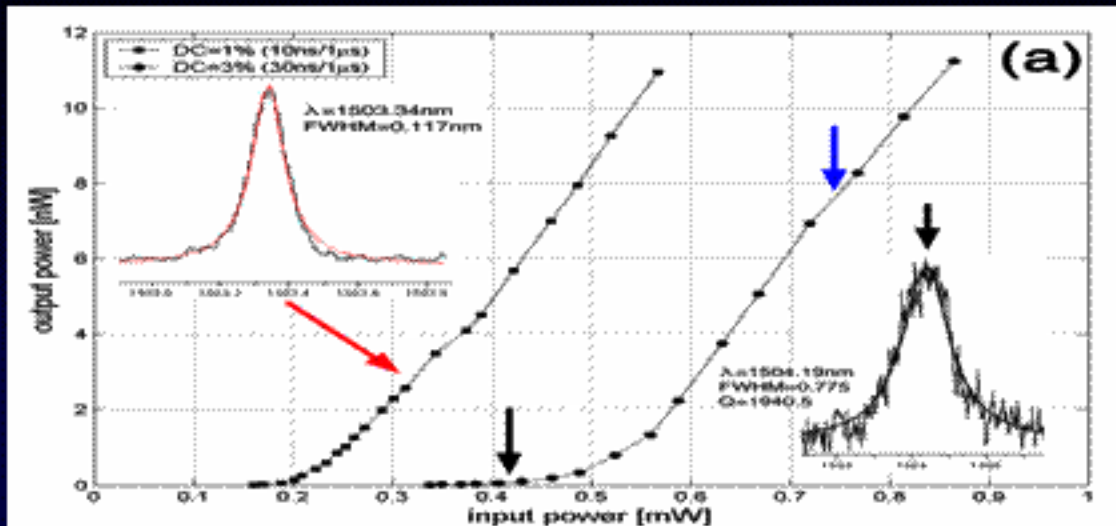
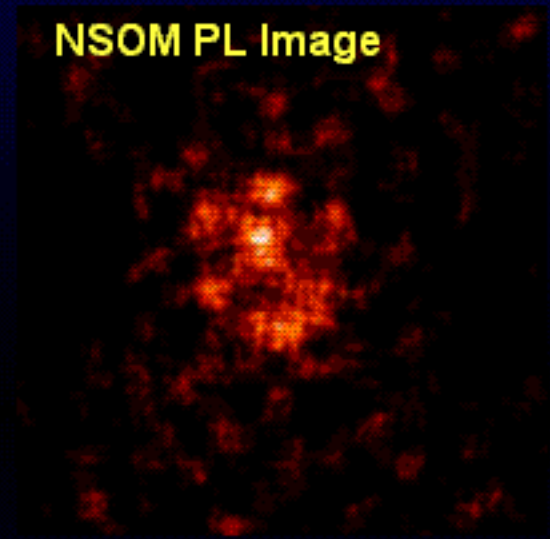
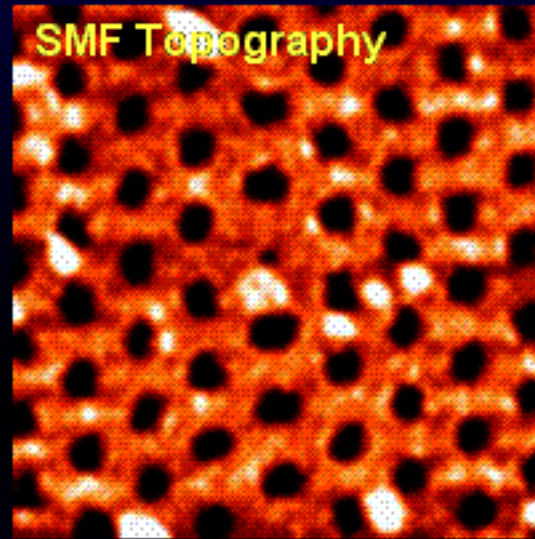
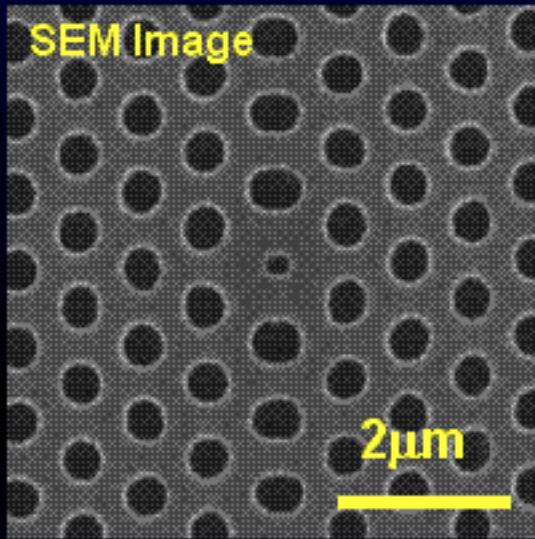


Nano Laser Cavity

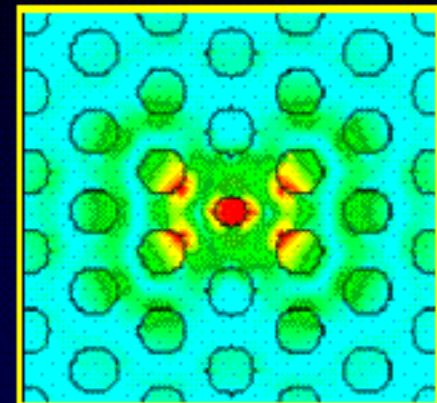
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$a=446$ nm, $r=128$ nm, $r/a=0.29$, $r'/a=0.18$ %, **Q~2000**

I-mode operation



3D FDTD analysis

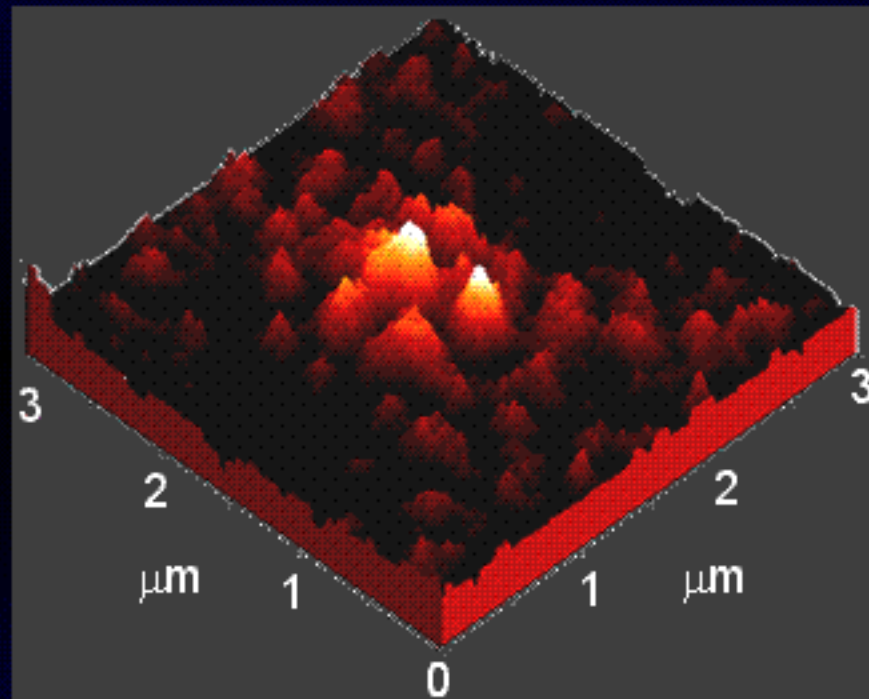




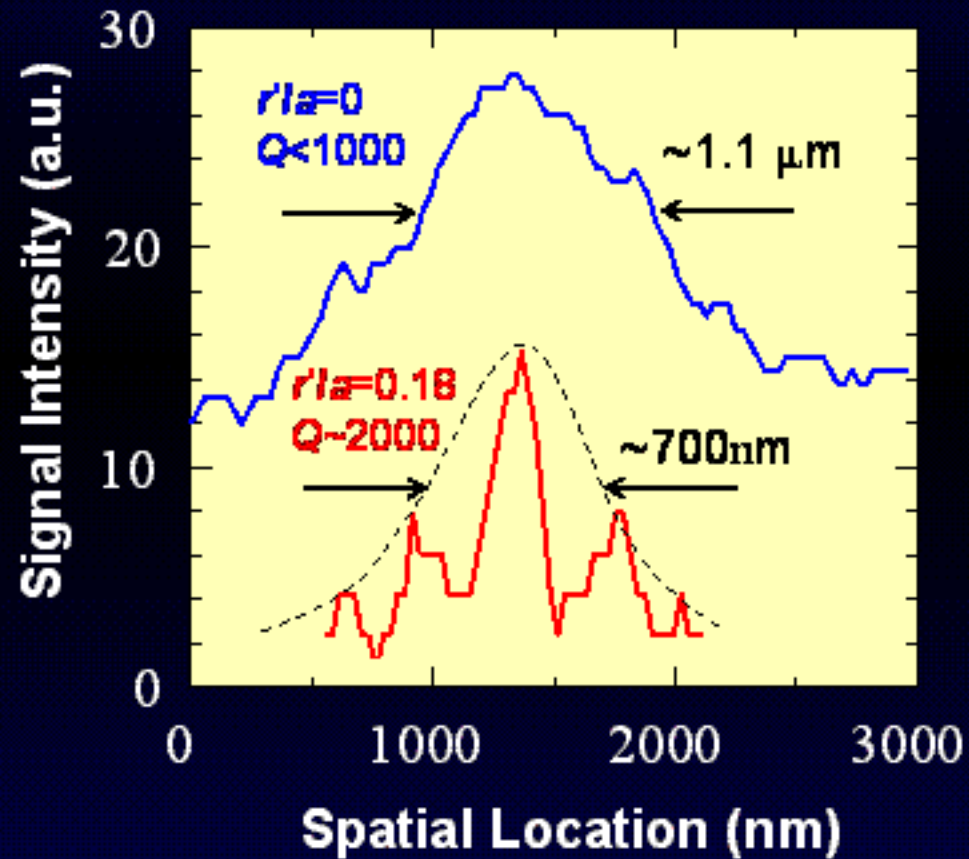
Optical Mode Volume

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$a=446$ nm, $r=128$ nm, $r/a=0.29$



NSOM-PL image of high-Q photonic crystal nanocavity laser ($Q\sim 2000$)

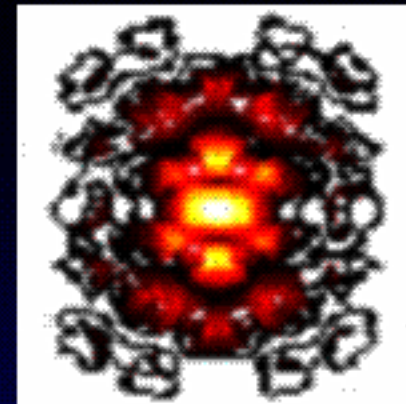
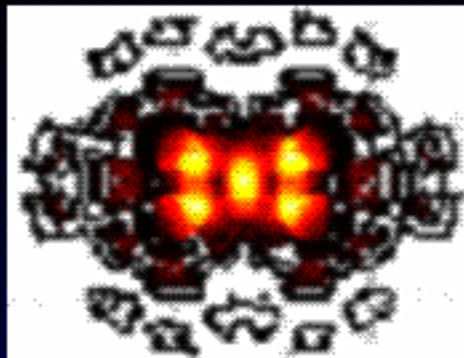
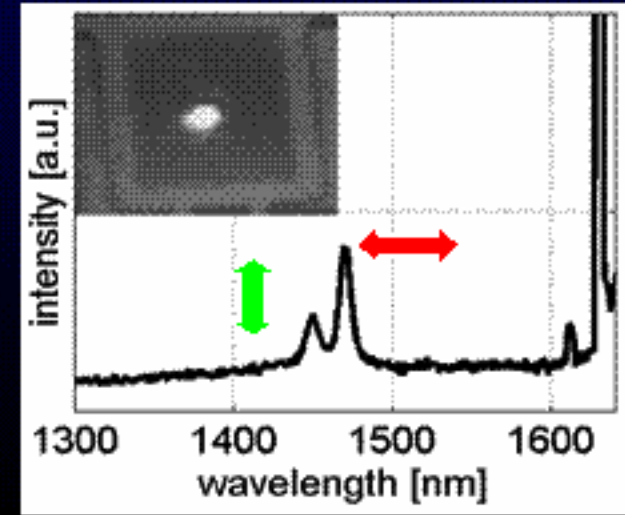
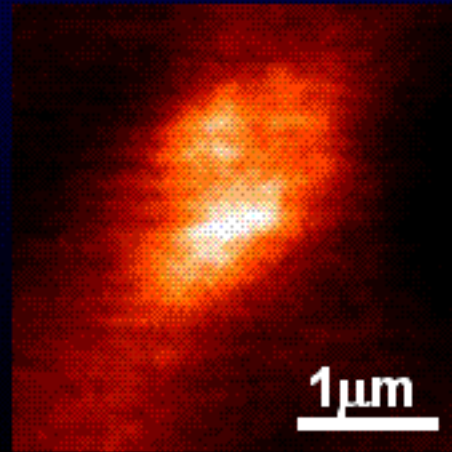
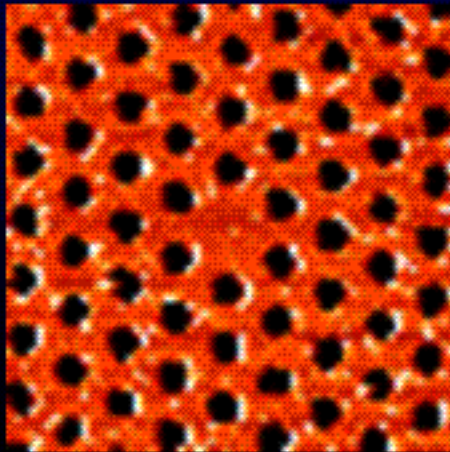




FDTD Calculation (Low Q)

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$r/a=0.32, r'/a=0, p/a=0$



0.2 0.4 0.6 0.8

$Q_{||}=246, Q_{\perp}=655, a/\lambda=0.2834$



0.2 0.4 0.6 0.8

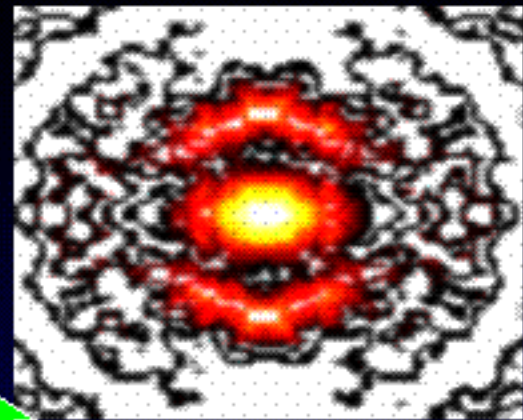
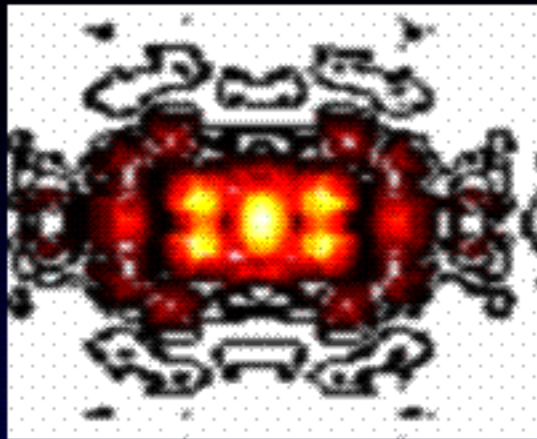
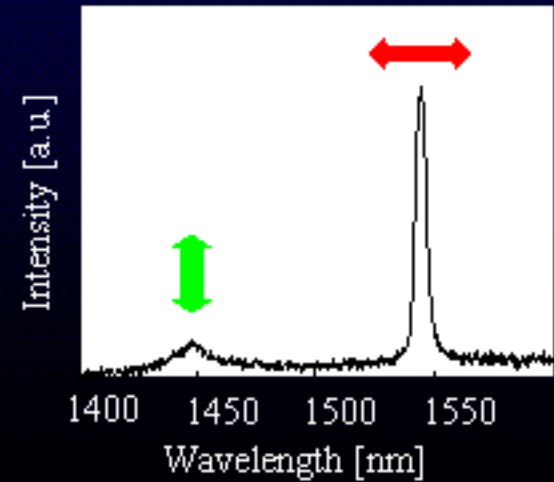
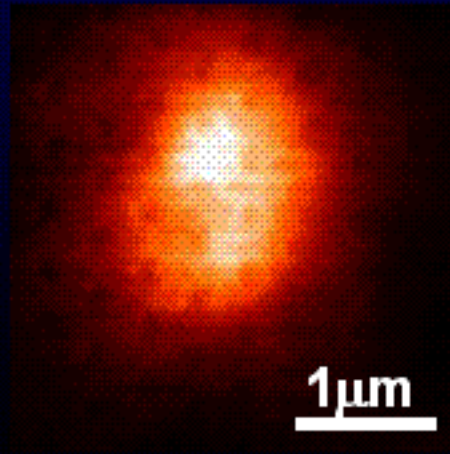
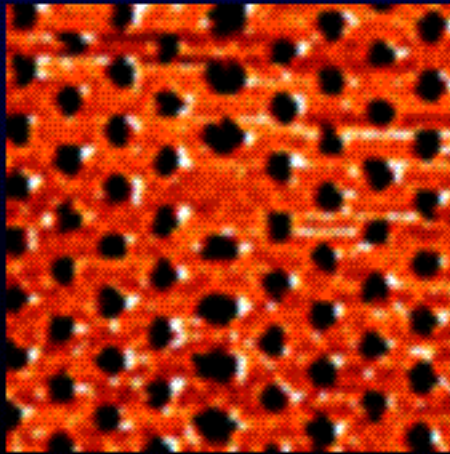
$Q_{||}=242, Q_{\perp}=611, a/\lambda=0.2842$



FDTD Calculation (Middle Q)

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$r/a=0.32, r'/a=0, p/a=0.25$



$Q_{||}=1207, Q_{\perp}=838, a/\lambda=0.2602$

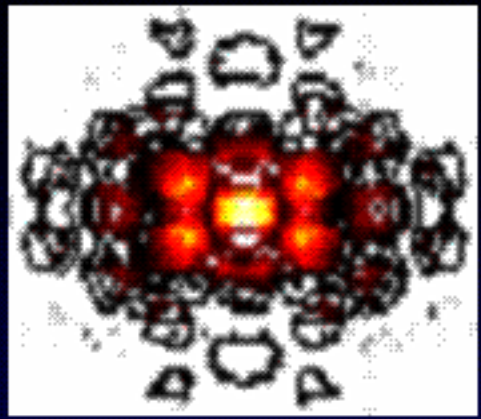
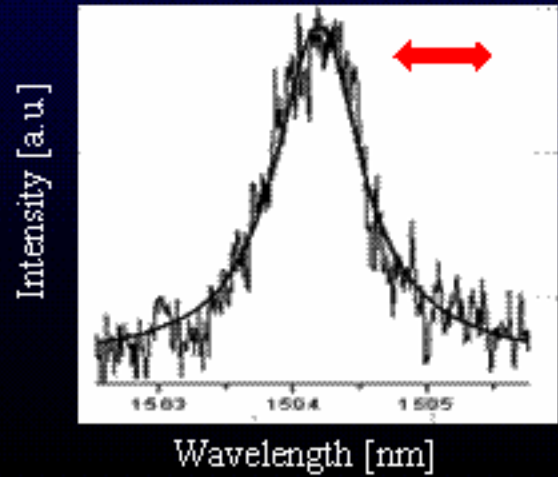
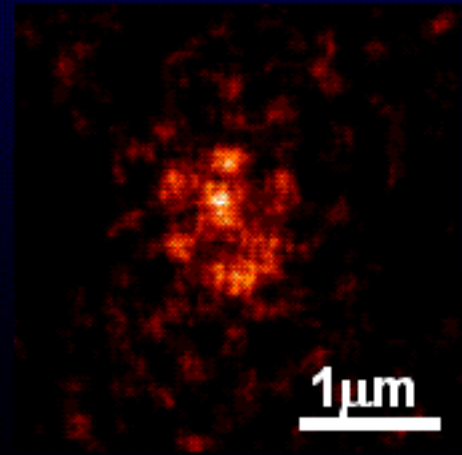
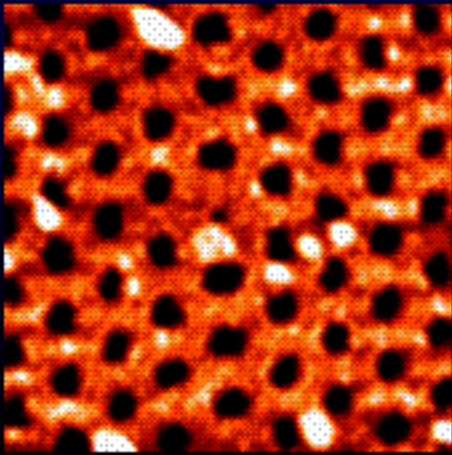
$Q_{||}=541, Q_{\perp}=193, a/\lambda=0.2602$



FDTD Calculation (High Q)

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$r/a=0.29$, $r'/a=0.18$, $p/a=0.25$



$Q_{||}=2760$, $Q_{\perp}=2013$, $d/\lambda=0.2842$



Summary

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- Near-field scanning optical microscopy (NSOM) was developed and used to observe higher spatially resolved optical mode images of photonic crystal nanocavities fabricated in active InGaAsP material.
- We have observed the dielectric band mode, air band mode, Fabry-Perot mode, and optical localized cavity modes in photonic crystal.
- We also found the polarization, elongated parameter, and defect hole size dependence of the mode volumes and optical intensities of localized cavity modes.