Introduction to Photonic Integrated Circuits

Min-Hsiung Shih*(施閔雄)*

Research Center for Applied Sciences (RCAS)
&
Taiwan International Graduated Program (TIGP)
Academia Sinica, Taiwan
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Outlines

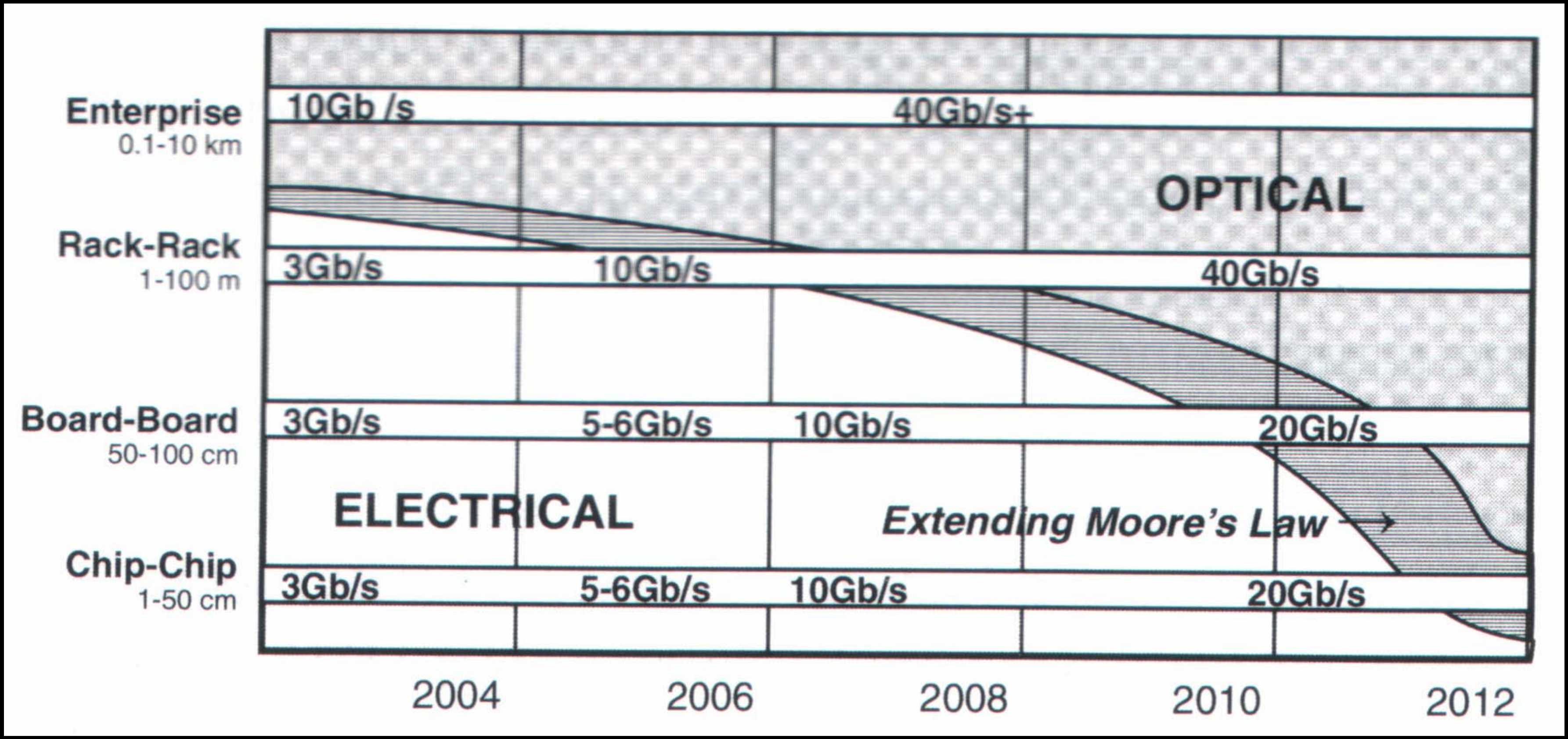
- **Optical communication and photonic integrated circuits**

- **Property of light**

- **Elements for optical communication system**
  1) Lasers and amplifiers
  2) Waveguides and fibers
  3) Modulators
  4) Multiplexer and Demultiplexer elements
  5) Photodectors

- **Photonic crystal waveguide and bending structures**

Speed Limitation of Electrical Communications



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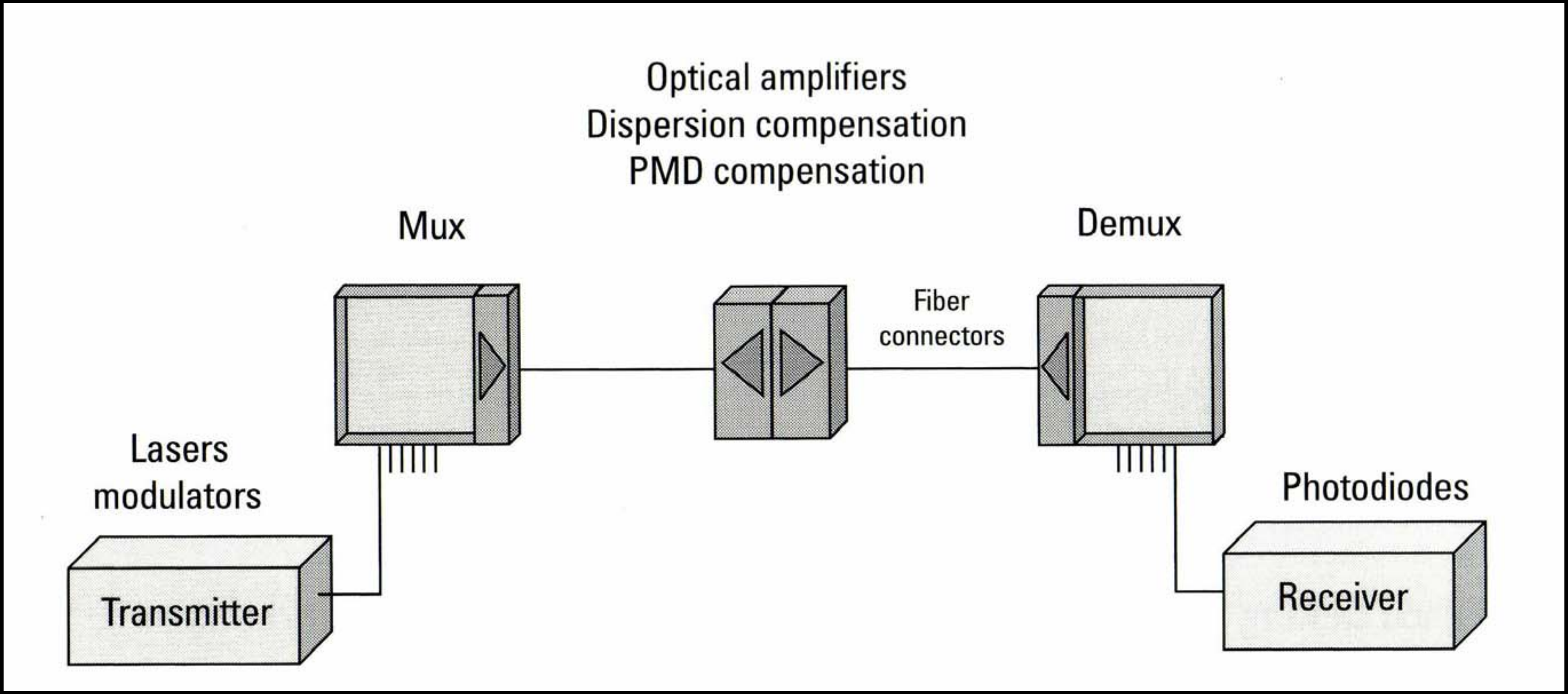
Optical Communication System



Typical DWDM (Dense Wavelength Division Multiplexing) system

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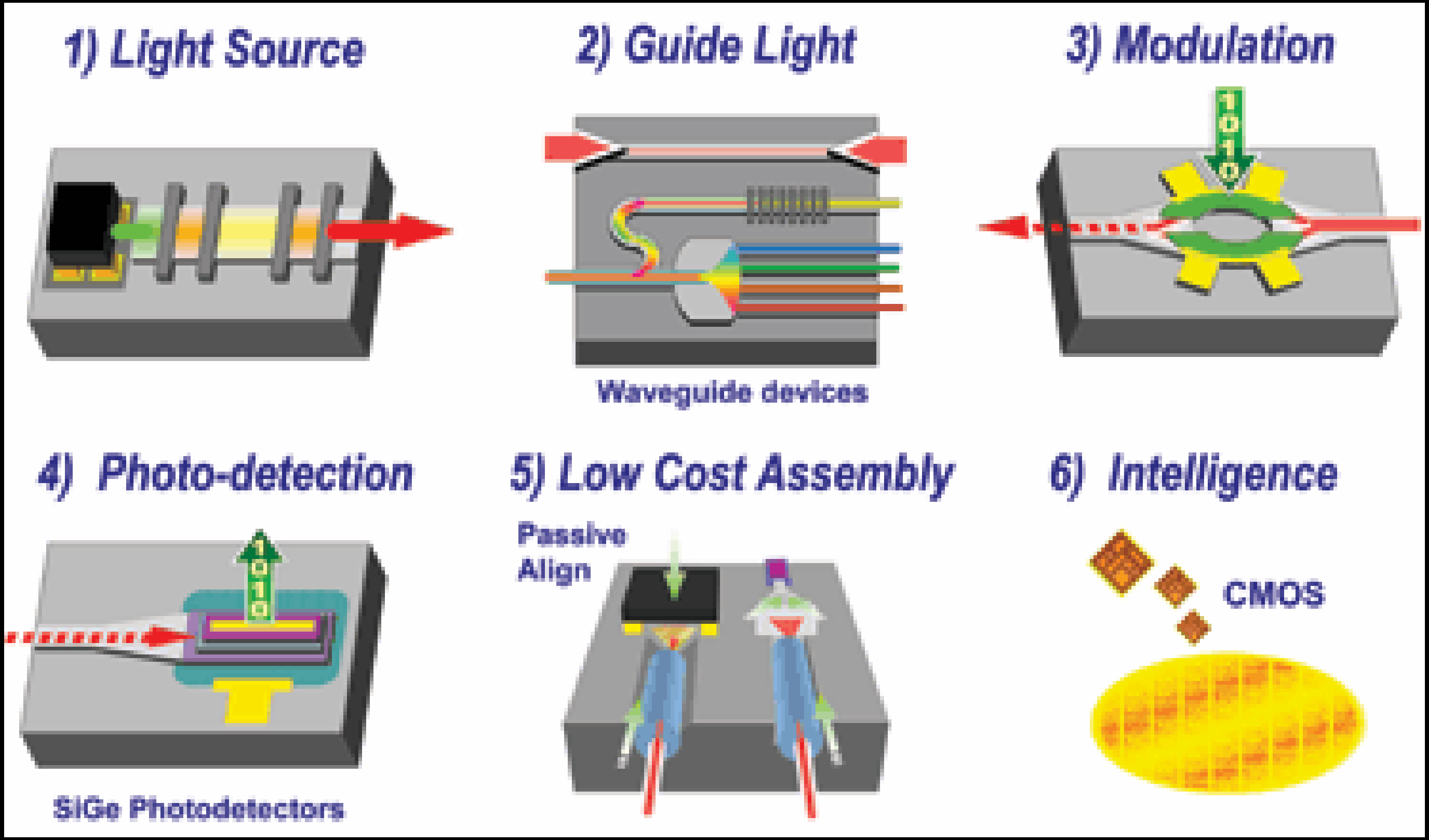
Elements for Photonic Integrated Circuits



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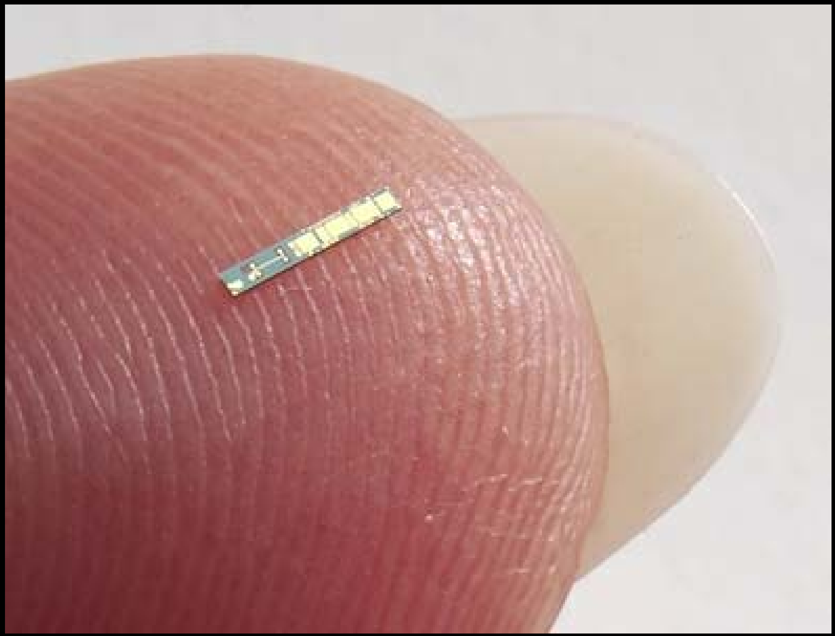
Example of Photonic Integrated Circuits



Photonic Integrated Circuit
combines tunable laser and optical modulator 10/09/2007

JDSU demonstrated a photonic integrated circuit (PIC) that combines a tunable laser and optical modulator, using a technology known as the Integrated Laser Mach Zehnder (ILMZ). The PIC will allow the company to develop smaller, higher performance and more cost-effective tunable solutions that support faster network speeds. Tunable lasers are a key element required or the deployment of agile optical networks (AON). Such networks are deployed by service providers to scale network infrastructures and replace slow, manual operations with simplified, dynamic network solutions that can quickly respond to fluctuating traffic traveling over fiber optic networks. Tunable lasers provide dynamic reconfigurability by allowing network operators to switch from one wavelength to another on demand, easing the cost of purchasing, storing and managing spare devices for wavelength management. The chip includes a widely tunable laser and Mach Zehnder modulator on a single chip that is small enough to fit on the tip of a finger. It will be incorporated into full-band tunable transponders and transceivers within compact packages, such as the 300-PIN small form factor (SFF) and pluggable small form factors (XFP) starting in 2008. This combination enables JDSU to support transmission speeds greater than 11.3 Gigabits per second and is scalable to support 40Gbit/s networks.

From www.epn-online.com

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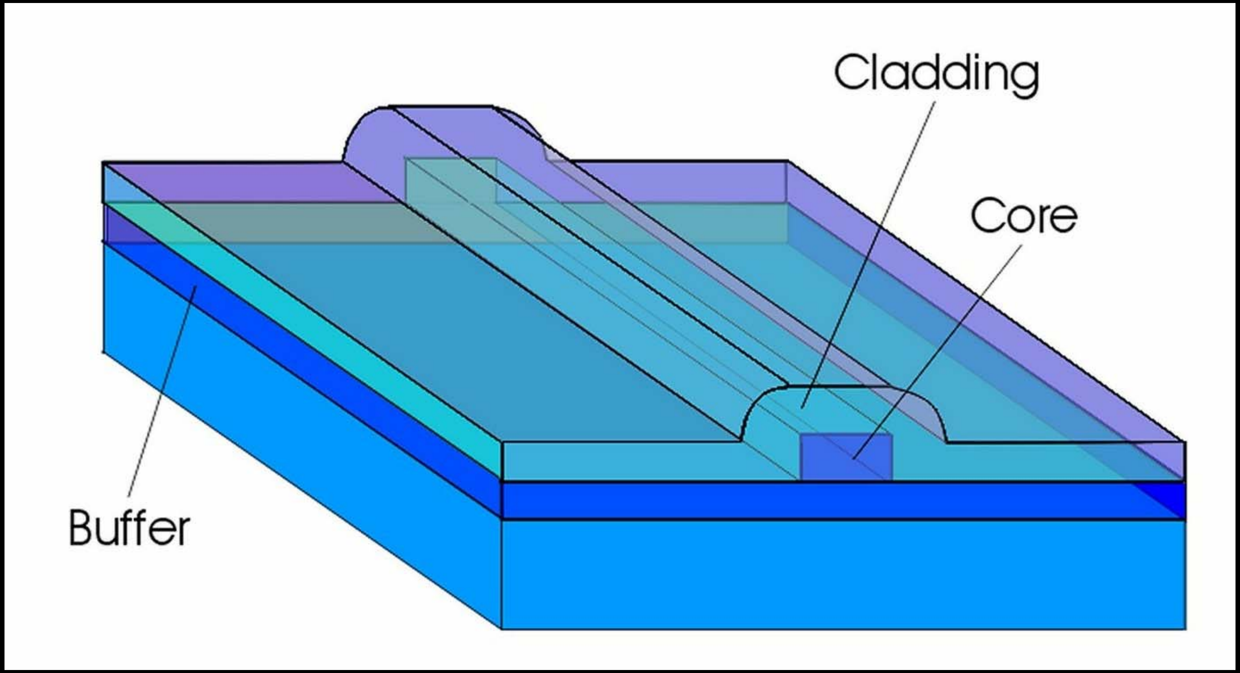
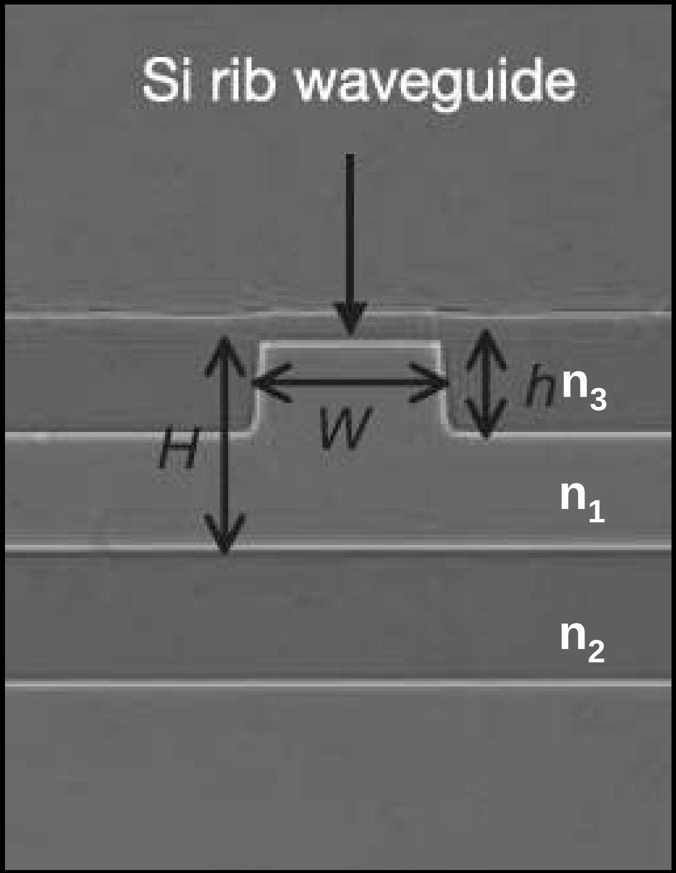
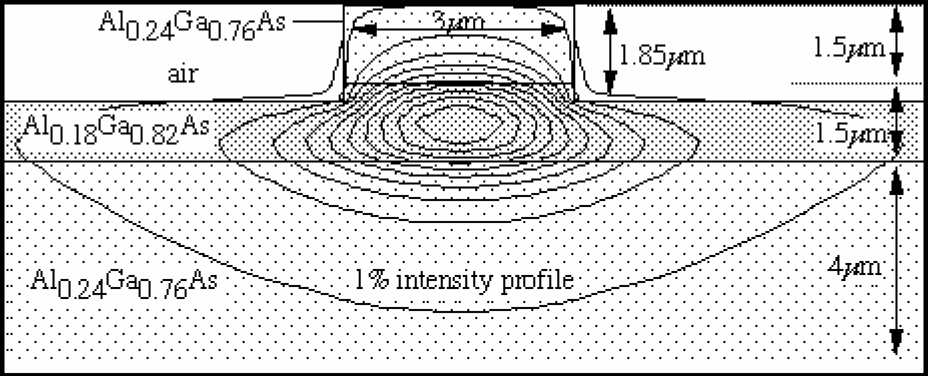
Optical Waveguides

Geometry of a Rib (Ridge) waveguide in planar photonic circuits



Types of Optical Waveguides





- SEM image of a dielectric rib (ridge) waveguide

- The calculated mode profile

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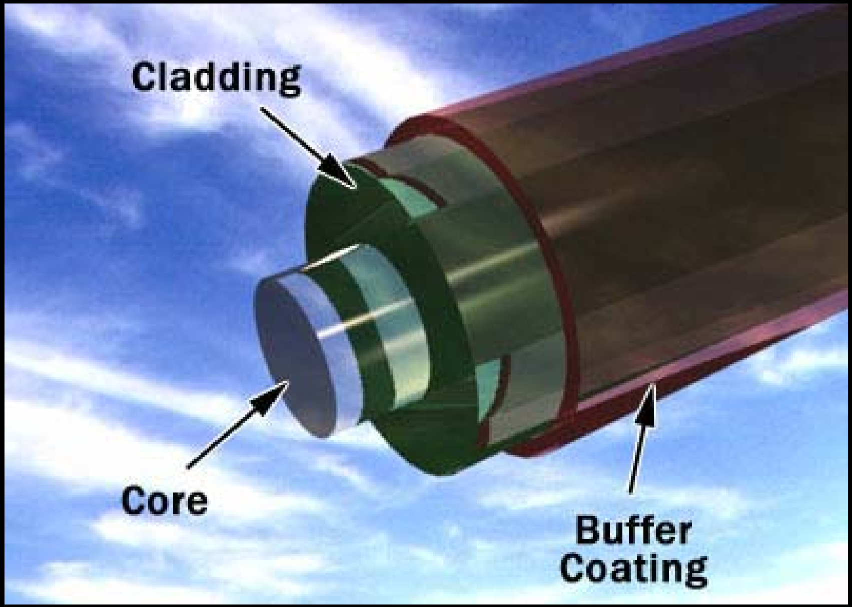
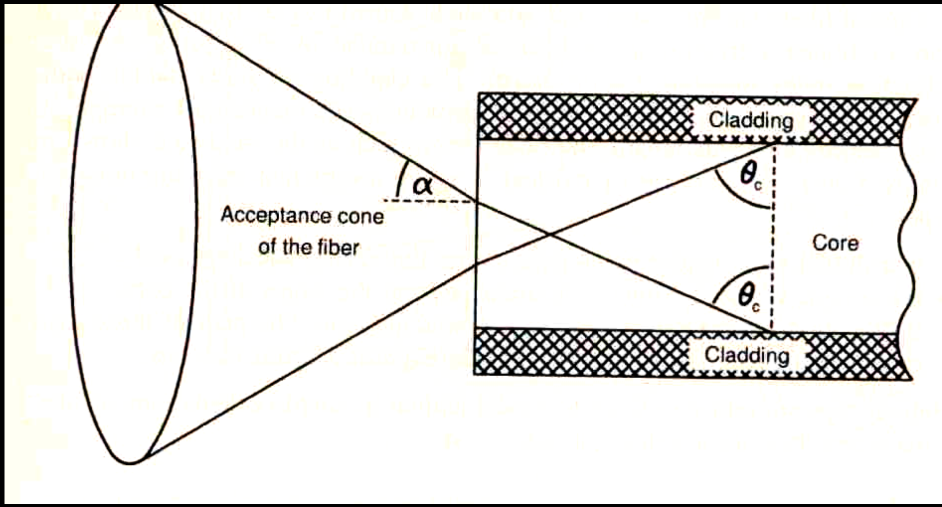
Optical Fiber





- High index core surround by lower index cladding
- The numerical aperture NA

$$NA = (n_{core}^2 - n_{cladding}^2)^{1/2}$$

$$\sin \alpha = \frac{NA}{n_0}$$

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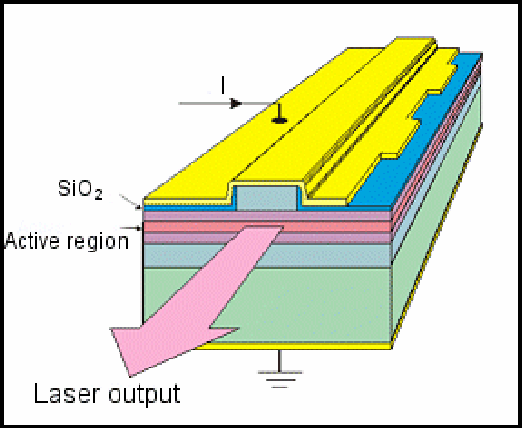
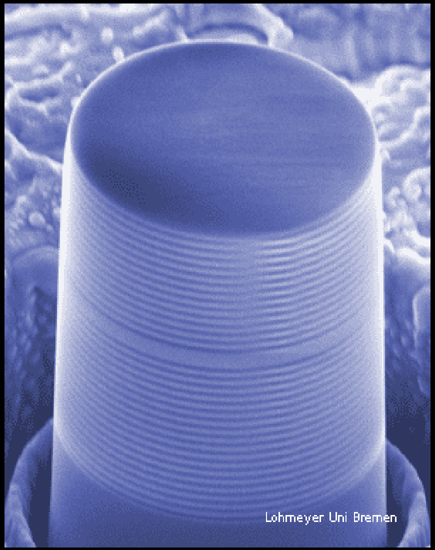
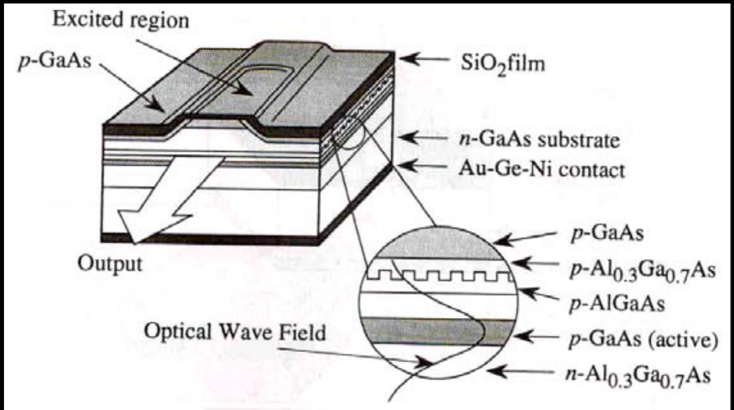
Semiconductor Lasers



Edge-emitting laser

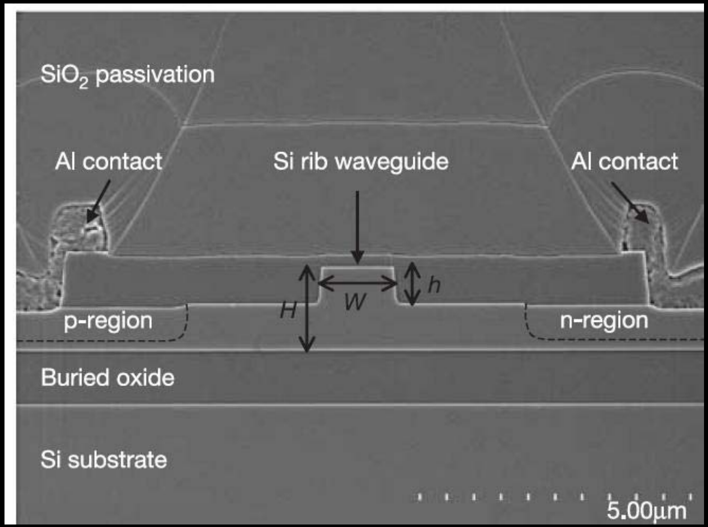
VCSEL





DFB laser

Si Raman laser



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Optical Amplifiers - EDFA

- Erbium doped fiber amplifier (EDFA)
- Advantages
  1. Cover wide wavelength range
  2. Large total output power (> 1000 mW)
  3. Large dynamic power range
- Disadvantages
  1. Not linear over the working range
  2. Total power keep constant for channels

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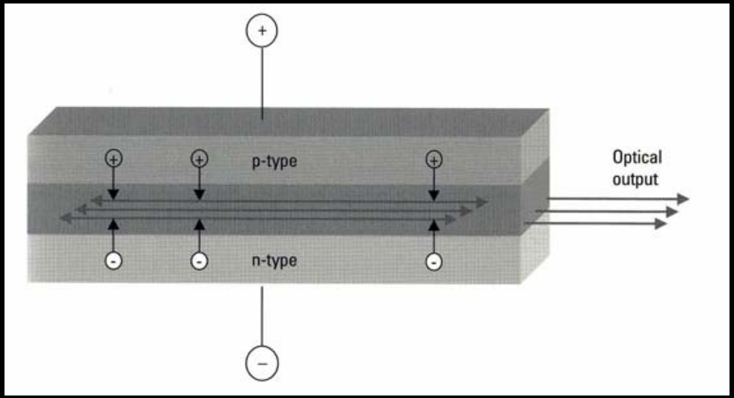
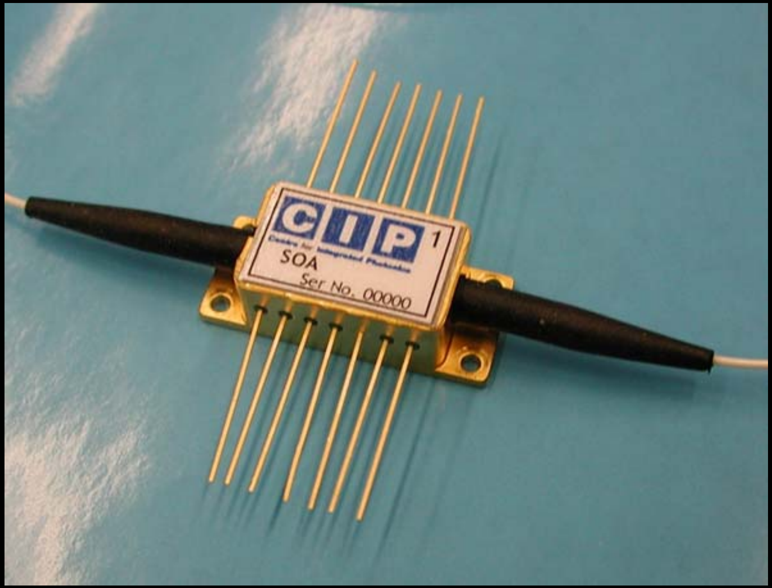
Optical Amplifiers - SOA





- Semiconductor optical amplifier (SOA)
- Advantages
  1. For larger range of wavelength
  2. Easy to integrate to other elements
- Disadvantages
  1. Lower output power(5-10 mW)
  2. Crosstalk influences

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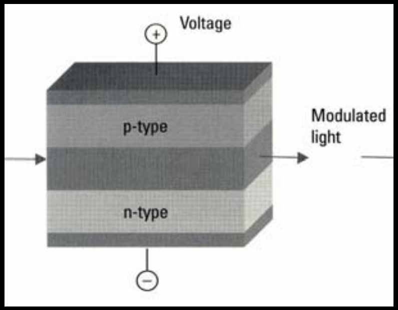
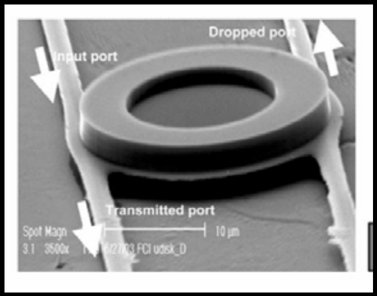
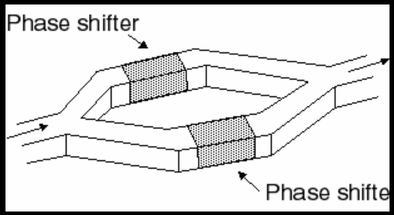
Different Types of Optical Modulators







	E-O Modulator	Resonant Microdisk	Mach-Zehnder Structure
Size	Large	Compact	Larger
Speed	> 10 GHz	> 10 GHz	~ 1 GHz
$V\pi$	High	Low	Low
Cost	Low	High	Low

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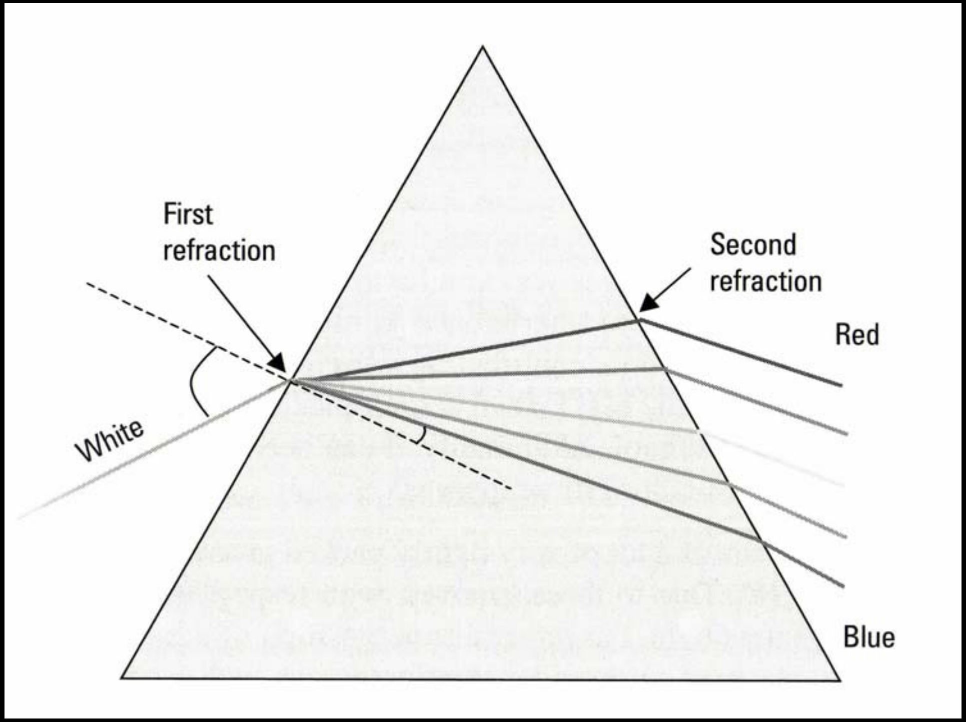
Demultiplexer Elements



Prism

- Not used in DWDM system

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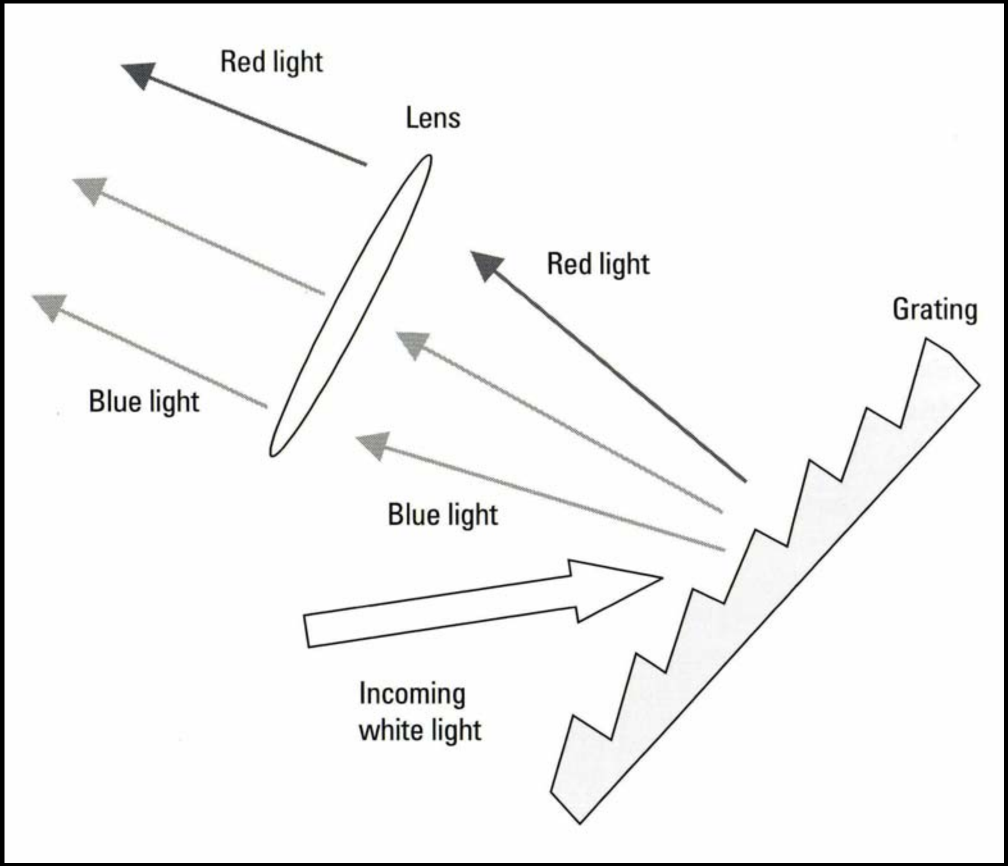
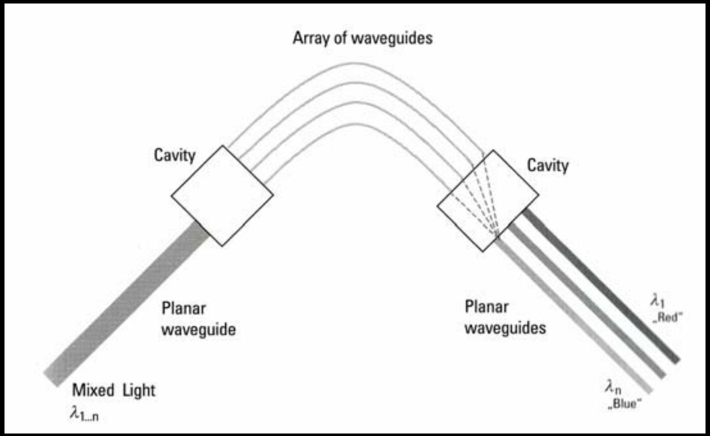
Demultiplexer Elements

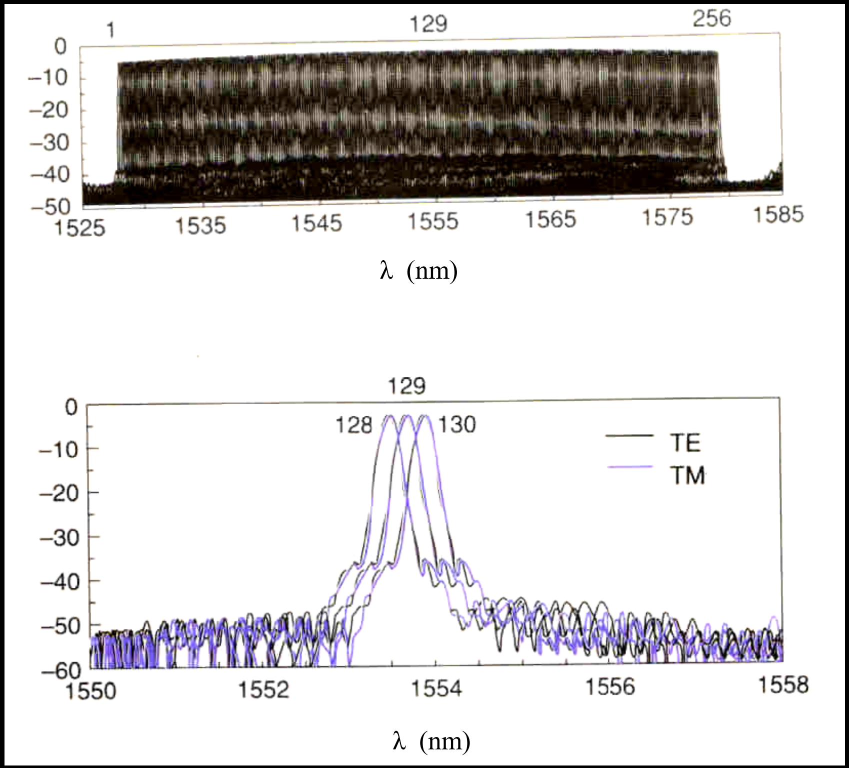


Diffraction Grating

- Reflection light is not homogeneous
- Not used in DWDM system

Demultiplexer Elements





<u>Array waveguide grating (AWG)</u>

- Array WGs make phase shift, and different focus in 2nd cavity
- Higher No. of channels (>64)
- Small wavelength spacing
- Temperature dependence & higher cost

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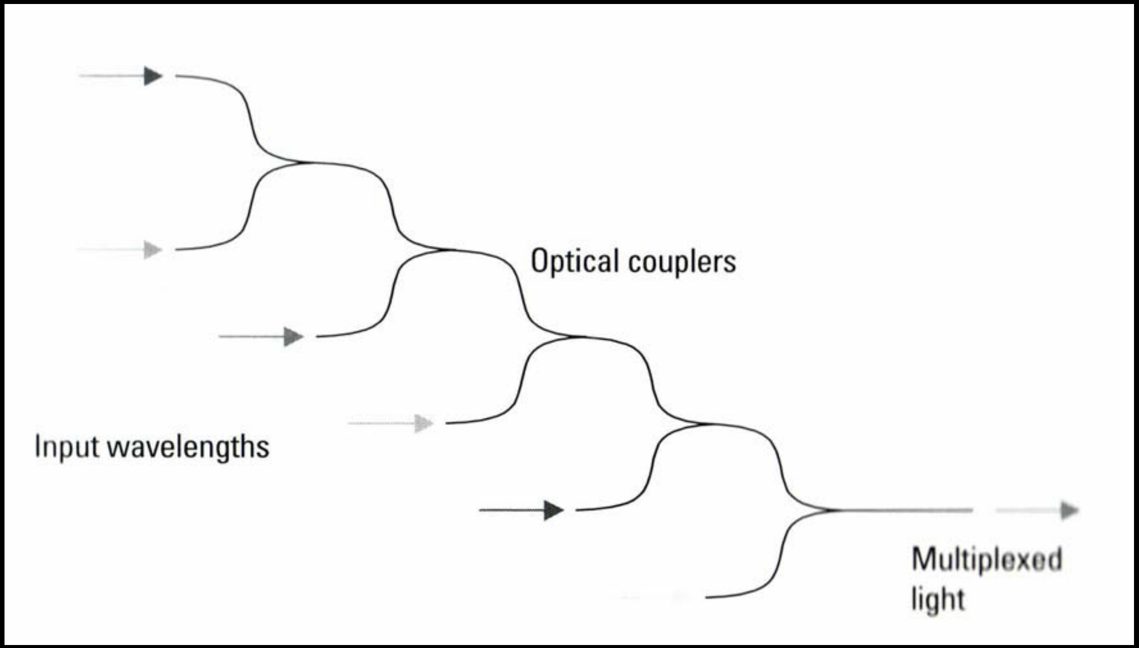
USC

Multiplexer Elements



- <u>Optical couplers</u>
  1. Simple, low cost
  2. High insertion loss
  3. Never be a DeMUX

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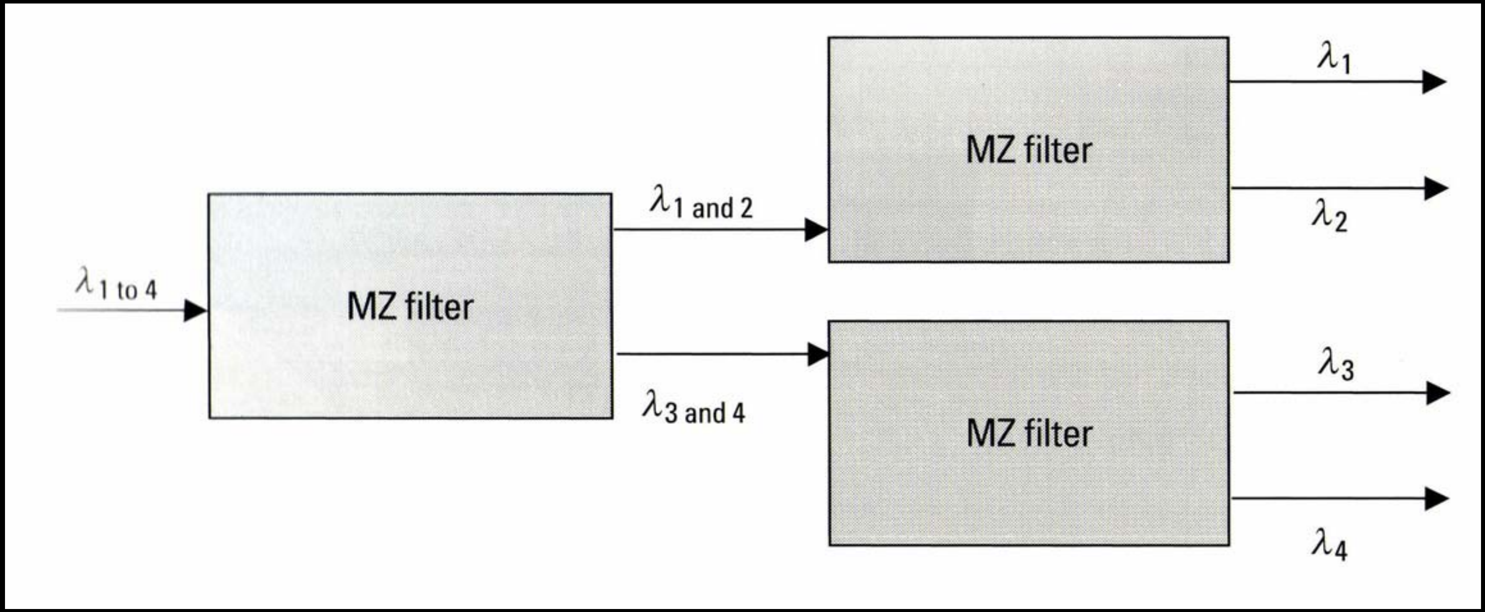
Multiplexer Elements



Cascaded Mach- Zehnders

- Easy integrated
- Can be used for MUX/DeMUX

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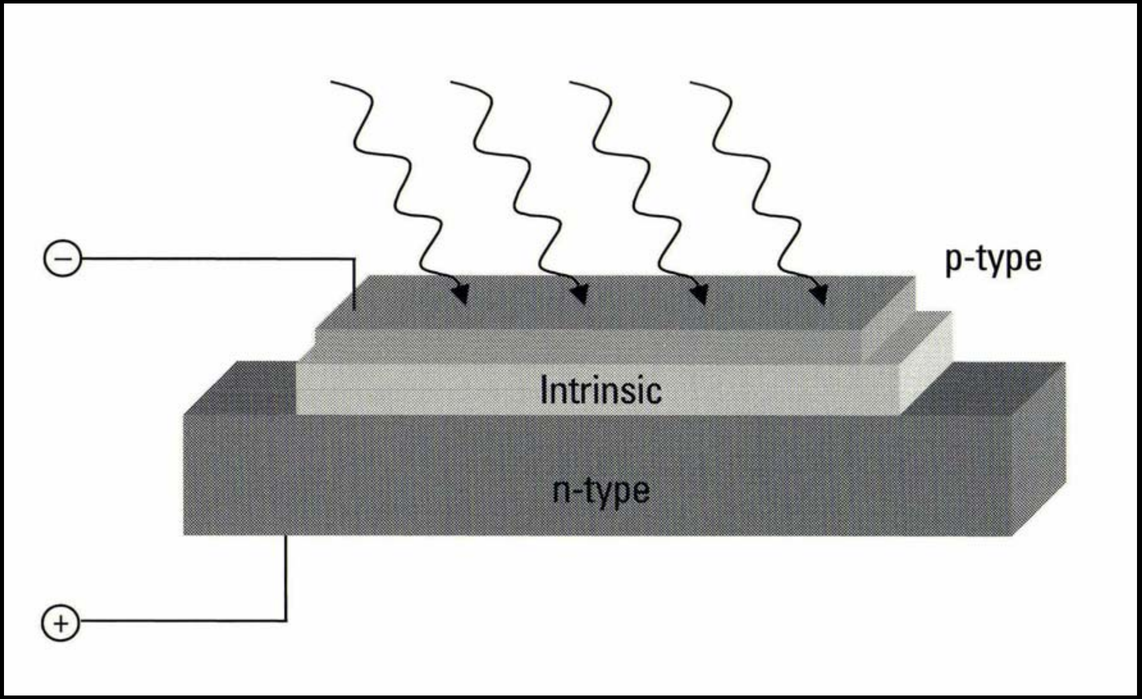
Photodectectors in Photonic Circuits



- Transfer optical signals to electrical signals
- The opposite way to lasers

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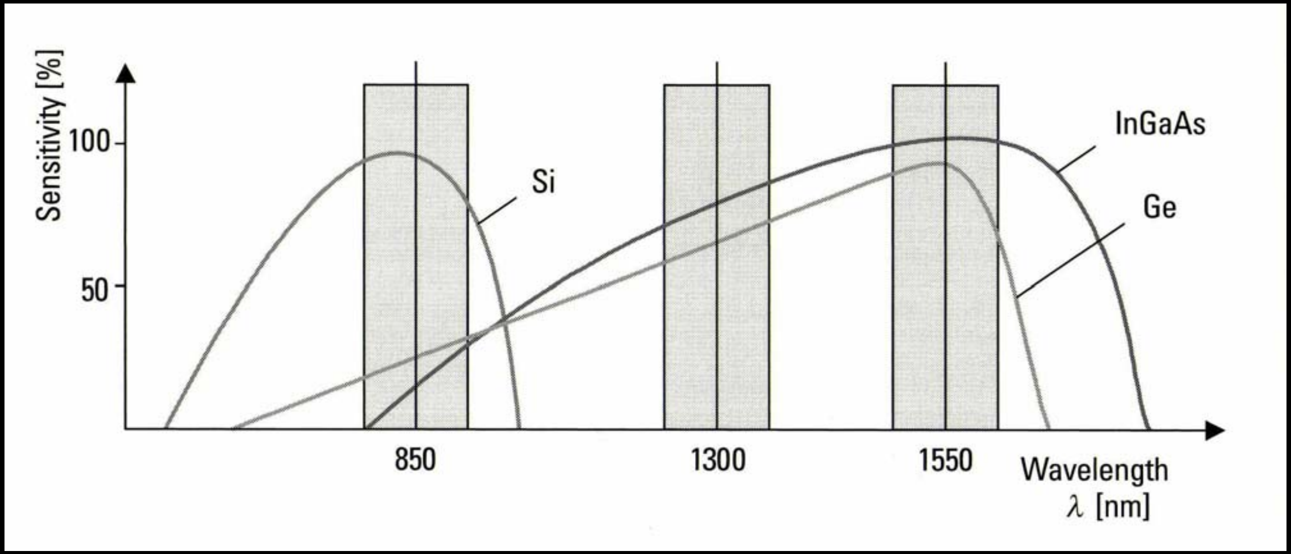
Photodectectors in Photonic Circuits



- Spectral response of different detector materials
- For fiber communication (~ λ =1300-1550nm), InGaAs and Ge are prefer materials for photodetectors

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End……

Photonic Crystal Devices for Photonic Integrated Circuits

Min-Hsiung Shih*(施閔雄)*

Research Center for Applied Sciences (RCAS)
&
Taiwan International Graduated Program (TIGP)
Academia Sinica, Taiwan
May 16, 2008

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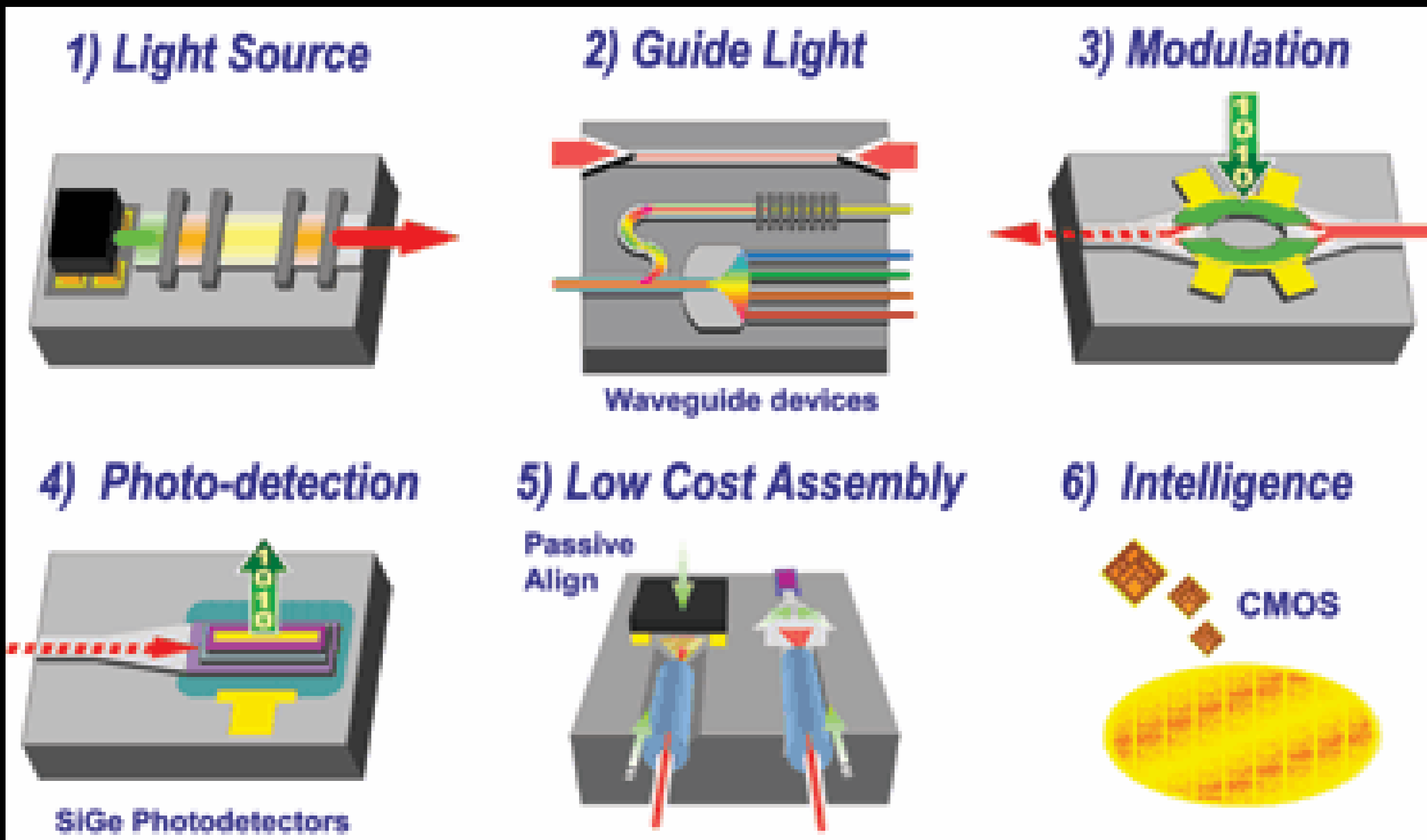
Elements for Photonic Integrated Circuits



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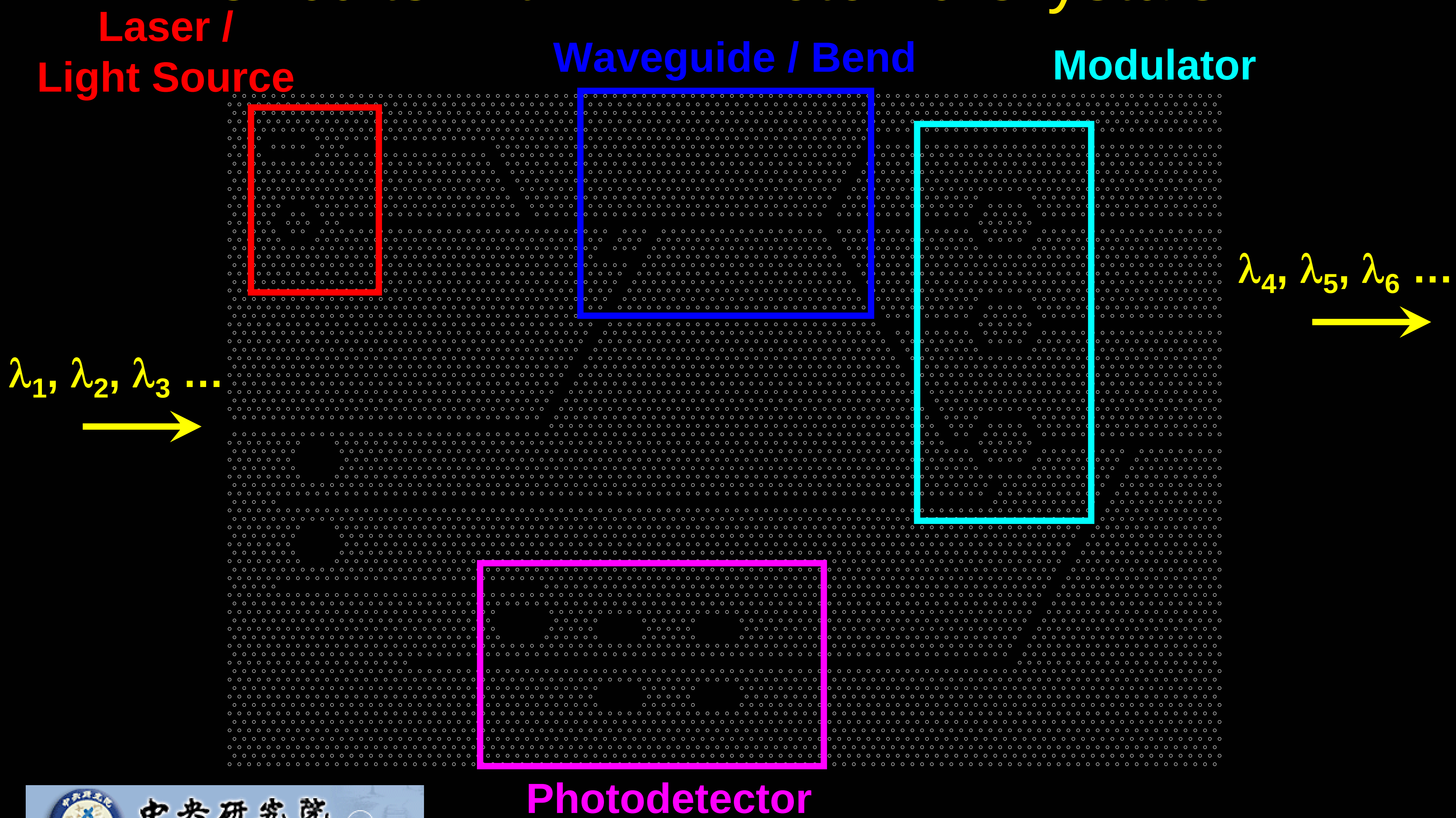
Building Blocks for Photonic Integrated Circuits with 2D Photonic Crystals



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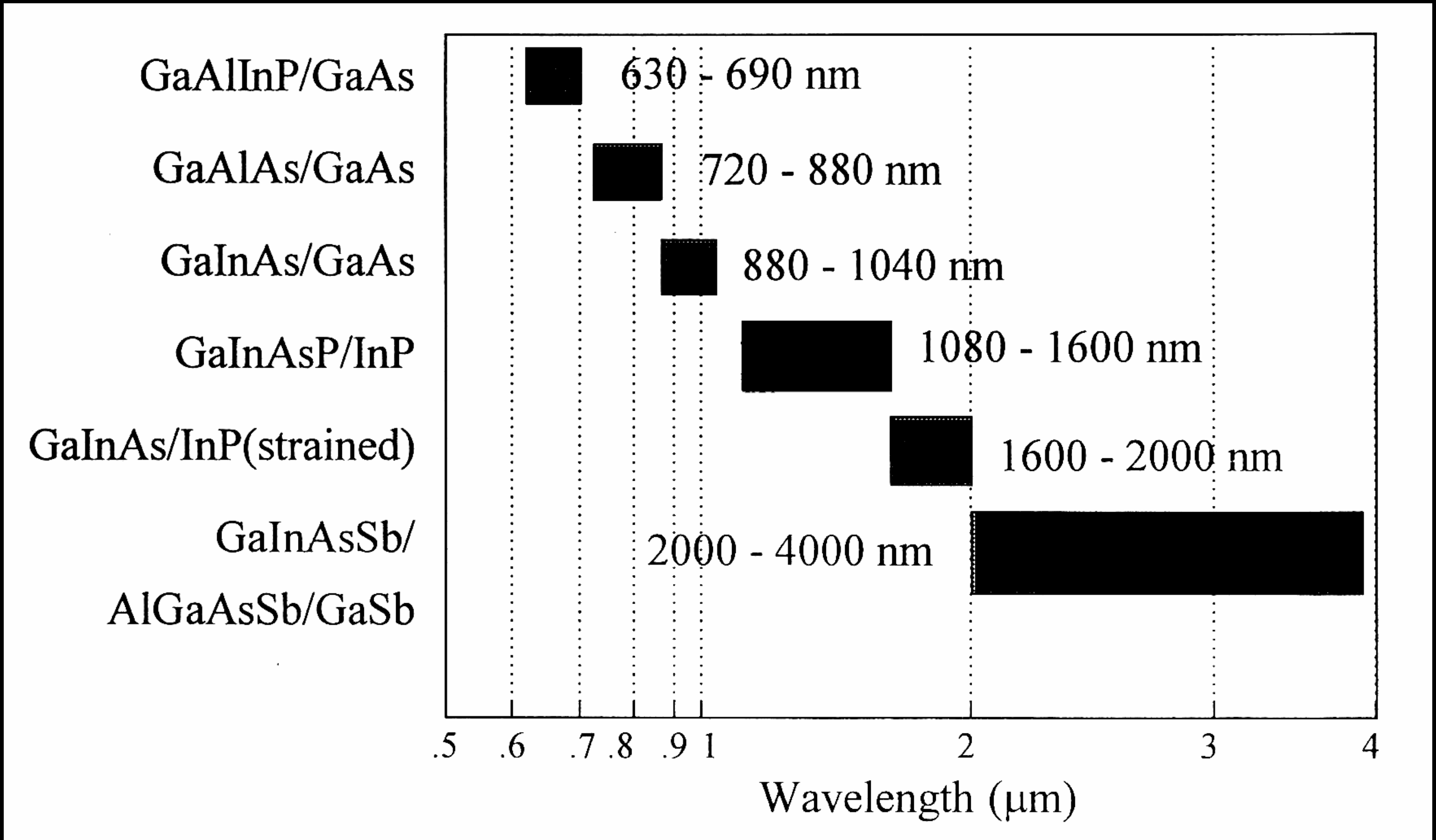
Photonic Crystal Defect Laser Cavity

- **Micro-Disk Lasers**
- **Photonic Crystal D3 Membrane Cavity**
- **Continuous-Wave (CW) Operation Photonic Crystal Laser Cavity under**

III-V Gain Materials for Semiconductor Lasers



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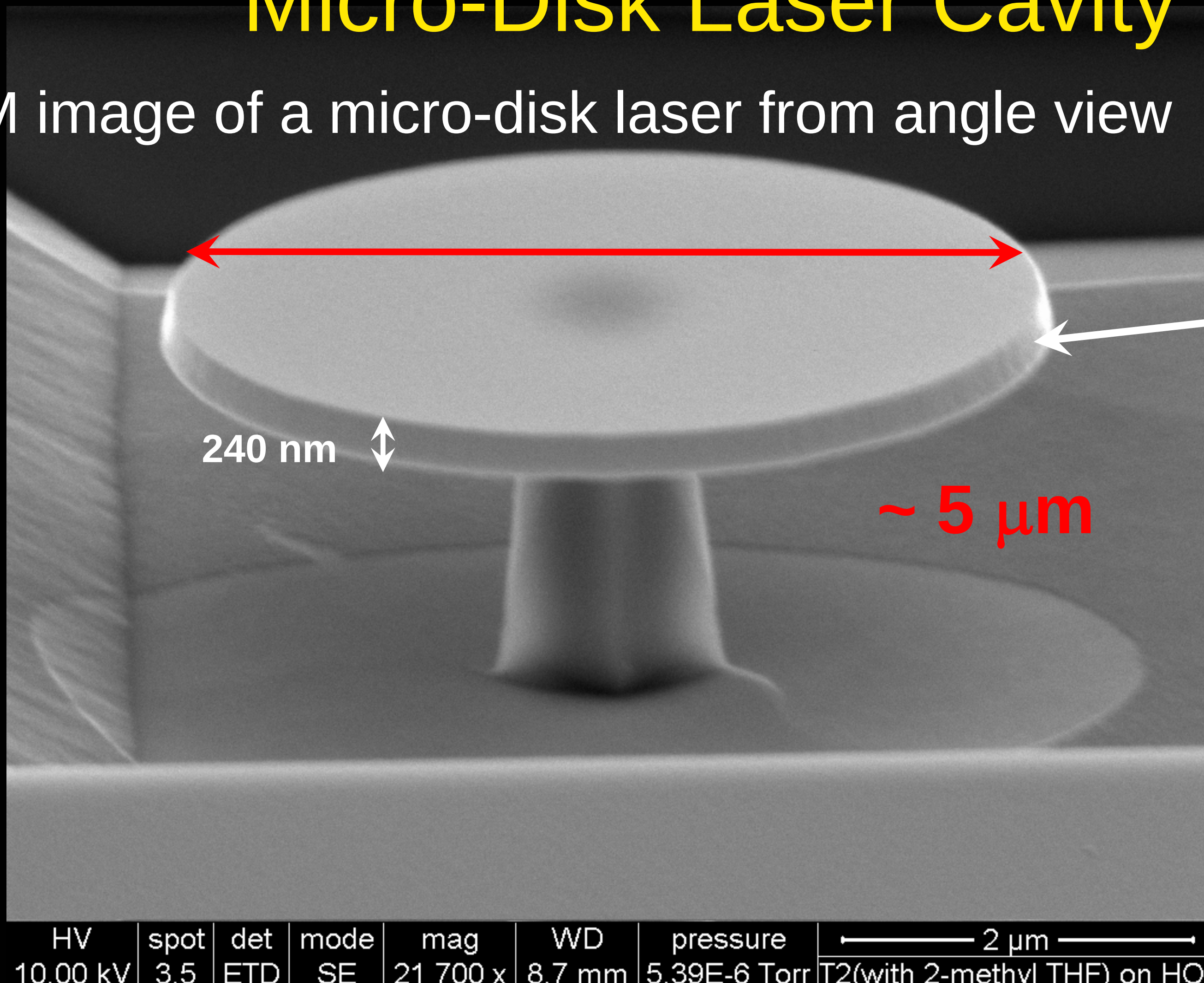
Micro-Disk Laser Cavity

SEM image of a micro-disk laser from angle view



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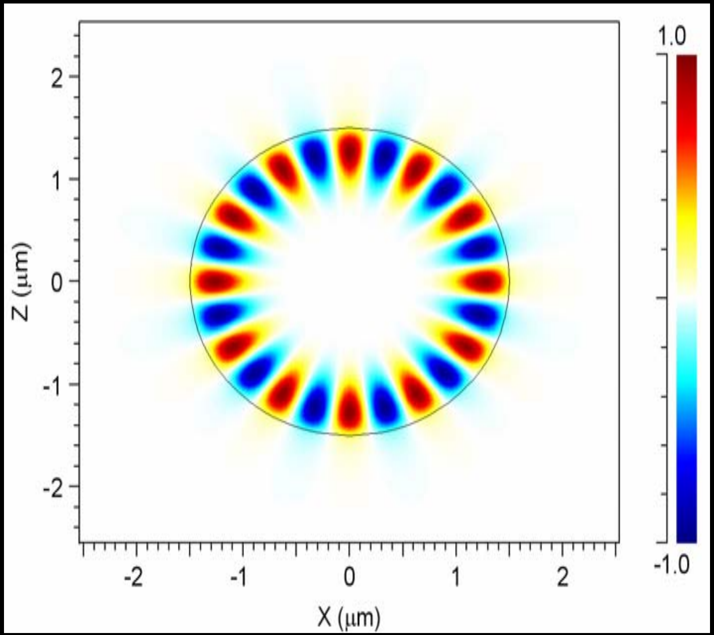
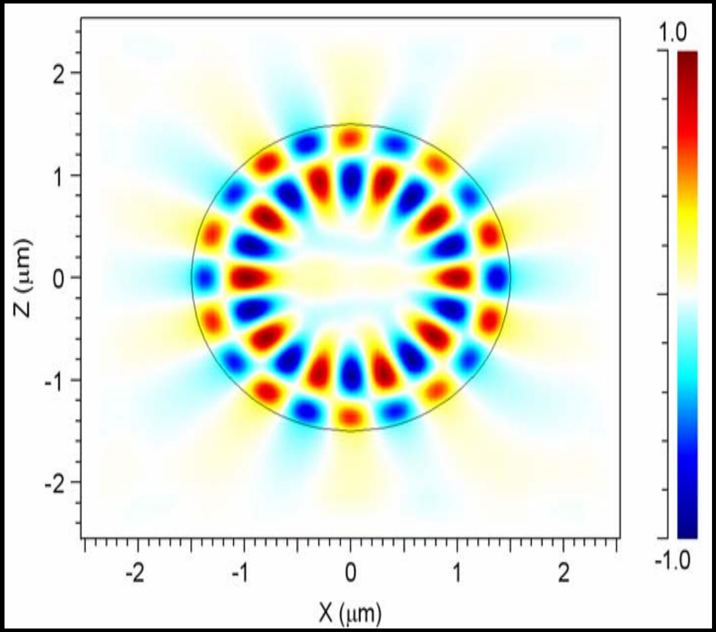
Micro-Disk Laser Cavity

Whispering-gallery resonant modes
of a micro-disk



1st order mode



2nd order mode

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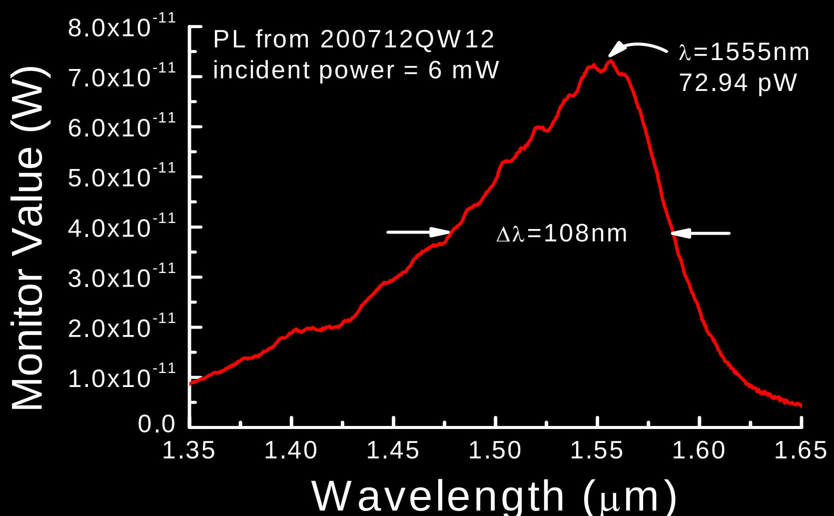
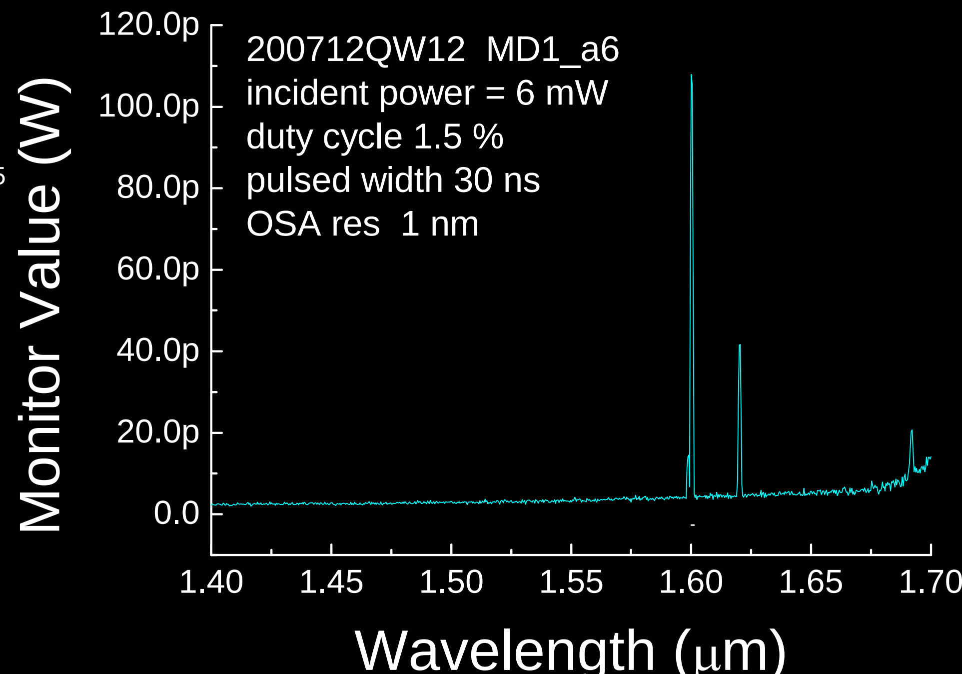
Micro-Disk Laser Cavity



PL spectrum

Gain peak ~ 1550 nm

Lasing spectrum



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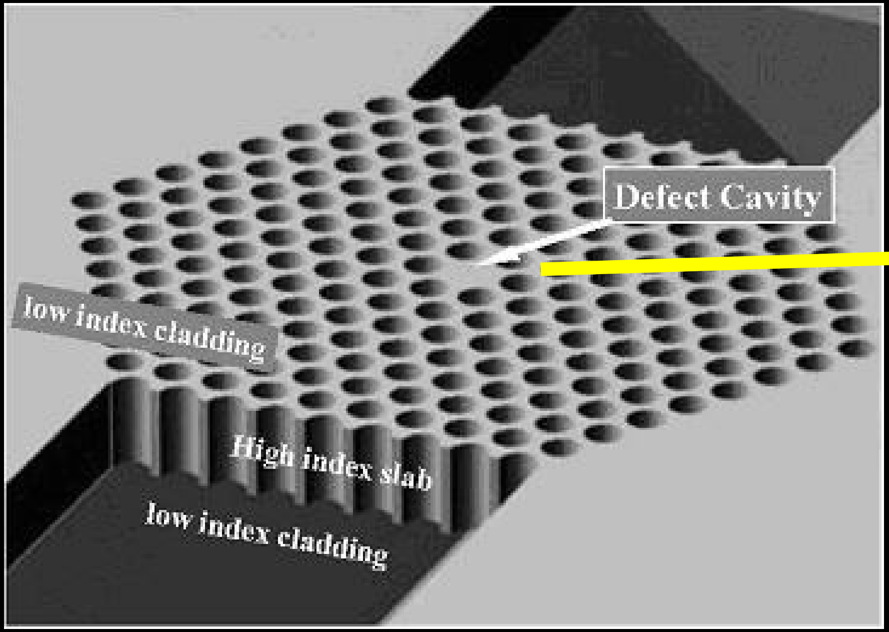
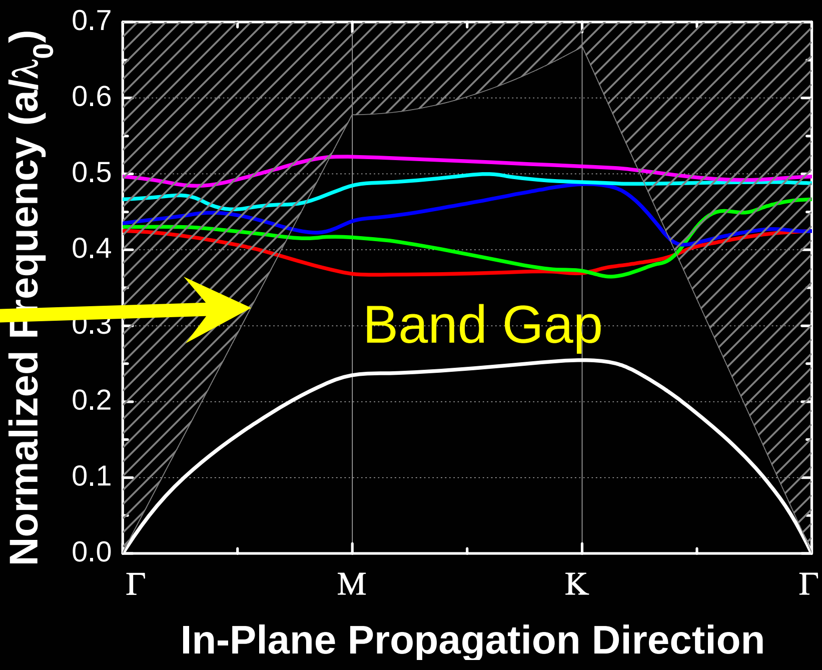
Membrane Photonic Crystal Defect Laser Cavity

Two dimensional triangular photonic crystal suspended membrane with r/a = 0.3, d/a=0.6 and dielectric constant ε=11.56

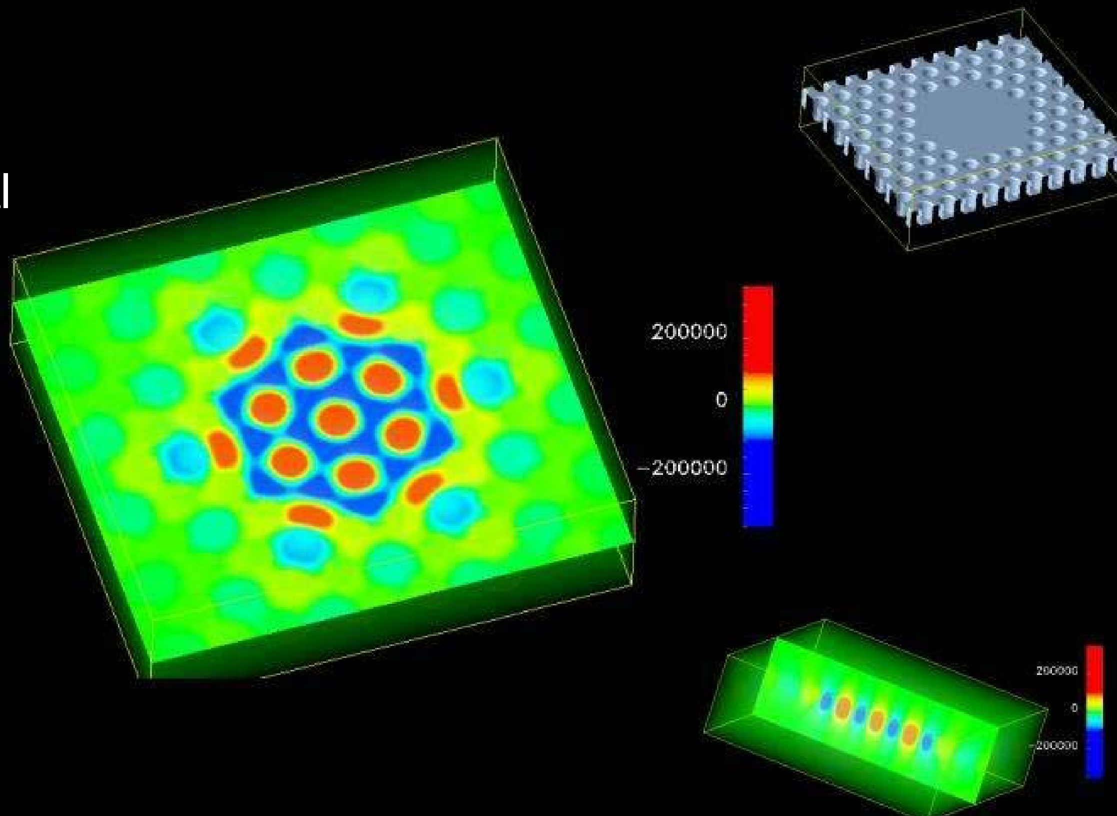
3D Band diagram of the photonic crystal membrane from finite-difference time-domain (FDTD) method





Finite-Difference Time-Domain Method Simulation

- The highly localized field in photonic crystal structures couldn't be solved analytically
- The finite-difference time-domain (FDTD) method can simulate the evolution of the field which governed by Maxwell's equation in real time space domain



Simulated H_z of a D3(19 missing holes) suspended membrane photonic crystal cavity by three dimensional FDTD method

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Quality Factor (Q) of Cavity

- The decay of energy in a cavity is expressed in term of the quality factor or Q.
- Different notations

1) Theoretical def.

$$Q = \frac{2\pi(\text{energy stored in the cavity at resonance})}{(\text{energy lost in a cycle of oscillation})}$$

2) Experimental data in frequency domain

$$Q = \frac{\omega_0}{\Delta\omega_{1/2}}$$

3) Photon life time, τ_p

$$\tau_p = \frac{Q}{\omega_0}$$

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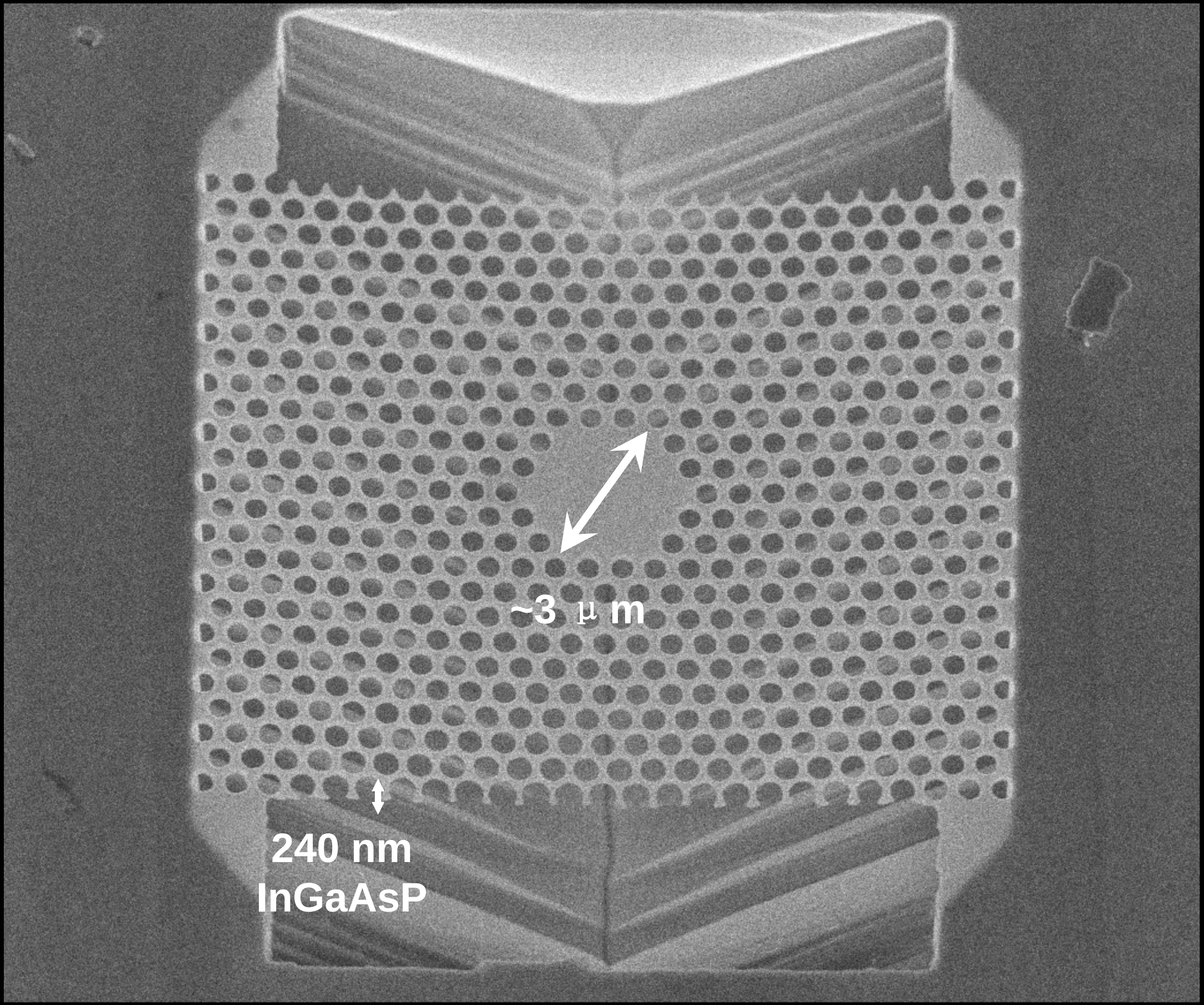
D3 Membrane Photonic Crystal Cavity



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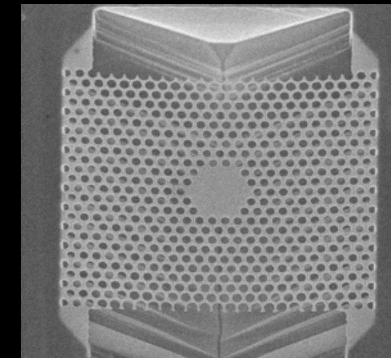
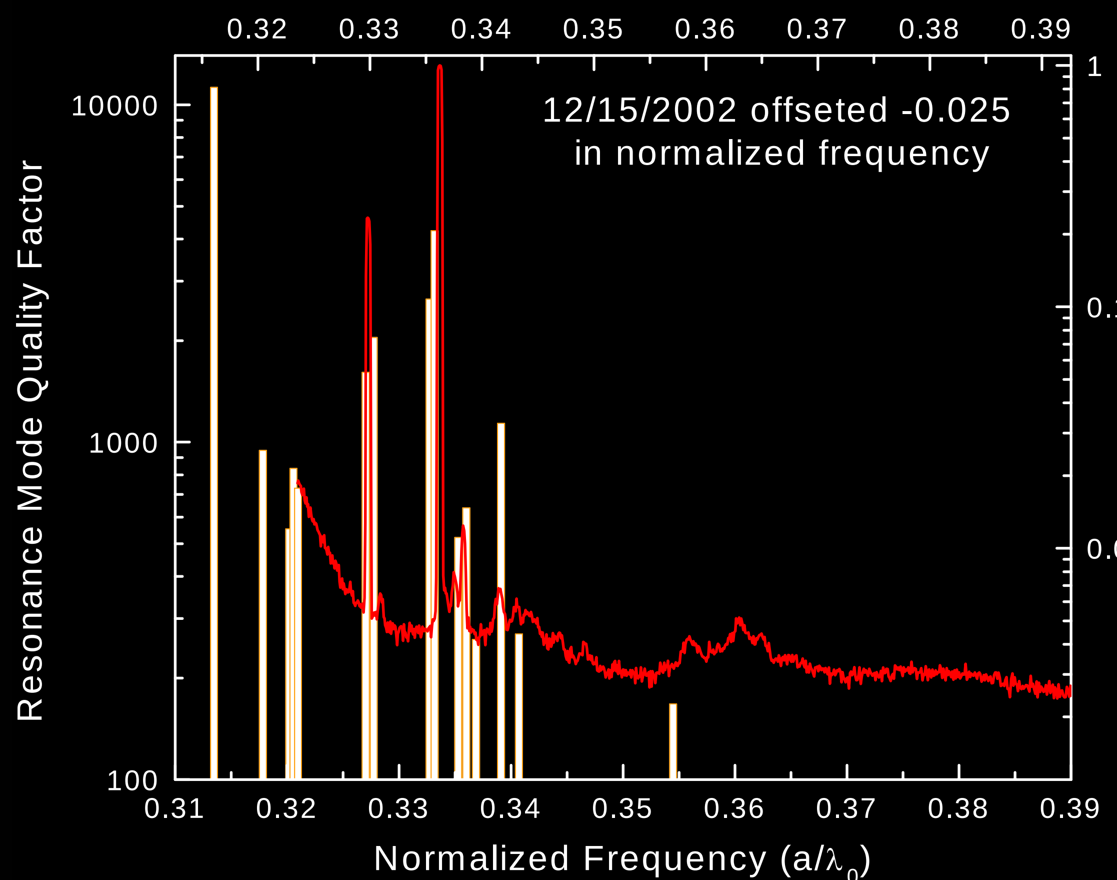
Lasing Data from D3 Membrane Photonic Crystal Cavity



- The lasing spectrum (red) of a suspended membrane D3 photonic crystal laser cavity.
- The resonance peaks of the spectrum match well in the predicted normalized frequency which have higher quality (Q) factors and inside the high gain region.



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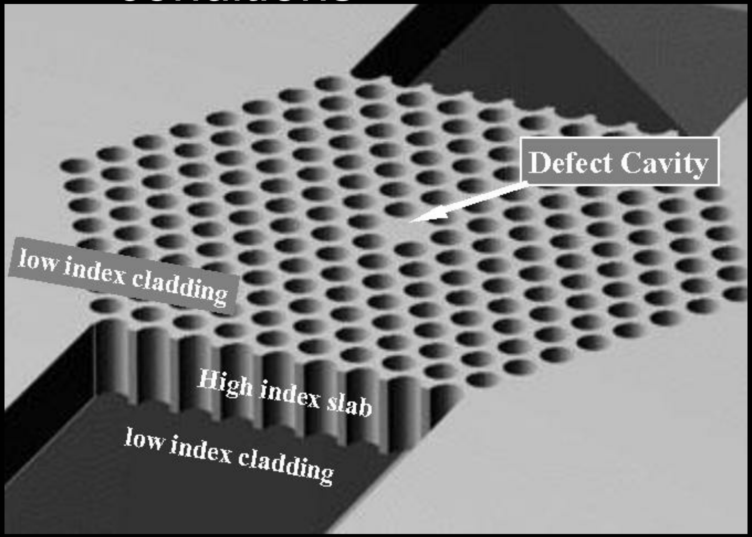
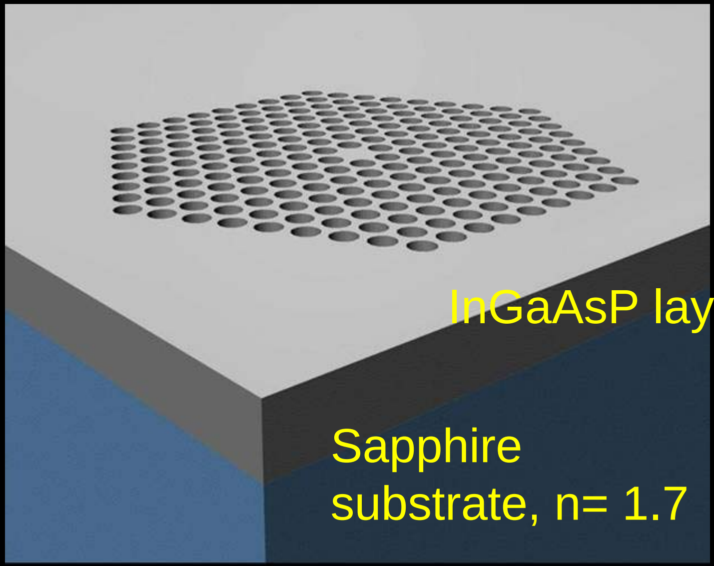
Suspended Membrane and Sapphire-Bonded Structure

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

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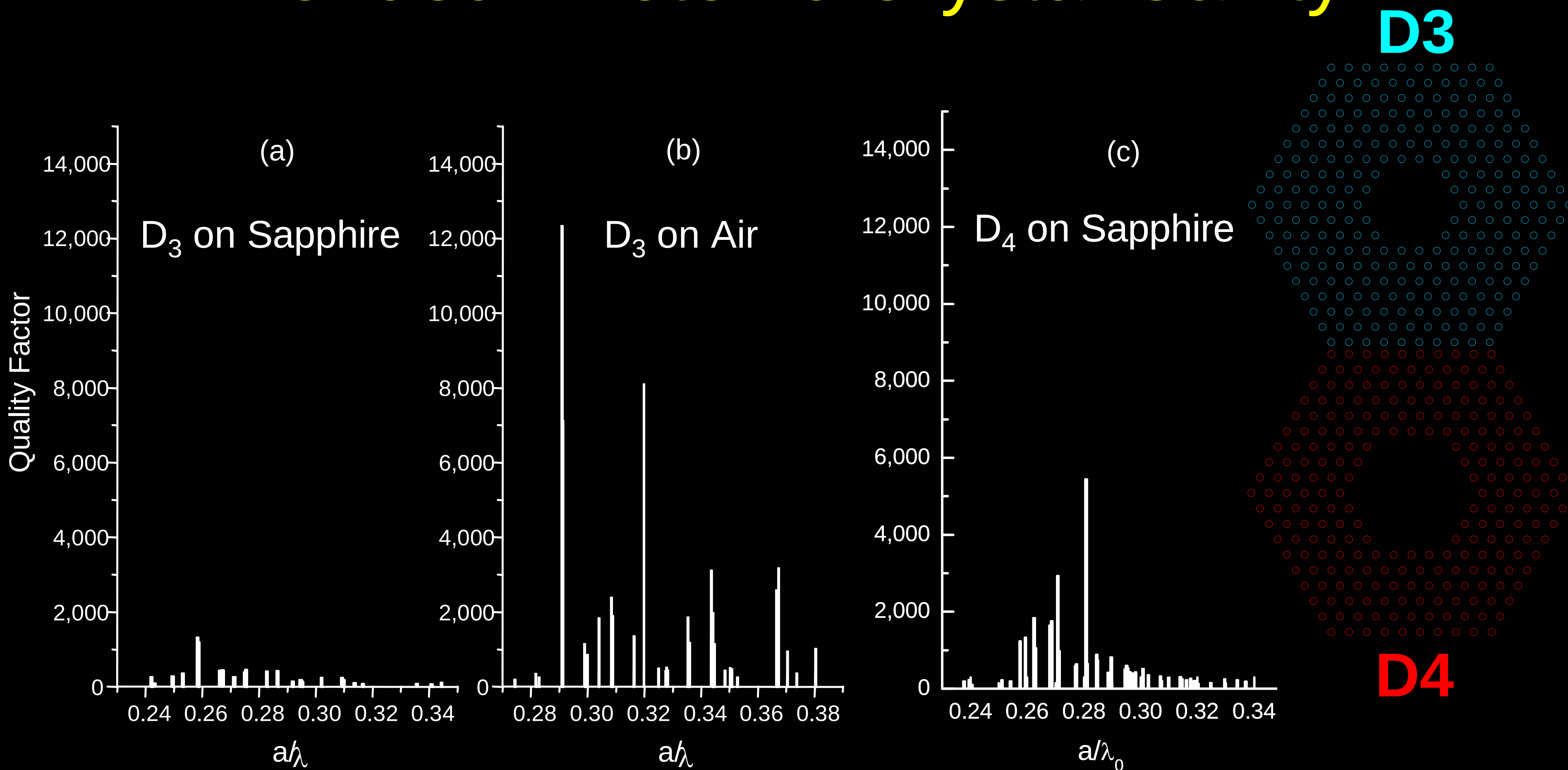
Quality Factor (Q) of Sapphire-Bonded Photonic Crystal Cavity



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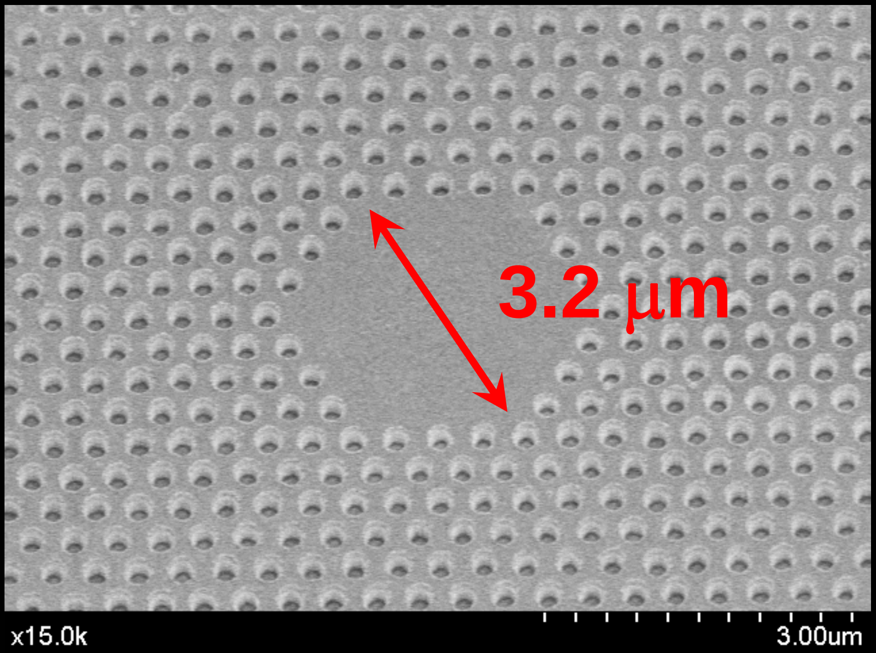
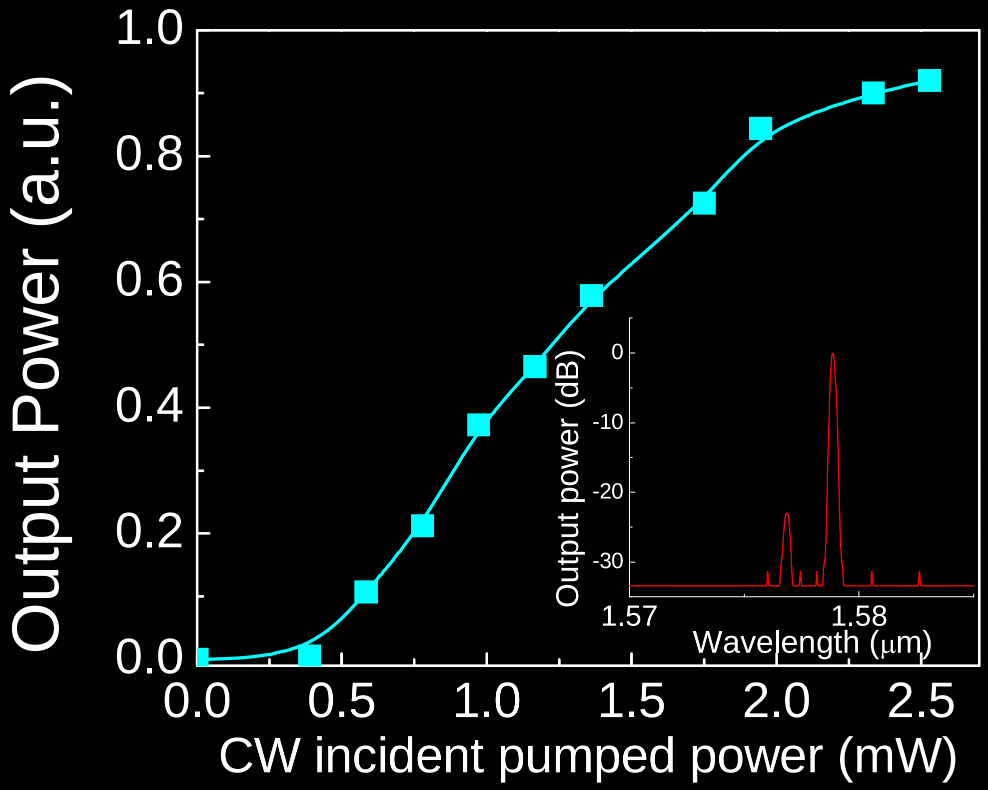
Continuous Wave (CW) Operation of Sapphire-Bonded Photonic Crystal Cavities

SEM image of D4 sapphire-bonded cavity from angle view





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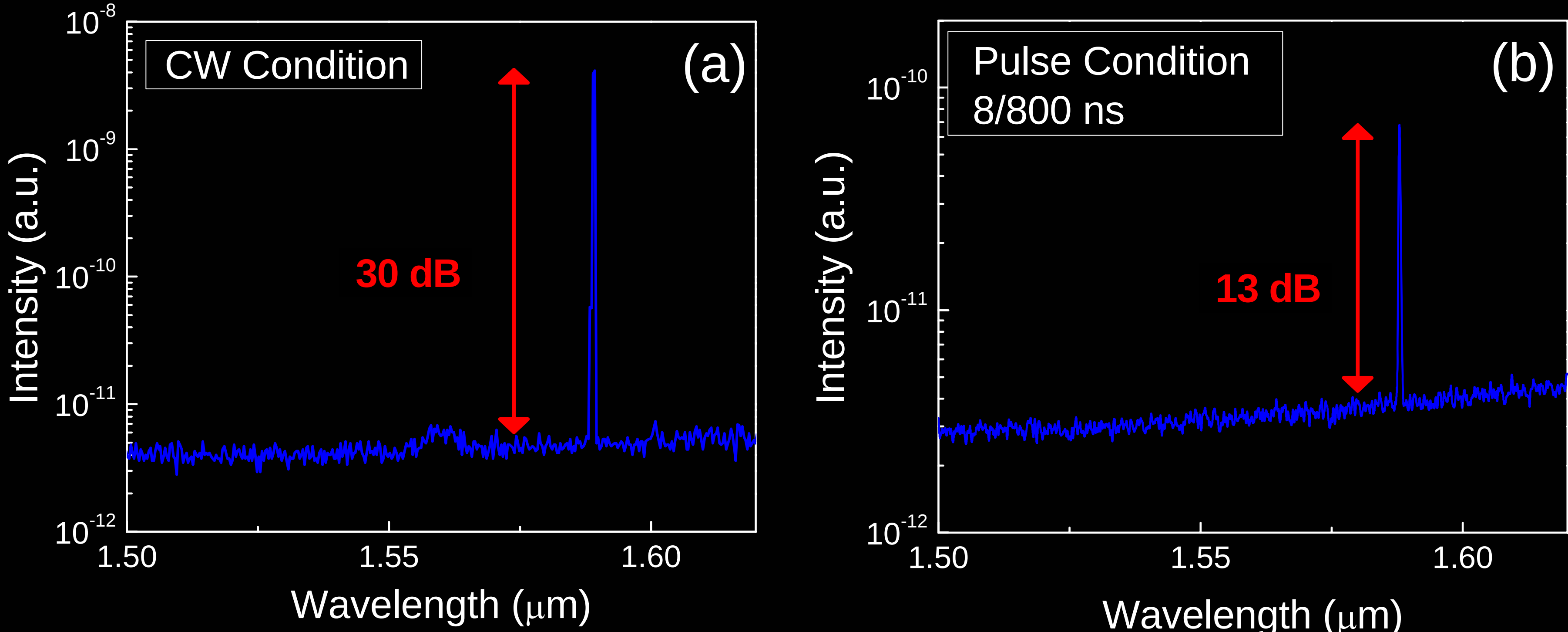
Side-Mode Suppression Ratio (SMSR) of Sapphire-Bonded PhC Cavities



In fiber communication or CATV system, SMSR > 25 dB is considered a single mode light source.

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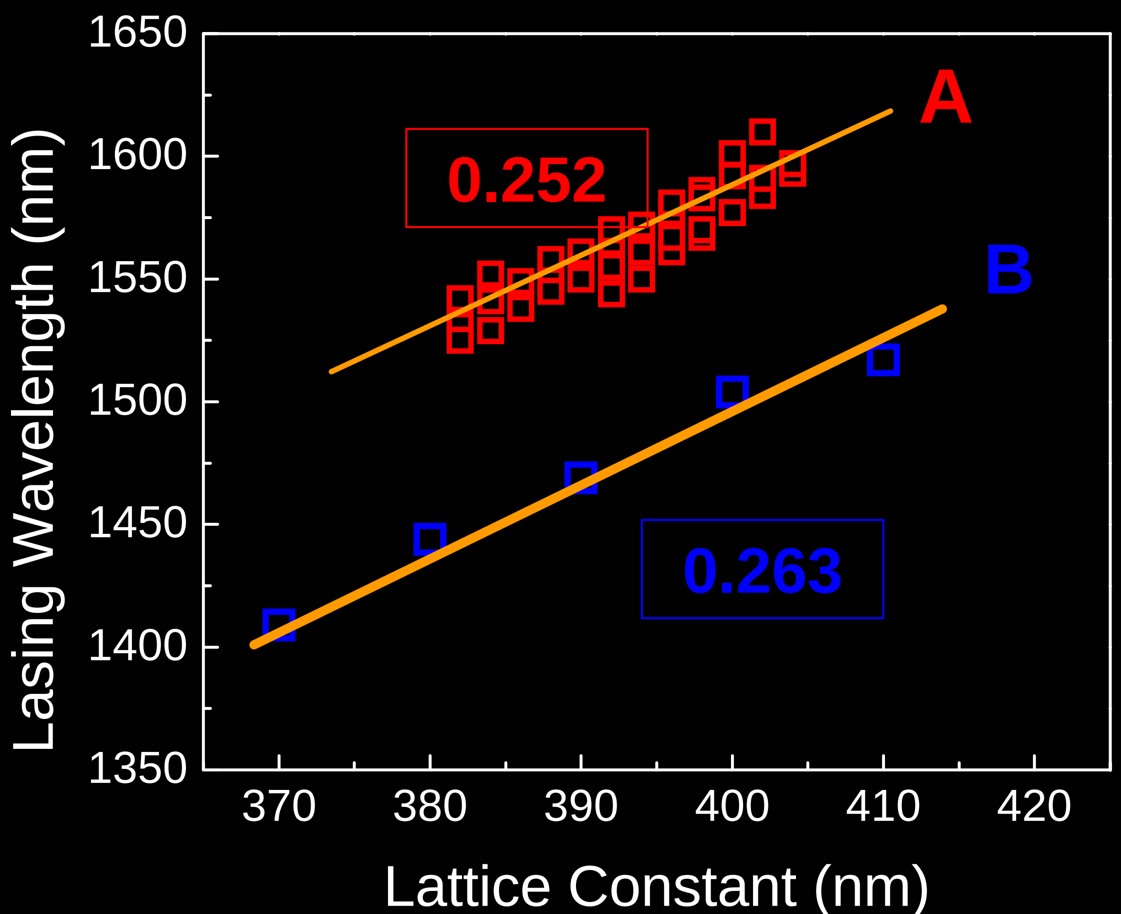
Lasing Modes of Sapphire-Bonded Photonic Crystal Cavities



- Since PhC is scalable, the lasing wavelength varied with PhC lattice constant.
- The lasing wavelengths are separated into two groups, group A has normalized frequency ~ 0.252, and group B has ~ 0.263.

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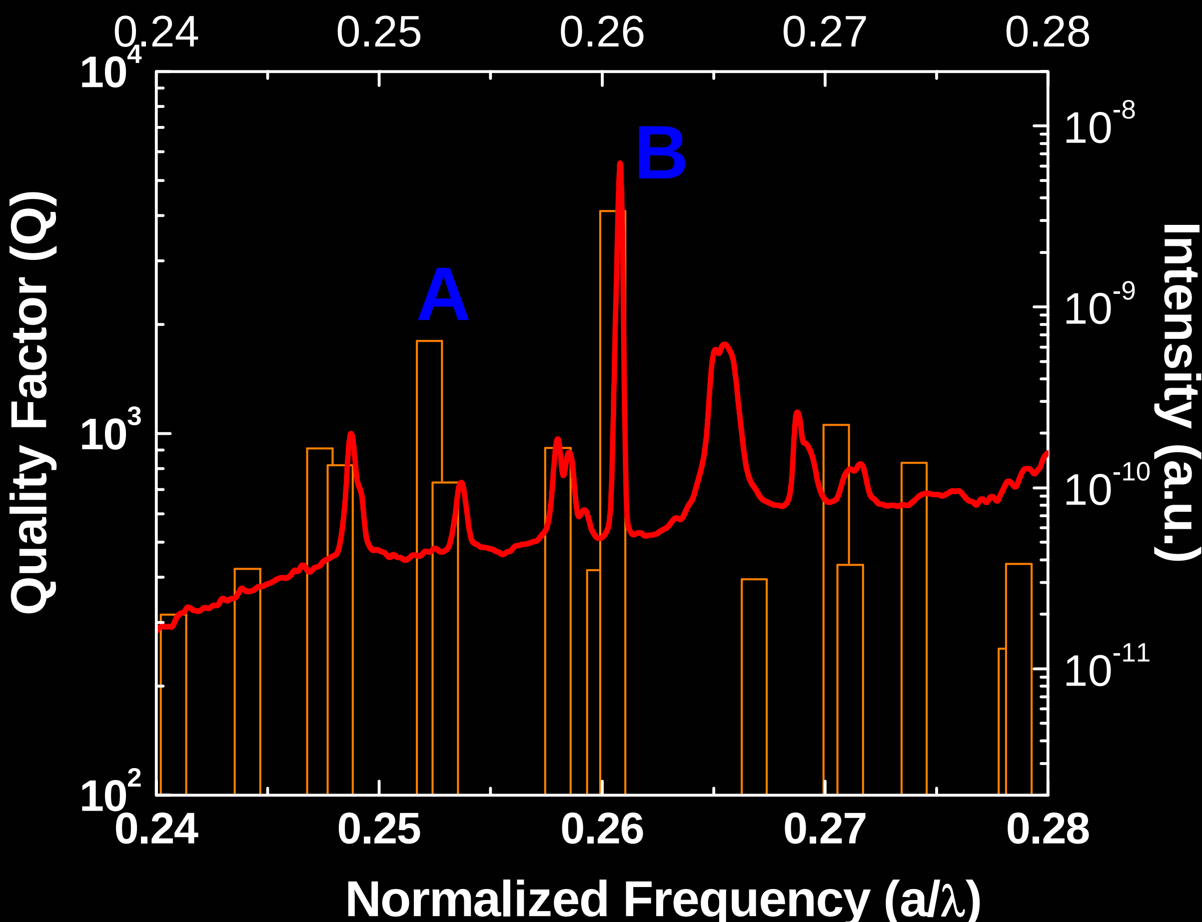
Comparison of Lasing Spectrum and 3D-FDTD Calculation



- Mode B lasing spectrum (red curve) from a PhC laser under CW pumping condition.
- 3D FDTD Calculated quality factor (Q) spectrum (orange) in normalized frequency axis.
- The shift between two spectra is about 1 %.

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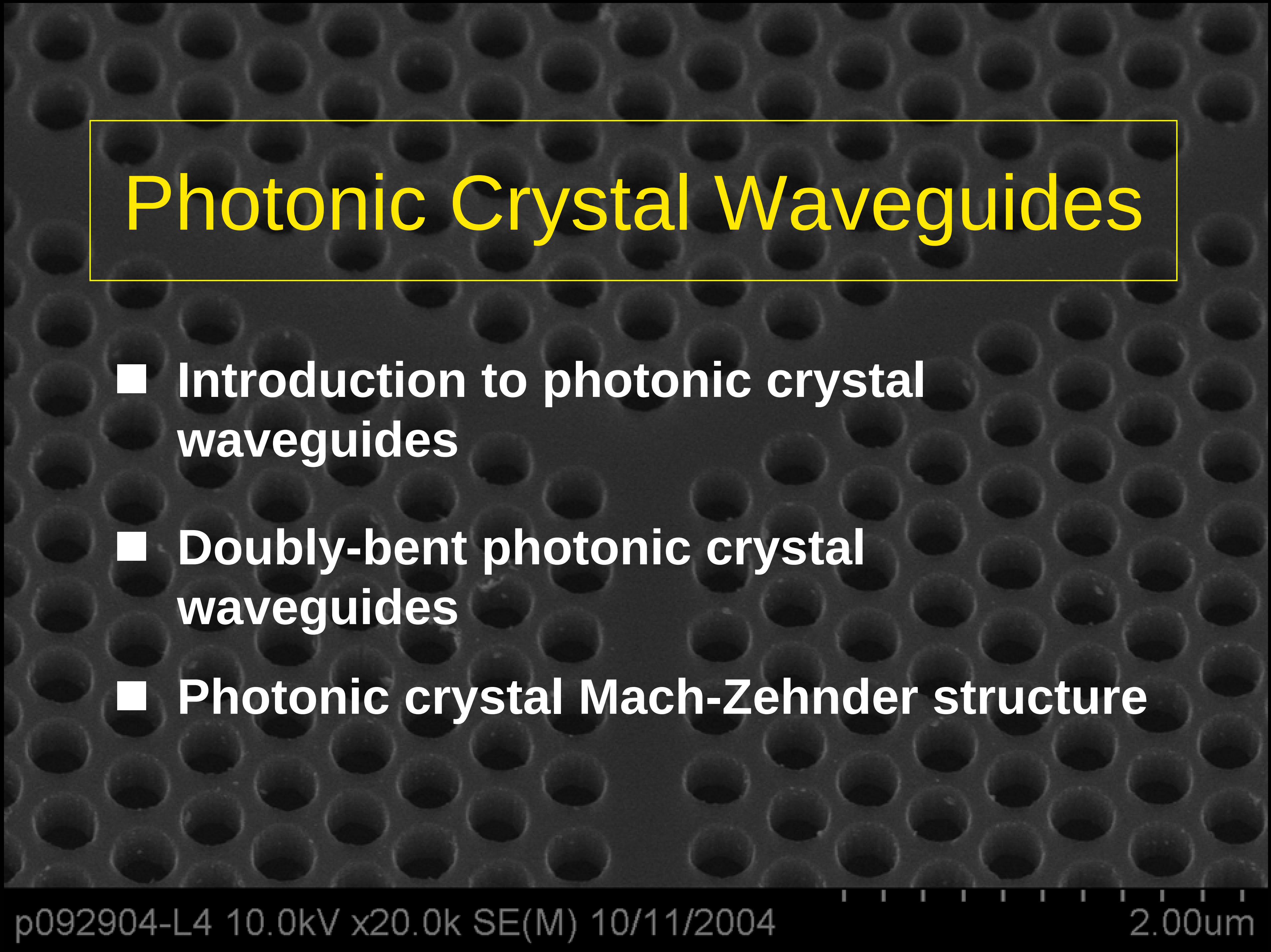
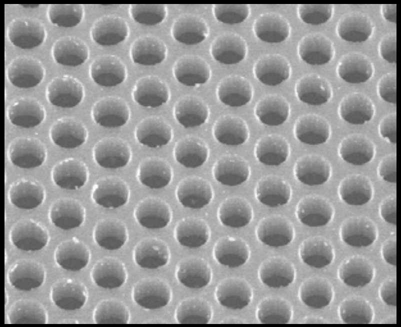
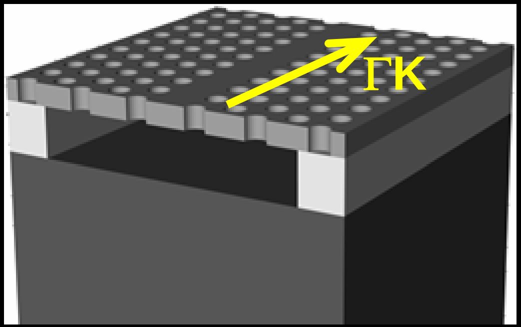
Photonic Crystal Waveguides

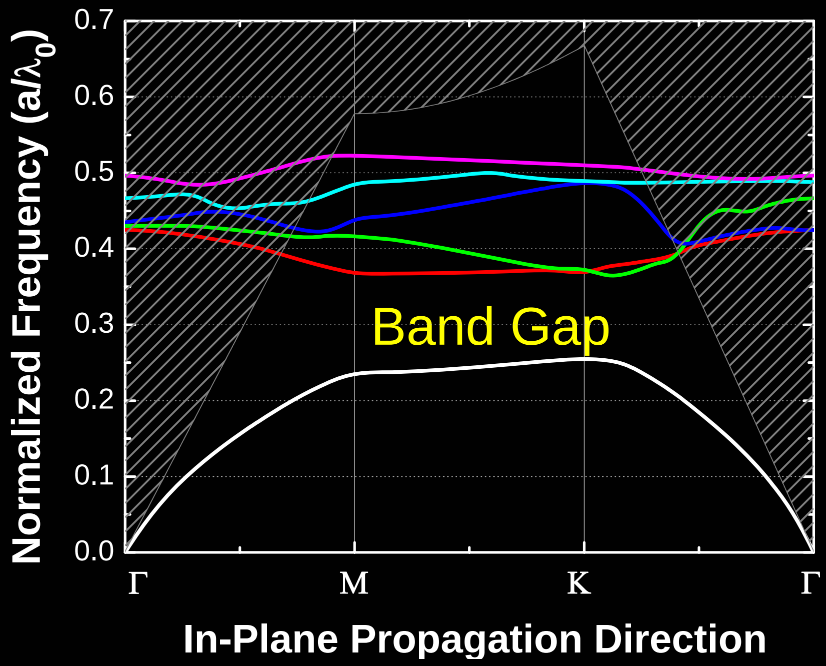
- Introduction to photonic crystal waveguides
- Doubly-bent photonic crystal waveguides
- Photonic crystal Mach-Zehnder structure

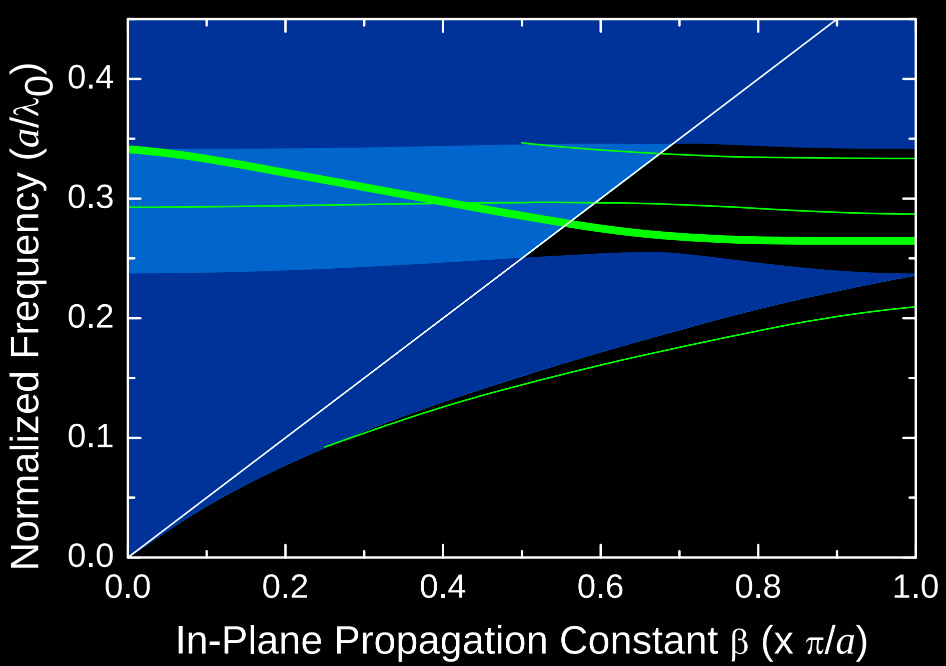


Introduction to Photonic Crystal Waveguide









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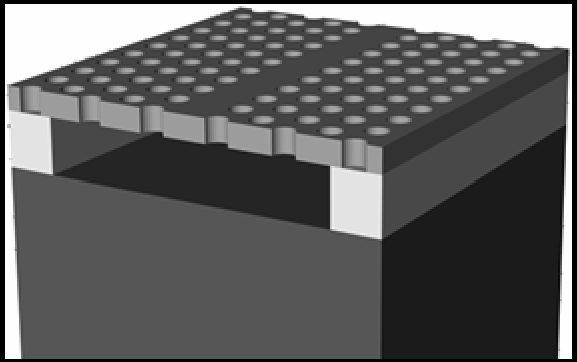
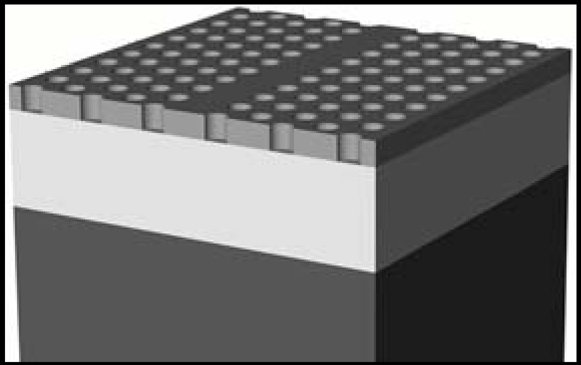
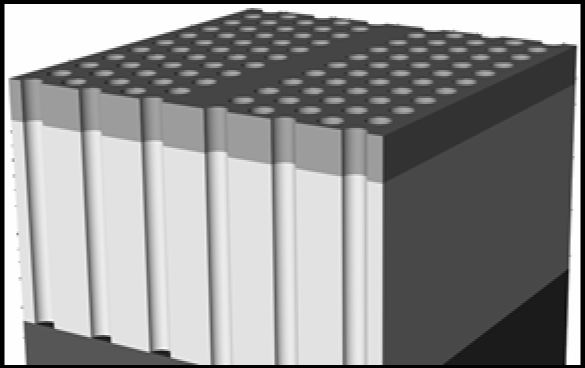
Types of Photonic Crystal Waveguides







Suspended Membrane

Oxide Substrate

Deeply Etched

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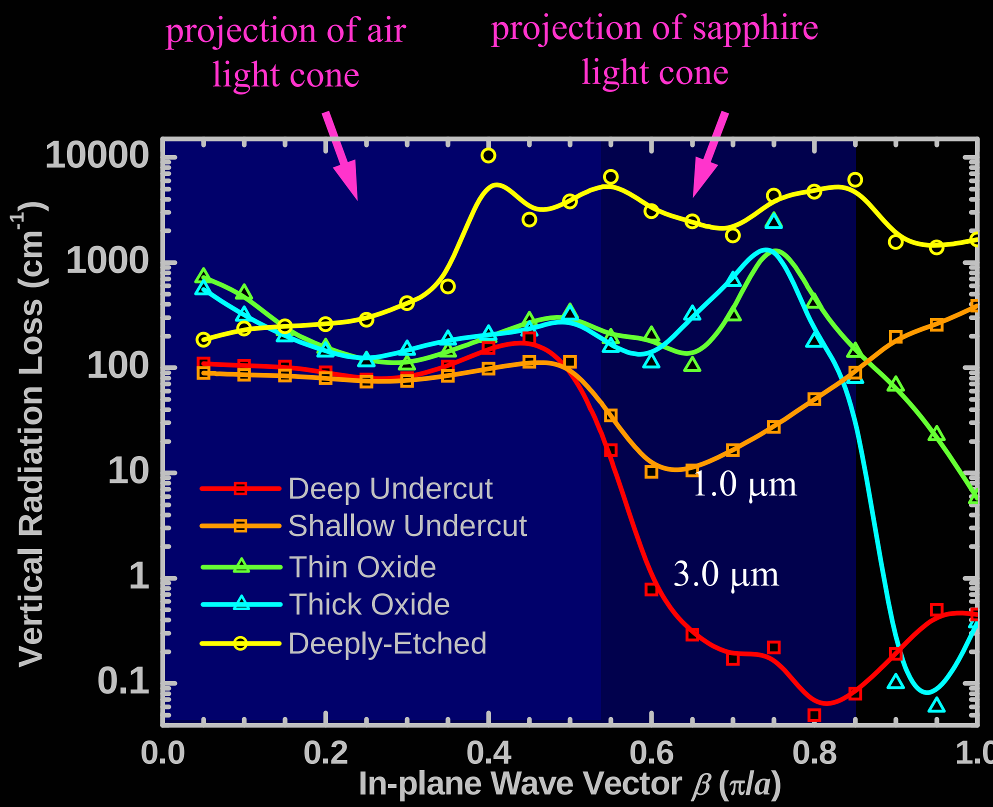
Loss in Photonic Crystal Waveguides from FDTD

- The out-of-plane radiation loss of the waveguide is generally large for modes in the radiation light cone.
- Low loss transmission for suspended membrane and oxidized lower cladding structures occurs at the vicinity of the Brillouin zone boundary.



From Wan Kuang, MPDG, USC

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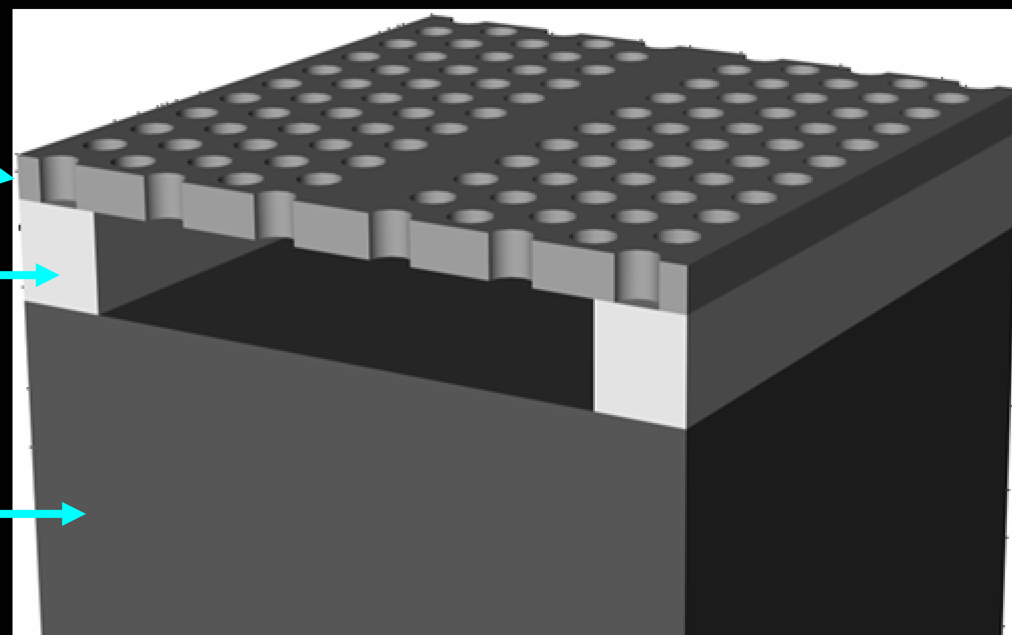
InGaAsP Membrane Photonic Crystal Waveguides

InGaAsP

InP scarified layer

InP substrate



Suspended Membrane

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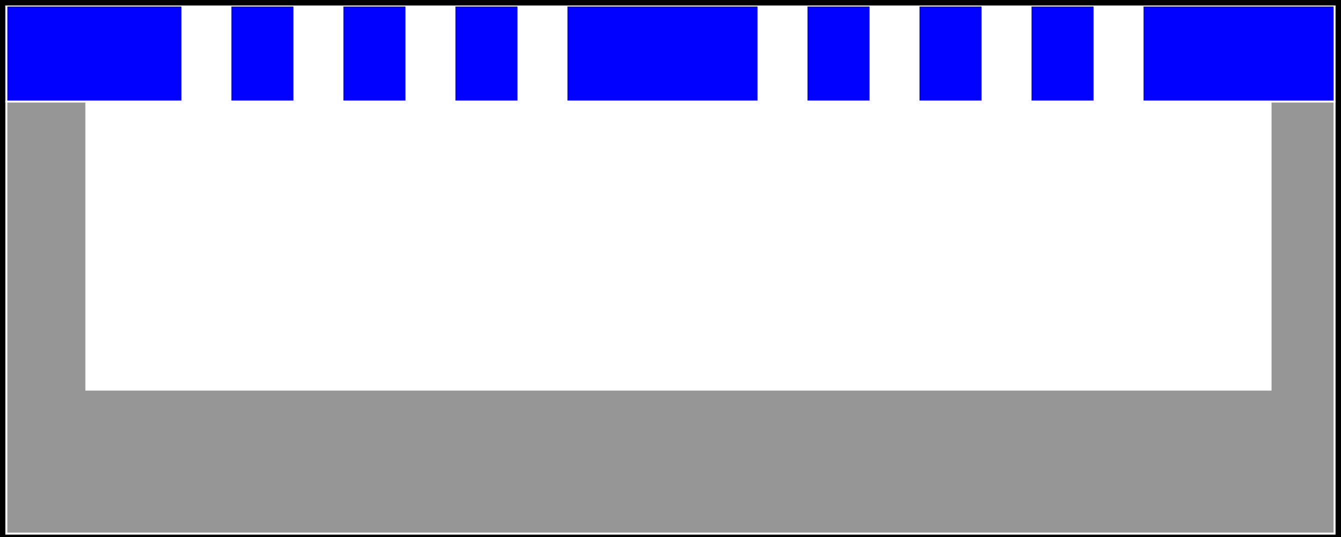
Fabrication of Photonic Crystal Membrane Waveguides

Remove all masks

lapping & cleaving



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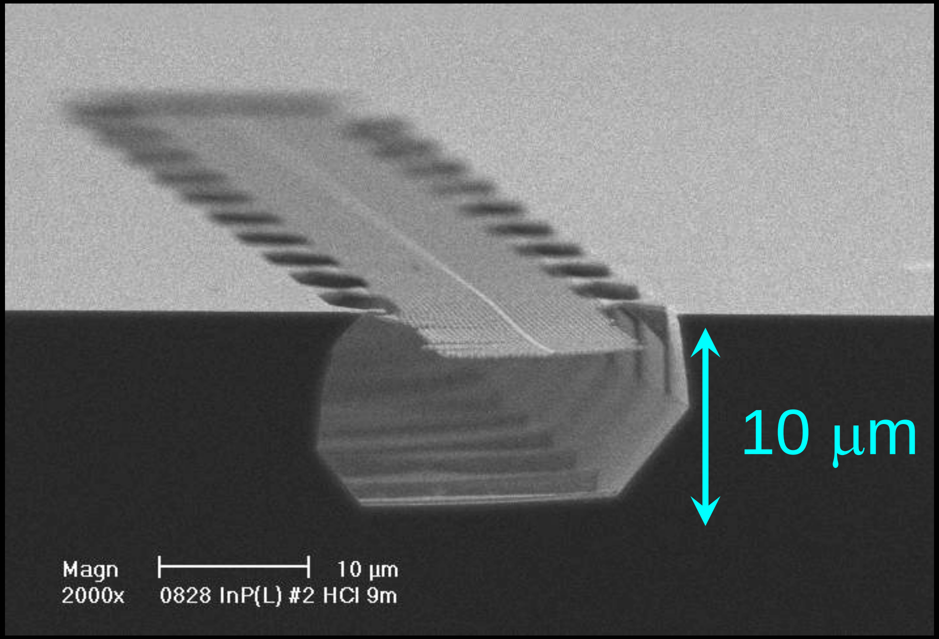
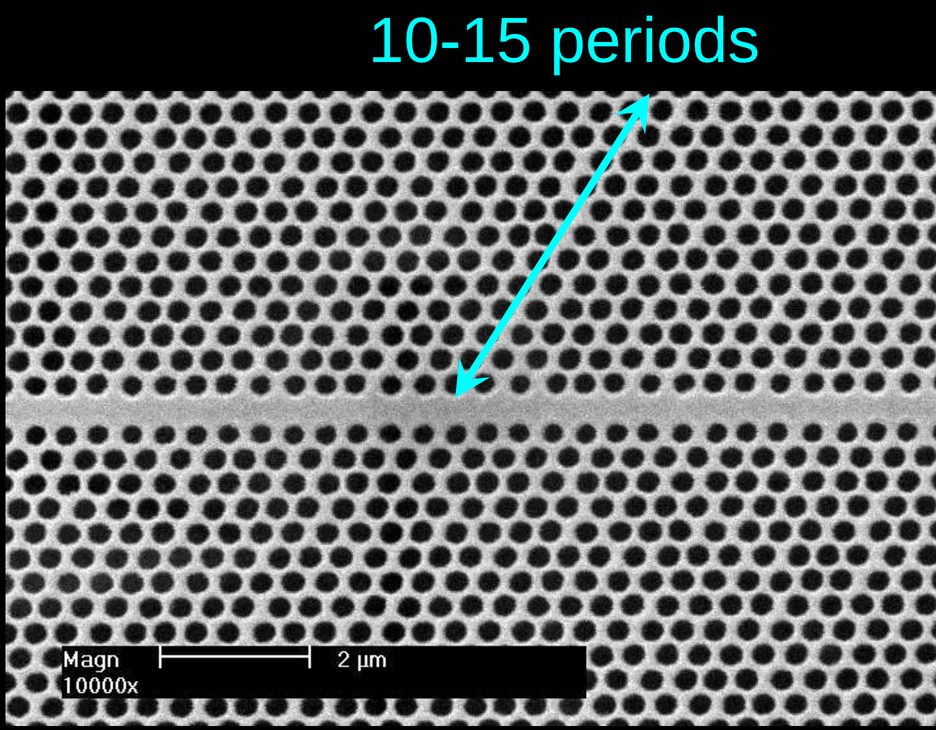
SEM Images of InGaAsP Membrane Photonic Crystal Waveguides





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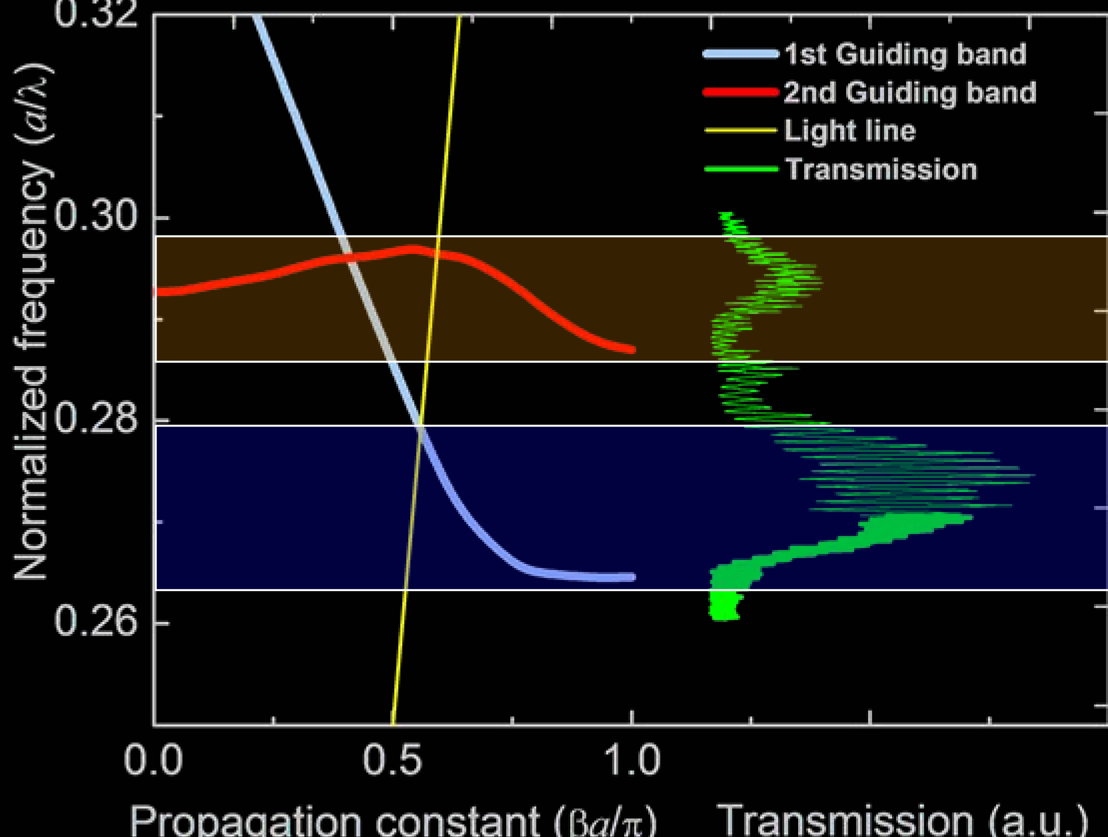
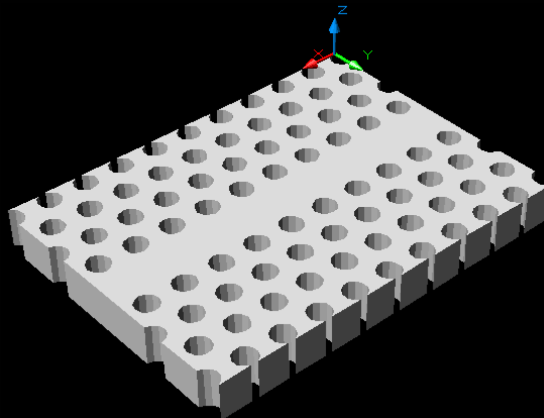
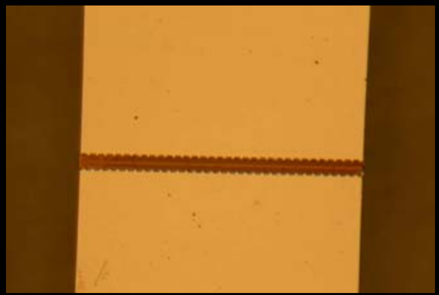
Transmission Through Straight Photonic Crystal Waveguides

Bandstructure and measured transmission of suspended membrane photonic crystal waveguide







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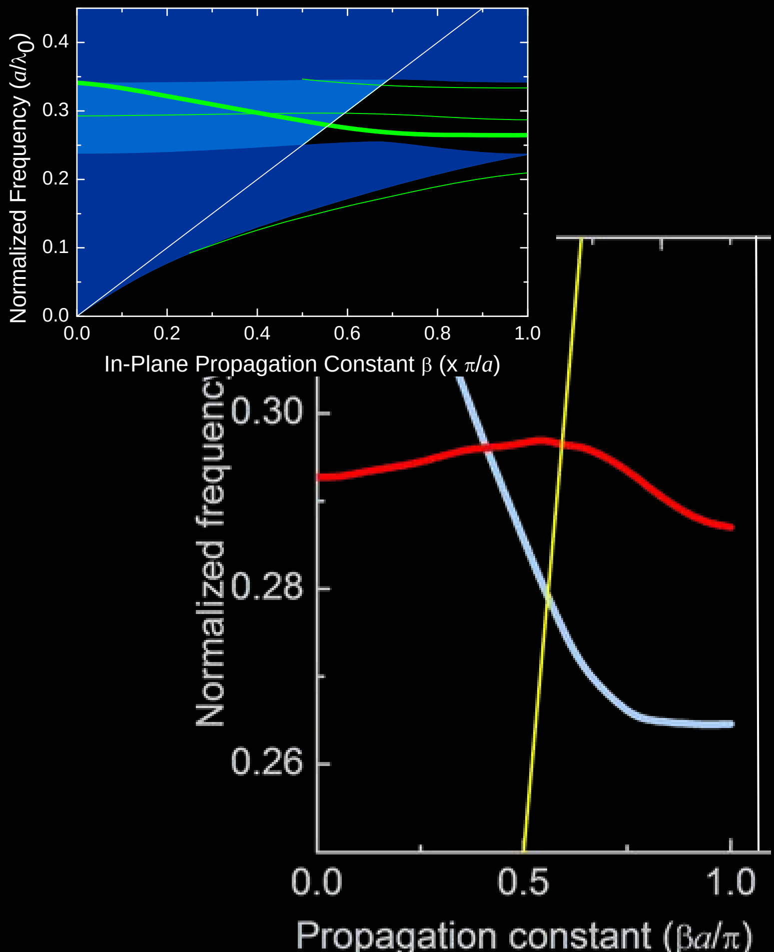
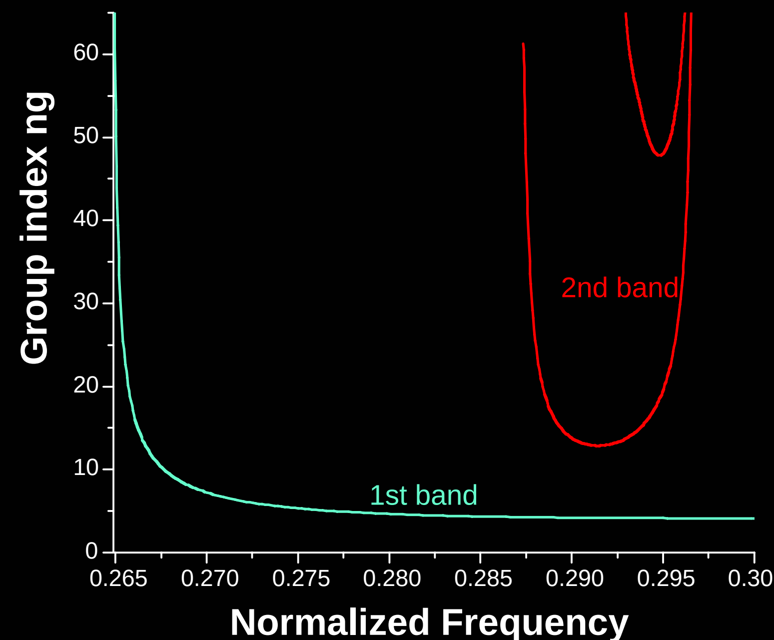
Group Index of Propagated Mode in Photonic Crystal Waveguides



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

Group Indices of two guided bands



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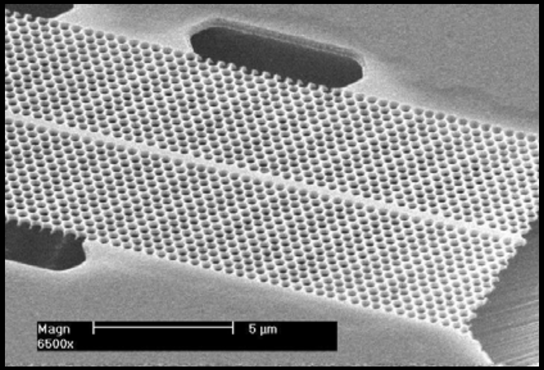
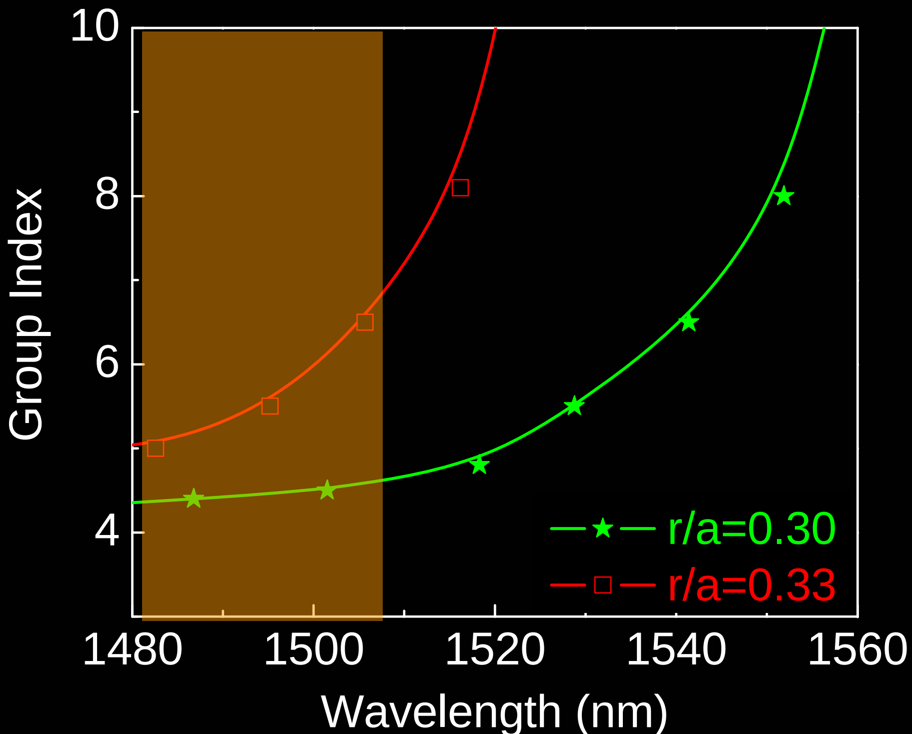
Comparison of the Predicted and Observed Group Indices of Photonic Crystal Waveguides

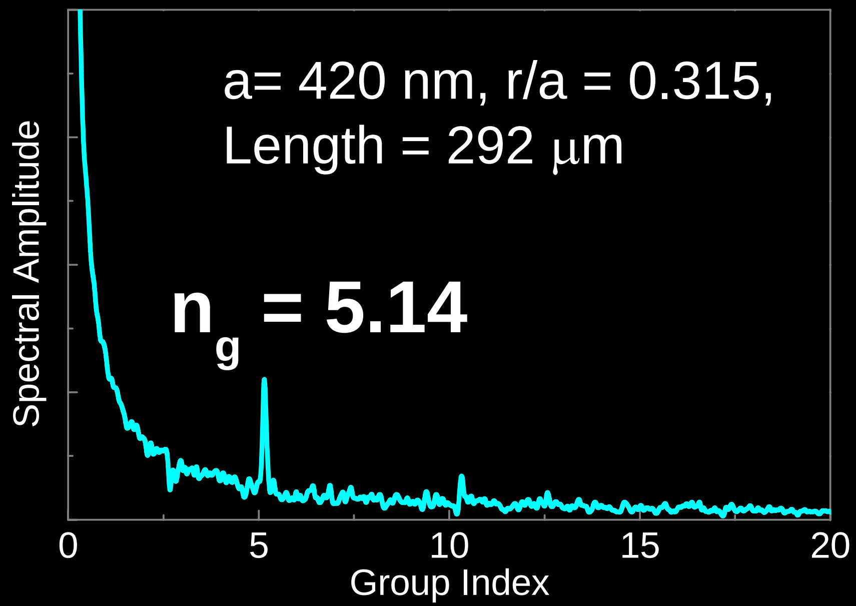




Group indices of defect waveguide modes obtained from bandstructure

Fabry-Perot oscillation period

$$\Delta\lambda = \frac{\lambda^2}{2n_g L}$$



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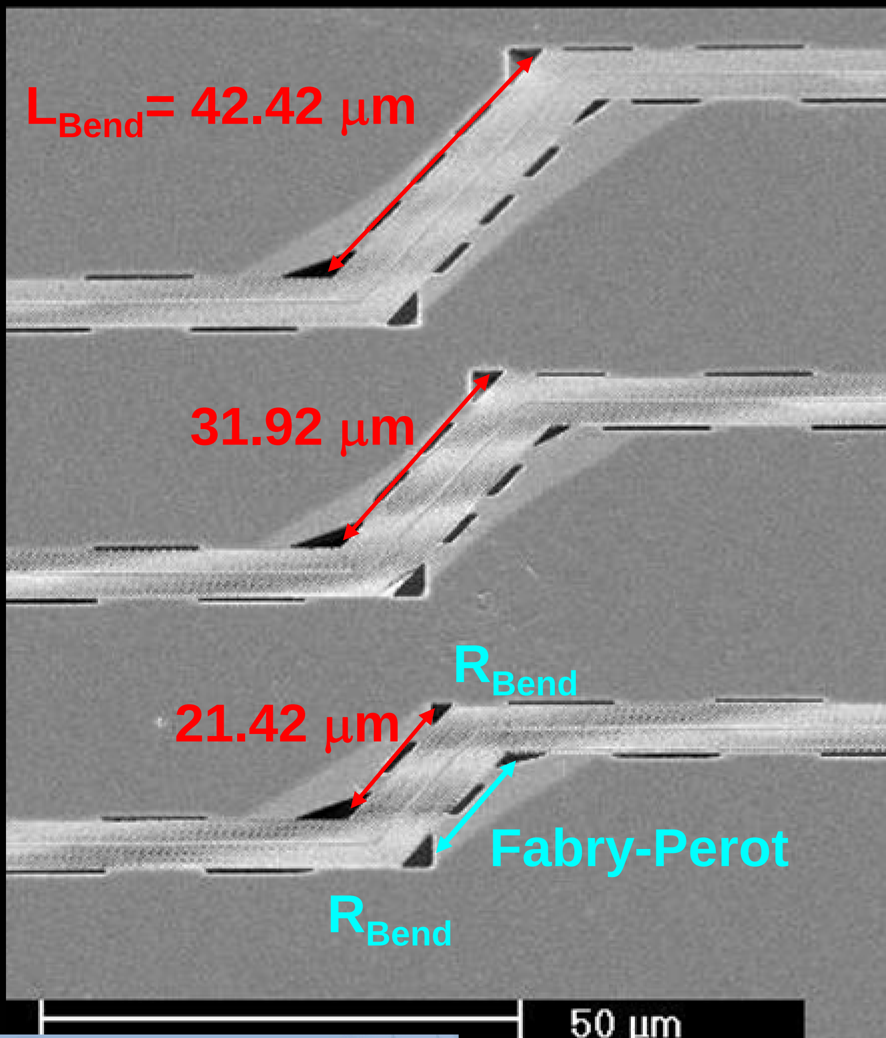
Fabry-Perot Oscillations from Doubly Bent Photonic Crystal Waveguides



Reflection from the two bends will lead to Fabry-Perot oscillations with a period that should be inversely proportional to L_{Bend}

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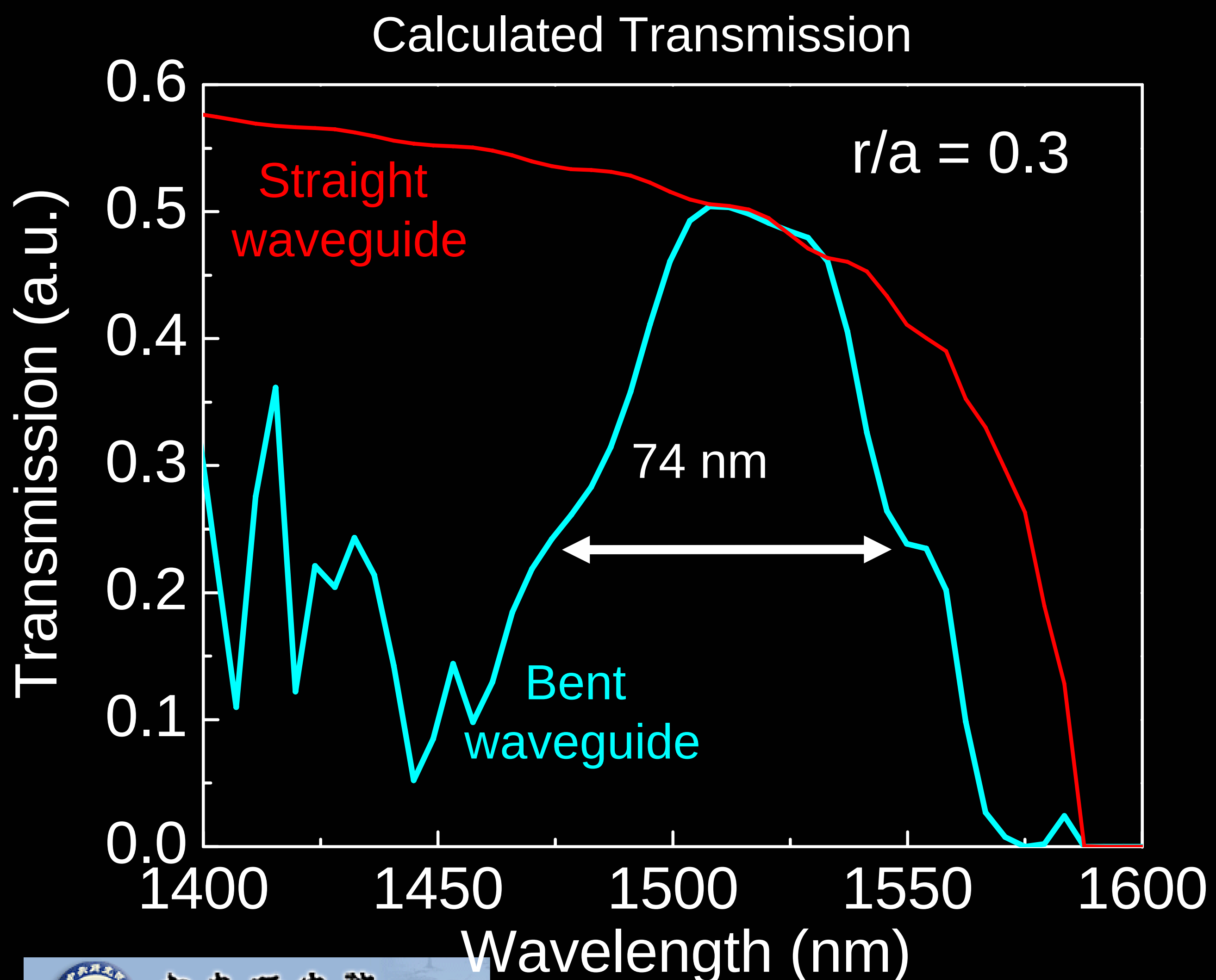
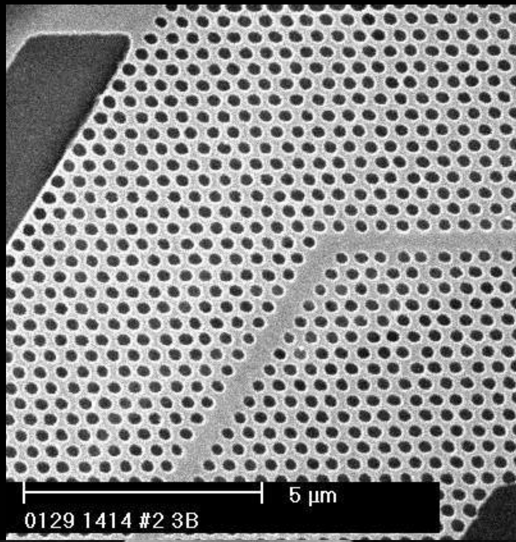
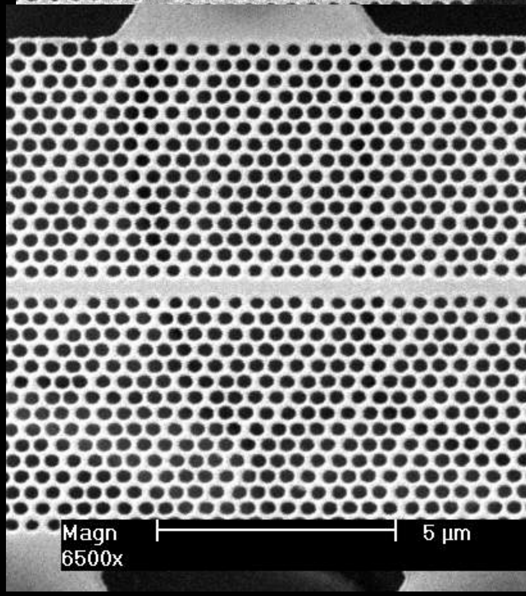
Theoretical Prediction of Transmission Through Photonic Crystal Waveguides by Finite Element Method







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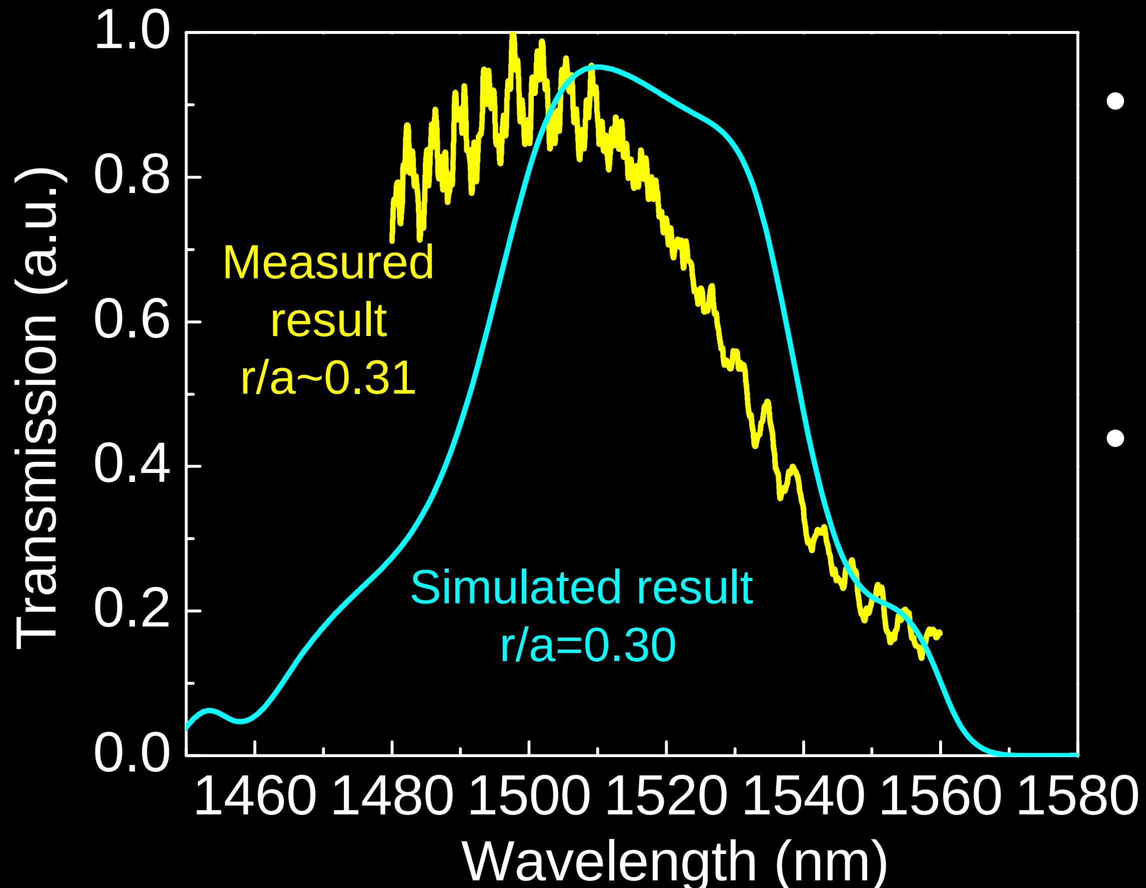
Comparison of Transmission Measurement and Simulation



- Fabry-Perot oscillations were observed in measured transmission.
- The oscillation from the bent section can be identified by the period.

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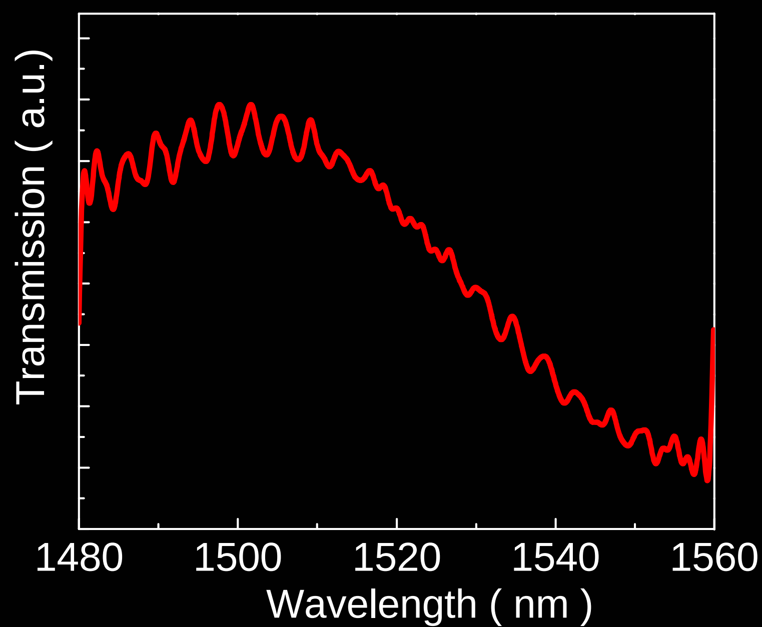
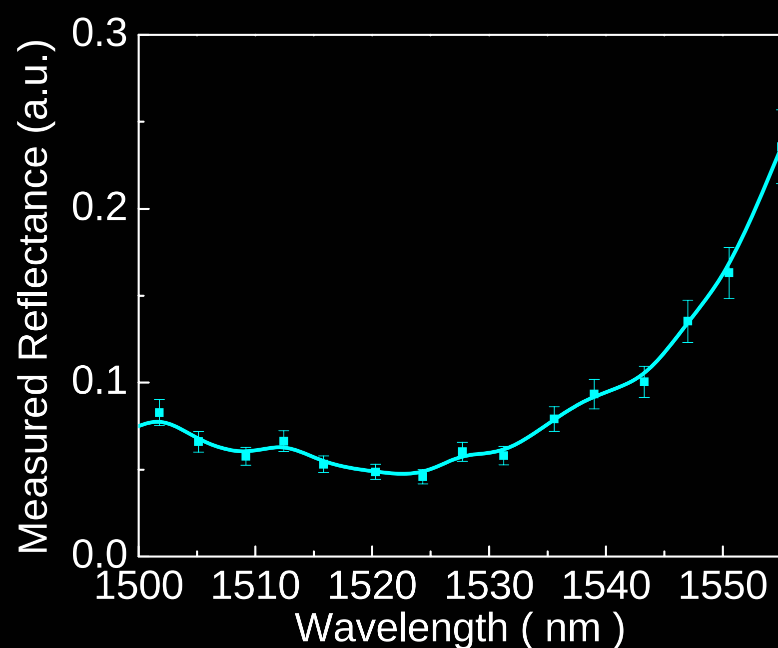
Reflectance Extracted from Measured Spectra

$$R = \left(\frac{\sqrt{K}-1}{\sqrt{K}+1}\right)10^{\left(\frac{\alpha_{dB}L}{10}\right)}$$

$K: peak-to-valley-ratio$

$L: length$





Error-bars represent the range of α_{dB} from 2 to 20 dB/mm.

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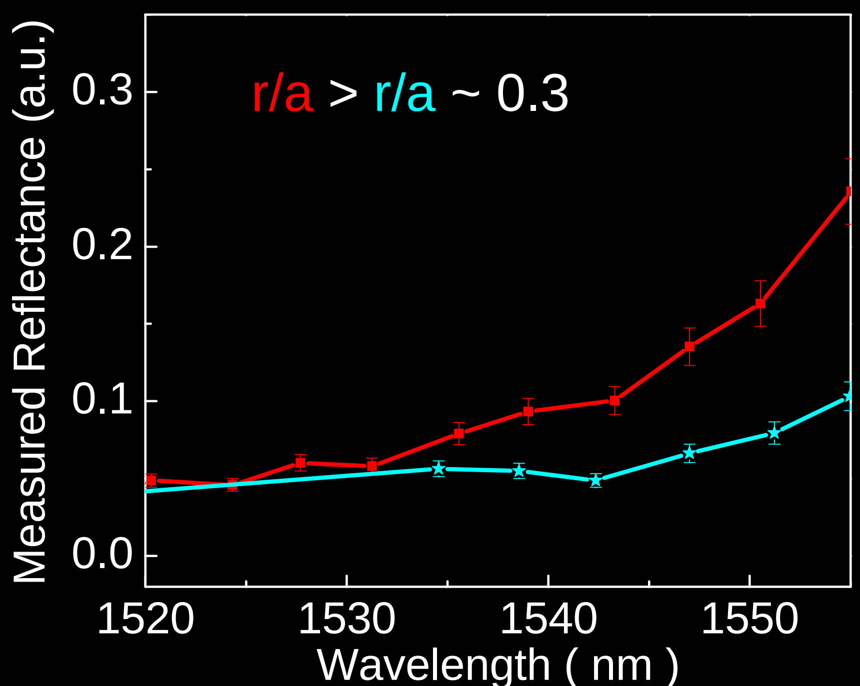
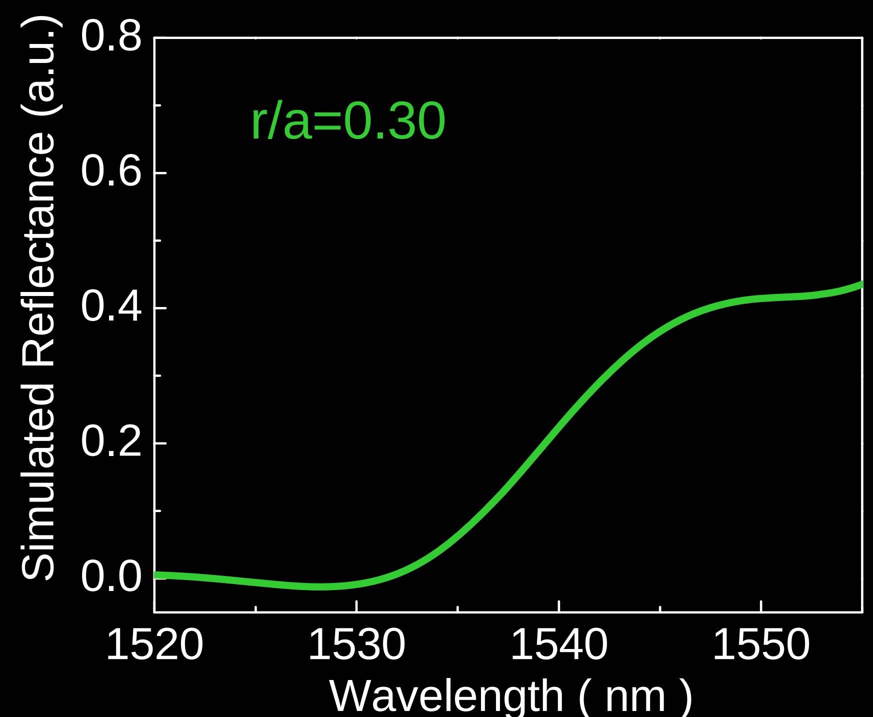
Comparison of Measured and Simulated Reflectance

Measured Reflectance



Simulated Reflectance



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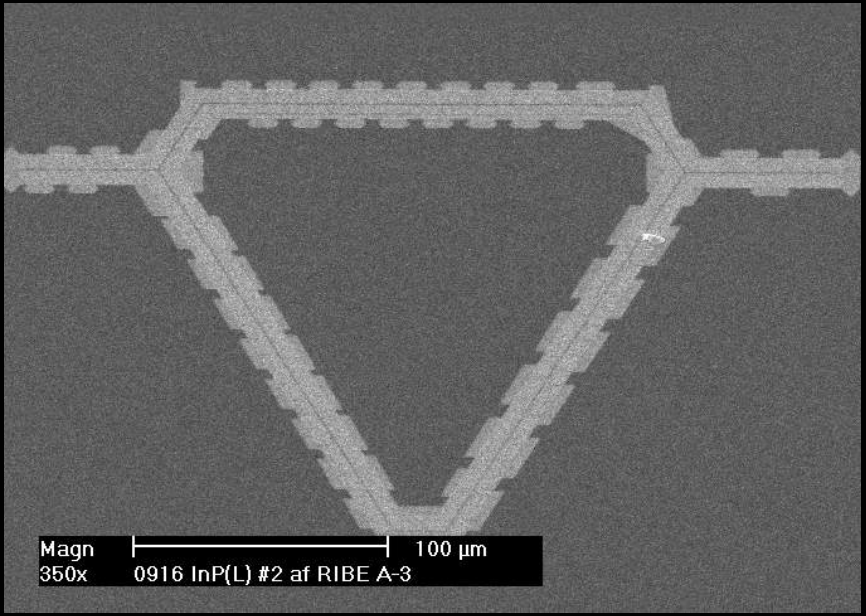
The Basic Idea of Mach-Zehnder Structure

- Fabricate asymmetric Mach-Zehnder interferometers and characterize the transmission as a function of wavelength.

- The Fourier transform of the transmission spectrum will contain information about the propagation coefficient of the photonic crystal waveguide mode.



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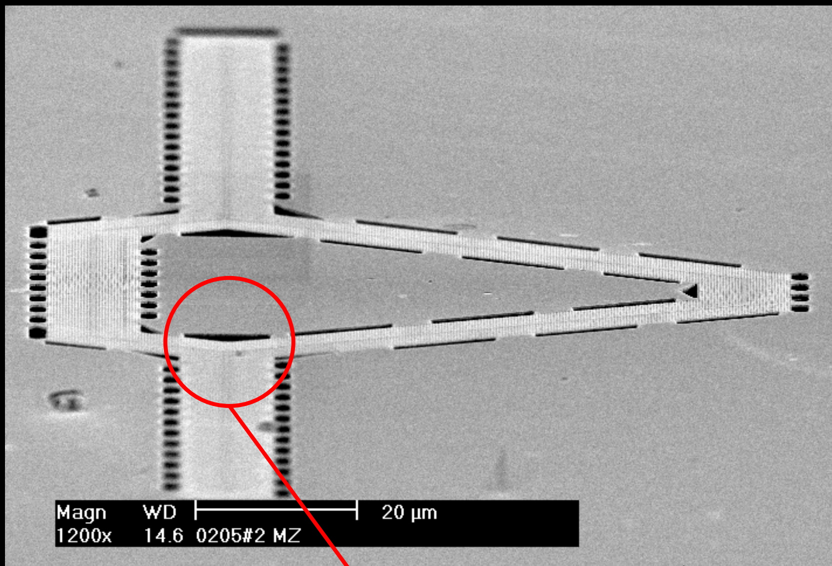
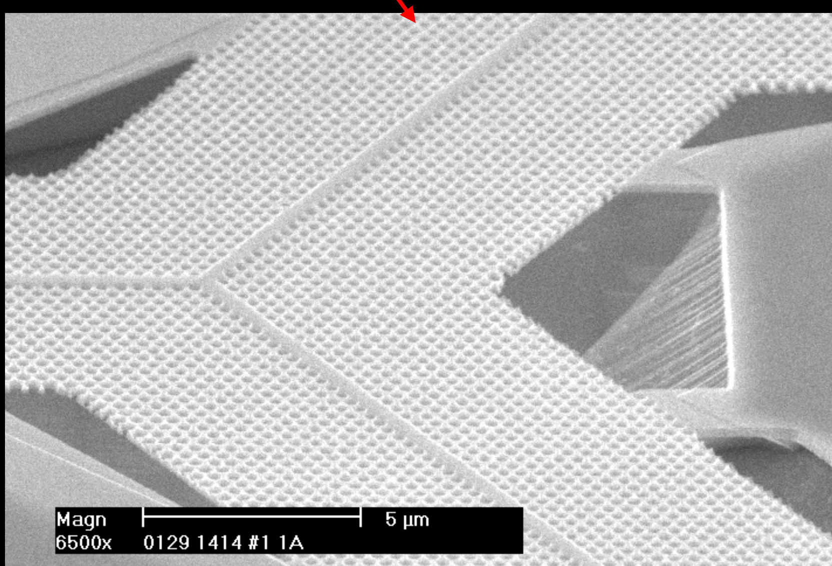
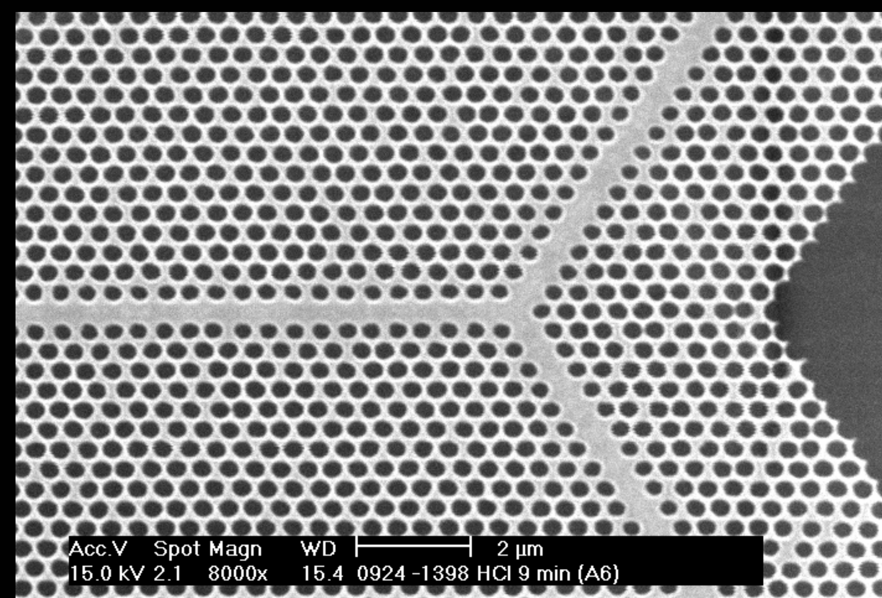
Photonic Crystal Mach-Zehnder Structures in InP

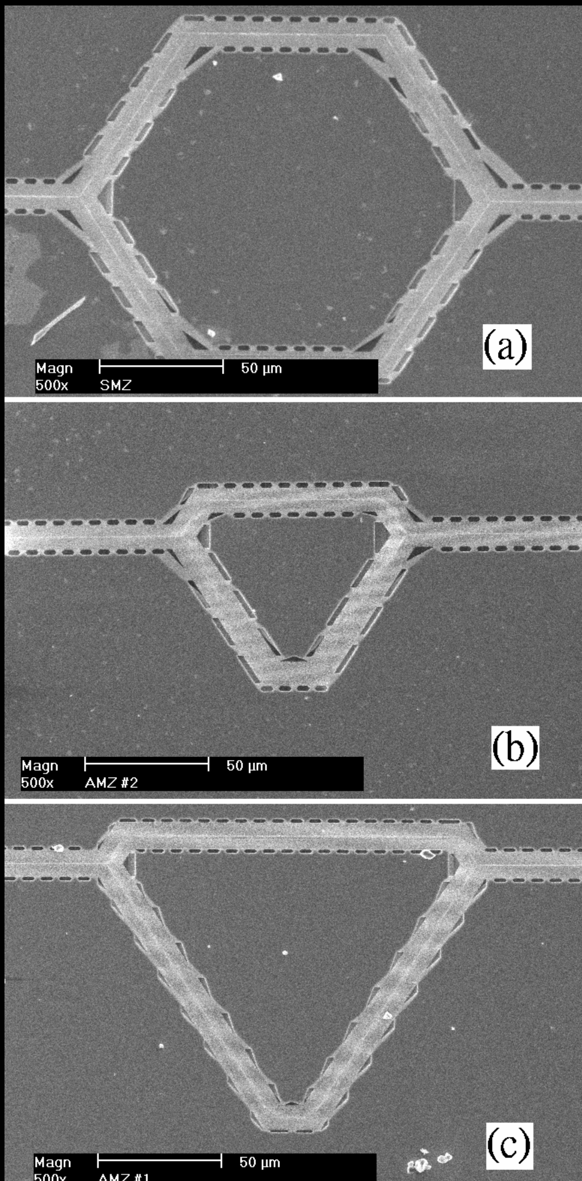


InGaAsP/InP Membrane Structure





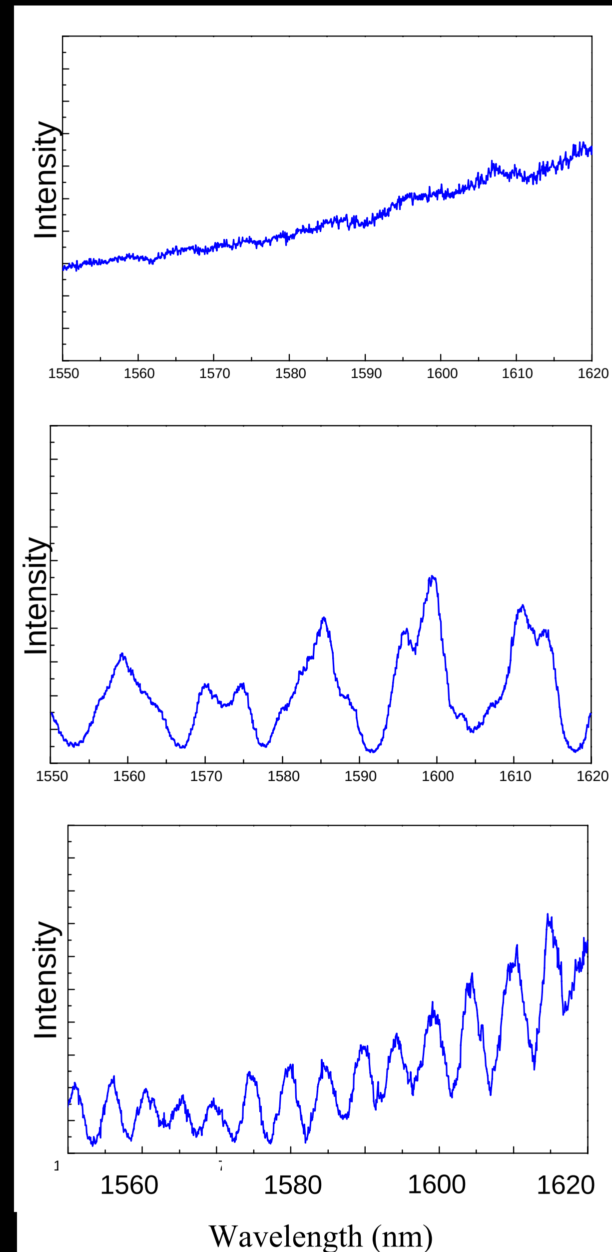
Mach-Zehnder Transmission Data



symmetric structure

path length difference 75 µm

path length difference 121 µm



expect transmitted intensity to contain oscillations that go as

$\cos(\beta \Delta L)$,

and

$\beta = \beta(n_g)$

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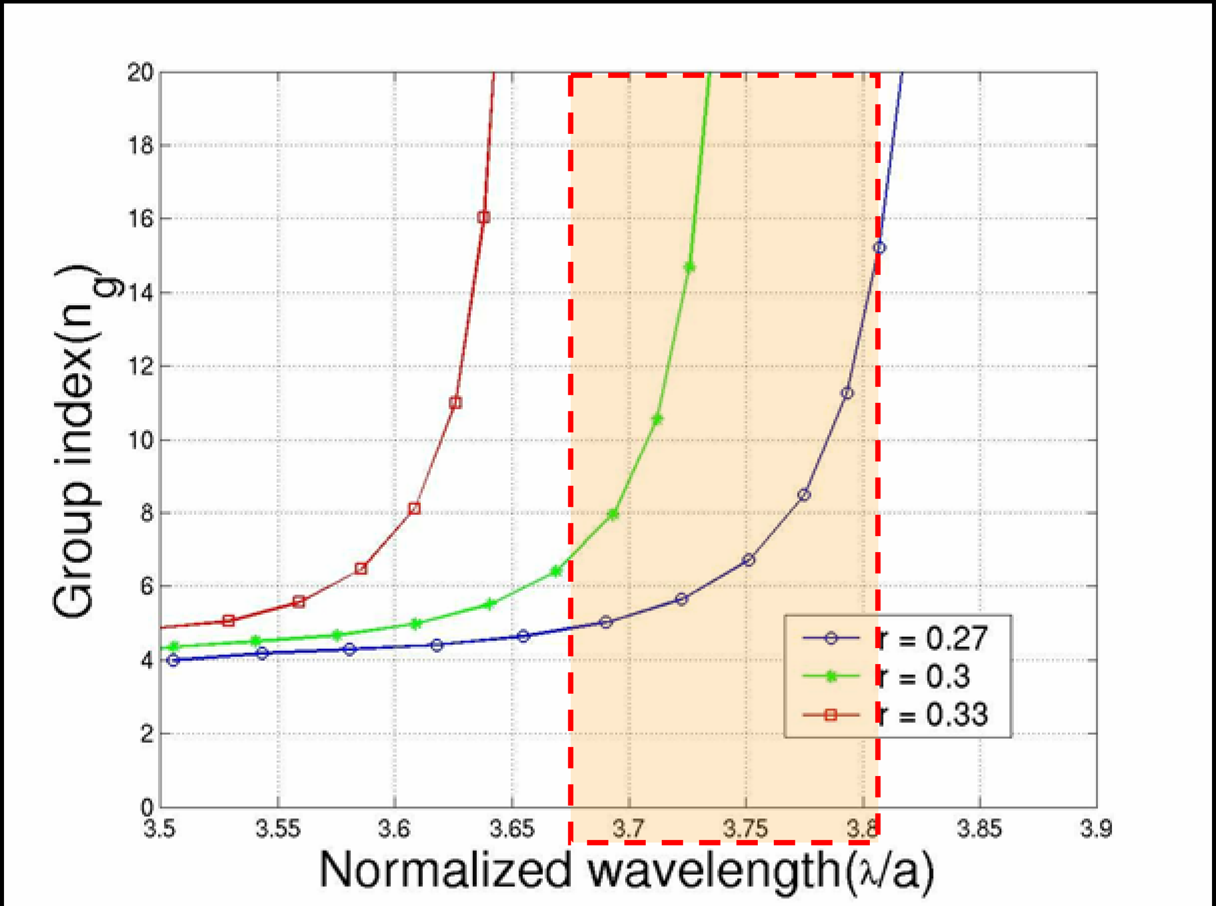
The Group Index of Photonic Crystal Waveguide



Three- Dimensional Finite Element Calculation

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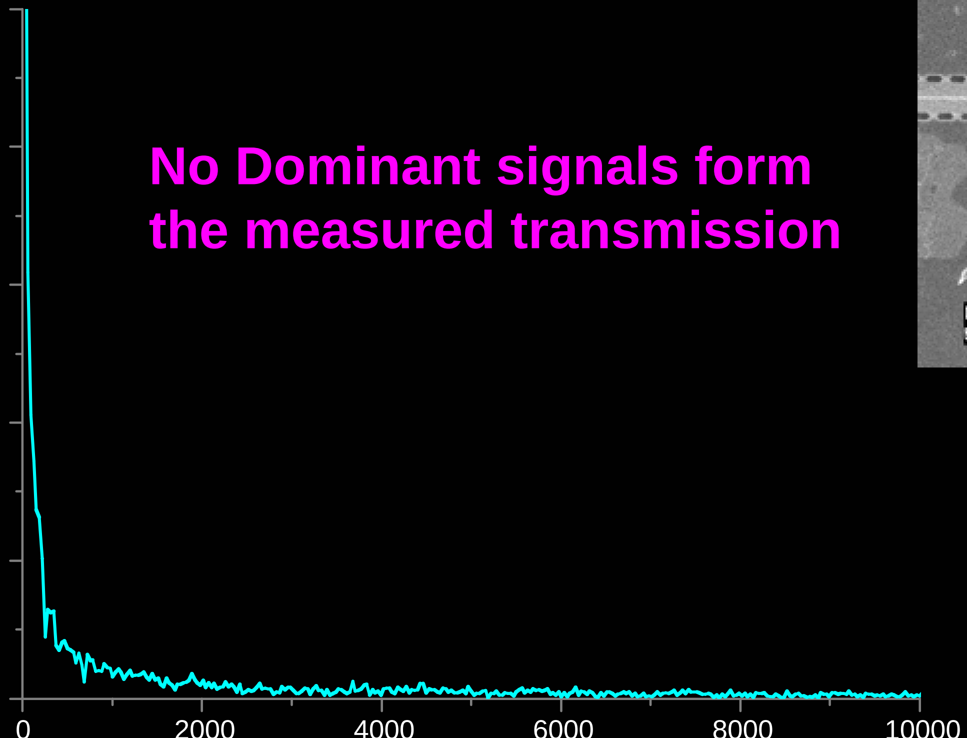
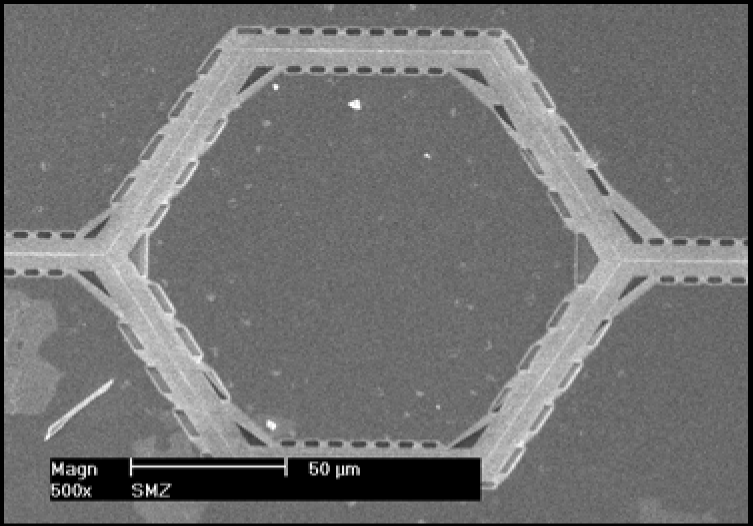
Fourier Transform of Transmission Spectra

Symmetric Mach-Zehnder



No Dominant signals form the measured transmission



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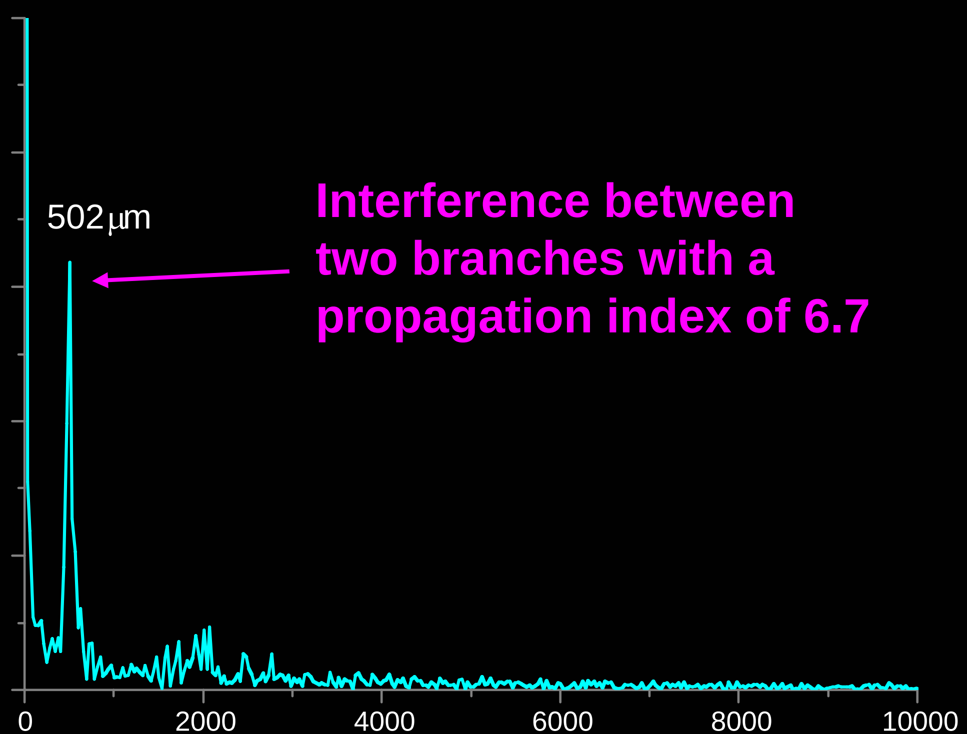
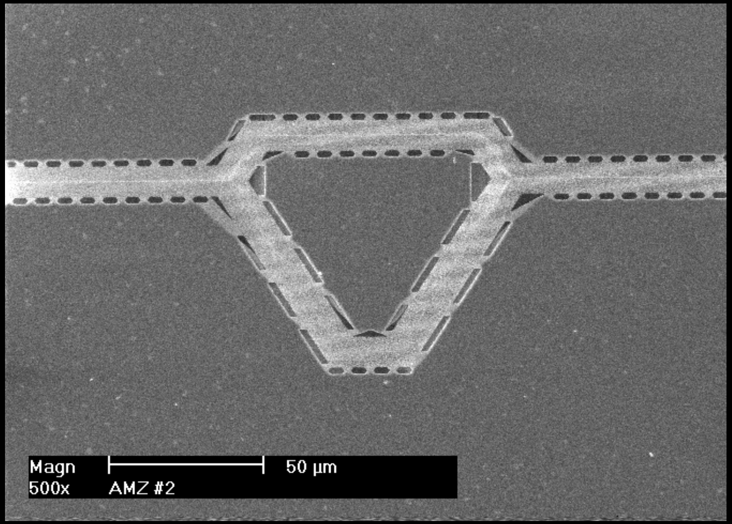
Fourier Transform of Transmission Spectra

Mach-Zehnder
with Path Length Difference of 75 μm





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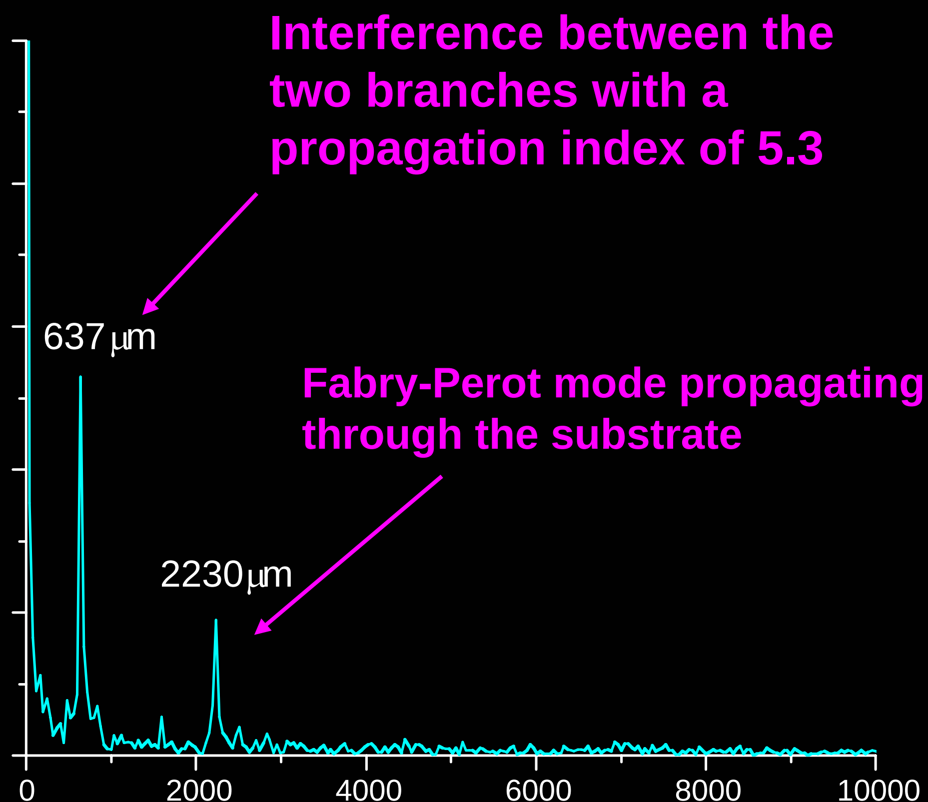
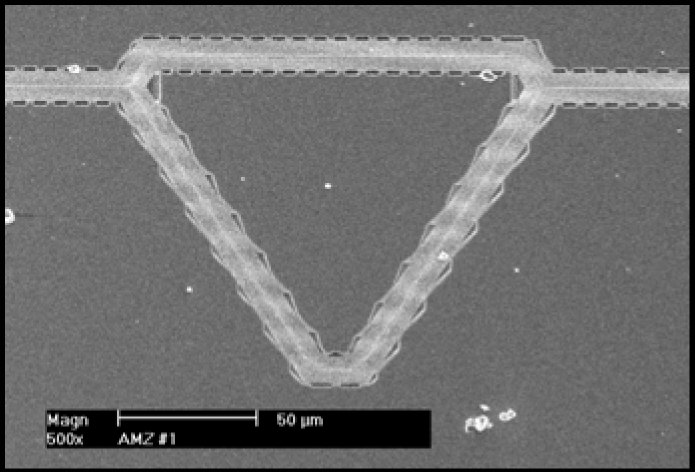
Fourier Transform of Transmission Spectra

Mach-Zehnder
with Path Length Difference of 121 μm





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Summary

- Photonic crystal device, can be engineered by changing the geometry, is a excellent candidate for dense photonic integrated circuits.
- Photonic crystal defect laser cavities were obtained from InGaAsP membrane.
- Smallest continuous-wave (CW) photonic crystal laser cavities was achieved on the sapphire substrate.
- Photonic crystal waveguides and its Mach-Zehnder structure are demonstrated.

Thank You

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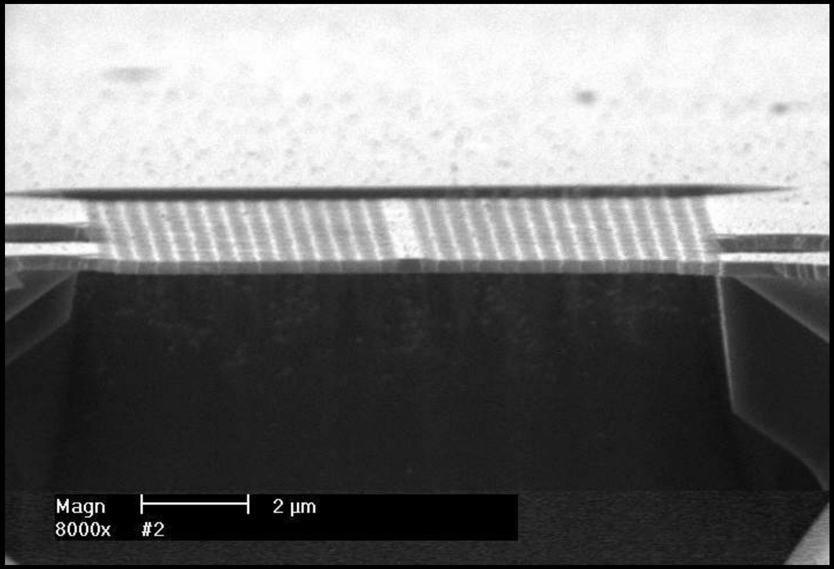
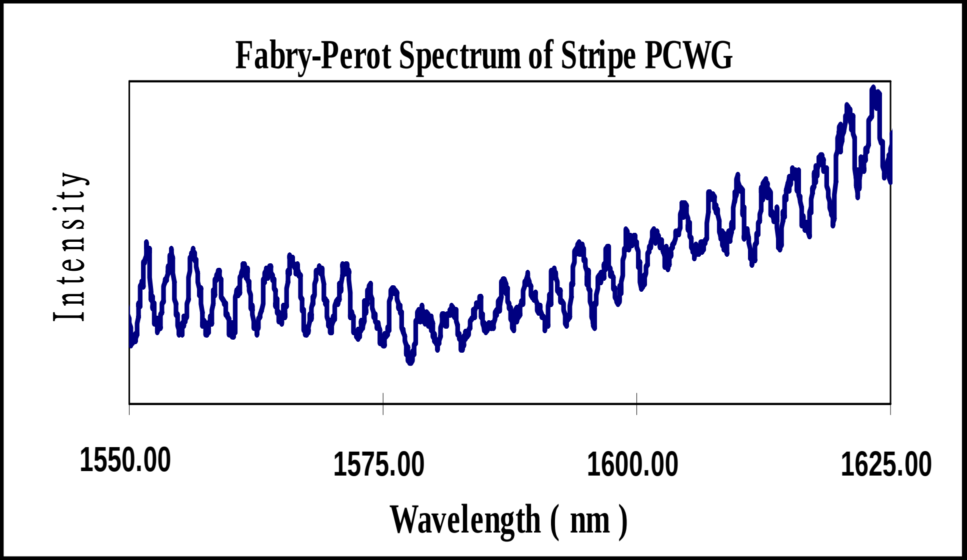
Propagation Loss Measurements using the Fabry-Perot Resonance Method

The Propagation Loss Γ_K

$$\Gamma_K = -20\log\gamma = -\frac{10}{L}\log\left[\frac{1}{R}\frac{\sqrt{K}-1}{\sqrt{K}+1}\right]$$



Γ_K = 6.80~ 10.56 dB/mm
(15.66 ~ 24.32 cm^{-1})



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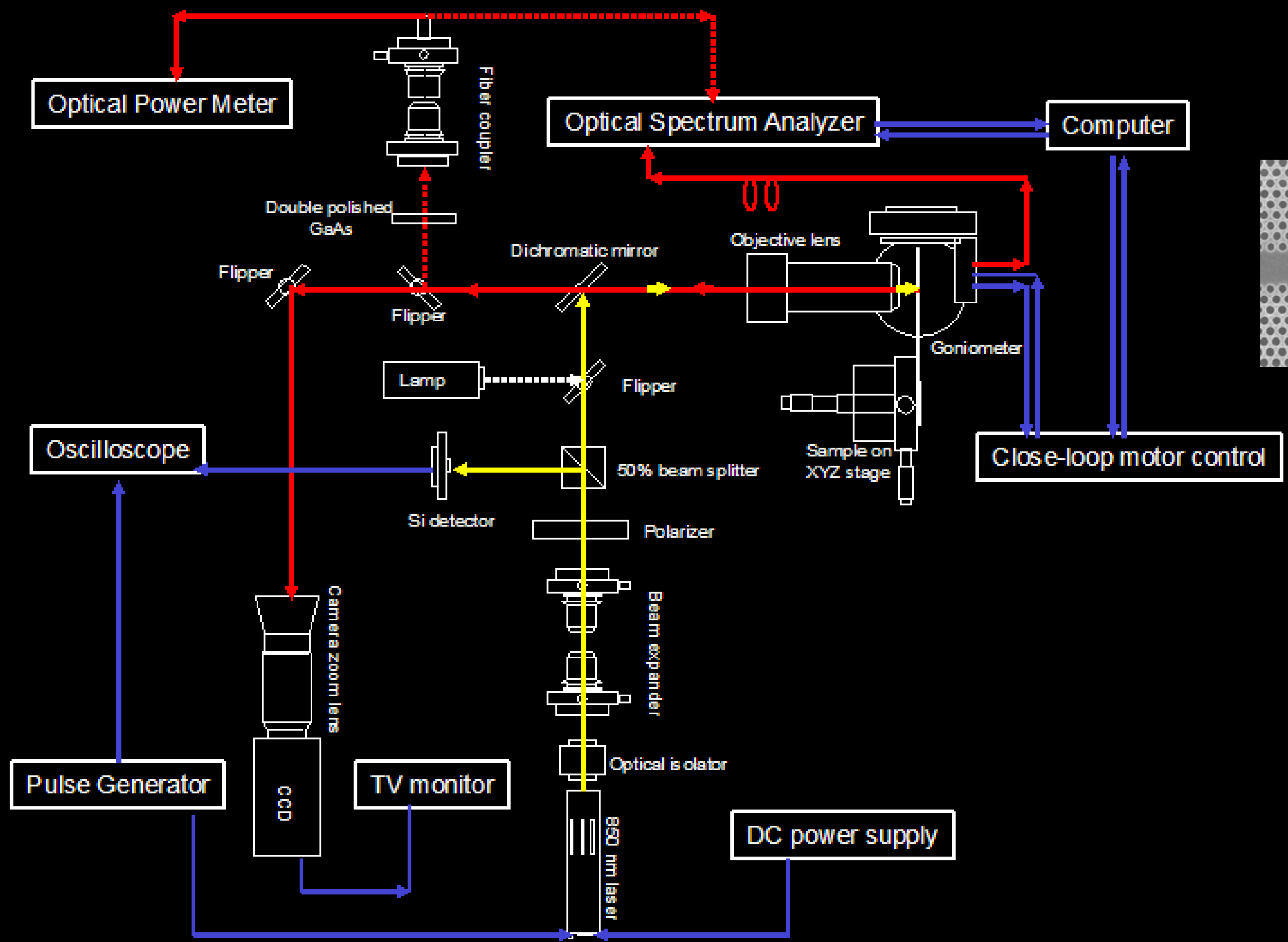
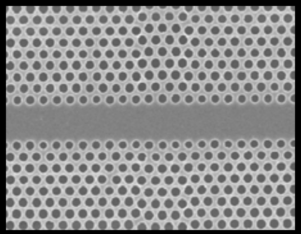
Characterization Setup





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