

Design and Characterization of Silicon-on-Insulator Passive Polarization Converter with Finite-Element Analysis

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Overview

- Introduction & Background (PR, SOI)
- FEM Eigenmode Solvers
- Design Rules for Slanted-Angle PRs
- Fabrication Tolerance Study
- FV-FE-BPM Simulation
- Bending & Loss / Coupling Analysis
- Conclusions



Introduction

Impetus and Objective:

- Birefringence in fibers & waveguides (WG)
  - Material anisotropy, geometric asymmetry, mechanical stress, thermoelastic, electro-optic effects
  - Signal distortion & system degradation
- Polarization manipulating device
  - Polarization splitter → MMI, MZI, Y-junction, etc.
  - Polarization converter → As simple as Rib structure

Active Polarization Rotator (PR)

- Electro-optic & thermal-strain effects
- Voltage-controlled electrode → Difficulties

Passive Polarization Rotating Waveguide (PRW)

- Periodic & single-section structures
- III-V (AlGaAs/GaAs & InGaAsP/InP) materials

Silicon-on-Insulator (SOI) Technology

- Main platform for Silicon Photonics
- Compatible with electronics → low cost OEIC
- Our first application in PR

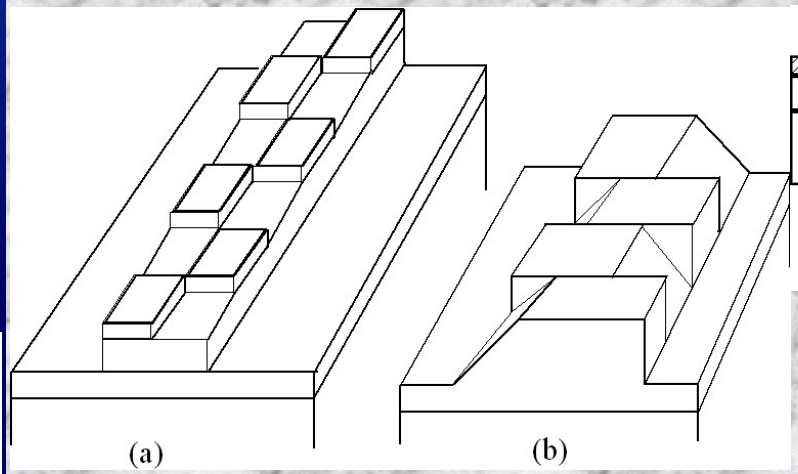
Passive Polarization Rotators

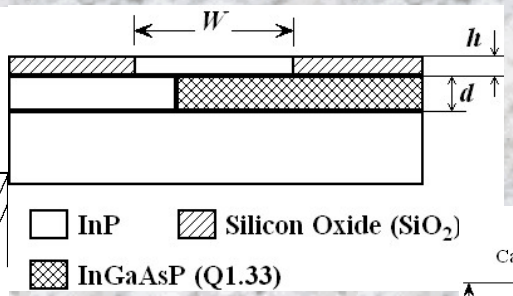
Longitudinally-Periodic Structure

- Weakly-hybridized mode; Accumulate at junctions.

Single-Section Configuration

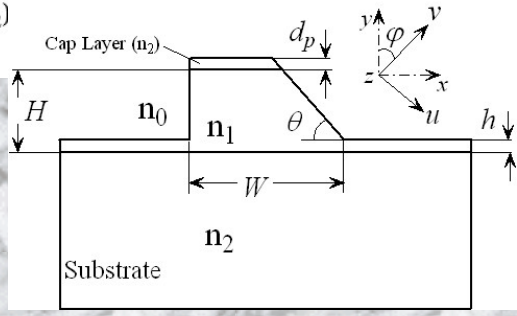
- Strongly-hybridized modes.
- Simulation: FDM, FEM, BEM, CMT, FD- /FE-BPM, etc.
- Easy fabrication (simple geometry), compact dimension, small insertion loss (no junctions)





Shani (91) , Heidrich (92) , Tol (95), Mertens (98), etc.

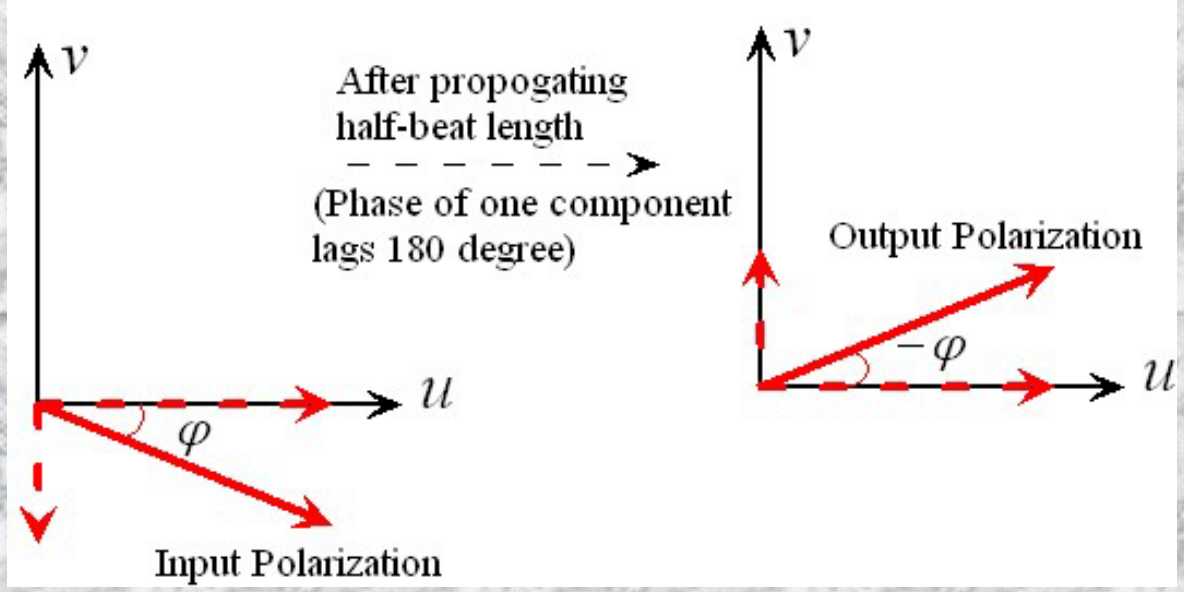
Tzolov (95) , Mertens (98), Huang (00) , Zhu (00, 01, 03, 04), Rahman (01, 02, 03), Yevick (01, 03, 04), etc.



Operation Principle

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Optical axes (u,v) → slow- and fast- axis → phase delay → half-beat length L_π



- Polarization angle to x-axis
  - *if* input φ, *then* output $-\varphi$ (*after* $L\pi$).
- Optical-Axis rotated 45° to x-axis
  - *if* input *TE* , *then* output *TM* (*after* $L\pi$).

Silicon-on-Insulator

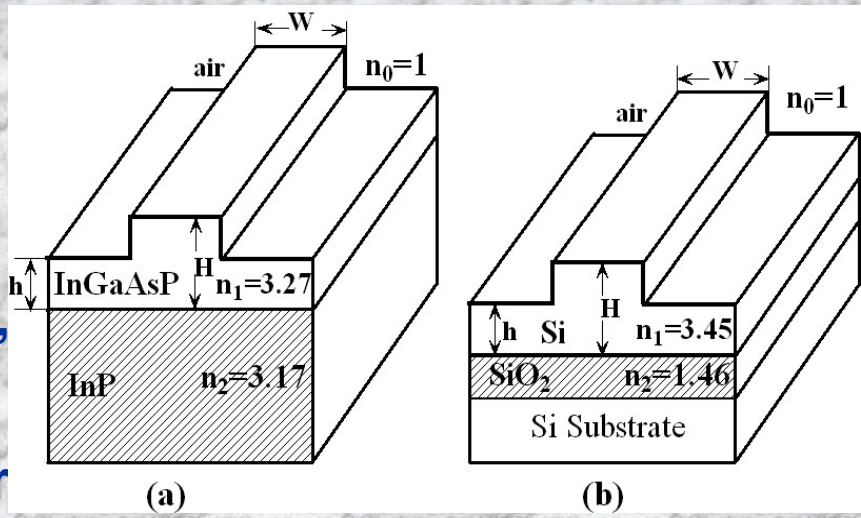
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Silicon Photonics

- SOI — Platinum for photonics & electronics
- Si-based OEIC — Compatible with VLSI CMOS Tech.
  - Economic advantage

SOI Waveguide

- Fabrication techniques
  - BE-SOI, Smart cut, SIMOX,
- Various applications
  - MZI, MMI, AWG, modulator



- Strong optical confinement — Low loss, Compact
- Single-mode condition of Rib WG

$$\frac{W}{H} \le const + \frac{h/H}{\sqrt{1-(h/H)^2}}, \quad with \quad const = 0.3$$

FEM Eigenmode Solver

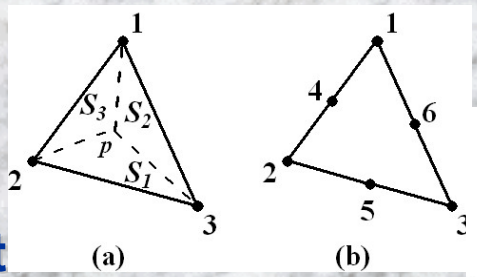
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Why Full-Vectorial FEM?

- Versatile, Accurate, Efficient
- Anisotropic, Lossy, Inhomogeneous, Discontinuous
- Non-uniform unstructured mesh & Adaptive Mesh
  - FDM software — Limited by rectangular grids
  - FDM — Inaccurate results for slanted-angle waveguides

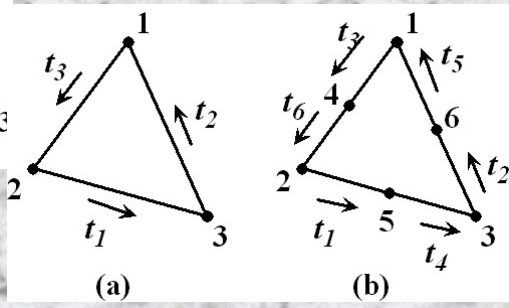
FEM Mode Solvers

- Scalar (SC)
  - No polarization effect
- Semi-Vectorial (SV)
  - Neglect coupling between transverse polarizations
- Full-Vectorial (FV)



Nodal elements

Mixed elements



FV-FEM with Mixed Element

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FEM Procedures:

- (1). Obtain functional; (2). Divide problem region; (3). Derive elementary matrix; (4). Assemble global system; (5). Solve eigenvalue equation.

Details

- FV-Helmholtz Eq. $\nabla \times ([p]\,\nabla \times \phi) - k_0^2\,[q]\,\phi = 0$
- Functional $$F = \iint_{\Omega} \left[(\nabla \times \phi)^* \cdot ([p]\,\nabla \times \phi) - k_0^2\,[q]\,\phi^* \cdot \phi \right] \mathrm{d}x\,\mathrm{d}y$$
- Mixed Element
  - Avoid spurious modes

$$\phi = \begin{bmatrix} \phi_x \\ \phi_y \\ \phi_z \end{bmatrix} = \begin{bmatrix} \{U\}^T \{\phi_t\}_e \\ \{V\}^T \{\phi_t\}_e \\ j\{N\}^T \{\phi_z\}_e \end{bmatrix} e^{j\beta z}$$

- Separate Transverse and Longitudinal Components

$$\nabla_t \times (p_z \nabla_t \times \phi_t) + \frac{\partial}{\partial z}\{[p]_t\,(\nabla_t \phi_z - \frac{\partial}{\partial z}\phi_t)\} - k_0^2\,[q]_t\,\phi_t = 0$$

$$\nabla_t \times \left[\{[p]_t\,(\nabla_t \phi_z - \frac{\partial}{\partial z}\phi_t)\} \times \boldsymbol{i}_z \right] - k_0^2 q_z \phi_z \boldsymbol{i}_z = 0$$

- Apply Galerkin Procedure

$$\beta^2[M_{tt}]\{\phi_t\} + \beta[M_{tz}]\{\phi_z\} - [K_{tt}]\{\phi_t\} = \{0\}$$

$$\beta[M_{zt}]\{\phi_t\} + [M_{zz}]\{\phi_z\} = \{0\}$$

$$[K_{tt}] = \sum_e \iint_{\Omega_e} [q_x k_0^2 \{U\}\{U\}^T + q_y k_0^2 \{V\}\{V\}^T - p_z \{U_y\}\{U_y\}^T$$

$$- p_z \{V_x\}\{V_x\}^T + p_z \{U_y\}\{V_x\}^T + p_z \{V_x\}\{U_y\}^T] \, \mathrm{d}x \, \mathrm{d}y$$

$$[M_{tt}] = \sum_e \iint_{\Omega_e} [p_y \{U\}\{U\}^T + p_x \{V\}\{V\}^T] \, \mathrm{d}x \, \mathrm{d}y$$

$$[M_{tz}] = [M_{zt}]^T = \sum_e \iint_{\Omega_e} [p_y \{U\}\{N_x\}^T + p_x \{V\}\{N_y\}^T] \, \mathrm{d}x \, \mathrm{d}y$$

$$[M_{zz}] = \sum_e \iint_{\Omega_e} [p_y \{N_x\}\{N_x\}^T + p_x \{N_y\}\{N_y\}^T - q_z k_0^2 \{N\}\{N\}^T] \, \mathrm{d}x \, \mathrm{d}y$$

FV-FEM Eigenvalue Eq.

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Only Transverse Components

- Generalized Eigen Eq.

$$[K_{tt}]\{\phi_t\} = \beta^2 \left([M_{tt}] + [M_{tz}][M_{zz}]^{-1}[M_{zt}]\right)\{\phi_t\}$$

- Matrix Inverse → Limitations (CPU & Memory)

Improved Formulation

- Perform a substitution $\phi_z = \beta\phi_z'$
- Directly solve for propagation constant

$$[K]\{\phi\} - \beta^2[M]\{\phi\} = \{0\}$$

$$[K] = \begin{bmatrix} [K_{tt}] & [0] \\ [0] & [0] \end{bmatrix}, [M] = \begin{bmatrix} [M_{tt}] & [Mtz] \\ [Mzt] & [Mzz] \end{bmatrix} \text{ and } \{\phi\} = \begin{Bmatrix} \phi_t \\ \phi_z' \end{Bmatrix}$$

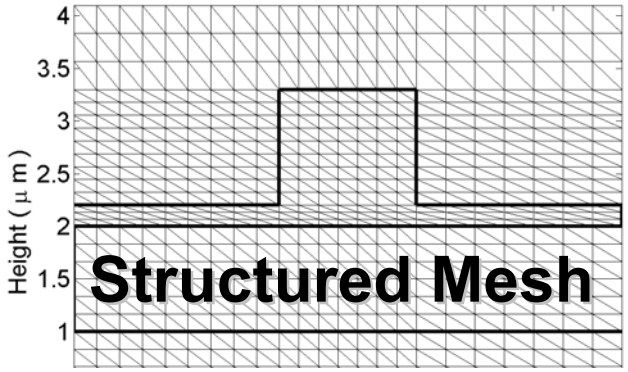
- All matrices sparse and symmetric

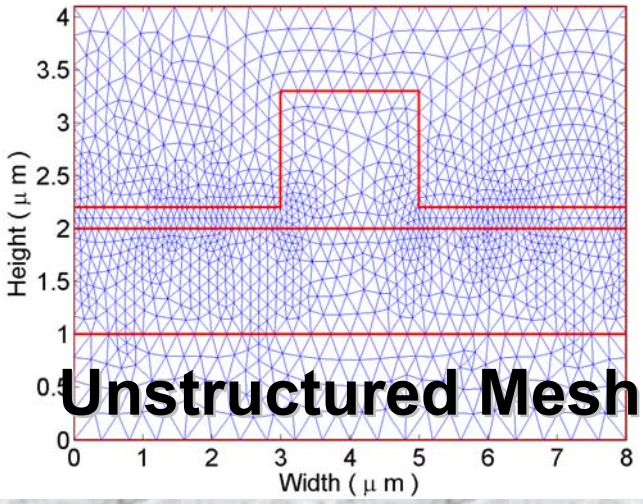
Numerical Accuracy (1)

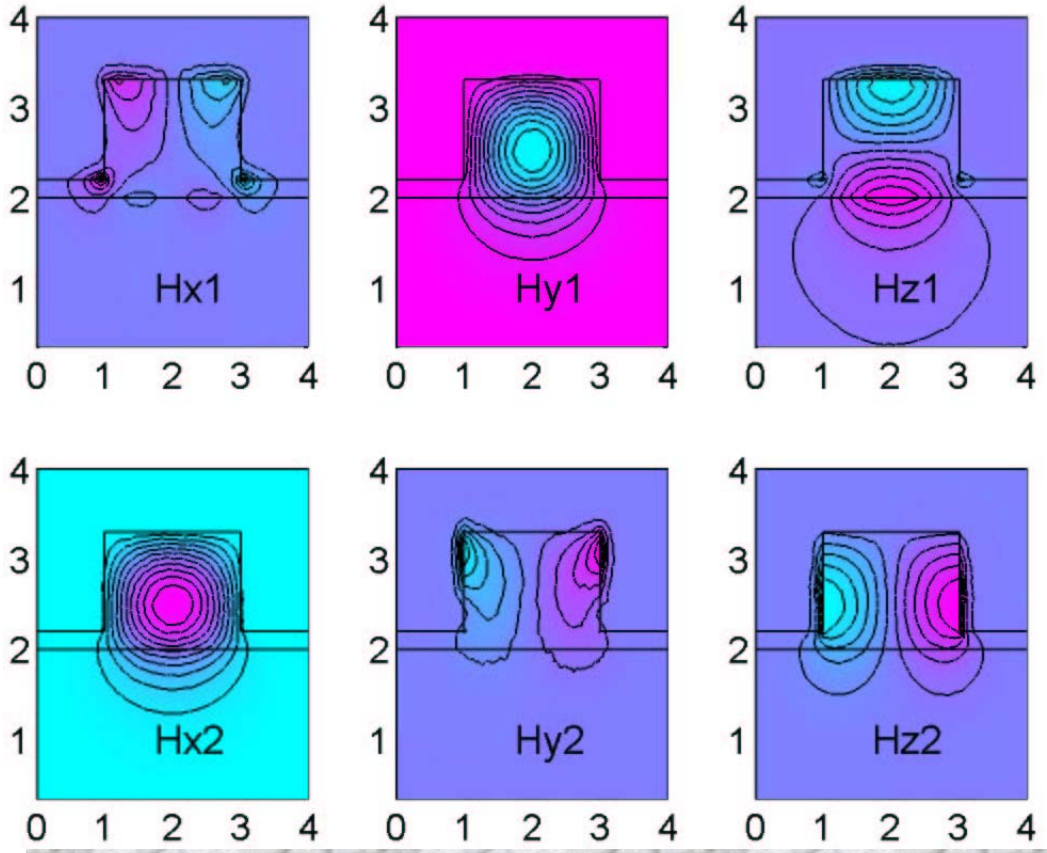
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For Rib Waveguide: (H, W, h) = (1.3, 2, 0.2) μm, n_1=3.44, n_2=3.34

- Error for Normalized Prop. Const. b : **0.1% ~ 0.4%**







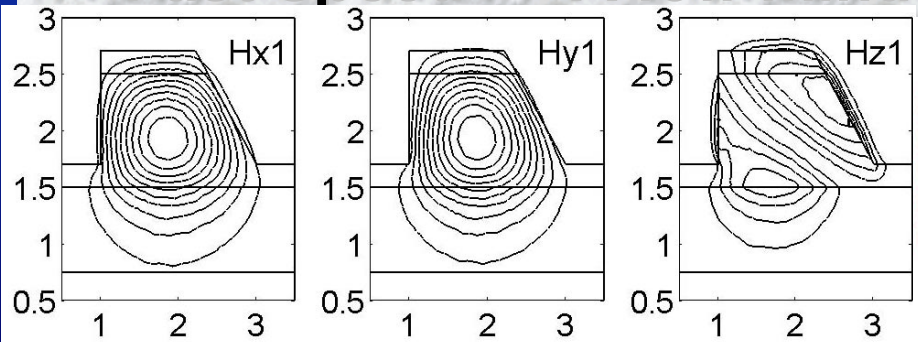
Eigenmodes

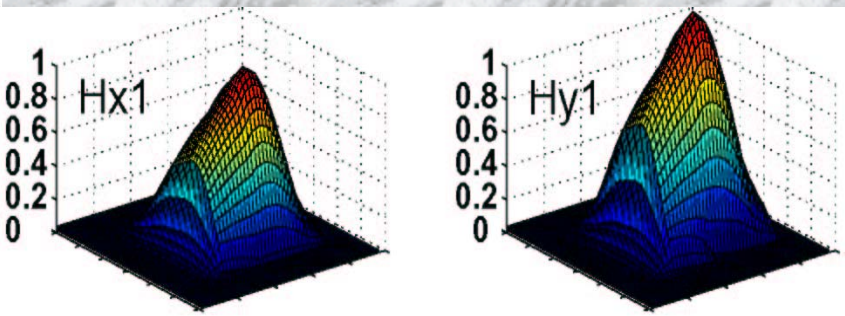
Numerical Accuracy (2)

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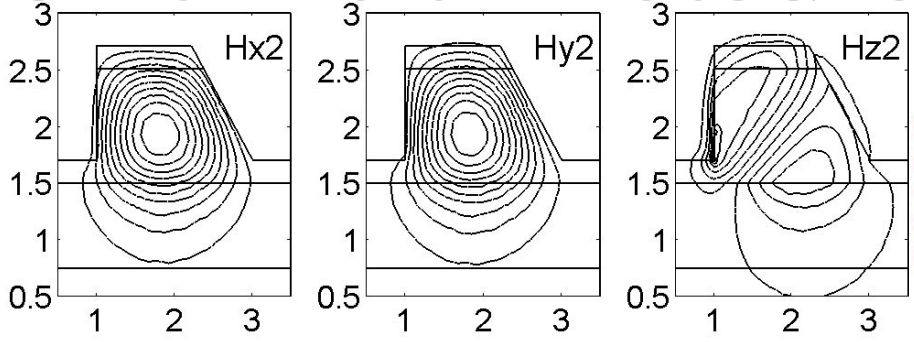
For III-V Slanted-Angle Polarization Rotator

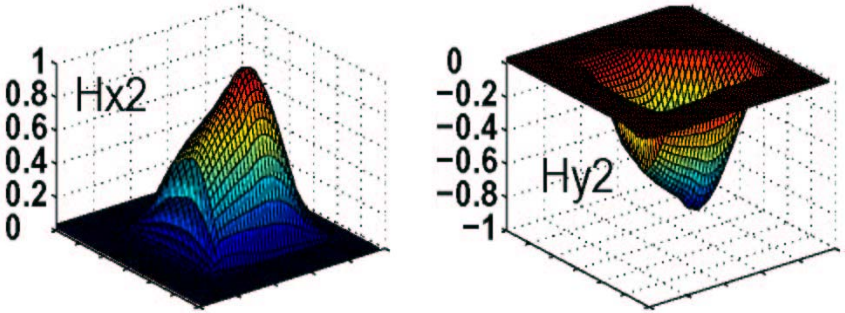
- *1. GaAs/AlGaAs PR (Huang, Rahman, et al.)*
  - H=1.3μm, W=2.5μm, h=0.1μm, θ=52°, n_1=3.370, n_2=3.324.
- *2. InP/InGaAsP PR (Tzolov)*
  - H=1μm, W=2μm, h=0.2μm, d_p=0.2μm, θ=45°, n_1=3.4, n_2=3.27.
- **Excellent accuracy & convergency**
- **Fast Speed — A few minutes for thousands elements**



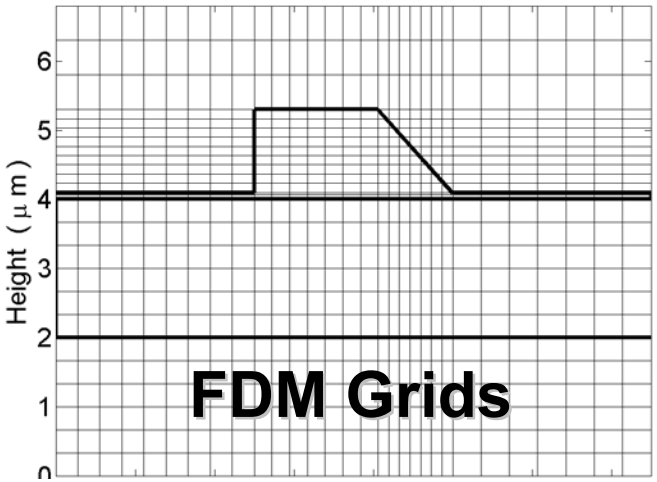


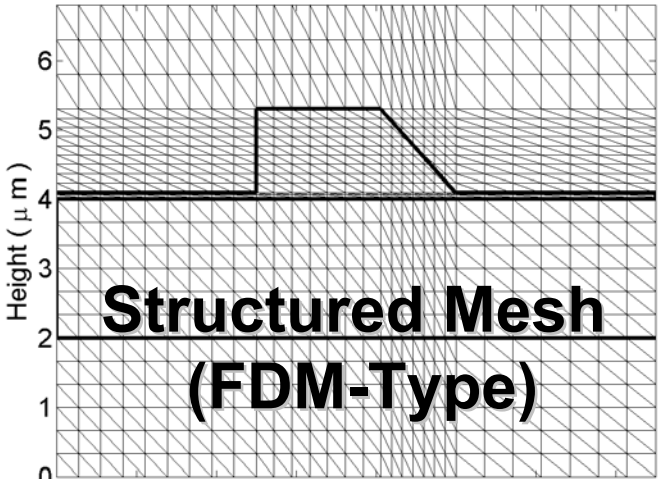
Similar TE and TM fields & Penetrate deep into substrate

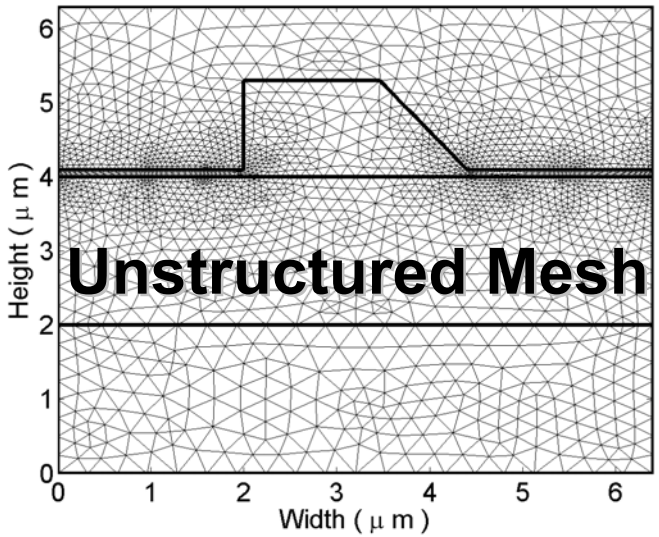


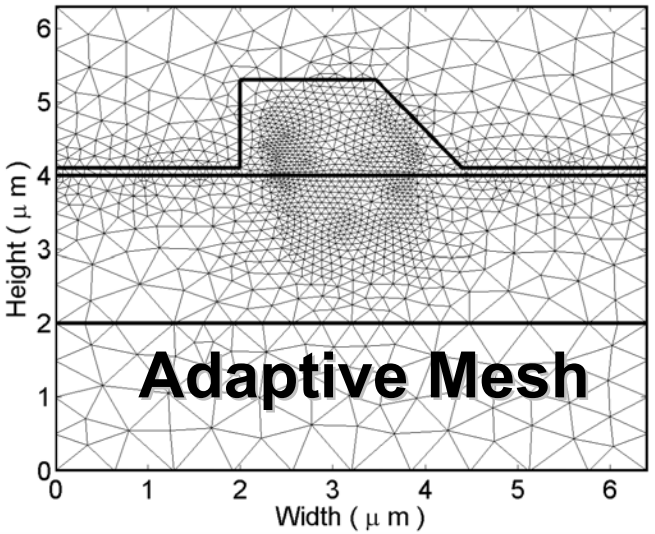


Meshes for FEM Analysis





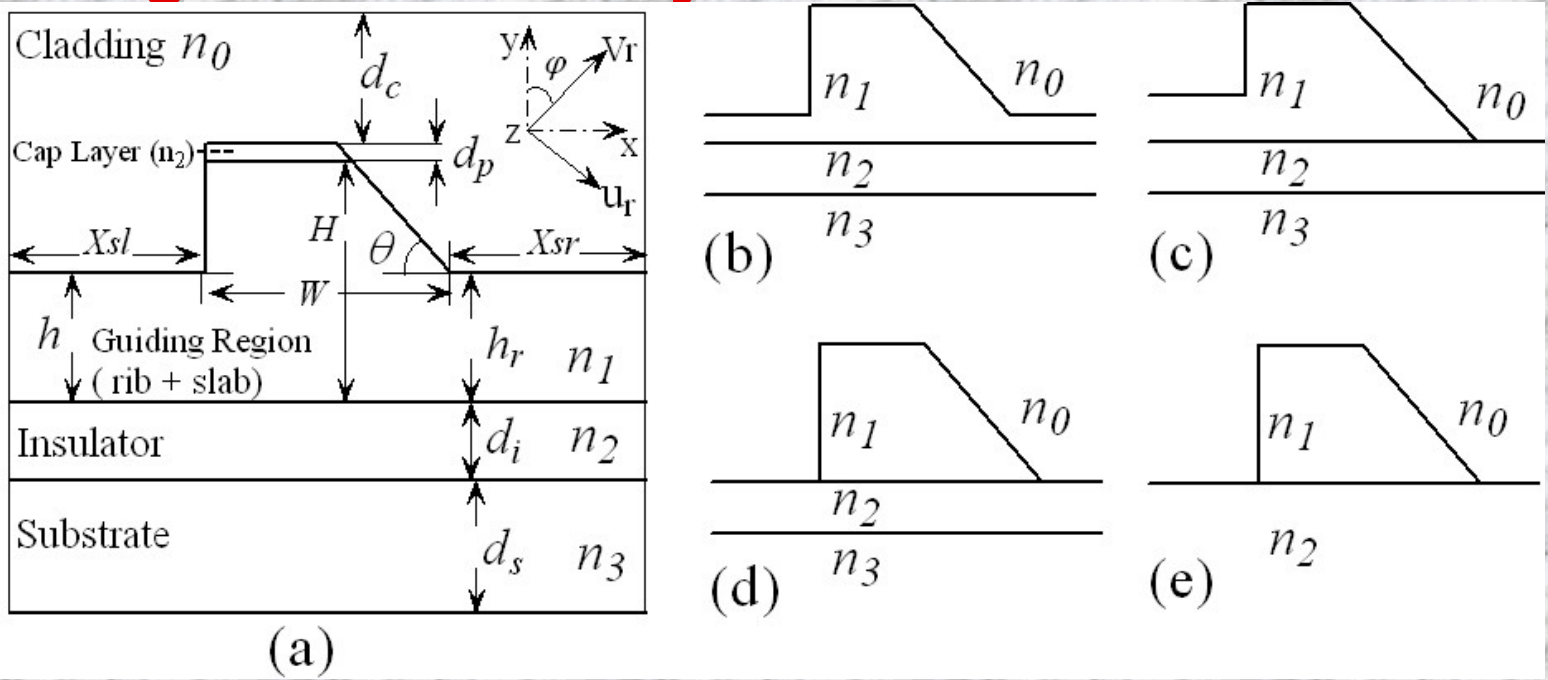




Unstructured meshes better than FDM-type grids

General Design Rules

Waveguide Geometry



Optical-Axis Rotation Contours

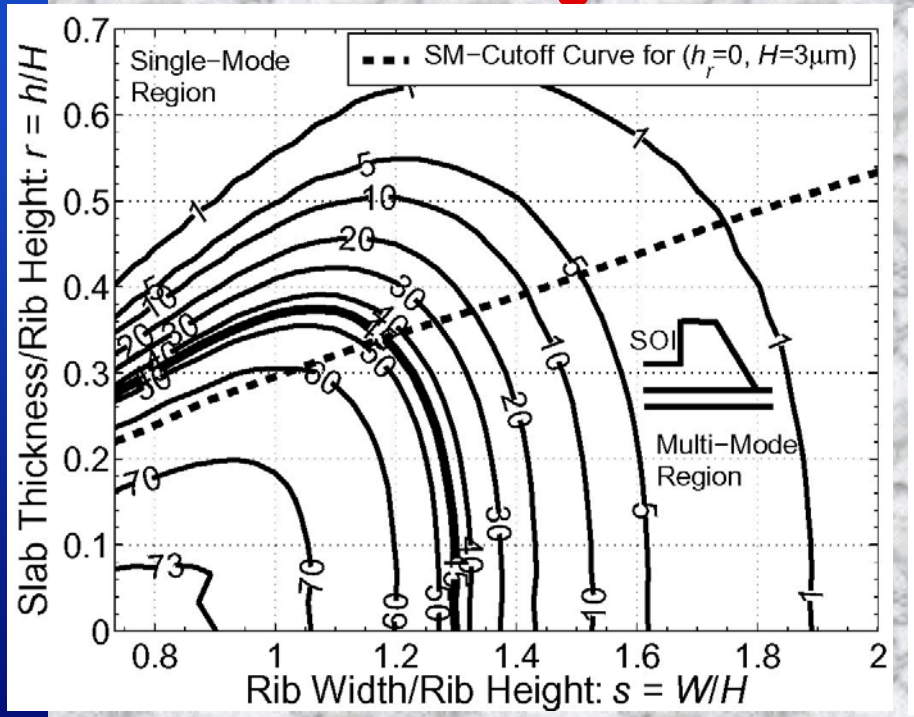
$$R = \frac{\iint_{\Omega} n^2(x,y) \cdot H_x^2(x,y)\,dx\,dy}{\iint_{\Omega} n^2(x,y) \cdot H_y^2(x,y)\,dx\,dy}$$

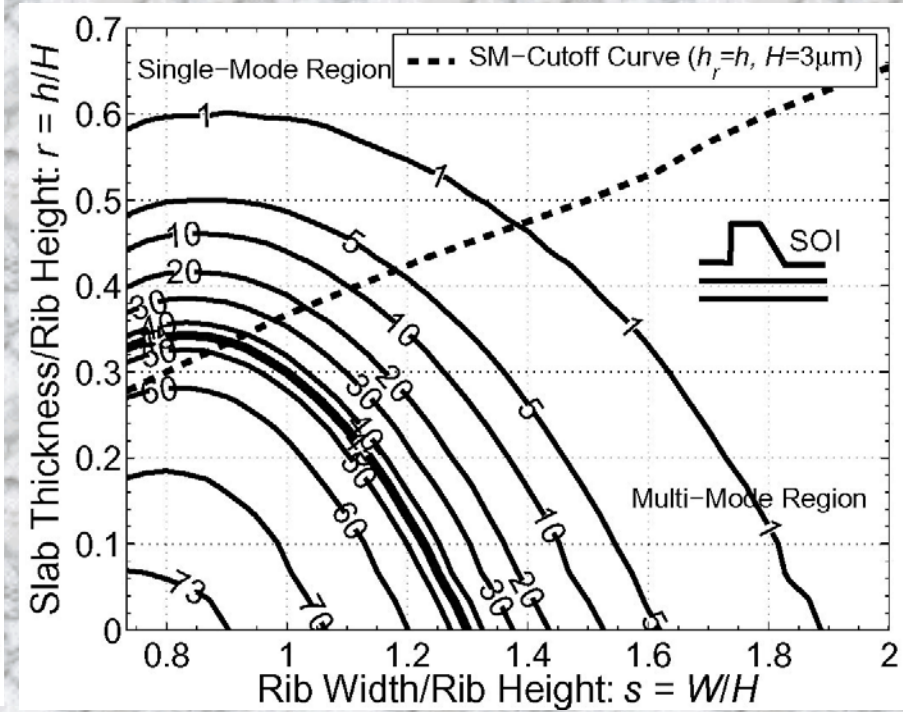
- **Rotation Parameter *R***
  - ***R*>>1 → *x*-polarized; *R*<<1 → *y*-polarized; *R*=1 → *PR***
- **Optical-Axis Rotation Angle φ** $\varphi = tan^{-1}(R)$

Normalized Design Charts

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SOI Slanted-Angle Polarization Rotator



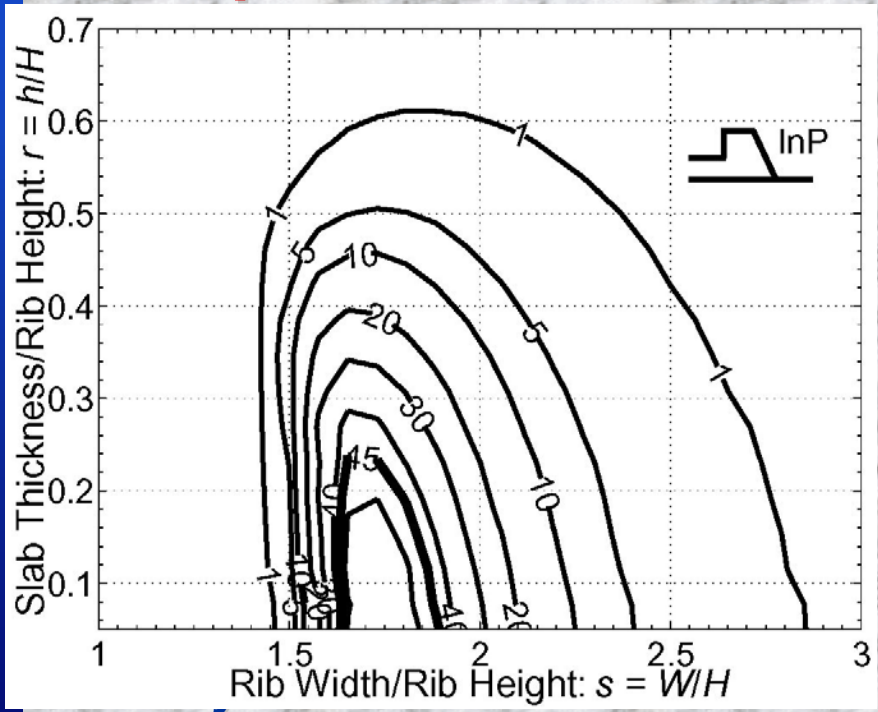


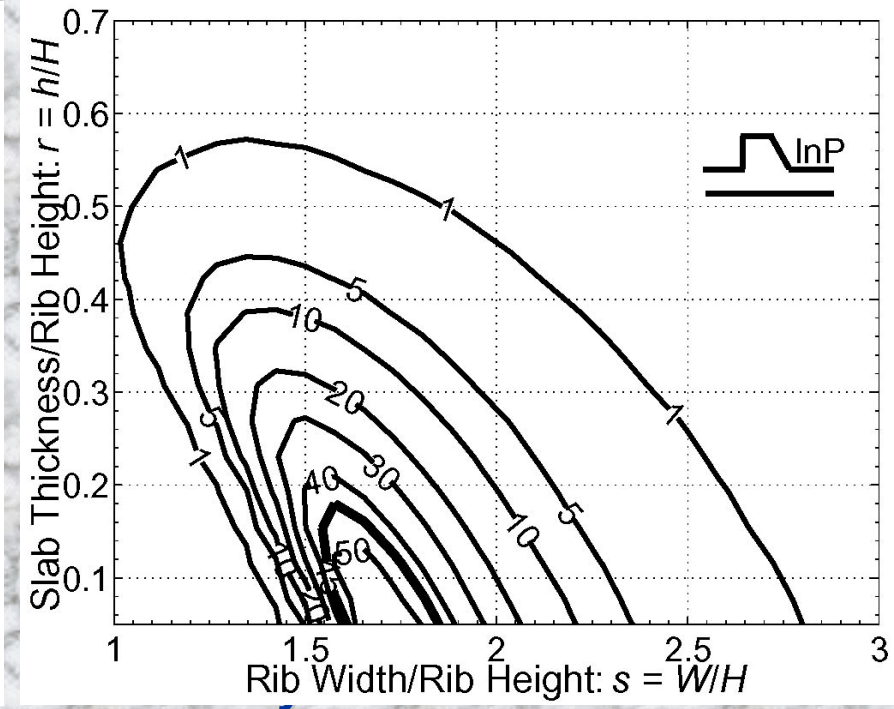
SOI Asymmetric Outer-Slab *SOI Symmetric Outer-Slab*

- **Serials of designs (*H* from submicron to ten μm)**
  - **$\varphi = 45°$ →single-section PR; $\varphi = 22.5°$ → two-section PR; etc.**
- **Asymmetric outer-slab → more parameter choices**
  - **Longer 45° contour**
  - **Larger single-mode region (modes squeezed towards slab)**
- **SM boundaries almost invariant for Deeply-etched devices**

Normalized Design Charts

Compare III-V Materials



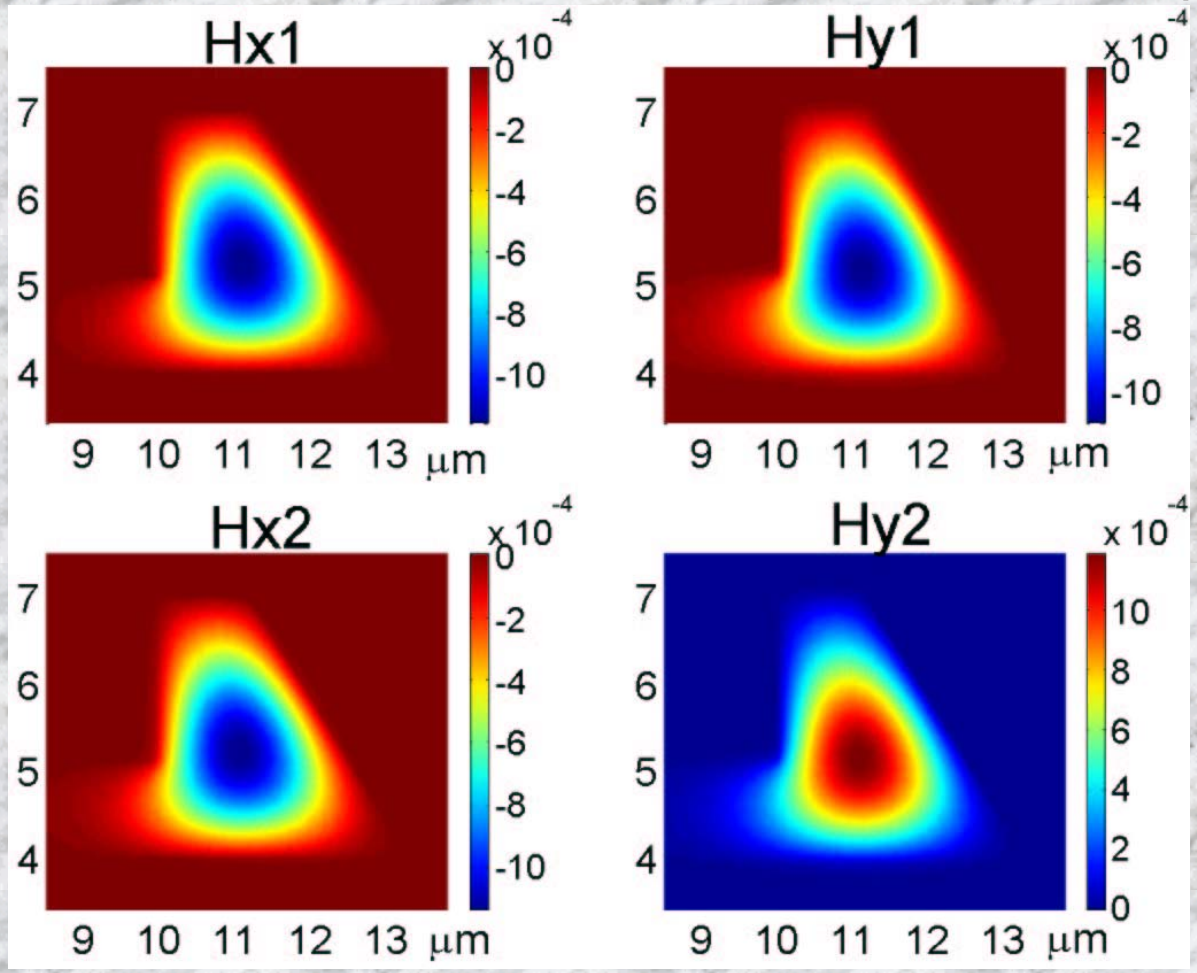


- **Cross-section has to be small (submicron)**
  - **Large coupling loss to single-mode fibers (SMF)**
  - **Single-mode due to small cross-section**
- **Less regions for strong polarization conversion**

Example of Novel SOI PR

A serial of designs, e.g.:

- H=3μm, W=3.3μm, h=1.1μm, h_r=0, θ=54.736°, n_1=3.48, n_2=1.45
- H=2.8μm, W=2.7μm, h=1μm, h_r=0, θ=54.736°, n_1=3.48, n_2=1.45



Identical TE and TM fields

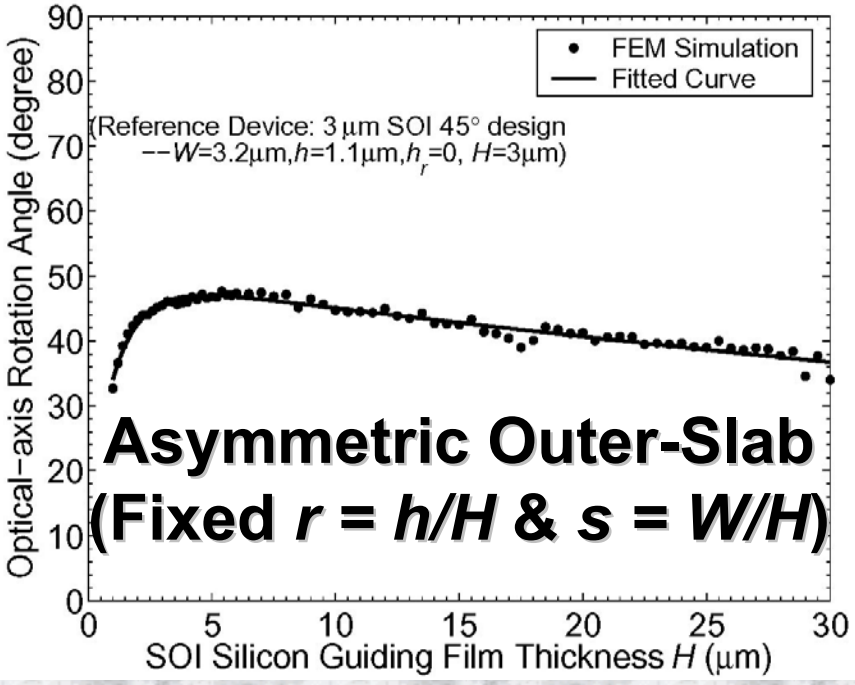
Confined in guiding region

Range of Validity & Empirical Formula for Design

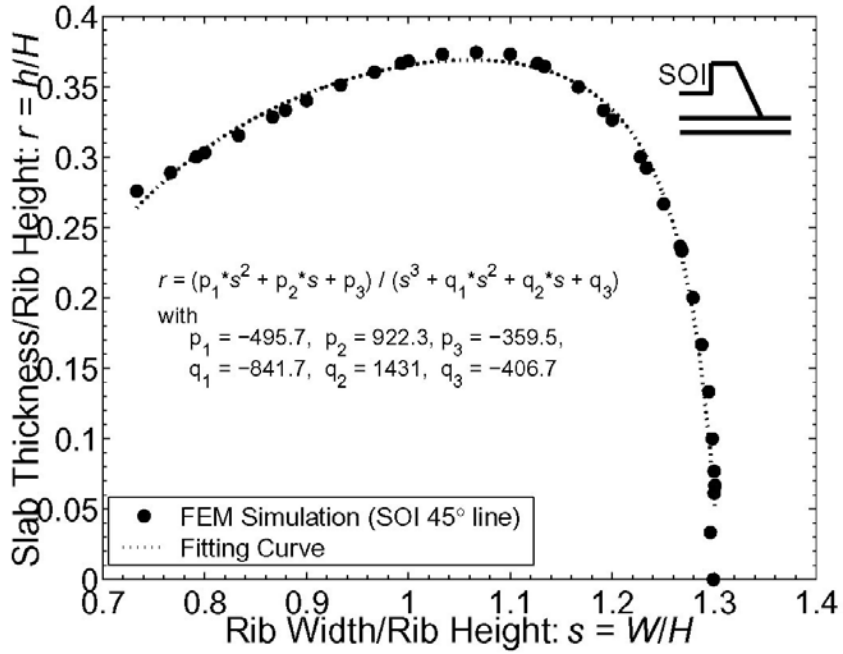
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Similar SOI PR Charts for Various *H*

For $1 \le H \le 30$ μm; Due to Strong Optical Confinement



Asymmetric Outer-Slab (Fixed $r = h/H$ & $s = W/H$)



Empirical Formula

- **Practical Interest: $\varphi = 45°$ → Single-Section PR**
- **Simple rational polynomial**
  - ***periodic & single-section PRs***
  - ***Asymmetric &Symmetric Slab***

$$r = \frac{p_1 \cdot s^2 + p_2 \cdot s + p_3}{s^3 + q_1 \cdot s^2 + q_2 \cdot s + q_3}$$

Fabrication Tolerance

Fabrication Precision:

- 0.1μm precision in low cost processing
- Affects designs differently

Polarization Conversion Efficiency (*PC*)

- Formula for longitudinal-invariant device

$$PC = 4\sin^2\varphi\cos^2\varphi\sin^2\left(\frac{\pi L}{2L_\pi}\right)\times 100\%$$

Polarization Extinction Ratio (*ER*)

- Related to *PC* $ER = 10\log[(1-PC)/PC]$

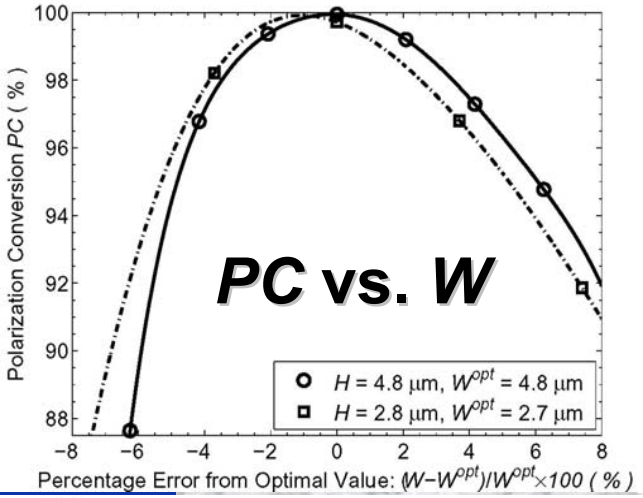
Complete Study for Variations in (*H*, *W*, *h*, θ, *n*)

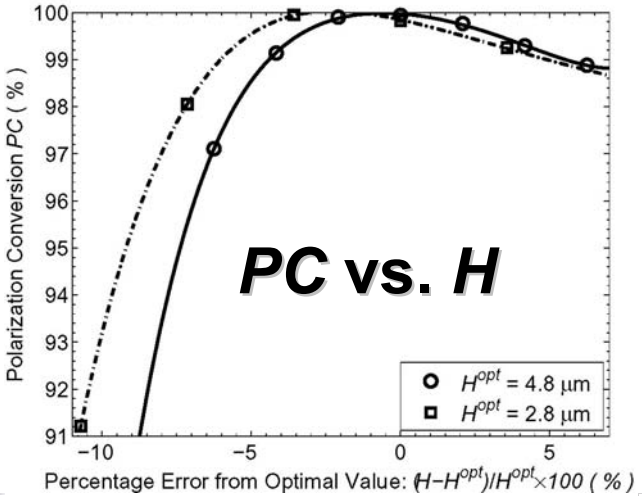
- 3μm design: (*H*, *W*, *h*, h_r) =(2.8, 2.7, 1, 0)μm, *R*=1.04, $L\pi$ =502.4 μm
- 5μm design: (*H*, *W*, *h*, h_r) =(4.8, 4.8, 1.8, 0)μm, *R*=1.01, $L\pi$ =2572 μm

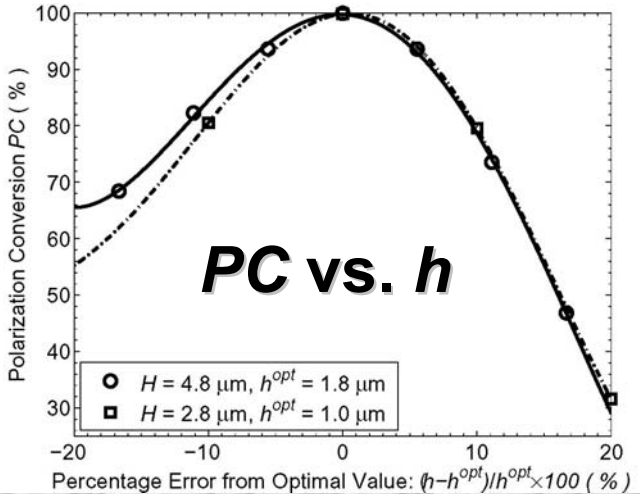
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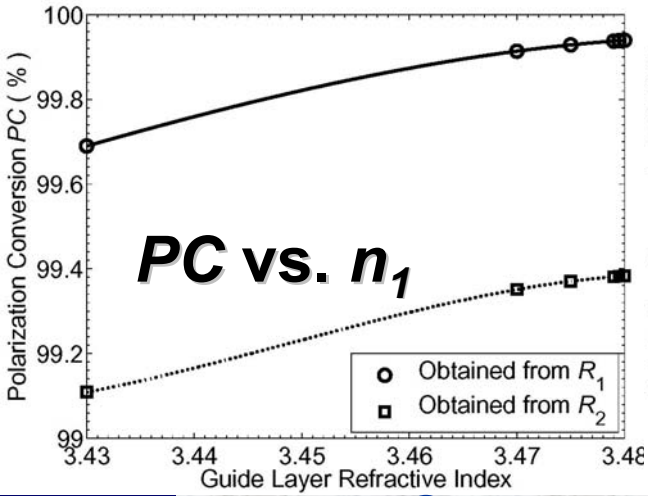
PC Efficiency Variation

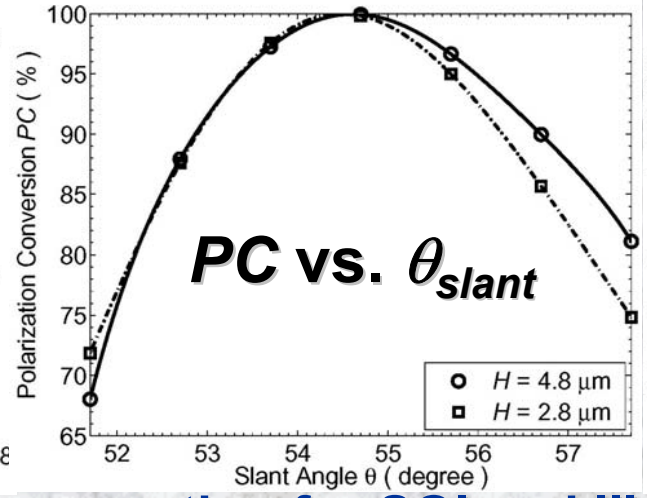
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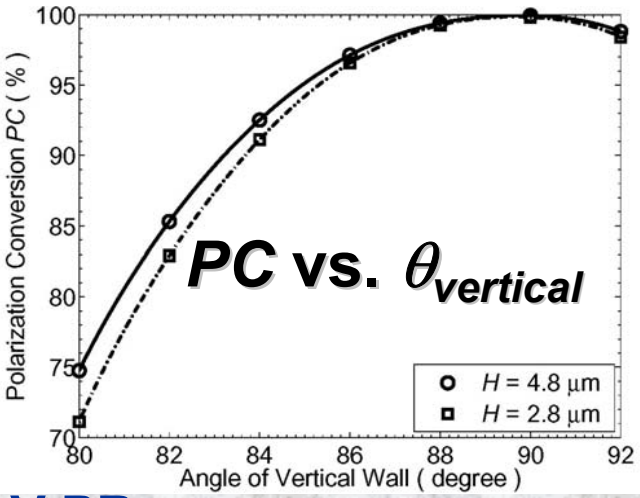






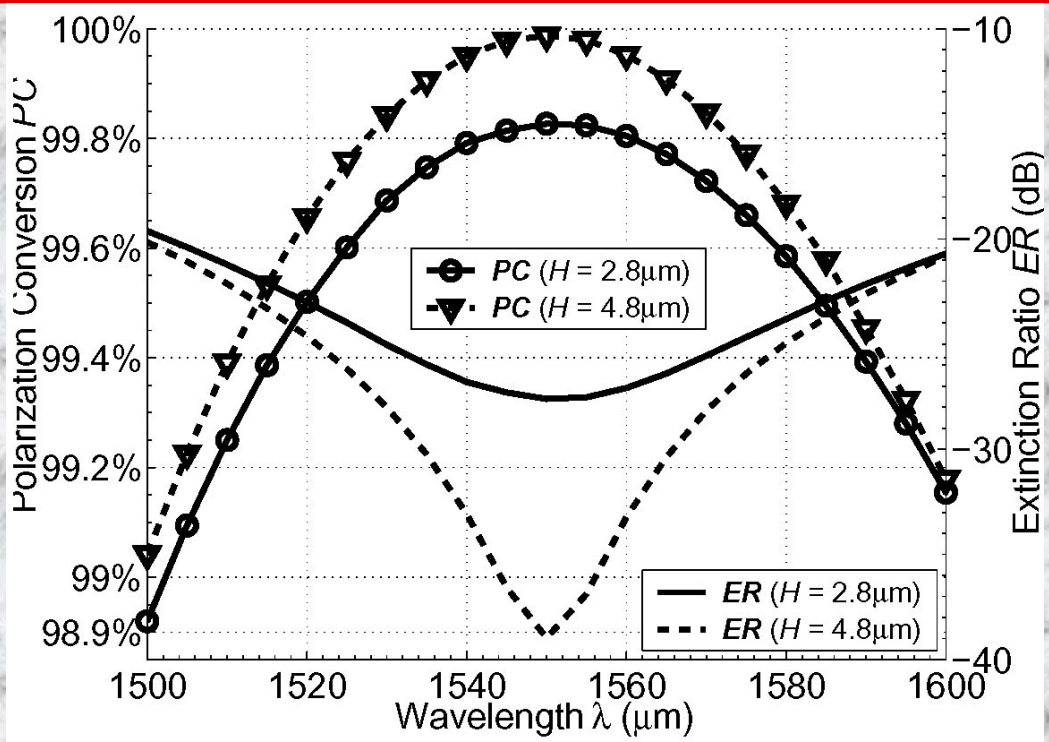






- **Same cross-section for SOI and III-V PRs**
  - → tolerance slightly less in SOI PR
- **SOI can have larger cross-section → better tolerance**
  - →Variation in outer-slab thickness contributes most
  - →Ultra-compact (e.g., <100 μm) SOI PR → Δ=50nm is better

Spectral Property



Excellent Stability for 1.50μm < λ < 1.60μm

- **PC > 99.7% in the ITU-T *C*-band**
- **–25dB (–30dB) polarization crosstalk for 3μm (5μm) device**

Quite suitable for DWDM and PLC

BPM Analysis on SOI PR

FE-BPM Algorithm

$$[A]_k\{\phi\}_{k+1} = [B]_k\{\phi\}_k$$

$$[A]_k = -2jk_0n_0[\widetilde{M}]_k + \alpha\Delta z\left([K]_k - k_0^2n_0^2[M]_k\right)$$

$$[B]_k = -2jk_0n_0[\widetilde{M}]_k - (1-\alpha)\Delta z\left([K]_k - k_0^2n_0^2[M]_k\right)$$

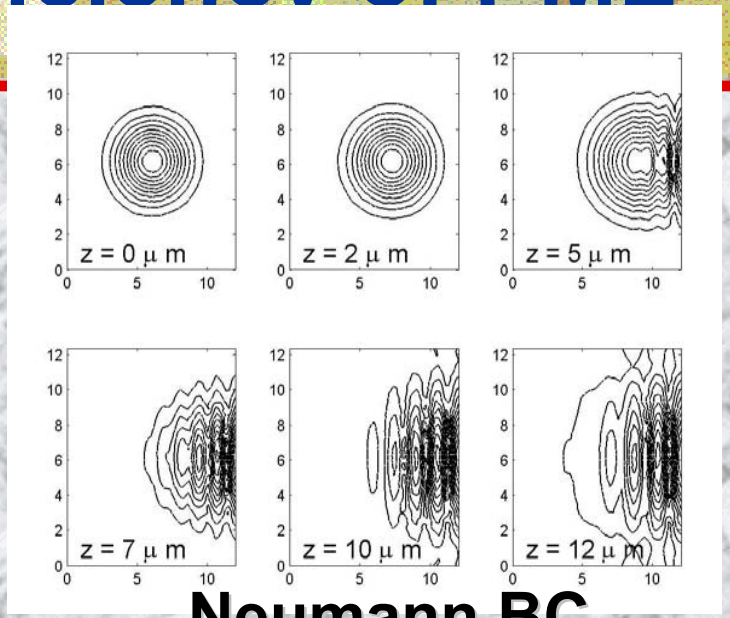
- Fresnel and Wide-Angle
- Crank-Nicholson (CN) α = 0.5, Quasi-CN α = 0.5 + ε

- Adaptive reference index n_0
- Imaginary-Distance BPM as Mode Solver
- Anisotropic Perfectly-Matched-Layer (PML) Boundary Condition (BC)

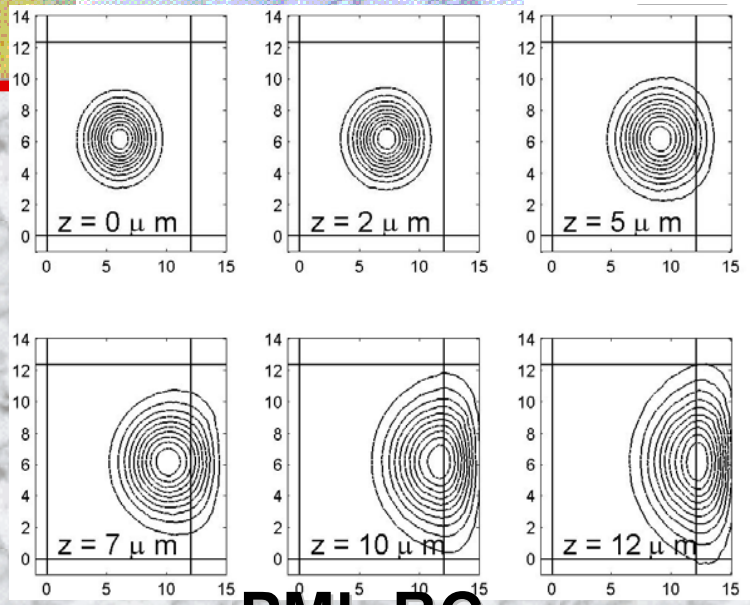
Efficiency of PML

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- Off-Axis BPM

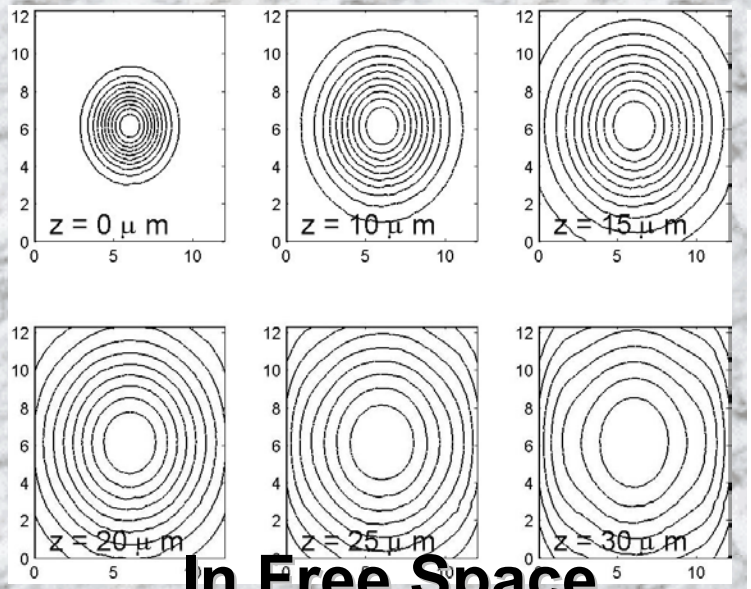


Neumann BC

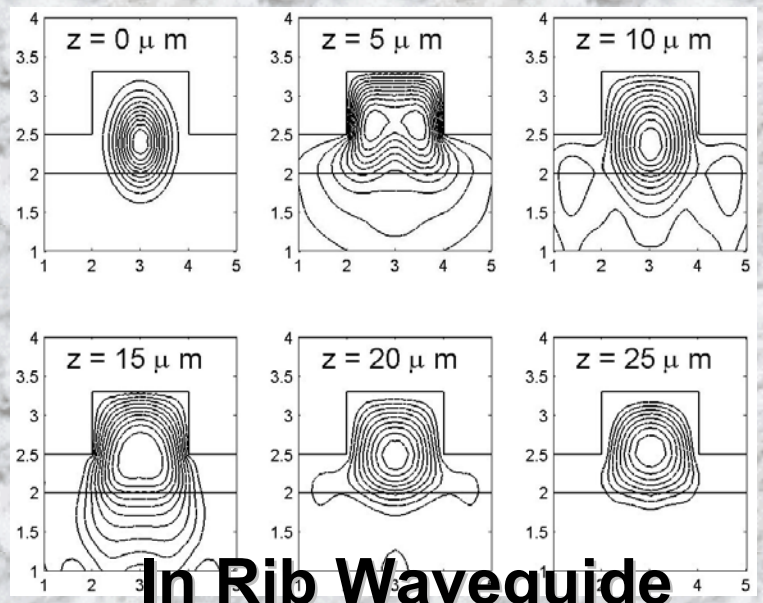


PML BC

- On-Axis BPM



In Free Space



In Rib Waveguide

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Nonunitary of FV-BPM

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Power can be conserved in Scalar FE-BPM

Complex Modes in Lossless Medium

- Matrices [K] and [M] in $[K]\{\phi\} - \beta^2[M]\{\phi\} = \{0\}$
  - Non-Hermitian (in FDM)
  - Hermitian (in FEM) → but $[M]^{-1}[K]$ not Hermitian
- Divergences in propagation scheme
  - Suppress by artificial dissipation (Quasi-CN scheme)
  - Absorbing BC, Complex Pade Operator, etc.

Rewrite BPM Scheme:

$$\{\phi\}\,|_{z+\triangle z} = e^{-j[Q]\triangle z}\{\phi\}\,|_z$$

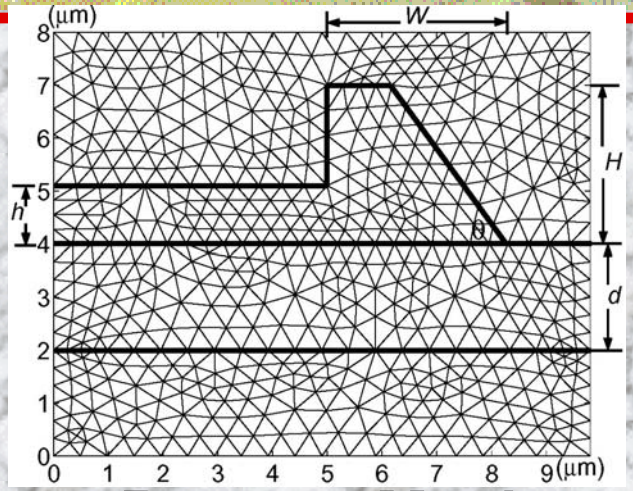
$$e^{-j[Q]\triangle z} = \frac{1-\frac{1}{2}j[Q]\triangle z}{1+\frac{1}{2}j[Q]\triangle z} + O(\triangle z)^3$$

$$[Q] = \frac{-1}{2k_0 n_0}[\widetilde{M}]^{-1}\left([K] - k_0^2 n_0^2[M]\right)$$

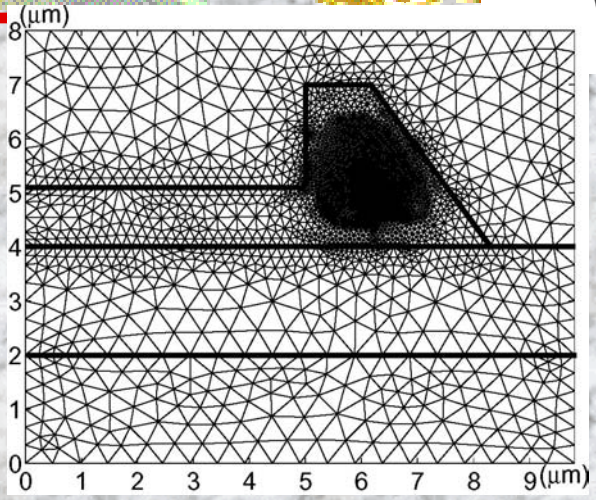
- ***exp(j [Q])*** **unitary for Hermitian [Q]**
- **Hermitian [K] and [M] → [Q] may not Hermitian**

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Mesh

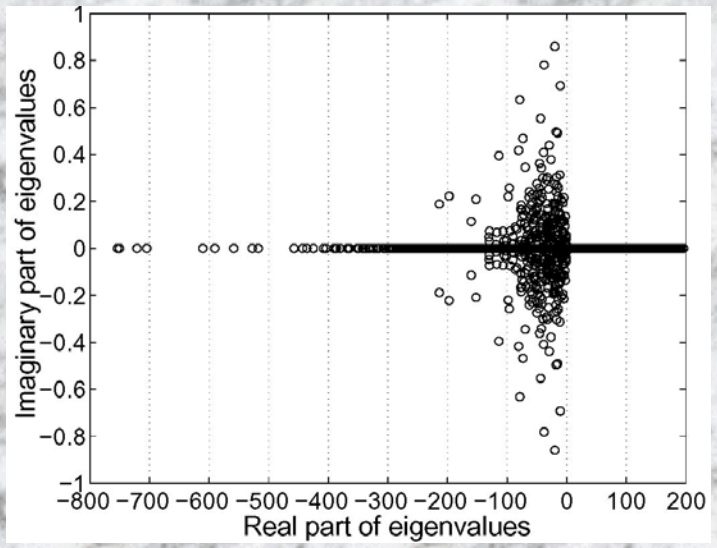


Regular Mesh

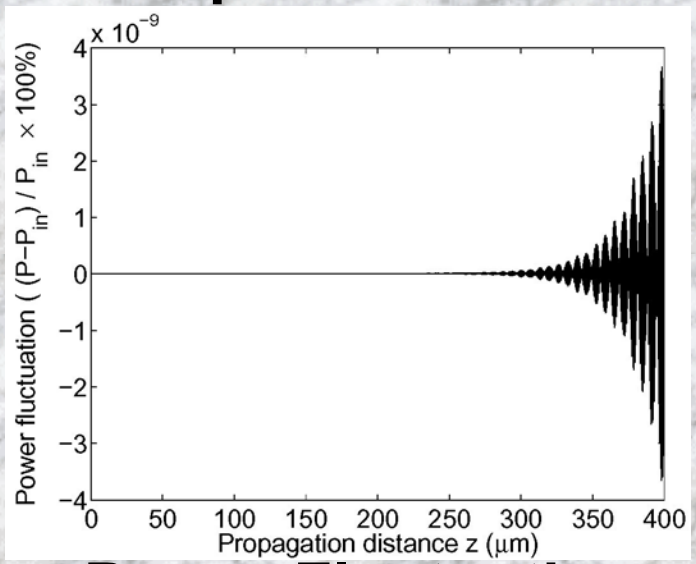


Adaptive Mesh

Eigen-mode & Power



Eigenmode Spectrum



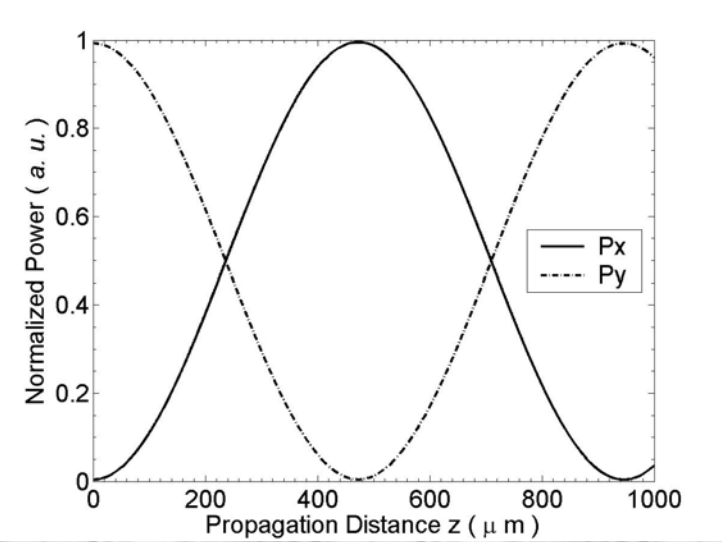
Power Fluctuation

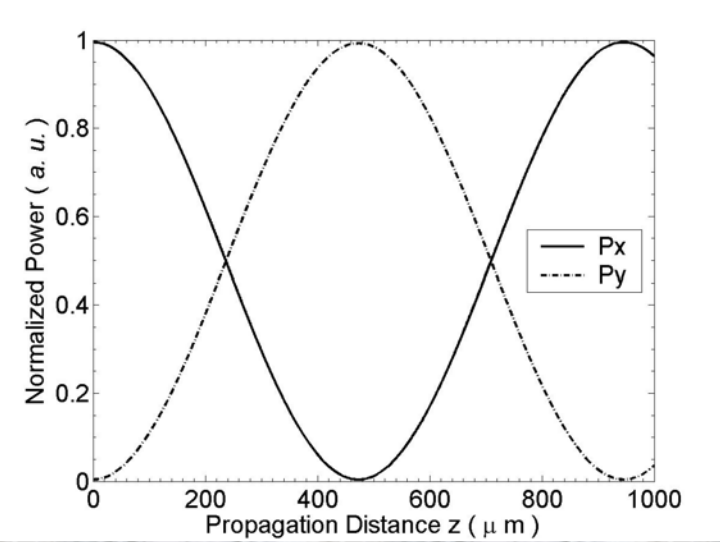
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BPM Results on SOI PR

Quasi CN (α=0.55)

Adaptive Complex Reference Index n_0

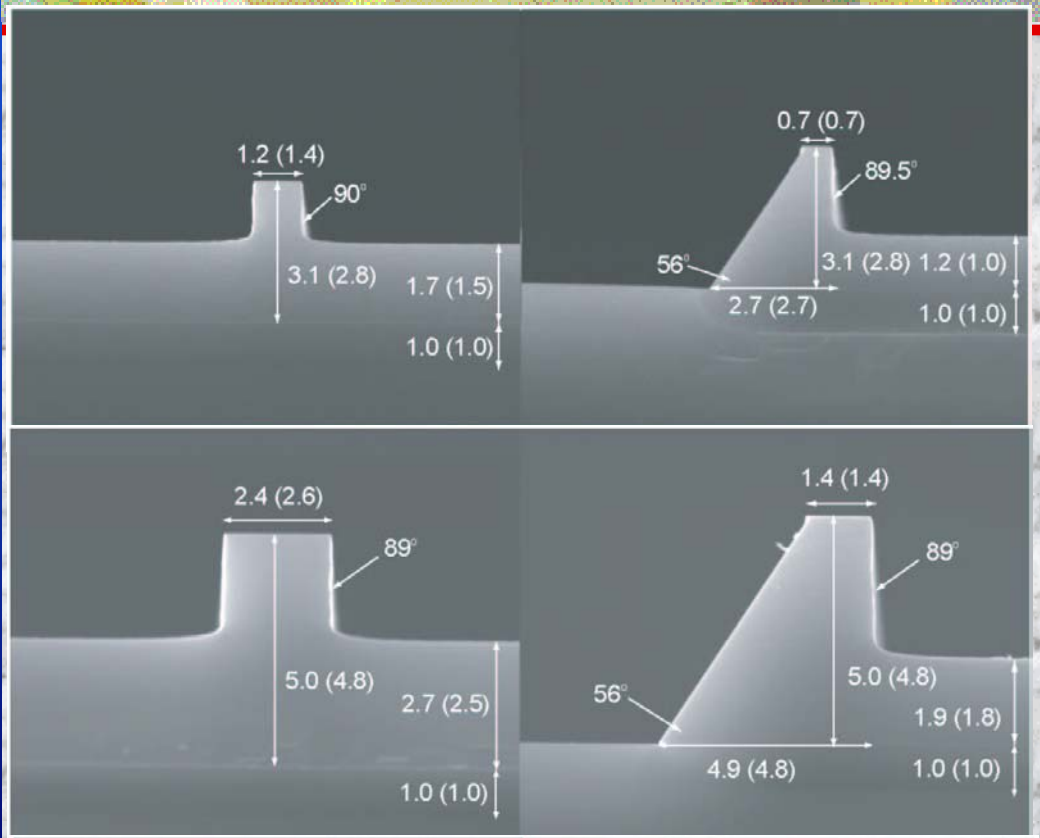


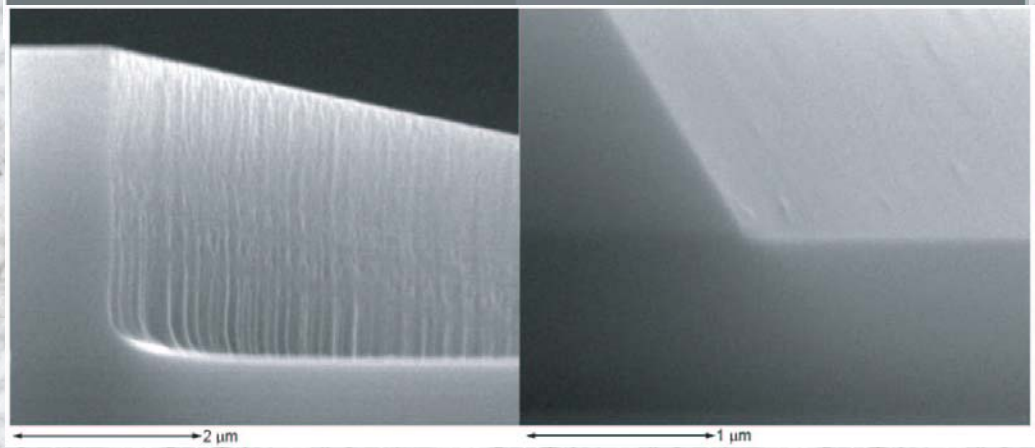


- TE-input TM-input
  - PC = 99.60% and 99.61% for TE- and TM- input
- Numerical Dissipation 0.00048dB/mm

BPM Results Verify the *PC* formula Very Well

Fabricated Device





Procedures

(by Chris Brooks and Prof. Paul E. Jessop)

- BE-SOI — wafer
- RIE — vertical wall
- TMAH — slanted wall.

Quality

- smooth slanted-facet

SEM Precision

- 0.1μm — height /width
- 1° — angles

http://www.eng.uwaterloo.ca/~hdeng/

Performance of Fabricated Devices

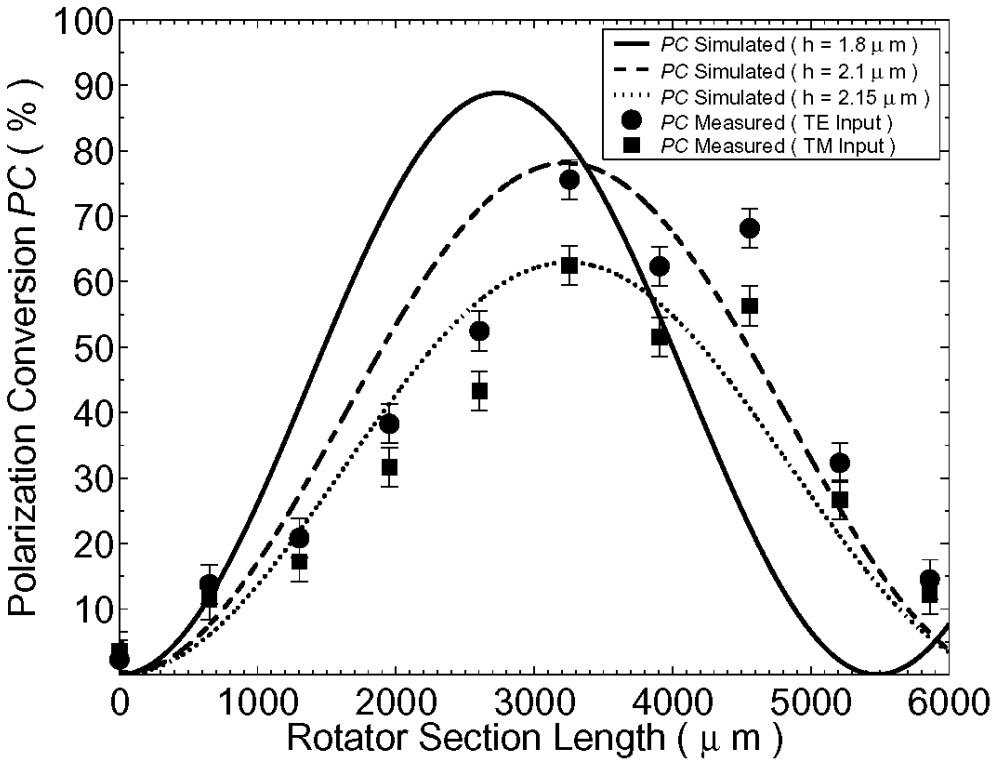
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Optimal Design (H, W, h, h_r) =(4.8, 4.8, 1.8, 0)μm

- R=1.01, $L\pi$ = 2572 μm, PC = 99.98%

Fabricated Device (H, W, h, h_r) =(5.0, 4.9, 1.9, 0)μm

- θ_{slant}=56°, $\theta_{vertical}$=89°, R=1.122, $L\pi$ = 2940 μm
  - Simulated: PC = 88 %
  - Measured: $PC_{TE\rightarrow TM}$ = 75% ± 3% and $PC_{TM\rightarrow TE}$ = 62% ± 3%



- Variation of *h*
  - Most important
- Simulation with *h* = 2.1 μm fits well
  - Rounding of the vertical sidewall corner

  → Effectively increases *h*

Bending Characteristics

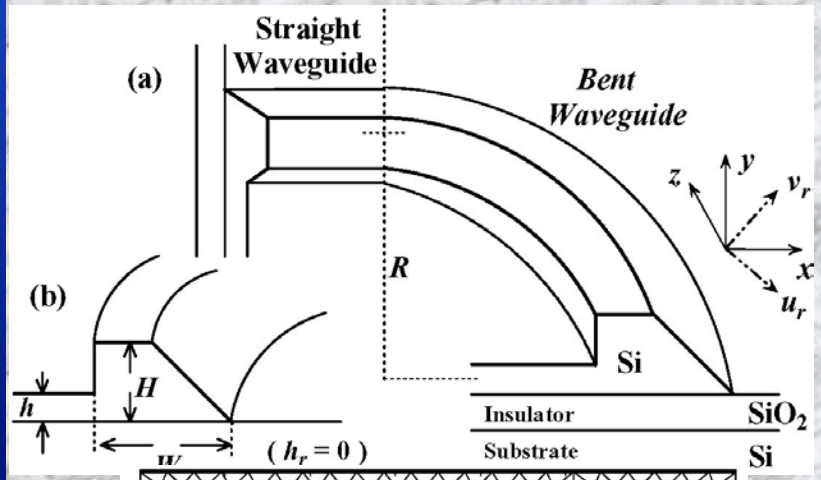
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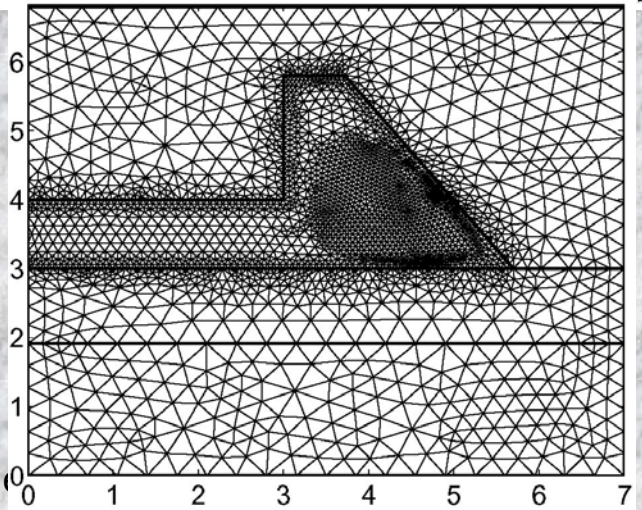
Conformal Mapping

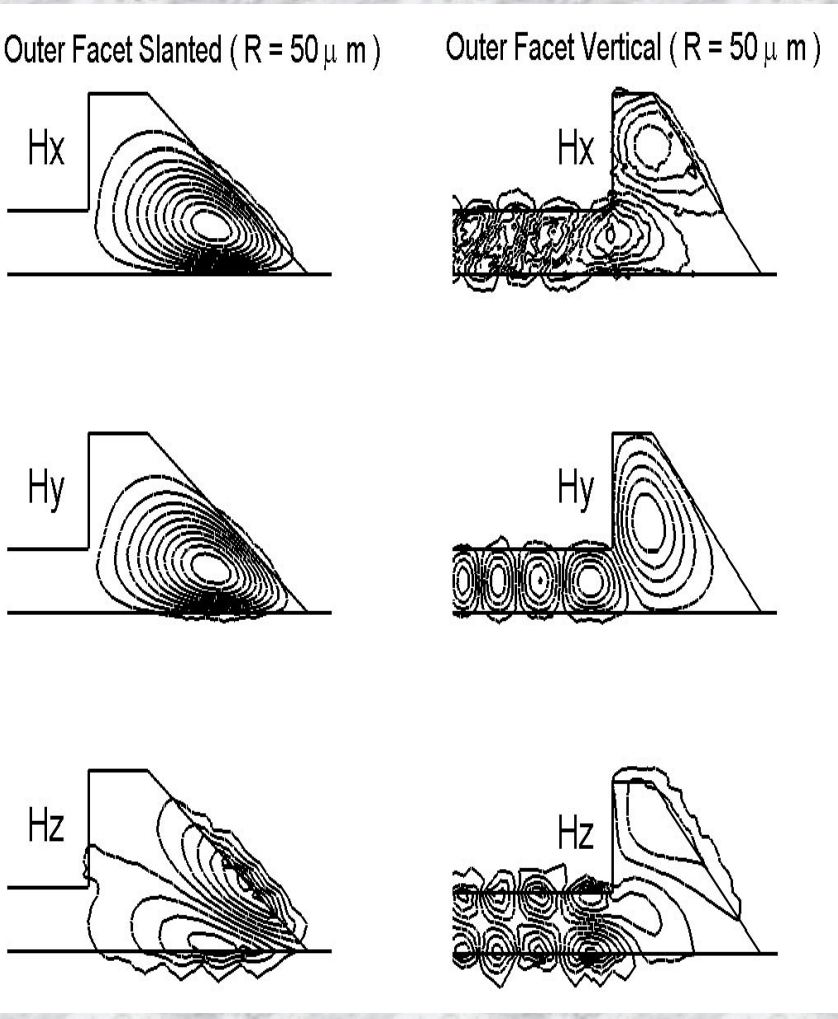
$$n_t(x,y) = n(x,y)(1 + \frac{x}{R_c})$$

- Effective Straight Waveguide (ESW)

Two Bending Directions







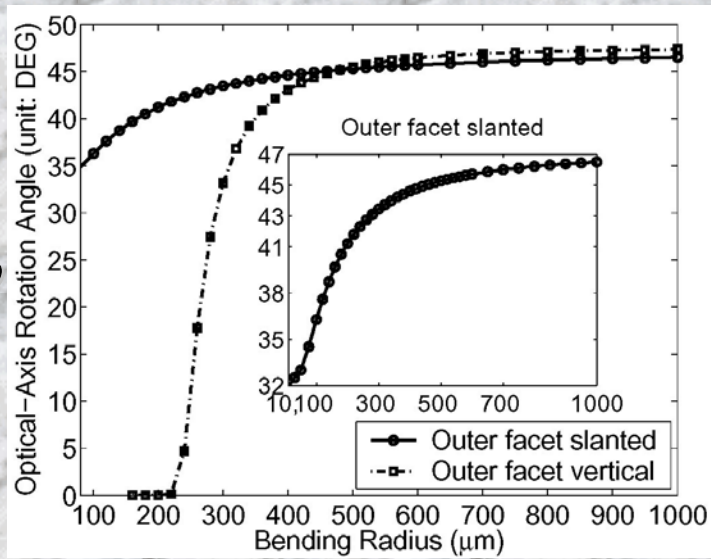
PC and $L\pi$ vs. Bending Radius R_c

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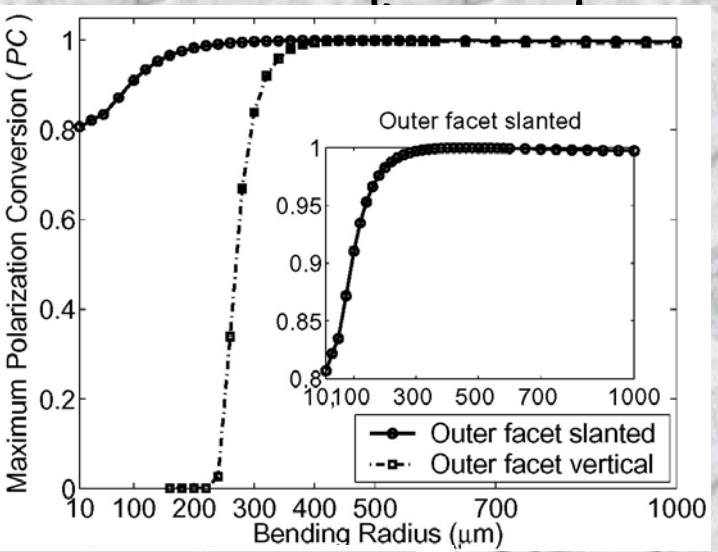
Polarization Conversion Efficiency *PC*

- Outer Facet Slanted → Very Insensitive to R_c > 200 μm

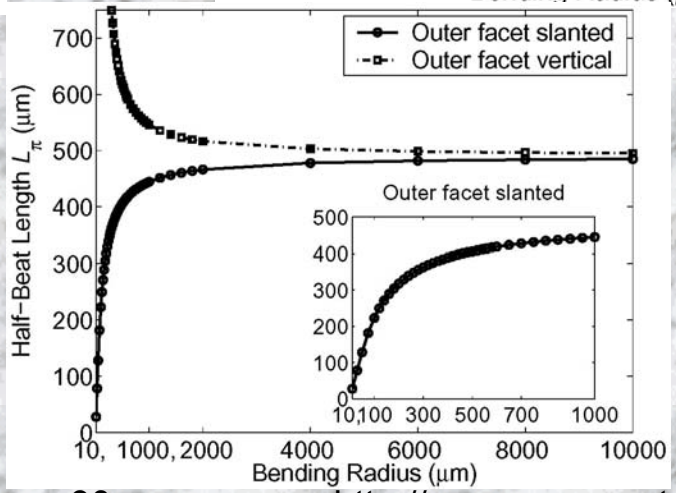
φ



PC



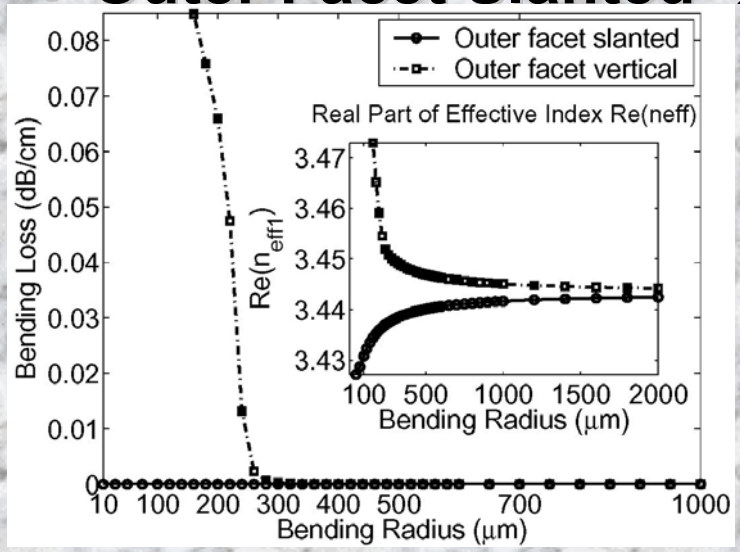
Half-Beat Length $L\pi$



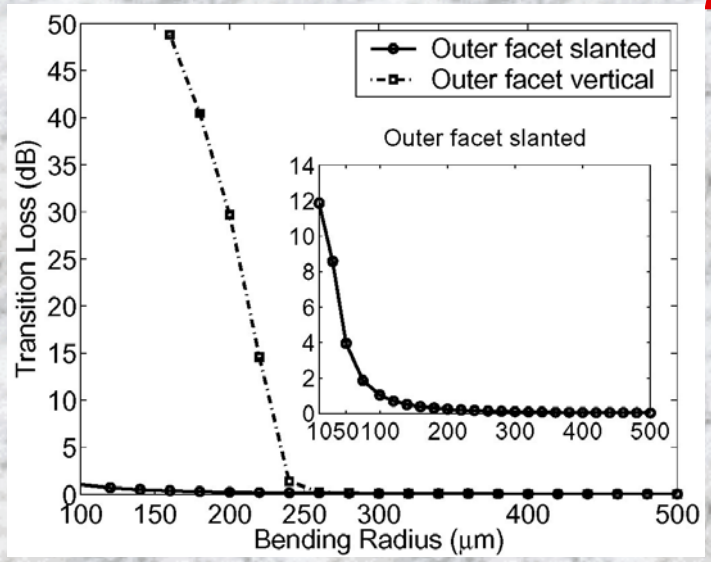
Bending Losses

Radiation Loss L_b

- Outer Facet Slanted → $L_b = 0$



Transition Loss L_T



Summary

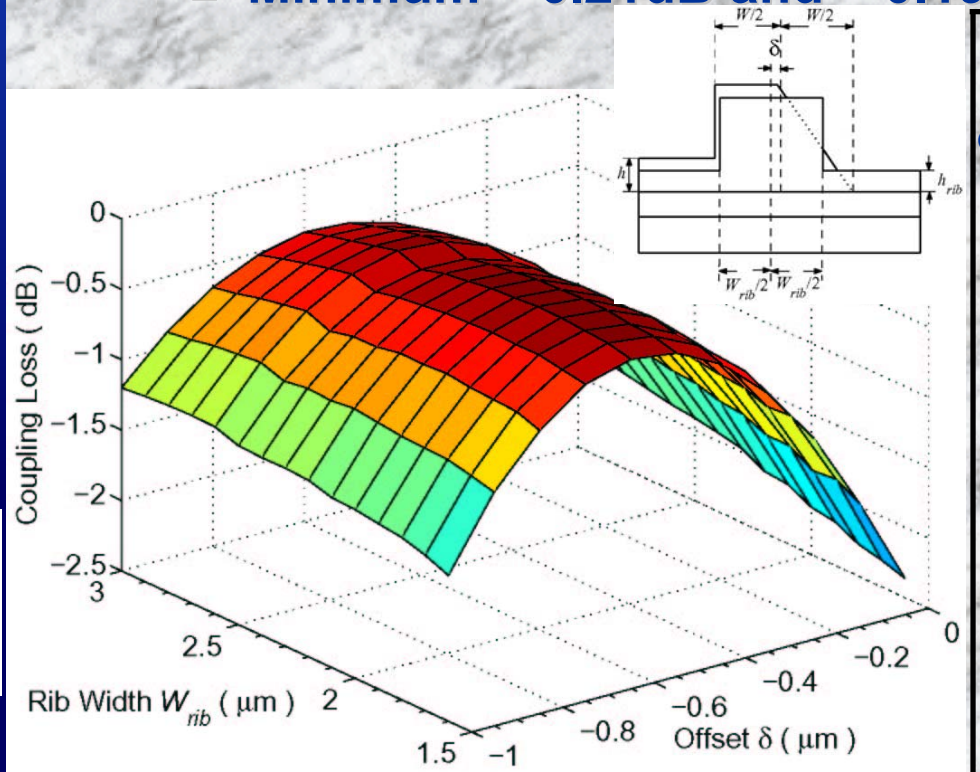
- Asymmetric bending behavior
- Changes both light direction and polarization
- Outer Facet Slanted
  - Very insensitive to bending radius
  - No radiation loss; Very small transition loss
  - Polarization-Insensitive AWG

Coupling Loss Analysis

University of Waterloo

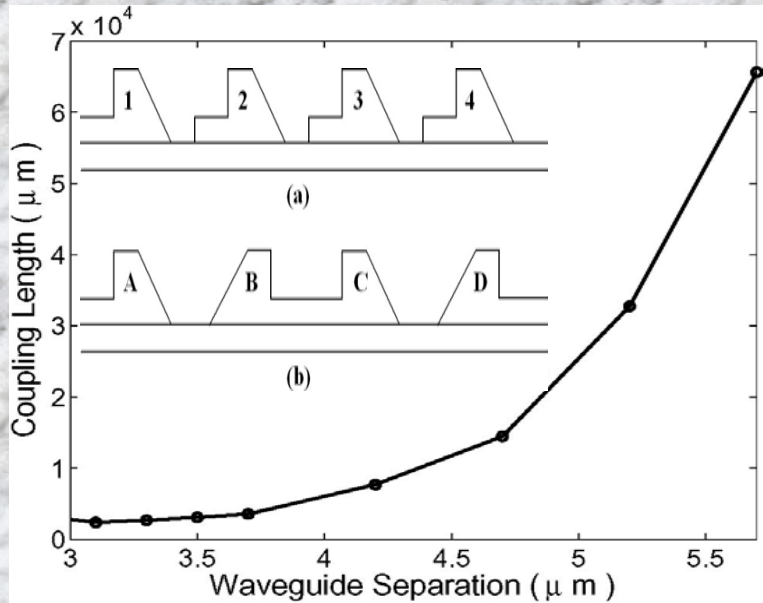
Loss of Butt-Coupled Output

- To Single-Mode Fibers (SMF)
  - Flexible cross-section enables low loss
- To Input/Output SOI Rib Waveguides
  - Good similarity of eigenmodes in PR and I/O WG
  - Position offset improves coupling efficiency
  - Minimum – 0.21dB and – 0.19dB for TE and TM inputs



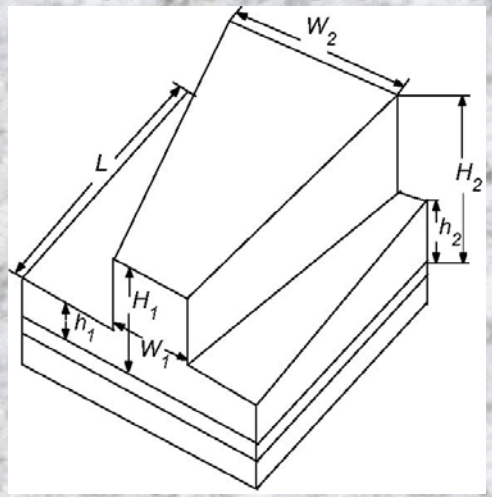
Loss of Parallel PRs

- Compact & Large-scale PIC

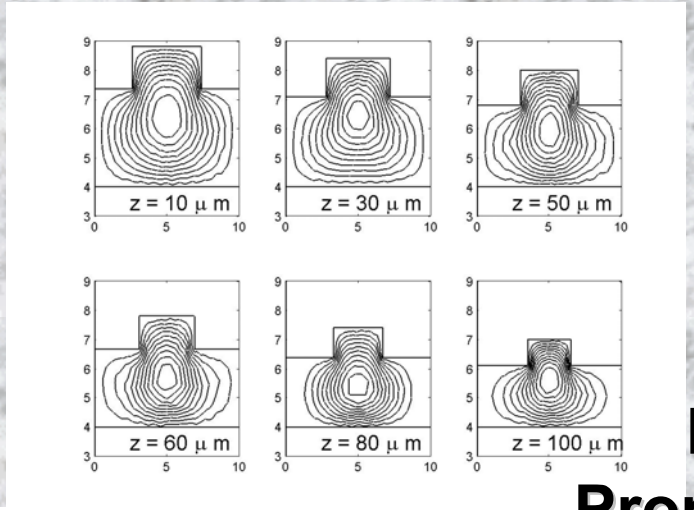


Loss of Tapered Output

- Vertical SOI Taper with mono-mode Cross-section

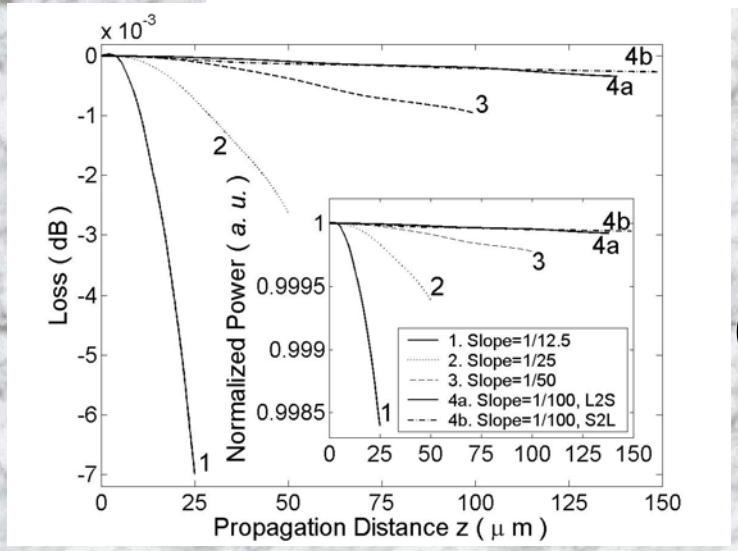


SOI Taper



Field Propagation

- Low loss
- Compact
  - As short as 25 μm



Loss ($\times 10^{-3}$ dB)

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Conclusions and Future Topics

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SOI Polarization Rotators

- A category of novel SOI PR
- General design rules (for SOI & III-V PRs)
- Novel asymmetric out-slab configuration
- Fabrication tolerance, power/polarization exchange, bending, loss & Coupling
- Experiment analysis

Numerical algorithms

- Accurate FV-FEM mode solver and BPM;
- Efficient PML BC and Unitarity analysis.

Suggested Future Research

- Numerical algorithm Adaptive remeshing; Node renumbering; FV-FE-BPM with nodal elements & no spurious modes; Tapered FE-BPM; Parallel bends (e.g.,in AWG)
- Silicon photonics Improved fabrication (nano-photonics) Single-mode and bending; PI-SOI-AWG; Other SOI tapers.



Acknowledgement & Publications

Acknowledgement

- Dr. D. O. Yevick, Dr. P. E. Jessop, Dr. S. K. Chaudhuri, C. Brooks

Related Publications

1. H. Deng, D. O. Yevick, C. Brooks, and P. E. Jessop, "Design rules for slanted-angle polarization rotators," *IEEE/OSA J. Lightw. Technol.*, vol. 23, no. 1, pp. 432—445, Jan. 2005.
2. H. Deng and D. O. Yevick, "The non-unitarity of finite-element beam propagation algorithms," *IEEE Photon. Technol. Lett.*, vol. 17, no. 7, pp. 1429-1431, July 2005.
3. H. Deng, D. O. Yevick, and S. K. Chaudhuri, "Bending characteristics of asymmetric SOI polarization rotators," *IEEE Photon. Technol. Lett.*, vol. 17, no. 10, Oct. 2005, to appear.
4. H. Deng, D. O. Yevick, C. Brooks, and P. E. Jessop, "Fabrication tolerance study of silicon-on-insulator polarization rotators," submitted to JOSA:A.
5. C. Brooks, P. E. Jessop, H. Deng, D. O. Yevick, and G. Tarr, "Passive polarization rotating waveguides in silicon-on-insulator," *Optical Engineering*, accepted.
6. H. Deng, D. O. Yevick, C. Brooks, and P. E. Jessop, "Design procedures for slanted-angle SOI polarization rotators," in OSA/IEEE *OFC'04*, Los Angles, CA, Feb. 22-27, 2004, MF-41.
7. C. Brooks, P. E. Jessop, H. Deng, D. O. Yevick, and G. Tarr, "Polarization rotating waveguides in silicon on insulator," in OSA *IPR'04*, San Francisco, CA, June 30-July 2, 2004, IFG4.
8. C. Brooks, "Polarization rotating waveguides in silicon-on-insulator," Master's thesis, McMaster University, Hamilton, Ontario, Canada, Mar 2005.
9. H. Deng, "Design and Characterization of Silicon-on-Insulator Passive Polarization Converter with Finite-Element Analysis, " Ph.D. Dissertation, University of Waterloo, Ontario, Canada, June 2005.

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Thanks for Comments

