TIGP Nanoscience A
Part 1: Photonic Crystals

1. Photonic crystal “band-edge” lasers
2. Photonic crystal “defect” lasers
3. Electrically-pumped photonic crystal lasers

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Mar 21, 2018

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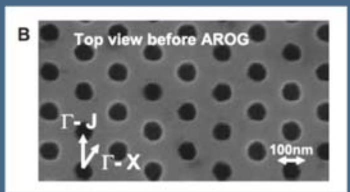
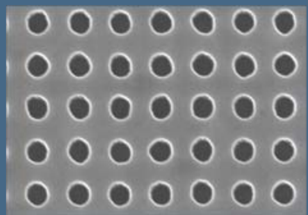
1. Photonic crystal “band-edge” lasers

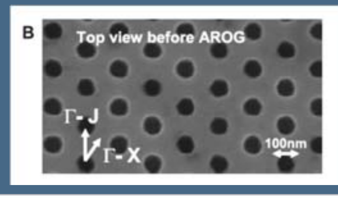
Photonic Crystal Band-Edge Lasers

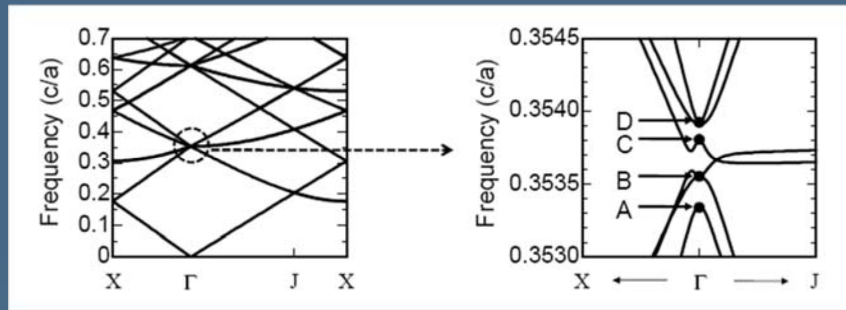




Science 319, 445 (2008); Optics Express 16, 6033 (2008)

Photonic Crystal Band-Edge Resonant Modes



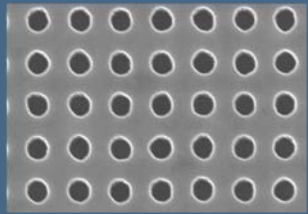


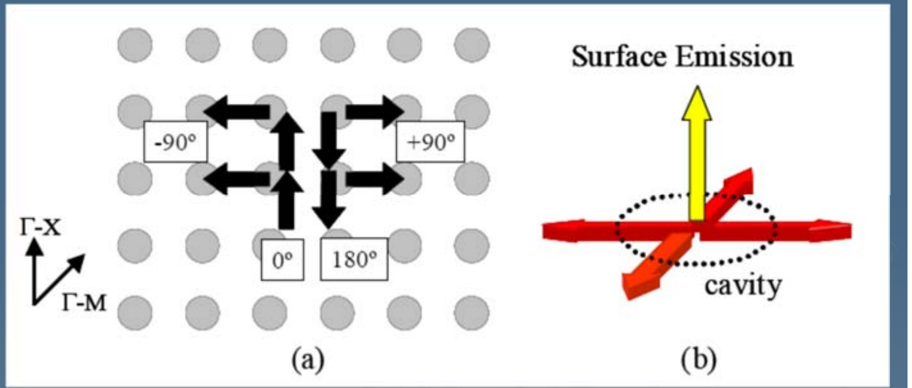
$$v_g = \frac{\partial \omega}{\partial \beta} = \frac{c}{n_g}$$

around “band-edge” , Vg ~ 0
i.e. high-Q resonant waves

Science 319, 445 (2008); Optics Express 16, 6033 (2008)

Photonic Crystal Band-Edge Lasers

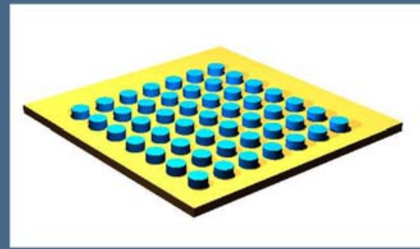


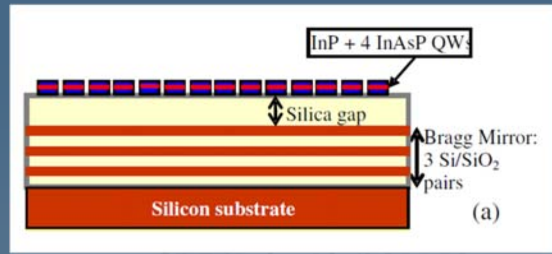


Optics Express 12,1562 (2004)

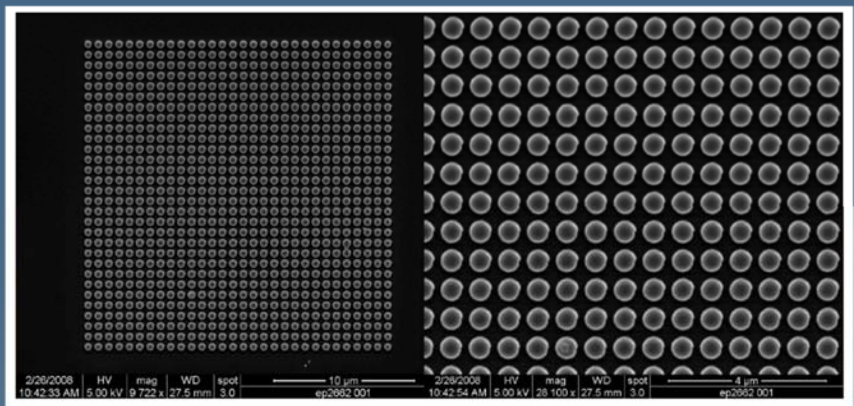
Photonic Crystal Rod Band-Edge Lasers

Optics Express 17, 9781 (2009)





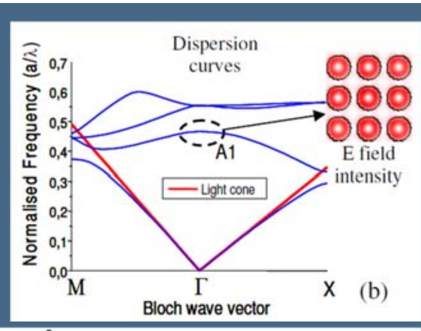
Photonic Crystal Rod Band-Edge Lasers

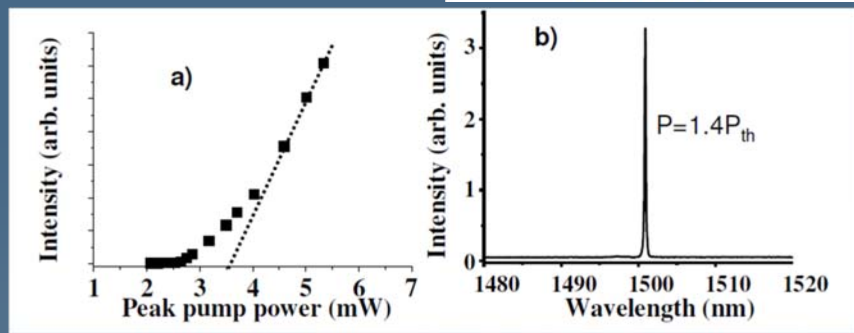


Optics Express 17, 9781 (2009)

Photonic Crystal Rod Band-Edge Lasers

Optics Express 17, 9781 (2009)

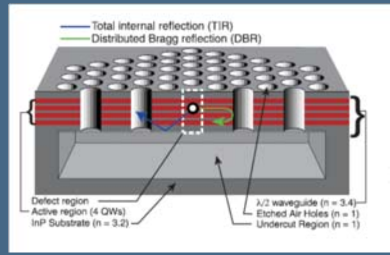


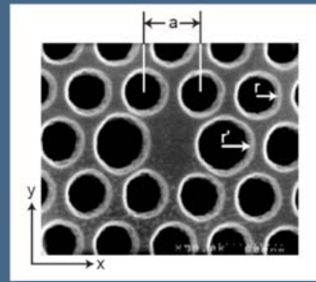


2. Photonic crystal "defect" lasers

- **D1 and larger cavities**
  - *Membrane vs. Substrate*
  - *Ultra-high Q cavities*
  - *Ultra-small cavities*
  - *Others*

D_1 Photonic Crystal Defect Lasers

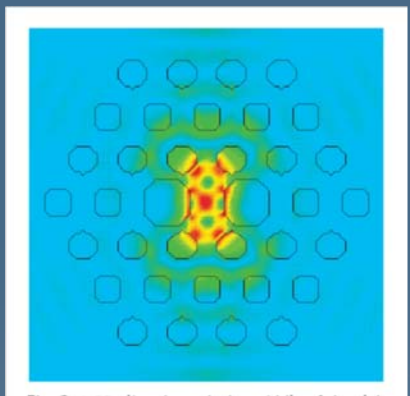




- First demonstration of the photonic crystal defect lasers
- InGaAsP Suspended membrane structure
- 2-D photonic crystals support in-plane confinement, while suspended membrane gives the vertical confinement
- Nano-fabrication technology improved a lot since 1999

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

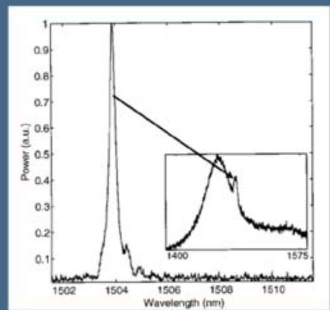
D_1 Photonic Crystal Defect Lasers

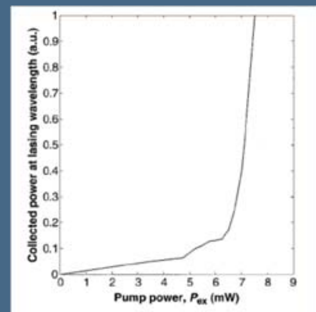


- The lasing mode profiles from finite-difference time-domain (FDTD) simulation
- The E-field amplitude of y-dipole mode
- The defect mode has a large overlap with the gain region due to the antinode at the center of the defect.
- The enlarged air holes: (1)Tune the y-dipole mode for max Q, and (2) Push the x-dipole mode out of gap
- A single-mode cavity

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

D_1 Photonic Crystal Defect Lasers

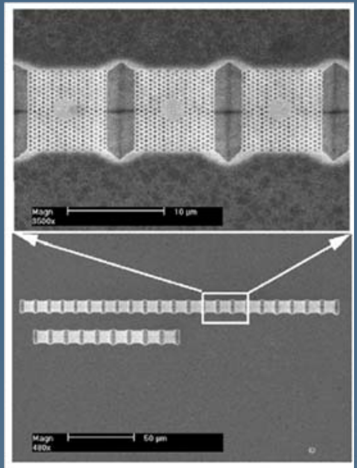




- Gain peak of MQWs is around 1550 nm communication wavelength
- Lasing wavelength is 1504 nm
- External threshold power is about 6.75 mW under optical pumping conditions(10ns pulse, 4% duty cycle) at 143K

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

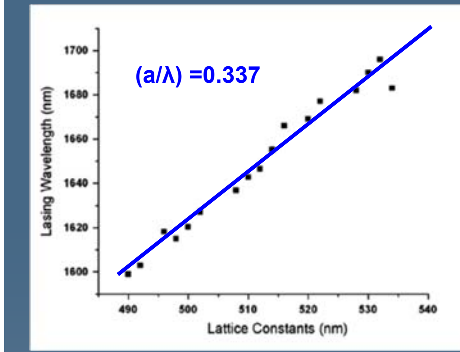
D_3 Suspended Membrane Photonic Crystal Defect Lasers



- How to characterized and verify the operated lasing modes in the photonic crystal lasers ??
- Fine tuning of lattice constant of photonic crystal D_3 defect lasers
- The lattice constant varied from 490 nm to 550 nm with an 2 nm tuning step

J. R. Cao, et al., J. Nanosci. Nanotech. 2,1-3 (2002)

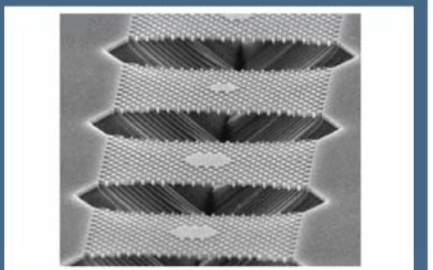
D_3 Suspended Membrane Photonic Crystal Defect Lasers

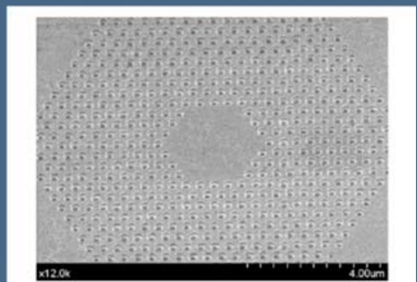


- The lasing wavelengths collected from the photonic crystal cavities with varied lattice constants
- The lasing wavelength is linear dependent with the lattice constant (a)
- The results indicate that the same cavity operated mode in those D_3 cavities
- The normalized frequency (a/λ) of this mode is 0.337

J. R. Cao, et al., Appl. Phys. Lett. 83, 4107 (2003)

Photonic Crystal Defect Lasers on a Substrate


(a)


(b)

Suspended membrane structure of photonic crystal lasers

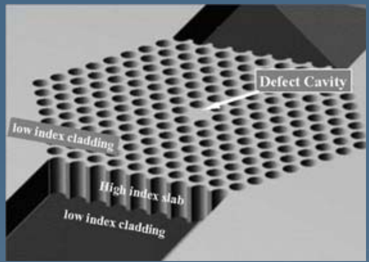
Semiconductor substrate structure of photonic crystal lasers

2. Photonic crystal "defect" lasers

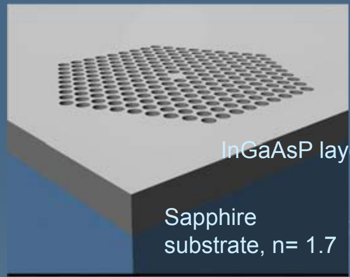
- *Membrane vs. Substrate*

Suspended Membrane and Sapphire-Bonded Structure

- Air-dielectric-air structure has better confinement for the localized fields
- The structure only lase under pulsed conditions



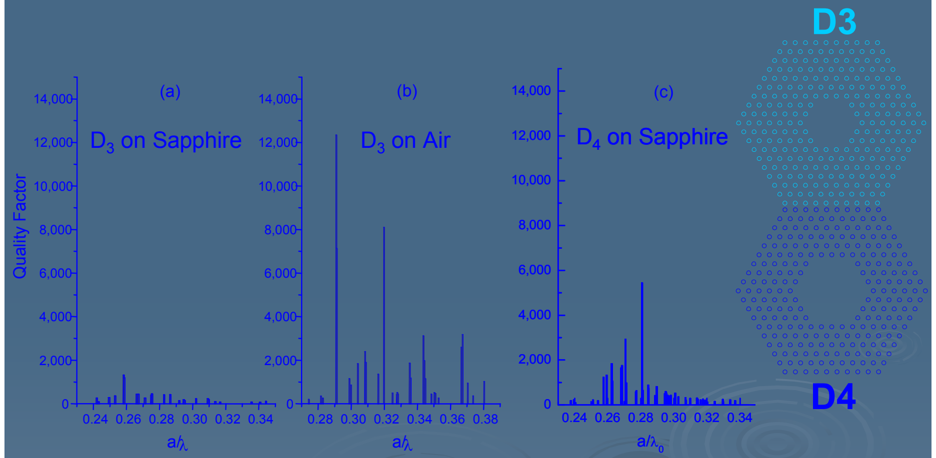
- Air-dielectric-sapphire structure has less confinement for the localized fields
- This structure can lase under continuous wave (CW) conditions



Thermal conductivity

Air : 2.5×10^{-5} W/cm·K and Sapphire : 5×10^{-1} W/cm·K

Quality Factor (Q) of Sapphire-Bonded Photonic Crystal Cavity



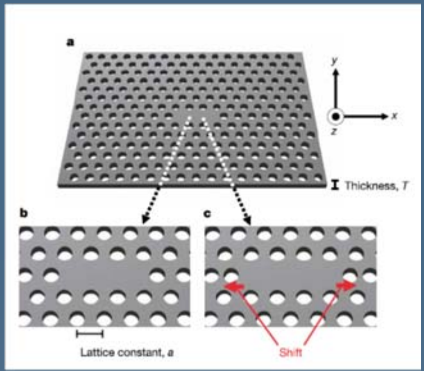
Big Issues ..

1. *High Q value*
2. *Small mode volume*
3. *Electrically injection*

2. Photonic crystal "defect" lasers

- *Ultra-high Q cavities*

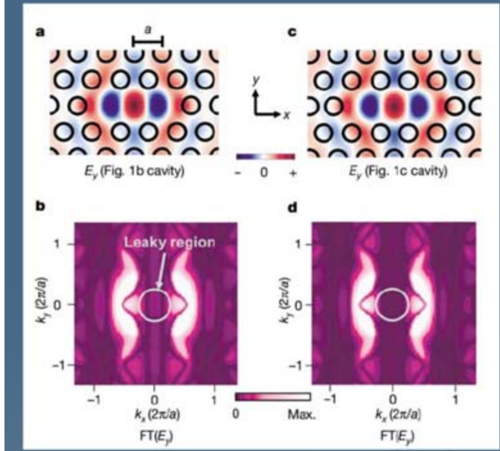
High- Q L_3 Photonic Crystal Cavity



- The lasing mode profiles from finite-difference time-domain (FDTD) simulation
- The E-field amplitude of y-dipole mode
- The defect mode has a large overlap with the gain region due to the antinode at the center of the defect.

Y. Akahane, et al., Nature 425,944 (2003)

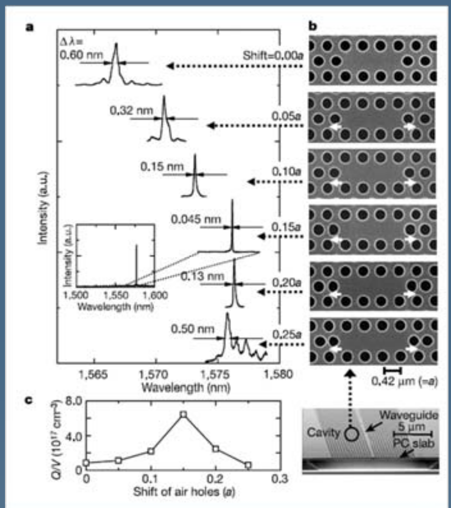
High- Q L_3 Photonic Crystal Cavity



- How to evaluate the leaky of the field of operated cavity modes from the mode profiles ?
- The E_y-field profile obtained from FDTD simulation for the L_3 cavities
- The 2-D Fourier transform spectra of the calculated mode profiles
- The leaky region surrounded by the light cone (white-circle) in k-space

Y. Akahane, et al., Nature 425,944 (2003)

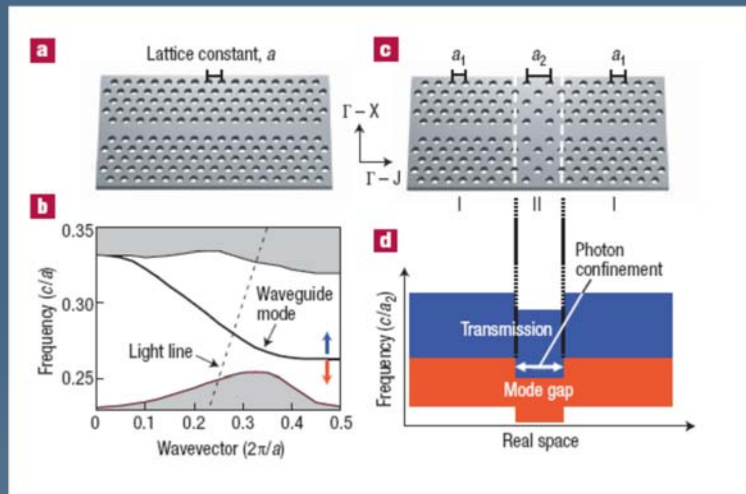
High- Q L_3 Photonic Crystal Cavity



- The fabricated photonic crystal waveguide - cavity coupled structure
- The measured spectra from the modified L_3 cavities with varied air hole shifts
- The highest Q is obtained from the cavity with 0.15a lattice shift

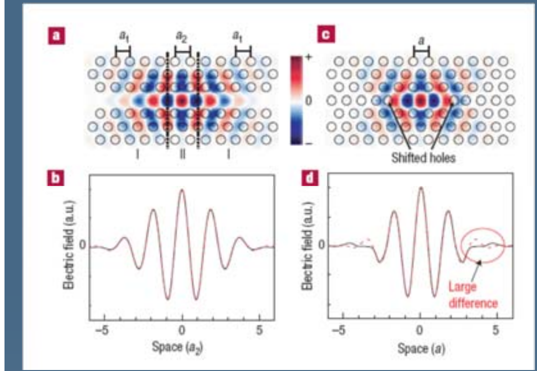
Y. Akahane, et al., Nature 425,944 (2003)

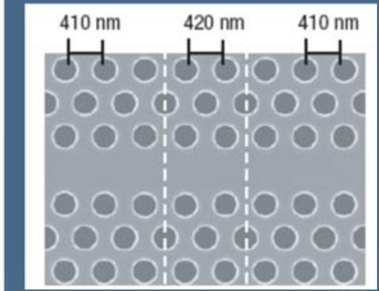
Photonic Crystal Heterostructure Cavity



B. S. Song, et al., Nature Materials 4, 207 (2005)

Photonic Crystal Heterostructure Cavity

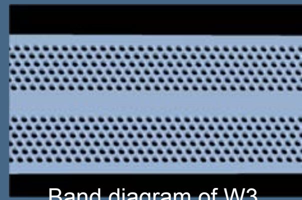


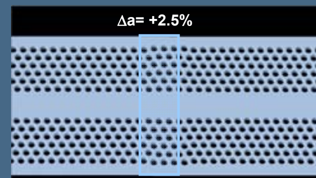


- Waveguide type cavity
- Q > 600,000

B. S. Song, et al., Nature Materials 4, 207 (2005)

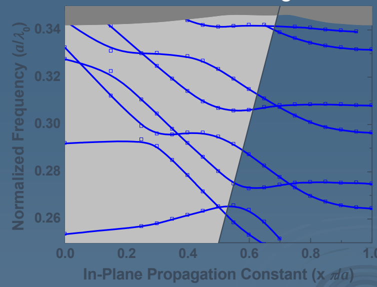
Photonic Crystal W3 Heterostructure Cavity

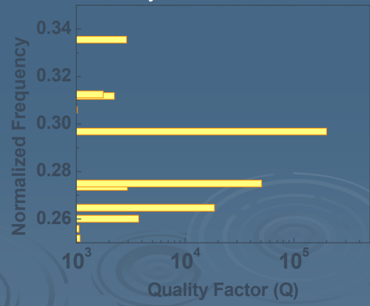




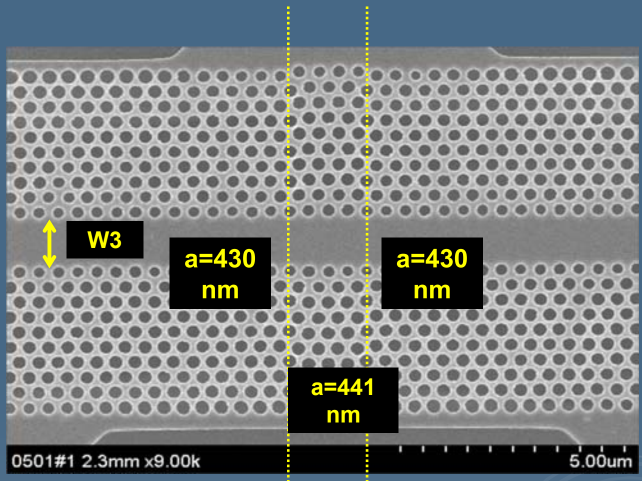
Band diagram of W3 membrane waveguide

Q spectrum of W3 heterostructure cavity from 3-D FDTD



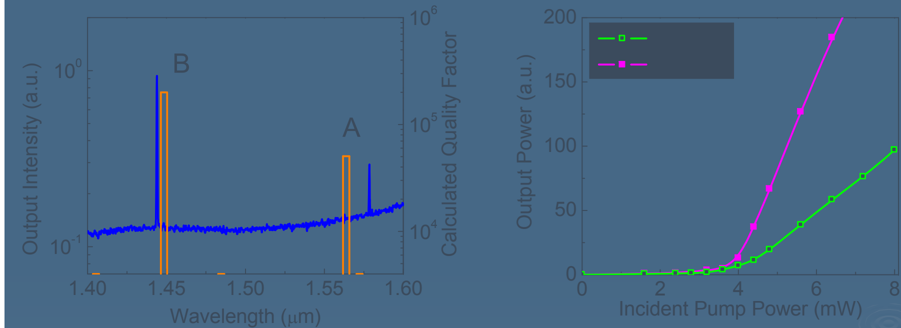


Photonic Crystal Heterostructure Laser



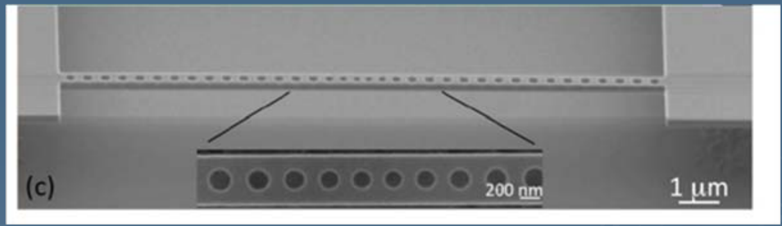
- Waveguide type cavity
- Q > 600,000

Photonic Crystal Heterostructure Cavity



- Waveguide type cavity
- Q > 600,000

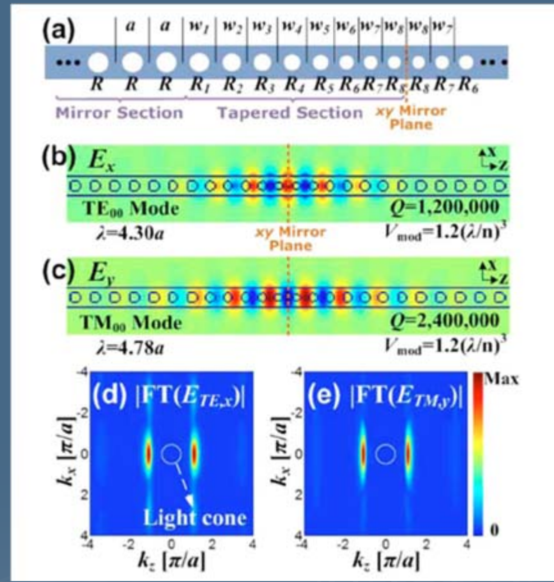
Photonic Crystal Nanobeam Cavity



1) APPLIED PHYSICS LETTERS, 94, 121106 (2009)
2) OPTICS LETTERS, 34, 2694 (2009)

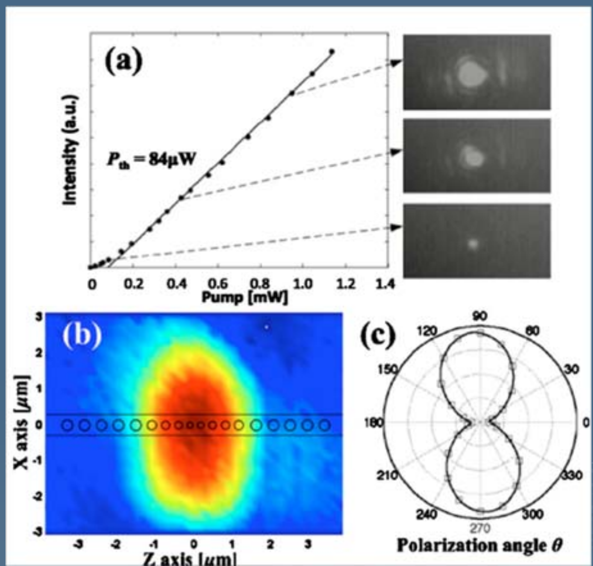
Photonic Crystal Nanobeam Cavity

- Single-line type cavity
- Q > 1,000,000



1) APPLIED PHYSICS LETTERS, 94, 121106 (2009)
2) OPTICS LETTERS, 34, 2694 (2009)

Photonic Crystal Nanobeam Laser



1) APPLIED PHYSICS LETTERS, 94, 121106 (2009)

Ultra-small Mode Volume Photonic Crystal Laser

Why Ultrasmall Cavity ??

- Cavity quantum electrodynamics (QED) :

- Purcell factor :
  (E.M. Purcell, *Phys. Rev*. 69, 681 (1946))
  Spontaneous emission rate enhancement factor

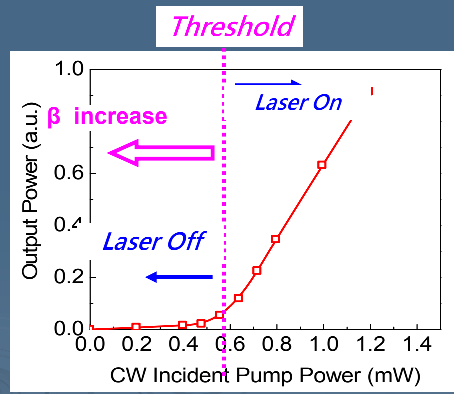
$$F_p = \frac{3}{4\pi^2}\left(\frac{\lambda_c}{n}\right)^3\left(\frac{Q}{V_m}\right)$$

Why Ultrasmall Cavity ??

- Spontaneous emission coupling factor β :

Efficiency of coupling emitter into a single resonant mode, and β=1 for "threshold-less" laser .

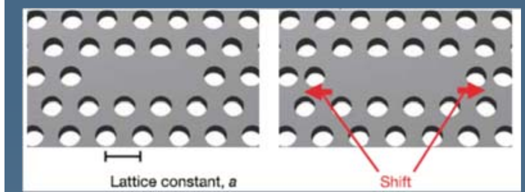
$$\beta = \frac{F_p}{F_p + \gamma} \leq 1$$

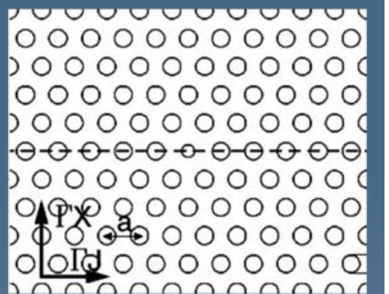


Zero-Cell Photonic Crystal Defect Cavity
-- from "Zero" ...

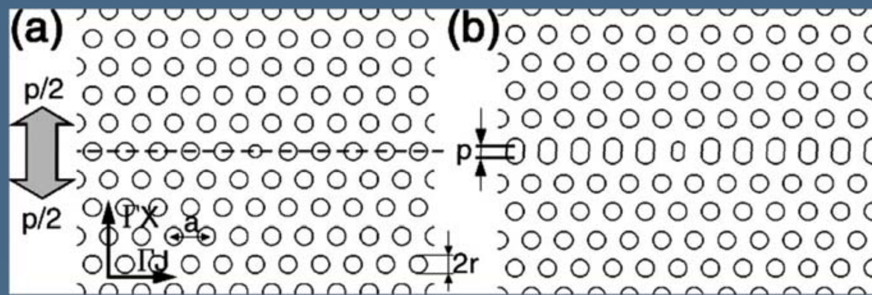
from L_3 cavity ......

from D_0 cavity ......



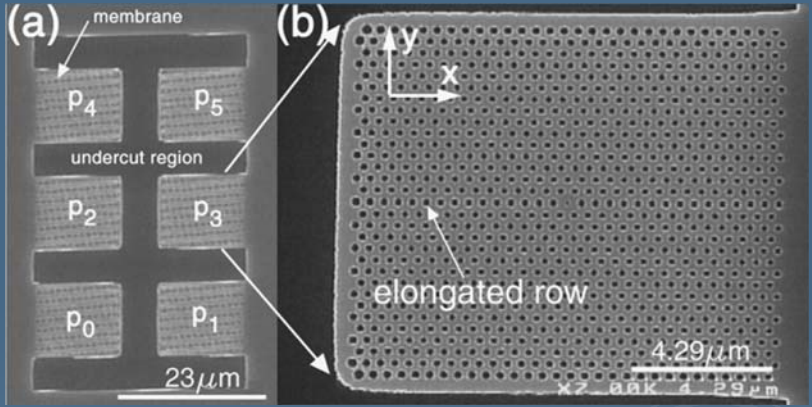


Ultrasmall Mode Volume Photonic Crystal Laser



Appl. Phys. Lett., Vol. 81, No. 15, pp.2680 (2002)

Ultrasmall Mode Volume Photonic Crystal Laser



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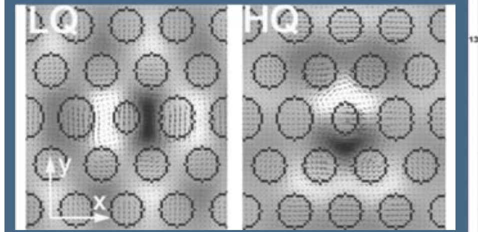

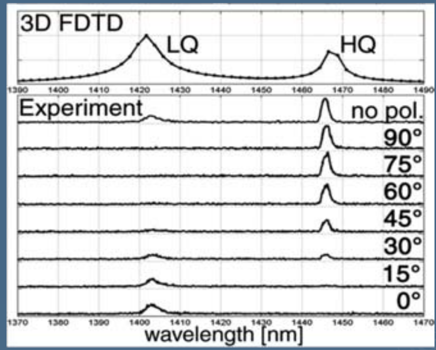

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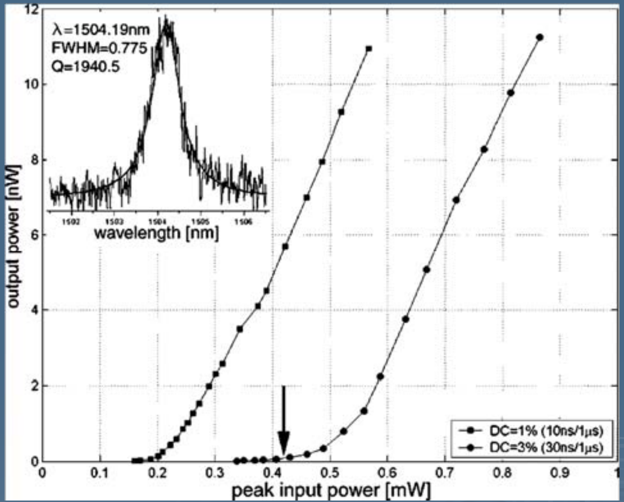
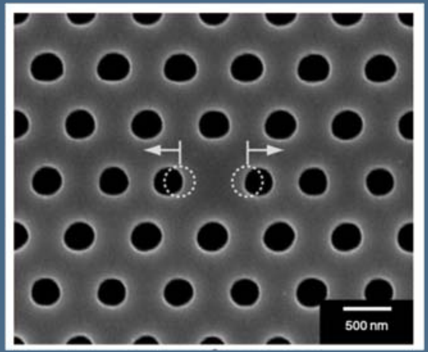
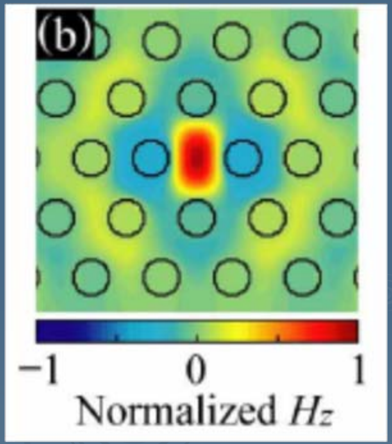
Ultrasmall Mode Volume Photonic Crystal Laser



Appl. Phys. Lett., Vol. 81, No. 15, pp.2680 (2002)

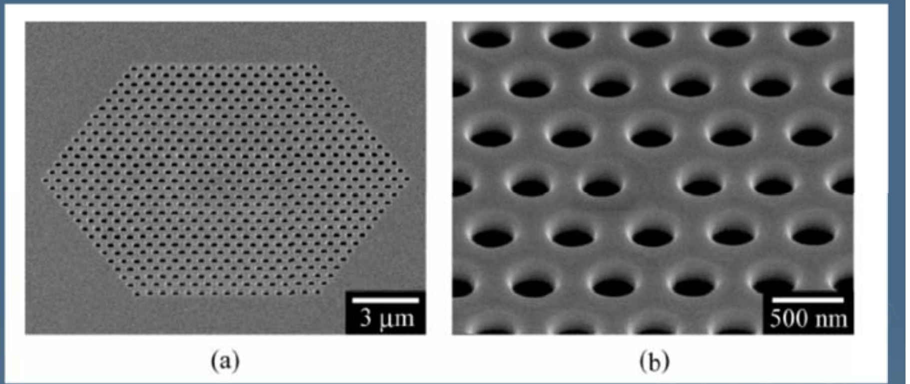
Photonic Crystal Point-Shift Cavity





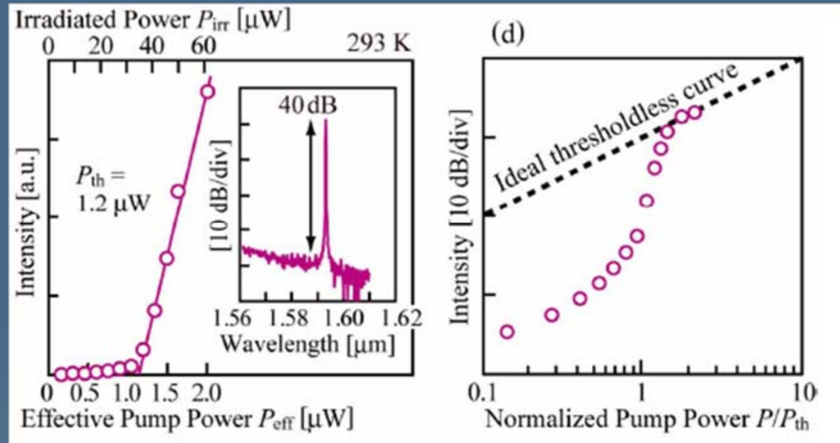
Optics Express 15, 7506 (2007)

Photonic Crystal Point-Shift Cavity



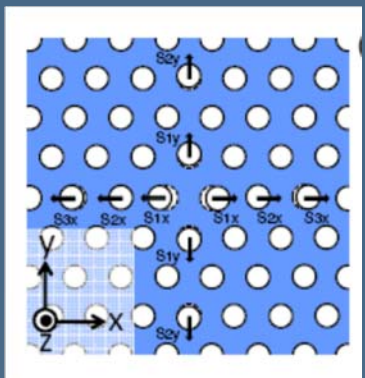
Optics Express 15, 7506 (2007)

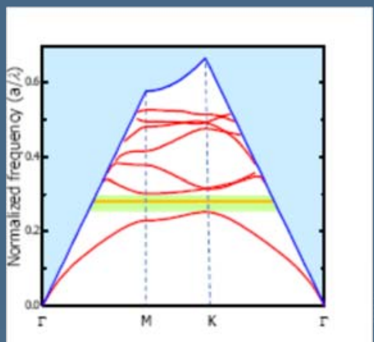
Photonic Crystal Point-Shift Cavity



Optics Express 15, 7506 (2007)

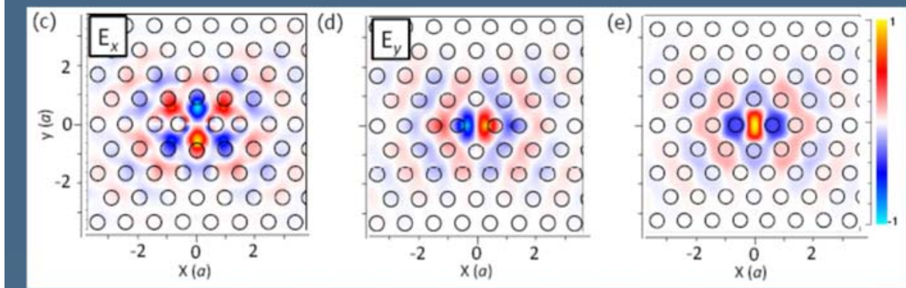
Zero-Cell Photonic Crystal Cavity (I)





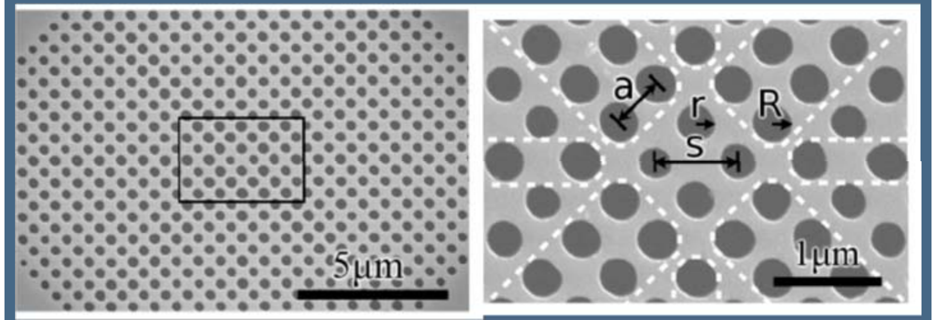
Appl. Phys. Lett., 97, 191108 (2010)

Zero-Cell Photonic Crystal Cavity (I)



Appl. Phys. Lett., 97, 191108 (2010)

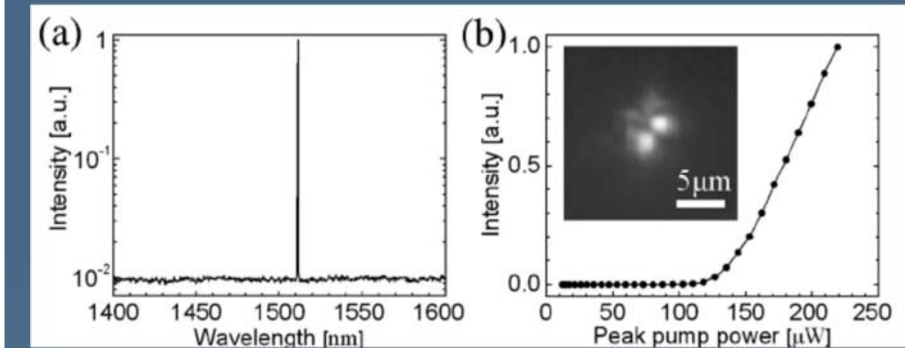
Zero-Cell Photonic Crystal Laser (II)



structural parameters are as follows: a=520 nm, r=0.33a, R=0.37a, and s =1.08$\sqrt{2}a$. Scale bar, 1 μm.

Appl. Phys. Lett., 97, 191108 (2010)

Zero-Cell Photonic Crystal Laser (II)



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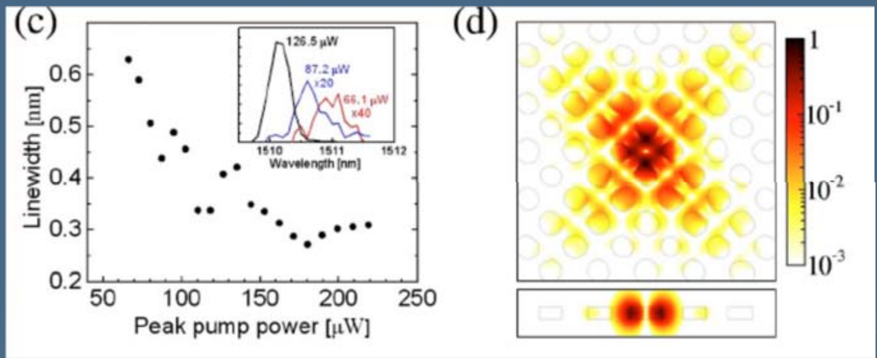
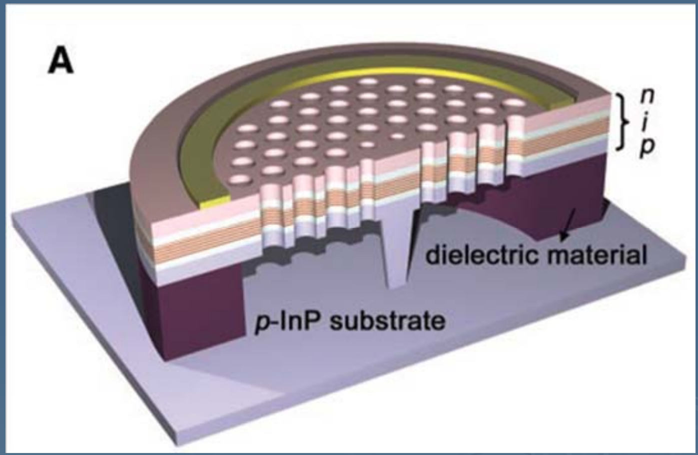


Appl. Phys. Lett., 97, 191108 (2010)

3. Electrically-Pumped Photonic Crystal Lasers

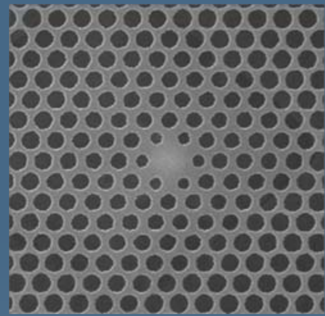
- *Vertical current injection structure*
- *In-plane current injection structure*

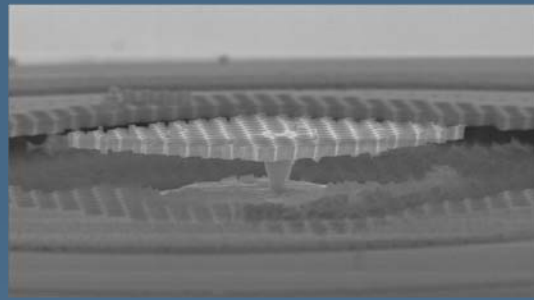
Electrically-Pumped Photonic Crystal Laser (I)



Science 305(5689) pp.1444-1447 (2004)

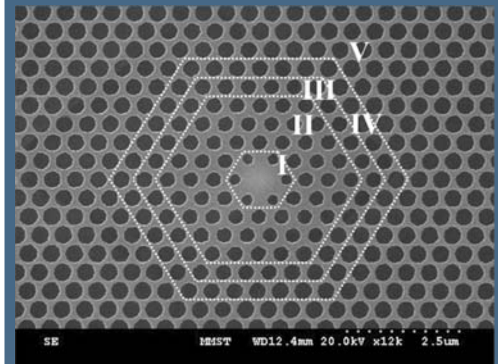
Electrically-Pumped Photonic Crystal Laser (I)

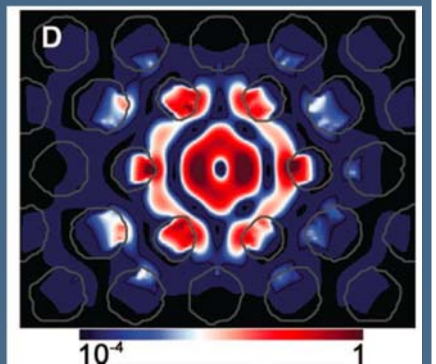




Science 305(5689) pp.1444-1447 (2004)

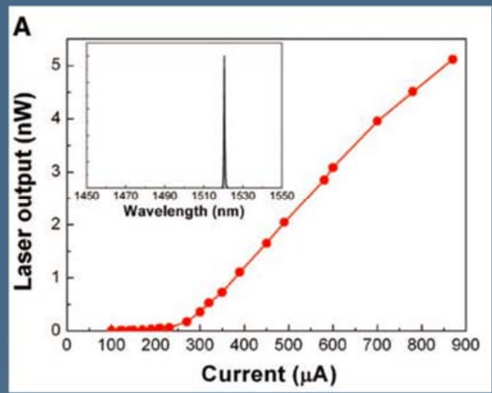
Electrically-Pumped Photonic Crystal Laser (I)





Science 305(5689) pp.1444-1447 (2004)

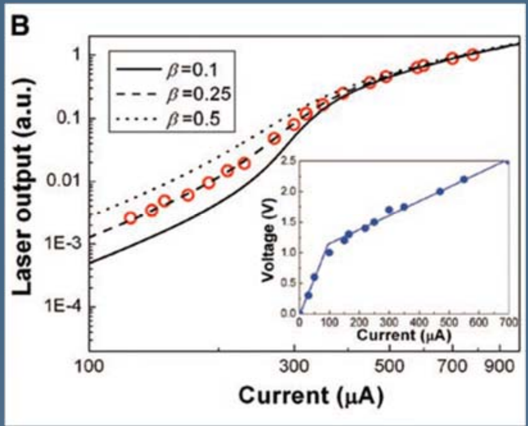
Electrically-Pumped Photonic Crystal Laser (I)



- ✓ Lasing wavelength ~ 1520 nm
- ✓ The threshold current ~ 250 μA

Science 305(5689) pp.1444-1447 (2004)

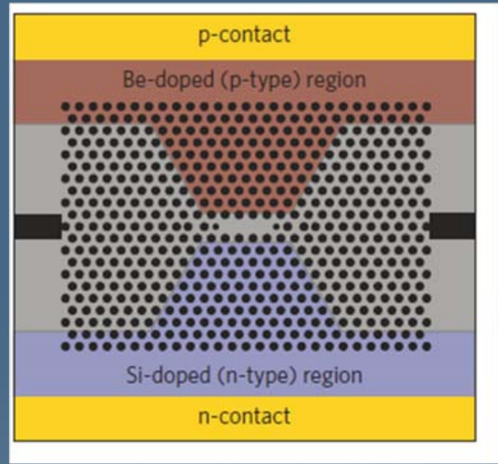
Electrically-Pumped Photonic Crystal Laser (I)



- ✓ The spontaneous emission coupling factor β ~ 0.25
- ✓ The electrical resistance ~ 2000 Ω

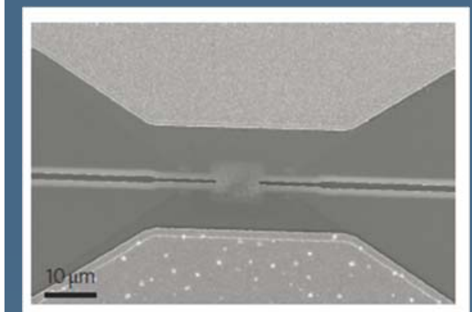
Science 305(5689) pp.1444-1447 (2004)

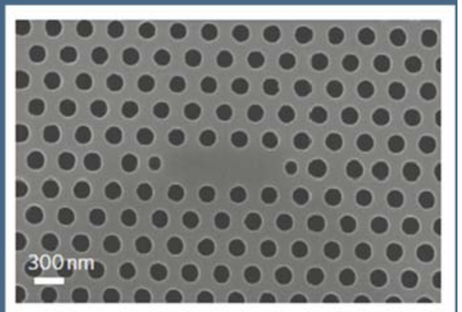
Electrically-Pumped Photonic Crystal Laser (II)



Nature Photonics 5, 297–300 (2011)

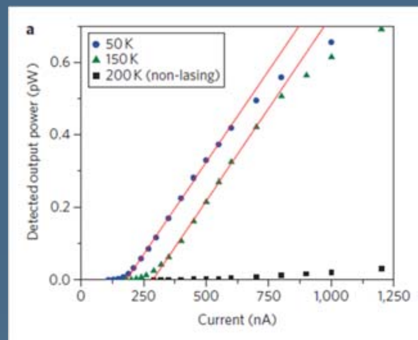
Electrically-Pumped Photonic Crystal Laser (II)

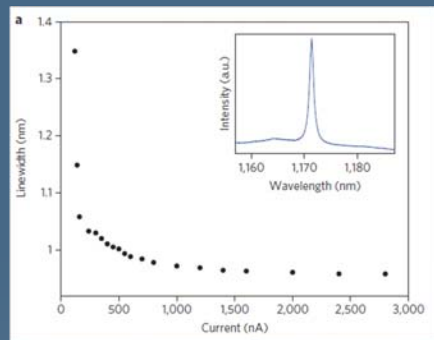




Nature Photonics 5, 297–300 (2011)

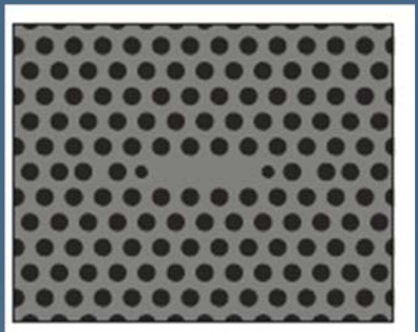
Electrically-Pumped Photonic Crystal Laser (II)

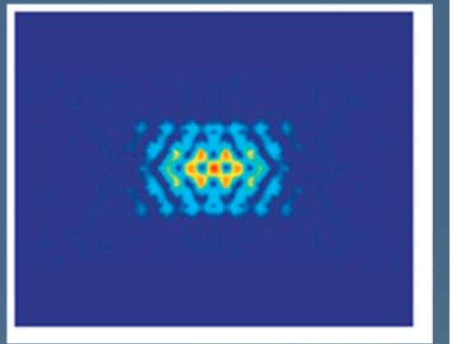




Nature Photonics 5, 297–300 (2011)

Electrically-Pumped Photonic Crystal Laser (II)

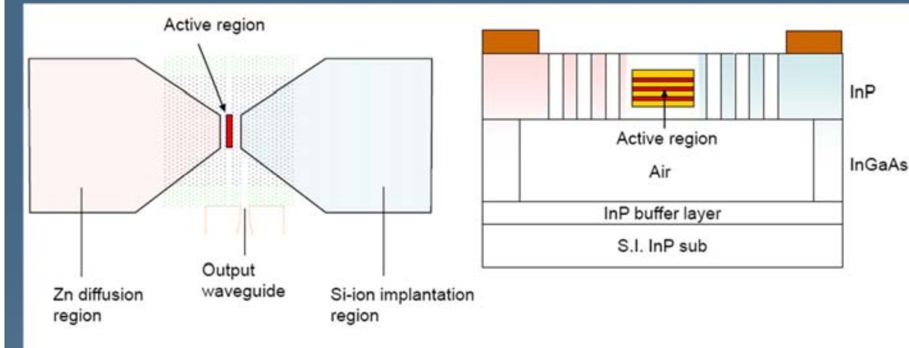




Nature Photonics 5, 297–300 (2011)

Electrically-Pumped Photonic Crystal Laser (III)

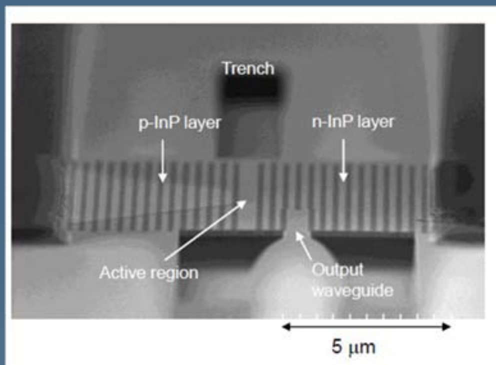
Directly Modulated PhC Nanolaser

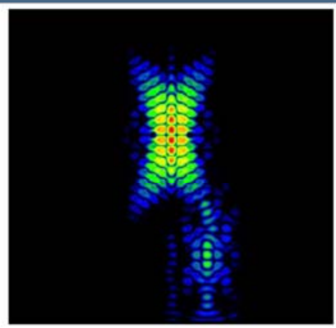


NTT Photonics Laboratories, Japan (2013)

Electrically-Pumped Photonic Crystal Laser (III)

Directly Modulated PhC Nanolaser

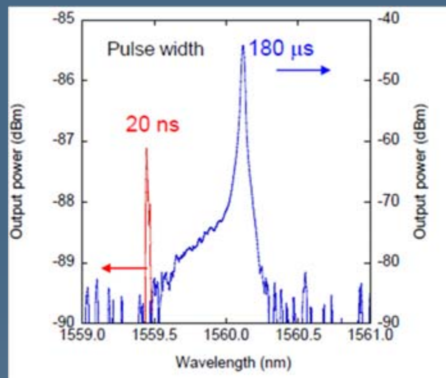


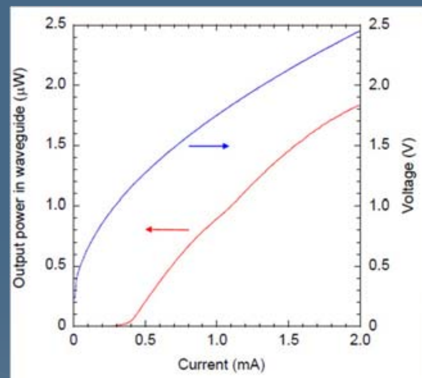


NTT Photonics Laboratories, Japan (2013)

Electrically-Pumped Photonic Crystal Laser (III)

Directly Modulated PhC Nanolaser





NTT Photonics Laboratories, Japan (2013)