TIGP Nanoscience A
Part 1: Photonic Crystals

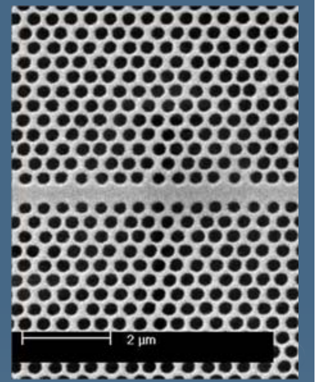
Introduction to Photonic Crystal Waveguides

Min-Hsiung Shih (施閔雄)

Research Center for Applied Sciences (RCAS), Academia Sinica, Taiwan

Mar 28, 2018

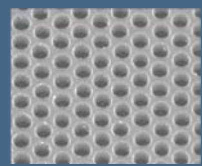
Photonic Crystal Waveguide

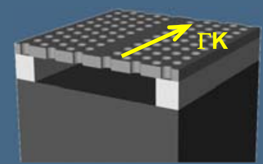


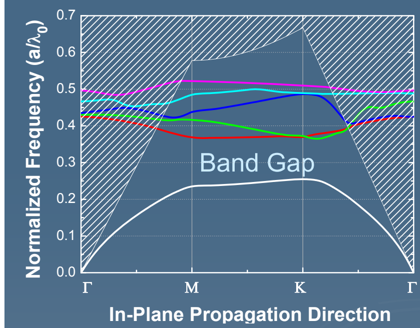
1. Photonic crystal waveguide types
2. Optical loss of the PhC waveguides
3. Photonic crystal "bending" waveguide
4. Slow-light behavior of PhC WG
5. Coupling issue ...

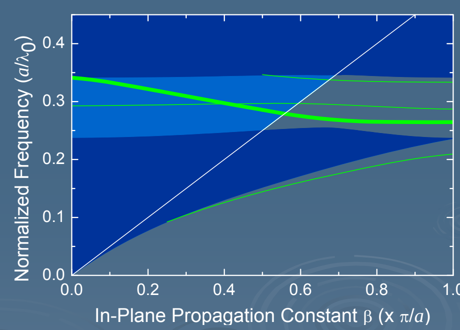
1. ***Photonic crystal "straight" waveguide***
2. Optical loss of PhC WG
3. Photonic crystal "bending" waveguide
4. Slow-light behavior of PhC WG
5. Coupling issue ...

Introduction to Photonic Crystal Waveguide

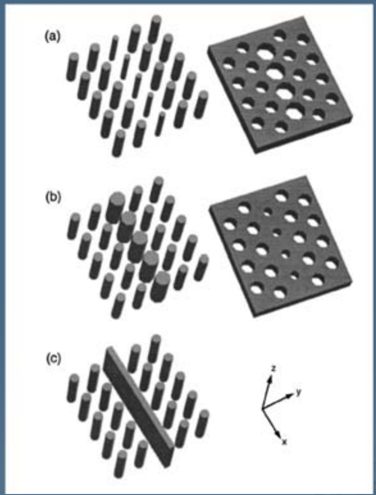








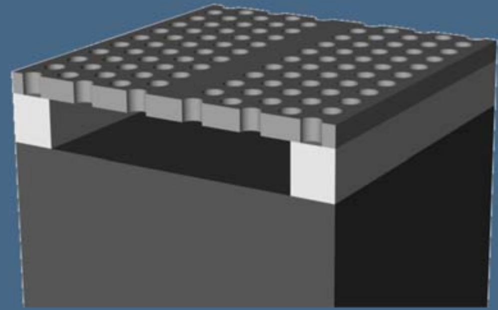
Photonic Crystal Defect Waveguides



- Linear defects, which give rise to waveguide modes
- (a) Reduced-index waveguides
- (b) Increased-index waveguides,
- (c) Dielectric-strip waveguide

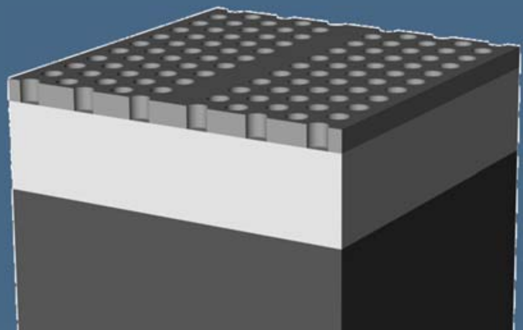
Phys. Rev. B, **62**, 8212 (2000)

Photonic Crystal Waveguides – Suspended Membrane



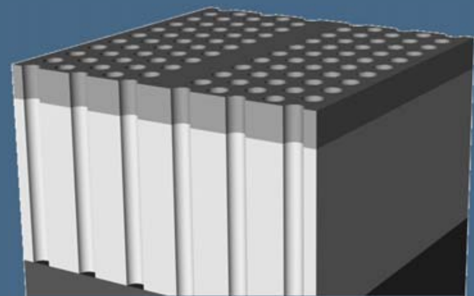
- Air (1.0)-dielectric (InP:3.17, GaAs:3.3, Si:3.4) -air structure
- Better vertical confinement
- Higher light line/cone
- Weaker mechanical strength

Photonic Crystal Waveguides – Oxide Structure



- Air (1.0)-dielectric (InP:3.17, GaAs:3.4, Si:3.4)-oxide (SiO2/ SiNx: 1.4-1.7)-substrate (>3) structure
- Weak vertical confinement
- Strong and easy fabricated

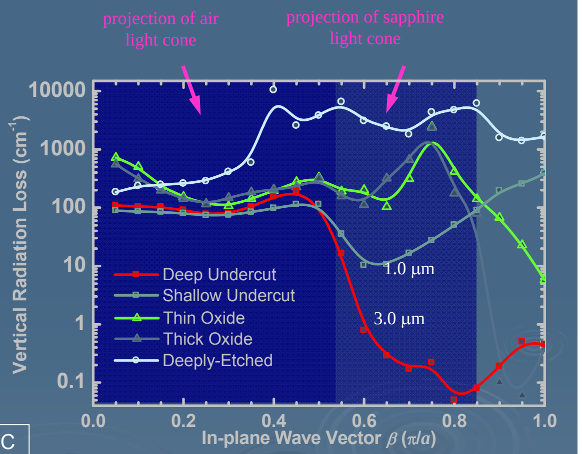
Photonic Crystal Waveguides – Deeply Etched Structure



- Air (1.0)-dielectric(>3)/oxide(~1.5) -substrate (>3) structure
- Weaker vertical confinement
- Strong structure
- Difficult to fabricate

Loss in Photonic Crystal Waveguides from FDTD

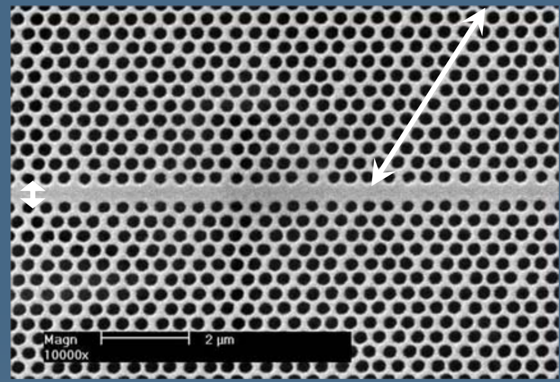
- The out-of-plane radiation loss of the waveguide is generally large for modes inside the light cone.
- Low loss transmission for suspended membrane and oxidized lower cladding structures occurs at the vicinity of the Brillouin zone boundary.



From Wan Kuang, MPDG, USC

SEM Images of InGaAsP Photonic Crystal Waveguides

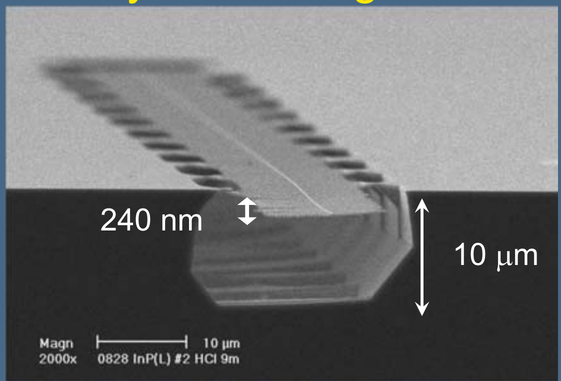
~ 500 nm



10-15 periods

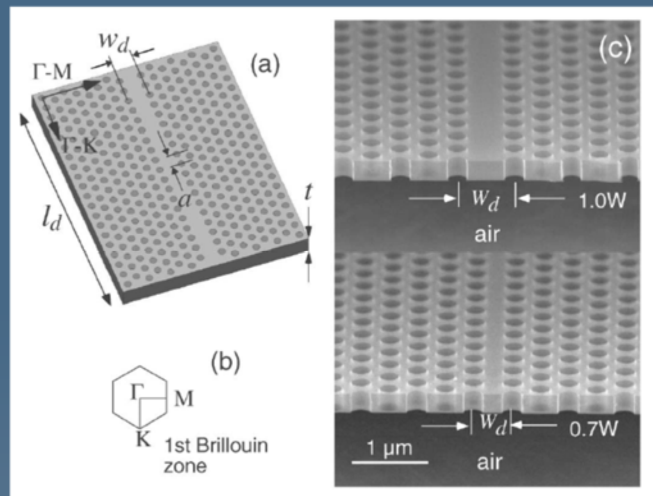
- Single-line defect (W1) photonic crystal waveguide
- Good in-plane confinement from 10-15 periods of photonic crystals

SEM Images of InGaAsP Photonic Crystal Waveguides



- 240 nm thick InGaAsP membrane
- More than 10 µm distance between InGaAsP and InP substarte prevent the energy leaky into substrate

Group Indices of Photonic Crystal Waveguides in the Si Membrane

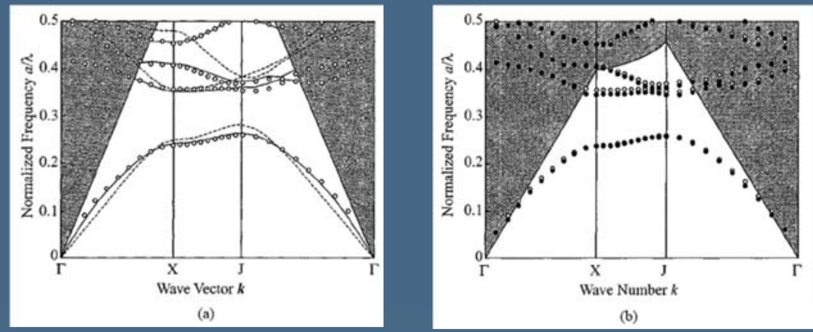


Phys. Rev. Lett., **87**, 253902-1 (2001)

Why Silicon Photonics ?

Materials	III-V materials (InP, GaAs)	Si
Band-gap	Direct	Indirect
Fabrication Technology	Good	Mature
Compatible with ICs	OK	Very good
Cost	High	Low

Photonic Crystal Waveguides on SOI Platform

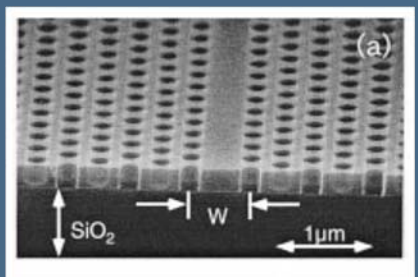


- Suspended membrane WG vs. SOI WGs
- Light line/cone bend down to reduce region of the allow states and increase the radiation loss of WGs

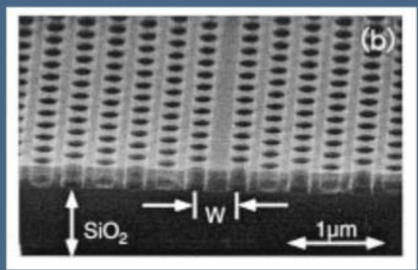
IEEE J. Quant. Electron., **38**, 736 (2002)

Photonic Crystal Waveguides on SOI Platform

W = 1.0 a



W = 0.7 a

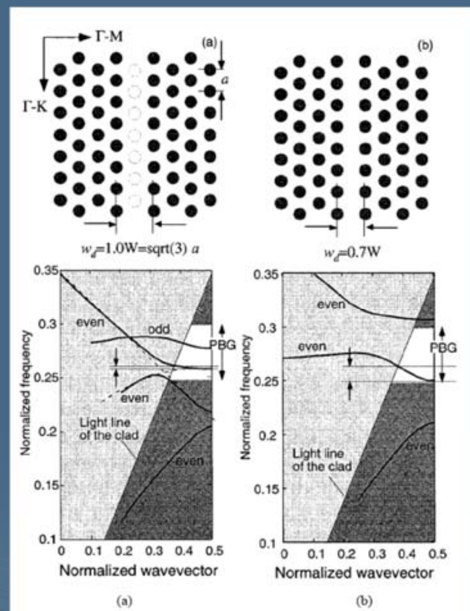


- Photonic crystal waveguide in SOI structure
- The width of the WGs is varied

IEEE J. Quant. Electron., **38**, 736 (2002)

Reduced Width of Photonic Crystal Waveguides on SOI Platform

- The width of the defect line of the photonic crystal waveguides were varied form 1.0a to 0.7a
- The change of width leads the shift of waveguide bands inside the band gap
- The lower 1st band might has smaller propagation loss because it is far away the light line



IEEE J. Quant. Electron., **38**, 736 (2002)

PhC Rod-Type Waveguide

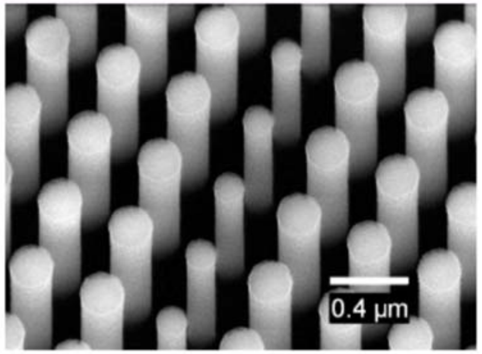
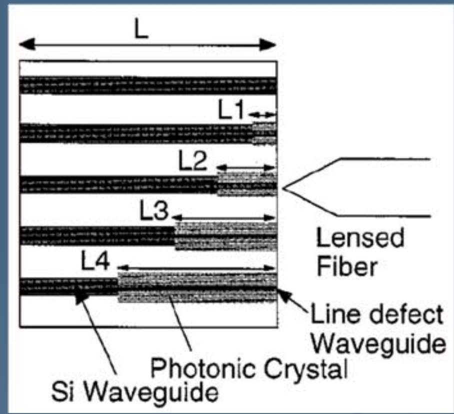


Figure 1: Oblique scanning-electron-micrograph of pillar-PC waveguide

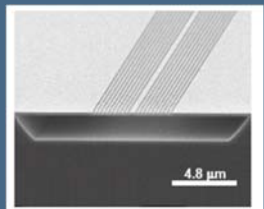
Propagation Loss of the Waveguides – Cut-Back Method

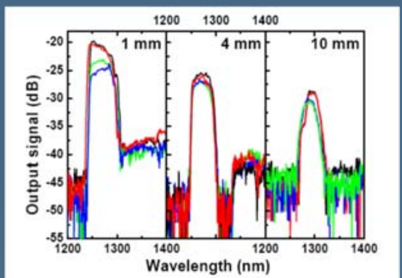
$$I = I_0 \, e^{-\Gamma \cdot L_{WG}}$$



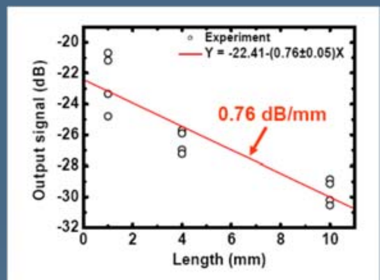
- *I*: Intensity
  I_0: Initial intensity
  Γ: Propagation loss
  L_{WG}: Waveguide length
- By varying the length of WGs, the propagation loss can be evaluated from the relation between the power/intensity and the length of WGs.

Propagation Loss of the Waveguides – Cut-Back Method





(a)



(b)

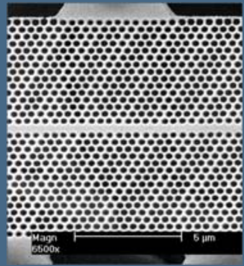
Opt. Express., **12**, 1090 (2004)

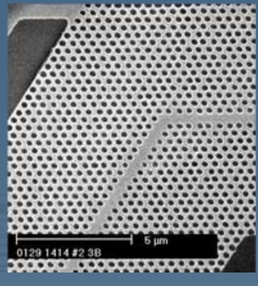
---

1. Photonic crystal “straight” waveguide
2. Optical loss of PhC WG
3. ***<u>Photonic crystal “bending” waveguide</u>***
4. Slow-light behavior of PhC WG
5. Coupling issue ...

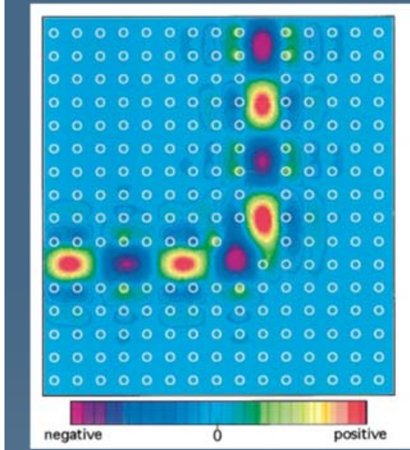
Bending Structure of Photonic Crystal Waveguides

- Due to lattice symmetry, photonic crystal waveguide can change the propagation direction of signals in a small region ~ few μm
- The variation of propagation direction dependent on the types of lattices, e.g. 90° in square lattices or 60°, 120° in triangular lattices

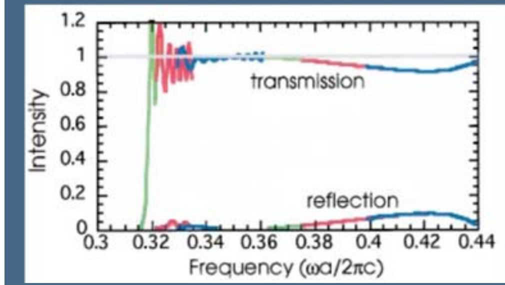




90° Bend in Square Photonic Crystal Waveguides

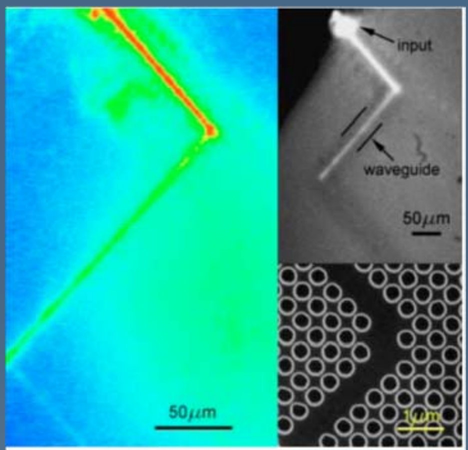


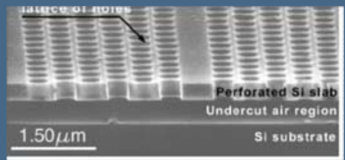
Calculated mode profile



Calculated transmission

90° Bend in Si Suspended Membrane

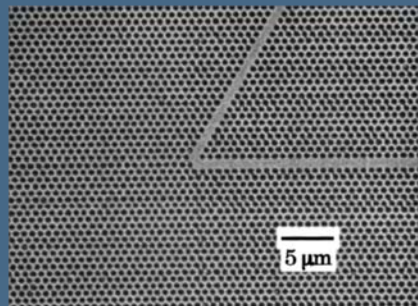


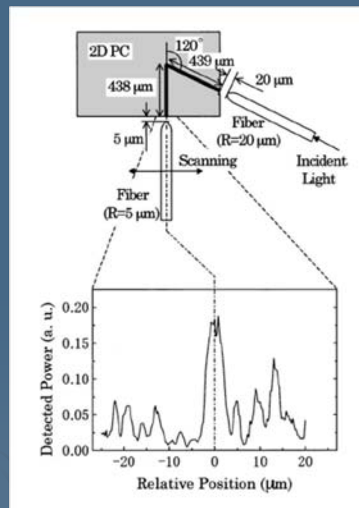


- PhC waveguide in Si suspended membrane
- SEM images from top and cross section view
- Light is guided in the WG segment from top viewz

Appl. Phys.Lett.,Vol.77, 1937 (2000)

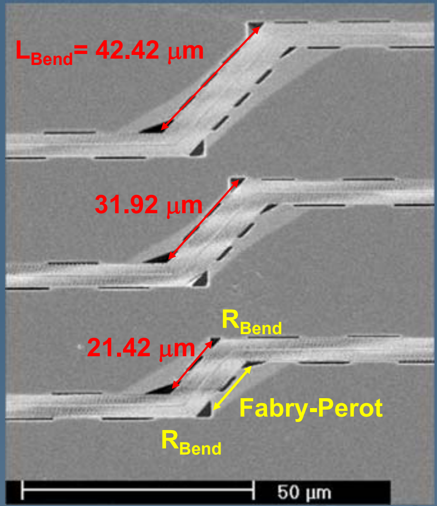
120° Sharp Bent in Photonic Crystal Waveguides





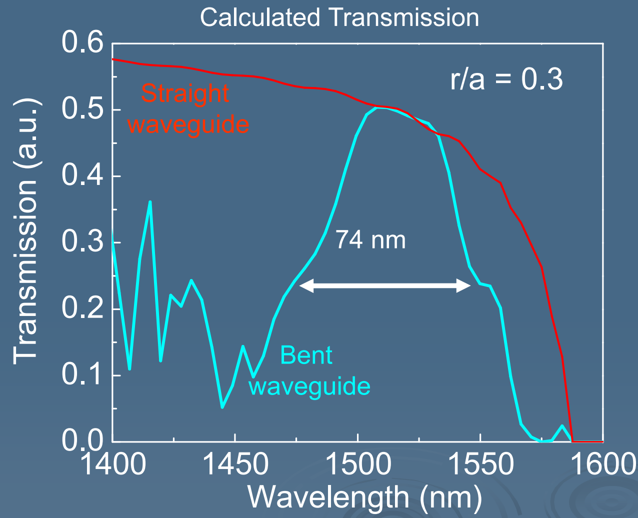
Multi-mode fiber input and single-mode fiber collection

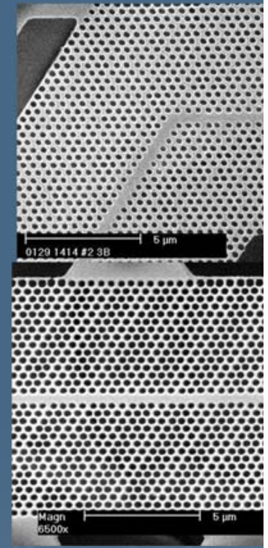
Fabry-Perot Oscillations from Doubly Bent Photonic Crystal Waveguides



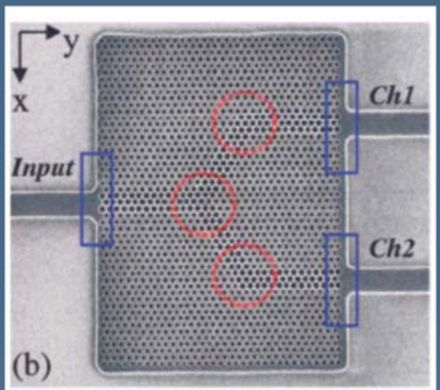
Reflection from the two bends will lead to Fabry-Perot oscillations with a period that should be inversely proportional to L_{Bend}

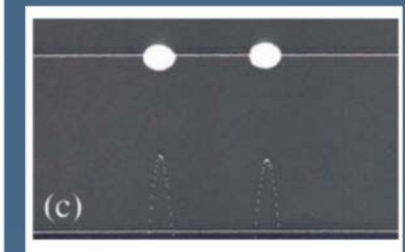
Theoretical Prediction of Transmission Through Photonic Crystal Waveguides by Finite Element Method





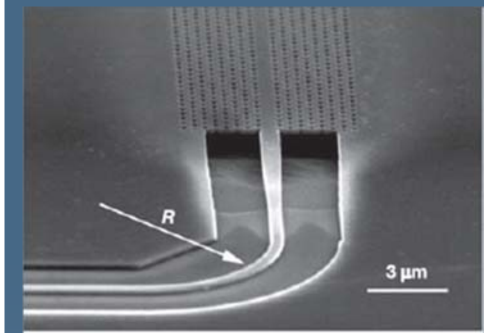
Photonic crystal waveguide branch structure

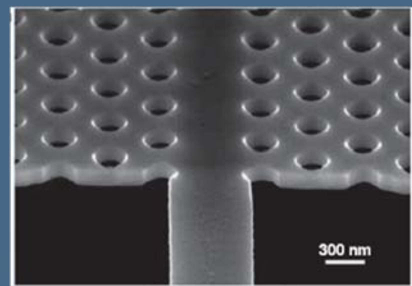




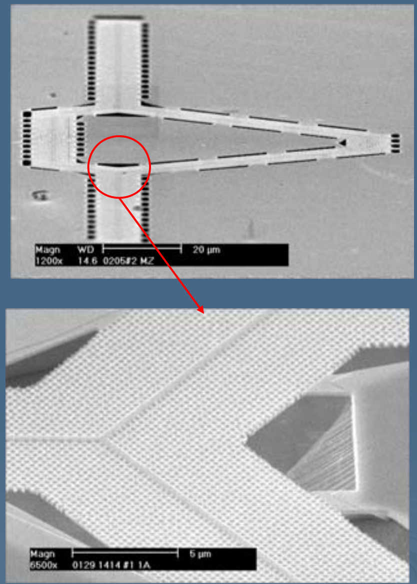
Optics Letters, Vol 27, 1400 (2002)

Photonic crystal waveguide branch structure



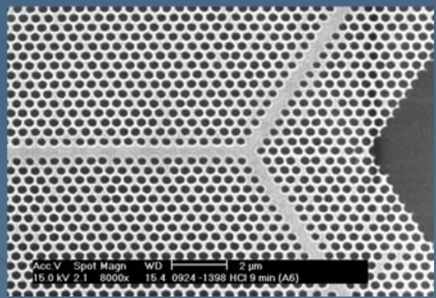


Nature, Vol 438, 65 (2005)



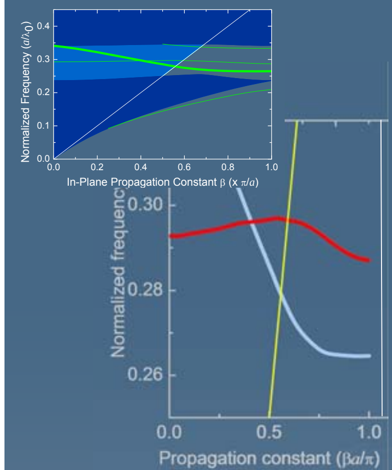
Photonic Crystal Mach-Zehnder Structures in InP

InGaAsP/InP Membrane Structure



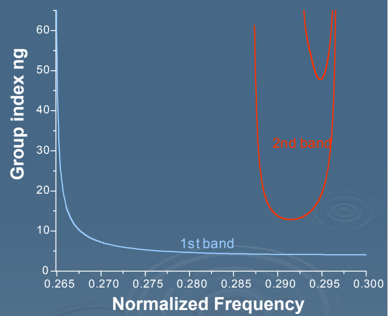
1. Photonic crystal waveguide types & optical loss
2. Photonic crystal "bending" waveguide
3. ***<u>"Slow-light" behavior of PhC WG</u>***
4. Coupling issue ...

Group Index of Propagated Mode in Photonic Crystal Waveguides



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

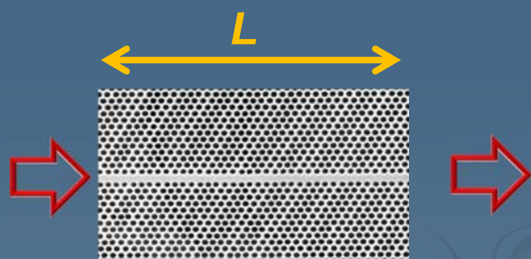
Group Indices of two guided bands

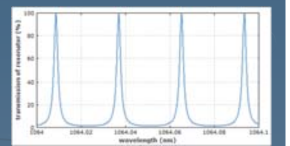


Group Indices of Photonic Crystal Waveguides from Experiment

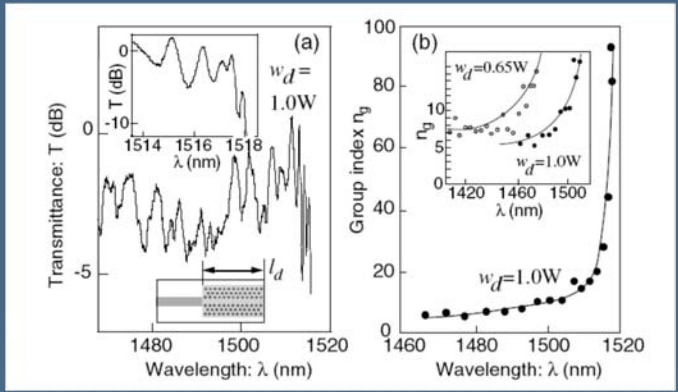
- Fabry-Perot oscillations embedded in the transmission of the WGs
- Group indices were obtained from the period of F-P oscillations

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





Group Indices of Photonic Crystal Waveguides in the Si Membrane

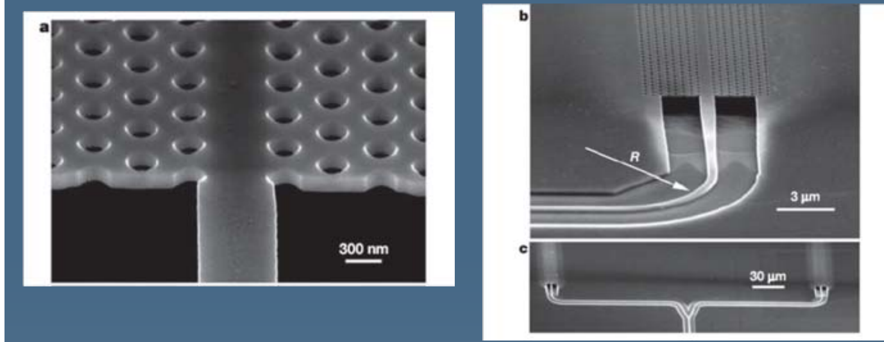


$$\Delta\lambda = \frac{\lambda^2}{2 n_g L}$$

- F-B oscillations embedded in the transmission of the WGs
- Group indices were obtained from the period of F-B oscillations

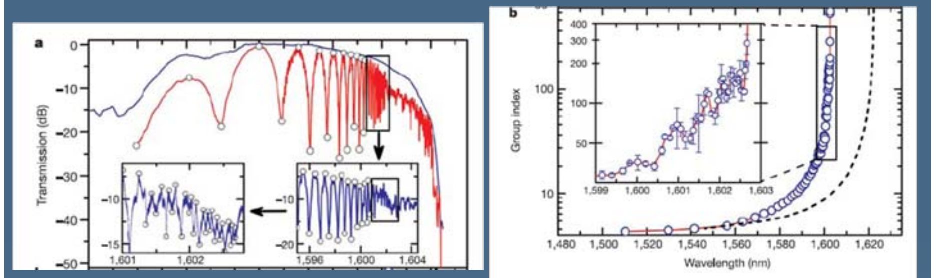
Phys. Rev. Lett., **87**, 253902-1 (2001)

”Slow-Light” of PhC WG



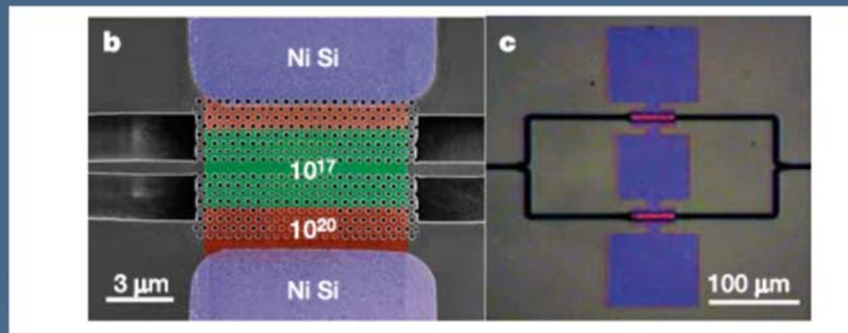
Nature, Vol 438, 65 (2005)

”Slow-Light” of PhC WG



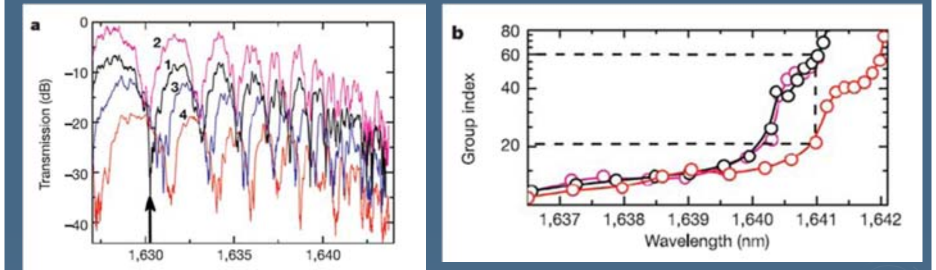
Nature, Vol 438, 65 (2005)

Active Control of Slow Light on PhC Waveguide



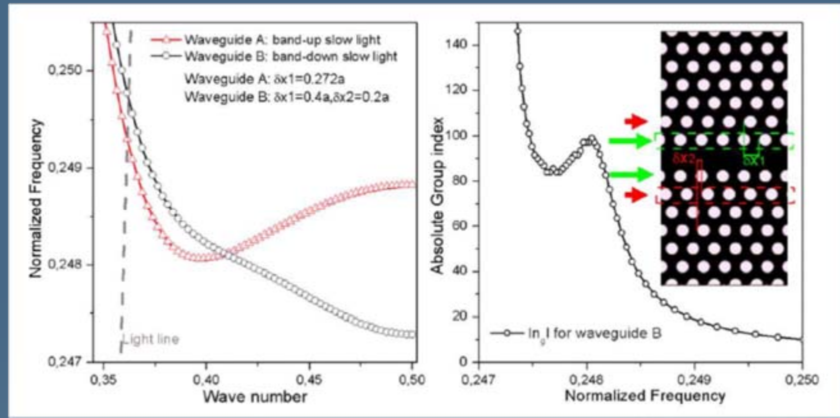
Nature, Vol 438, 65 (2005)

Active Control of Slow Light on PhC Waveguide



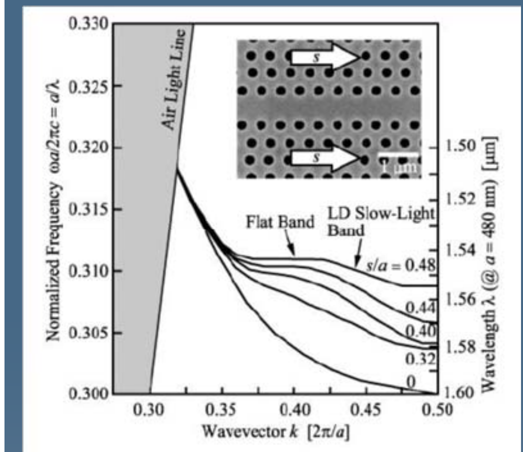
Nature, Vol 438, 65 (2005)

"Slow-Light" of PhC WG



Optics Express, Vol 18, 16309 (2010)

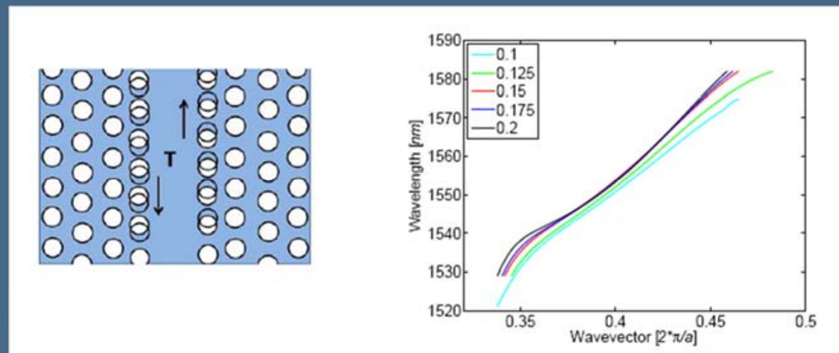
"Slow-Light" of PhC WG and Strip WG



s/a	n_g	$\Delta\lambda$ [nm]	$n_g\Delta\lambda/\lambda$
0.32	19	27	0.33
0.40	14	23	0.20
0.44	15	17	0.16
0.48	28	8	0.14

Optics Express, Vol 18, 26675 (2010)

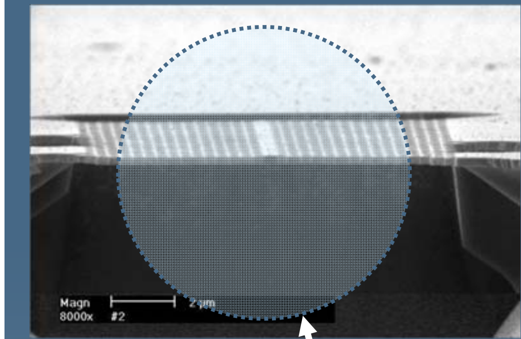
"Slow-Light" of PhC Strip WG



Optics Express, Vol 21, 4495 (2013)

1. Photonic crystal waveguide types & optical loss
2. Photonic crystal "bending" waveguide
3. "Slow-light" behavior of PhC WG
4. ***<u>Coupling issue …</u>***

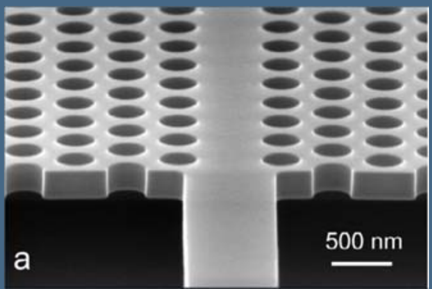
Insertion Loss of Photonic Crystal Waveguides

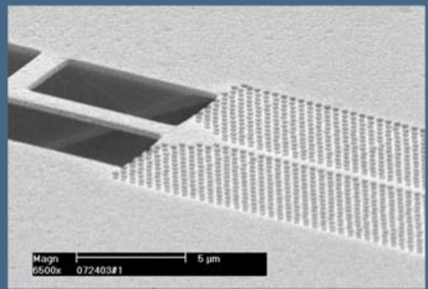


Single-mode fiber

- PhC WG core size ~ 0.3 μm x 0.24 μm
- Regular single mode fiber core size ~ 9 μm
- Huge insertion loss from butt coupling

Coupling Between PhC WG and Strip WG

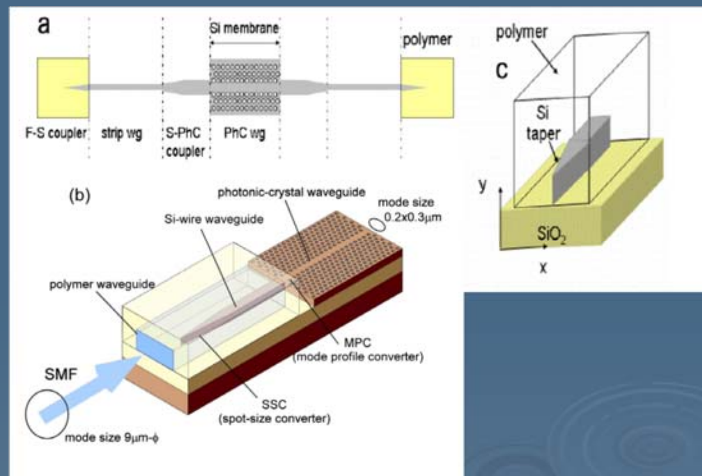




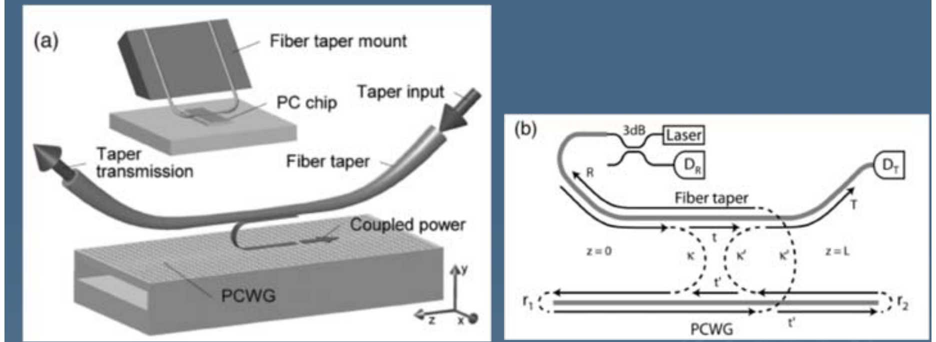
Wo/ modified lattices

W/ modified lattices around the WG ends

Coupling Between Strip WG and Fiber

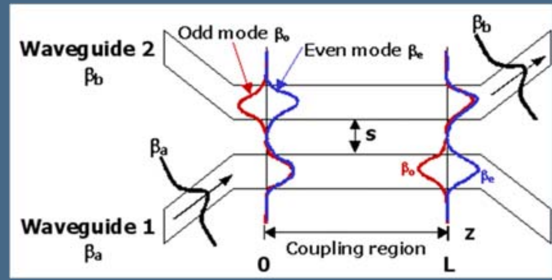


Coupling between PhC WG and Taper Fiber



Optics Letters, 29, 697 (2004)

Directional Coupler



Optical waves ψ_a and ψ_b propagating along the coupled waveguides 1 and 2:

$$\psi_a(x,y,z,t) = A(z)e^{-i\beta_a z} f_a(x,y)e^{iwt}$$

$$\psi_b(x,y,z,t) = B(z)e^{-i\beta_b z} f_b(x,y)e^{iwt}$$

where $f_a(x,y)$ and $f_b(x,y)$ are field distribution functions that are normalized by power flow over a cross section

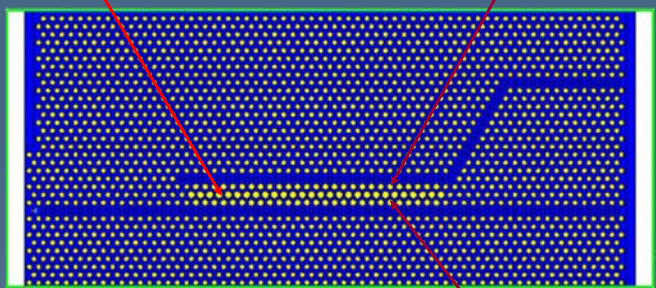
Proposed 2-D Photonic Crystal Waveguide Directional Coupler

Two single-line-defect waveguides in a triangular lattice 2-D slab with a periodic array of air holes (r/a=0.3)

$r_c/a = 0.4$

$r_{s2}/a = 0.35$

Input



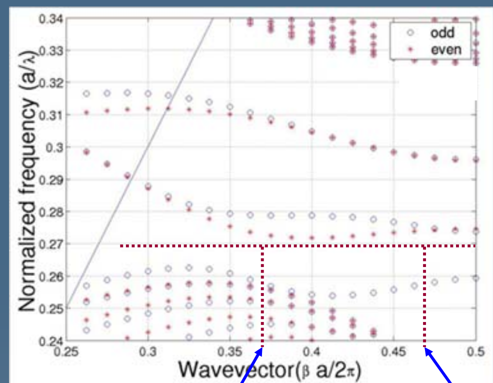
Port 2

Port 1

$r_{s1}/a = 0.35$

* Courtesy of W.-J. Kim, MPDG, USC

Proposed 2-D Photonic Crystal Waveguide Directional Coupler (cont.)



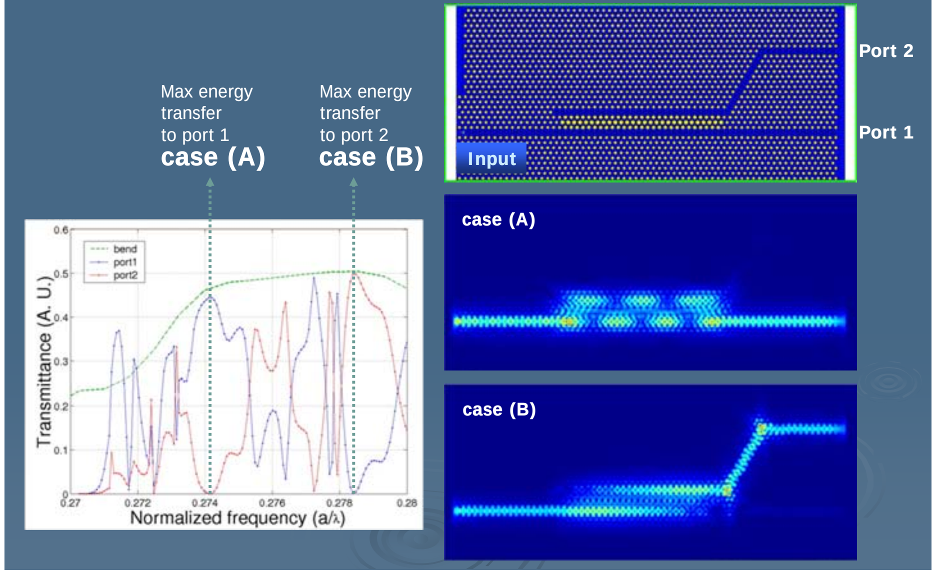
β_o β_e

$$L = \frac{\pi}{2\beta_c} = \frac{\pi}{\beta_e - \beta_o}$$

$$L = \frac{\pi}{2\kappa}$$

* Courtesy of W.-J. Kim, MPDG, USC

Proposed 2-D Photonic Crystal Waveguide Directional Coupler (cont.)



Thanks and end of photonic crystals part