

Silicon-on-Insulator Polarization Converter and Photonics-Related Research

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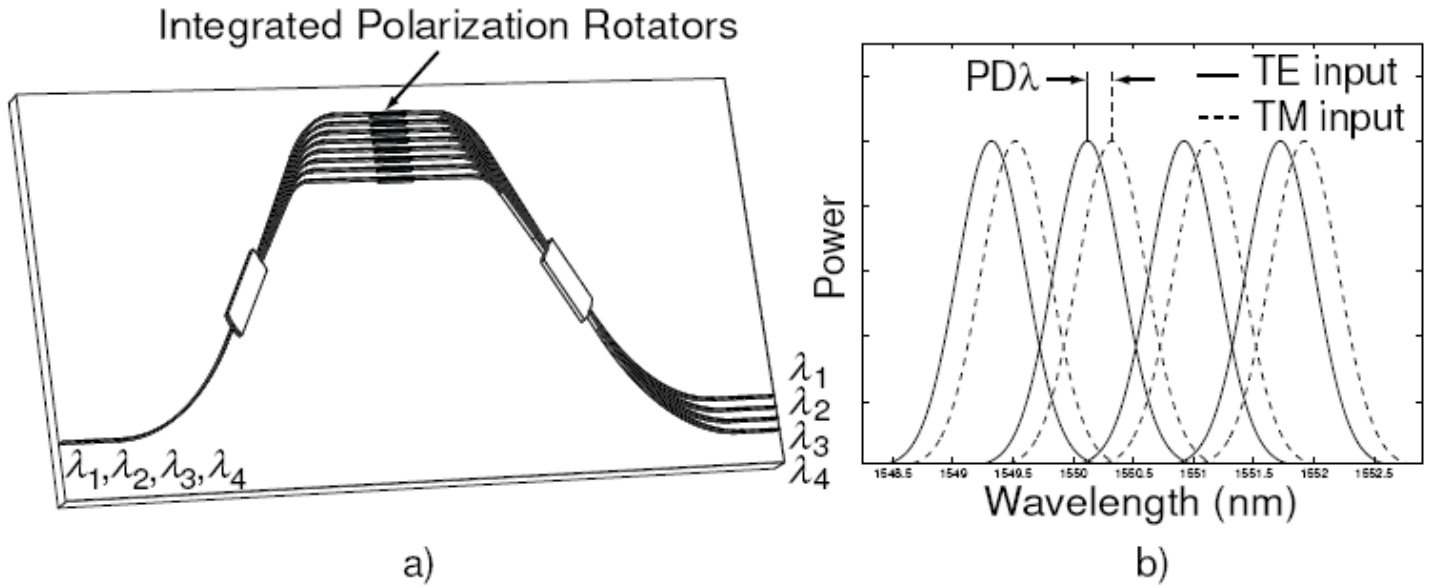
Sept. 19, 2007

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Overview

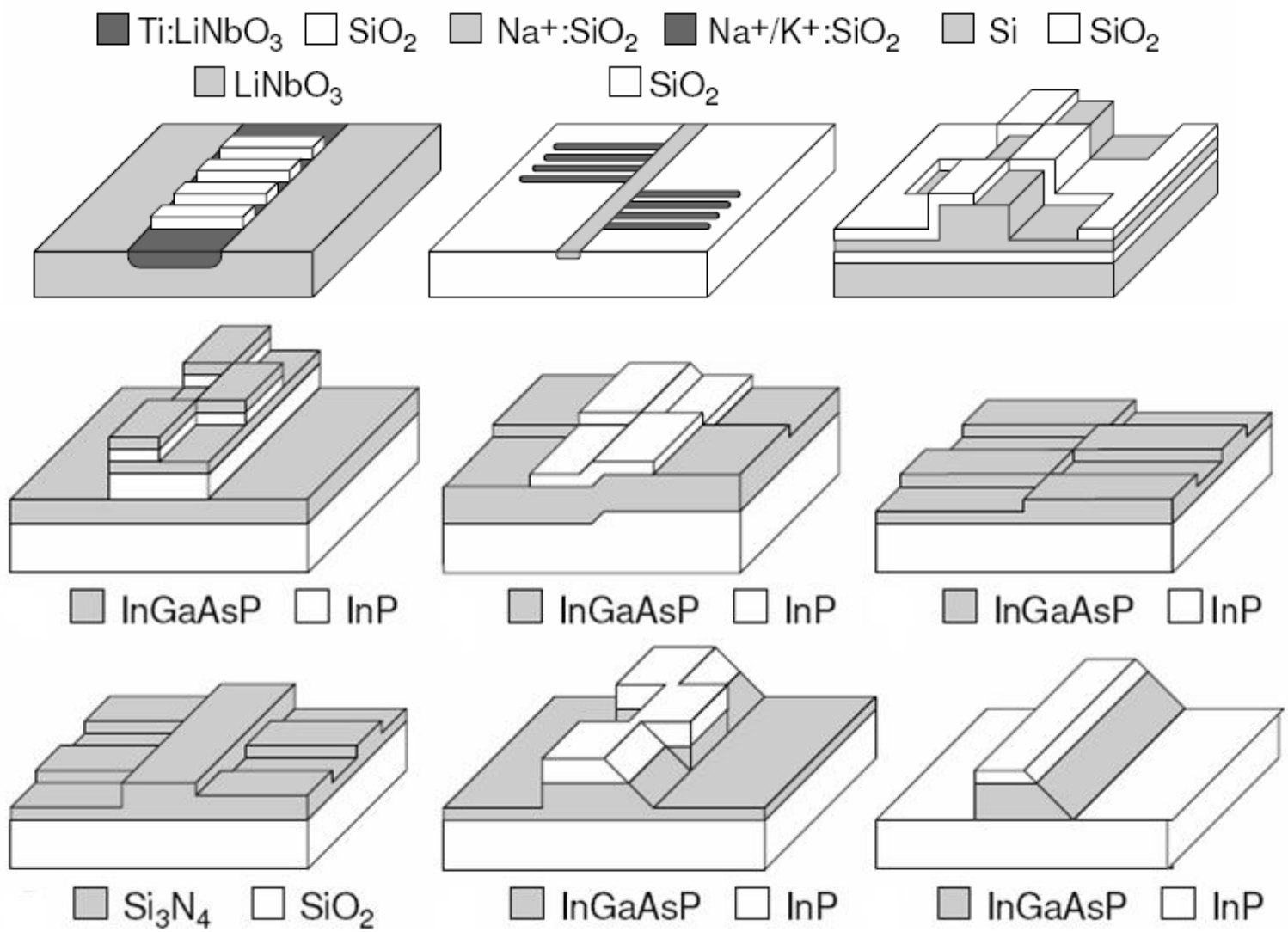
- Integrated Photonic Polarization Converter
  - Silicon-on-Insulator (SOI)
  - Finite-Element Method (FEM) and Finite-Element Beam-Propagation Method (FE-BPM)
  - Fabrication and Measurement
  - Bending and Coupling Analysis
- Other Photonics-Related Experience
  - Optical Communication Network
  - Nanophotonics and Nanofabrication
  - Electronic Design Automation
- Summary

Importance of Polarization Control



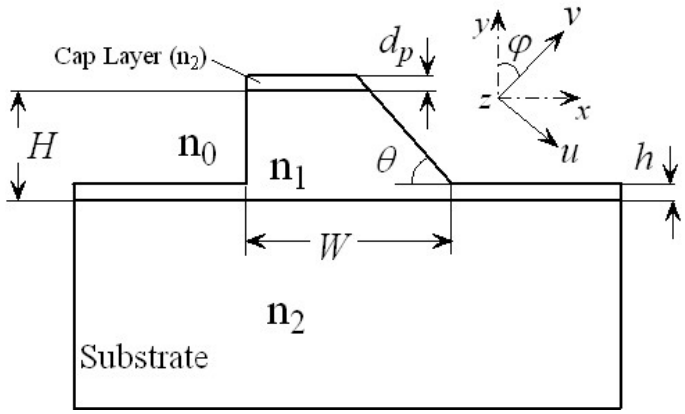
- **Birefringence causes PMD and PDL**
  - **Signal distortion and loss**
  - **Bit rate and bandwidth limitation**
- **Polarization converter**
  - ***Active***
    - **Electro-optic and thermal-strain effects**
    - **Voltage-controlled electrode → Difficulties**
  - ***Passive***
    - **III-V materials (AlGaAs/GaAs and InGaAsP/InP)**

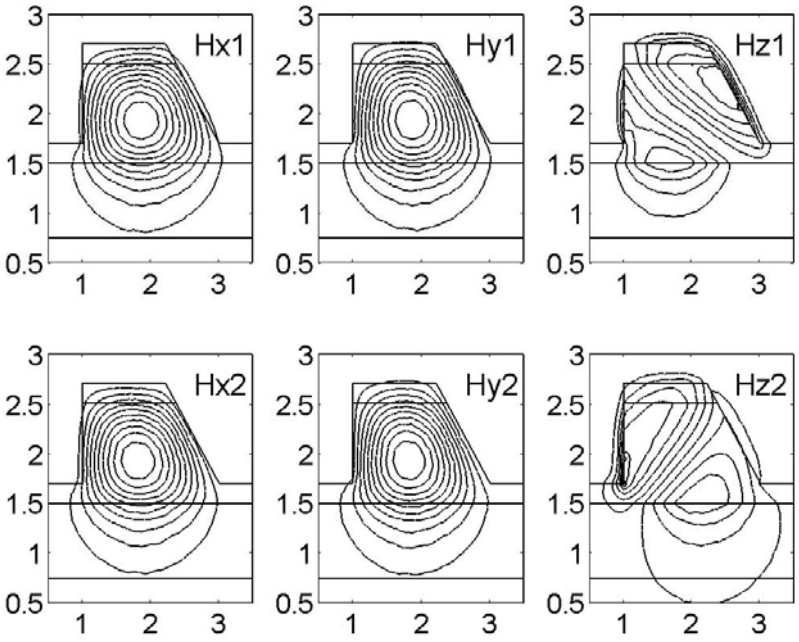
Previous Polarization Converters

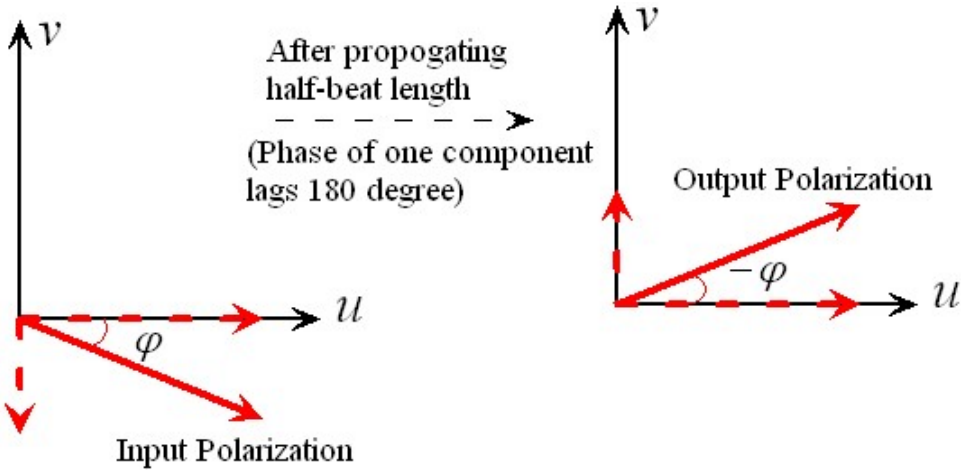


Single-Section Polarization Rotator (PR)

- **Advantage**
  - Strongly-hybridized modes.
  - Easy fabrication. Compact size. Low loss.
- **Principle**
  - Rotation of optical axes (*u*,*v*)
    - *slow- / fast- axis → Phase delay*
    - *Half-beat Length Lπ*
  - Polarization angle to *x*-axis
    - *φ* in → *−φ* out
  - Optical-Axis rotated 45°
    - *TE* in → *TM* after *Lπ*

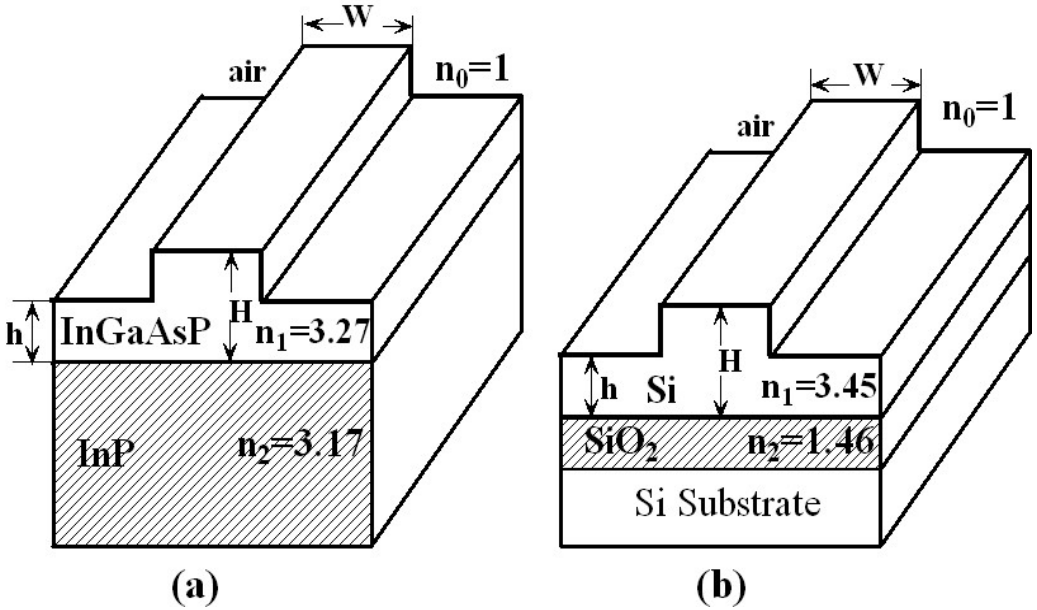






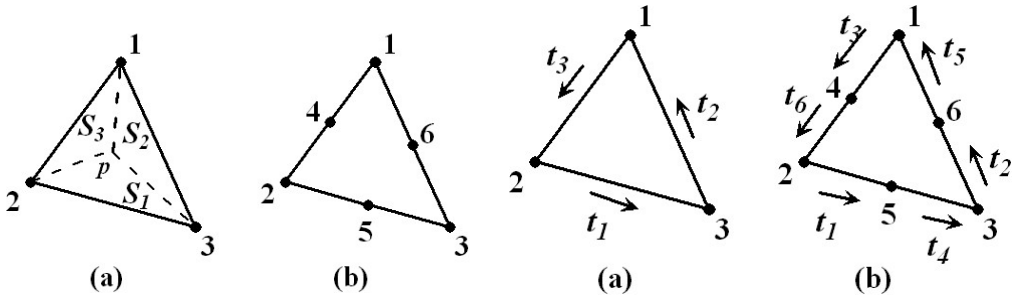
Silicon-on-Insulator (SOI)

- Main platform for *Silicon Photonics*
- Compatible with electronics (VLSI CMOS)
  - low cost OEIC
- Strong optical confinement
  - Compact and low loss
- Our first application in PR



Finite Element Method (FEM)

- **Category by Polarization Effect**
  - **Scalar (SC)**
  - **Semi-Vectorial (SV)**
  - **Full-Vectorial (FV)**



Nodal elements

Mixed elements
(Avoid spurious modes)

- **Advantage**
  - **Accurate and efficient**
  - **Versatile**
    - ***Arbitrary-shape, anisotropic, inhomogeneous, lossy***
  - **Non-uniform unstructured mesh & Adaptive Mesh**
    - **FDM –– Limited by rectangular grids. Inaccurate results for slanted-angle waveguides.**

FV-FEM with Mixed Element

- **Procedure**
  - **Obtain functional → Divide problem region → Derive elementary matrix → Assemble global system → Solve eigenvalue equation**

$$\nabla \times ([p] \nabla \times \phi) - k_0^2 [q] \phi = 0 \qquad F = \iint_{\Omega} \left[(\nabla \times \phi)^* \cdot ([p] \nabla \times \phi) - k_0^2 [q] \phi^* \cdot \phi \right] \mathrm{d}x \, \mathrm{d}y$$

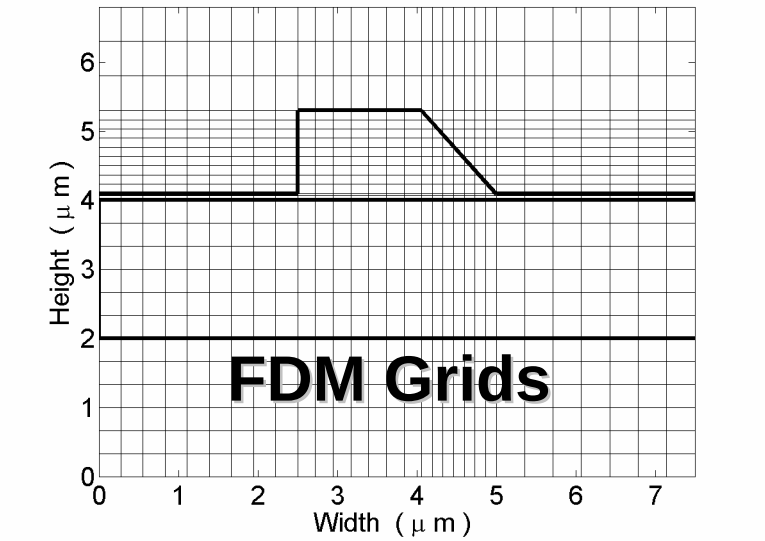
$$\phi = \begin{bmatrix} \phi_x \\ \phi_y \\ \phi_z \end{bmatrix} = \begin{bmatrix} \{U\}^T \{\phi_t\}_e \\ \{V\}^T \{\phi_t\}_e \\ j\{N\}^T \{\phi_z\}_e \end{bmatrix} e^{j\beta z}$$

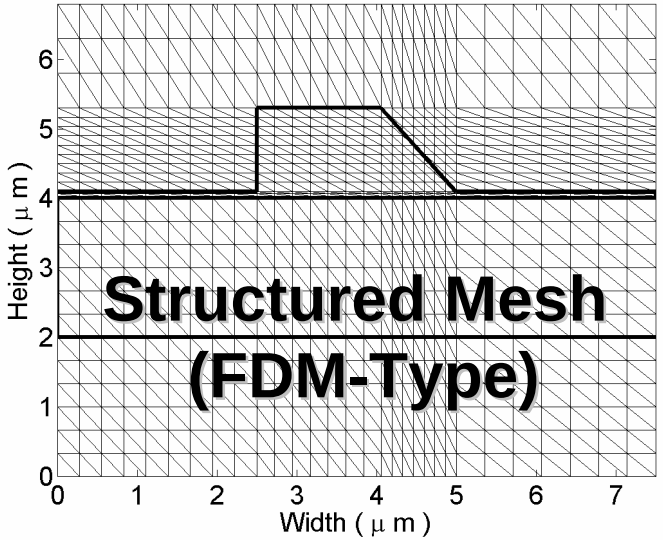
- **General Eigenvalue Equation**
  - **Only Transverse Components** $[K_{tt}]\{\phi_t\} = \beta^2 \left([M_{tt}] + [M_{tz}][M_{zz}]^{-1}[M_{zt}] \right) \{\phi_t\}$
    - **Matrix Inverse → Limitations (CPU, Memory, Sparsity)**
  - **Improved Formulation through** $\phi_z = \beta \phi_z'$

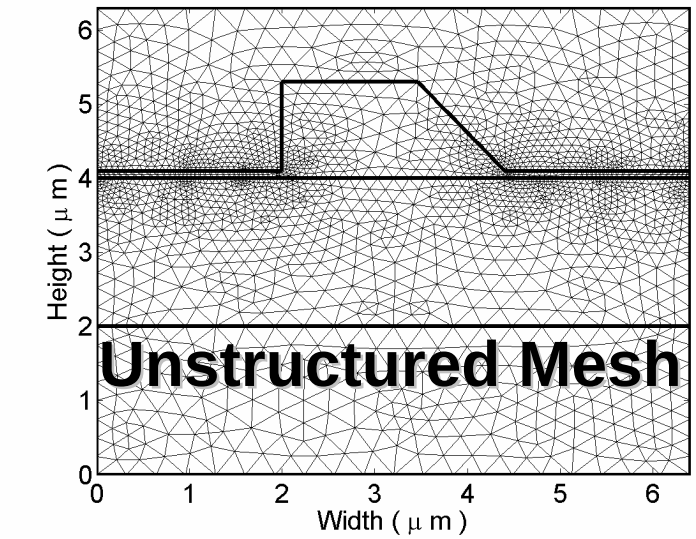
$$[K]\{\phi\} - \beta^2 [M]\{\phi\} = \{0\}$$

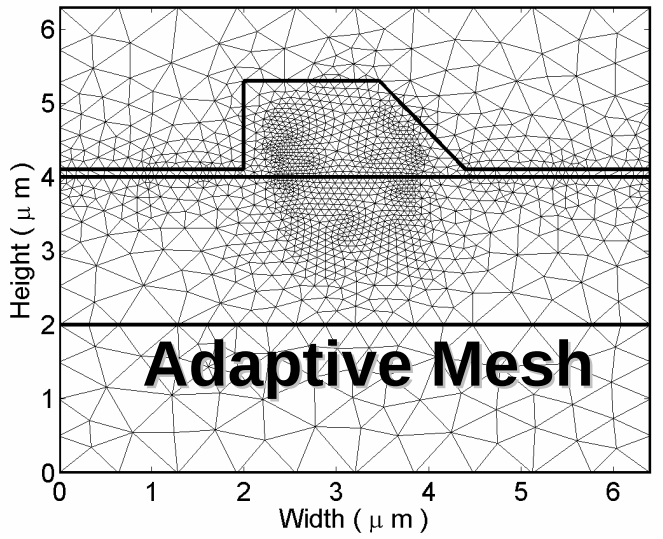
$$[K] = \begin{bmatrix} [K_{tt}] & [0] \\ [0] & [0] \end{bmatrix}, [M] = \begin{bmatrix} [M_{tt}] & [Mtz] \\ [Mzt] & [Mzz] \end{bmatrix} \text{ and } \{\phi\} = \begin{Bmatrix} \phi_t \\ \phi_z' \end{Bmatrix}$$

Meshes









Unstructured meshes better than FDM-type grids

Finite-Element Beam-Propagation Method (FE-BPM)

- **FE-BPM Final Algorithm**

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

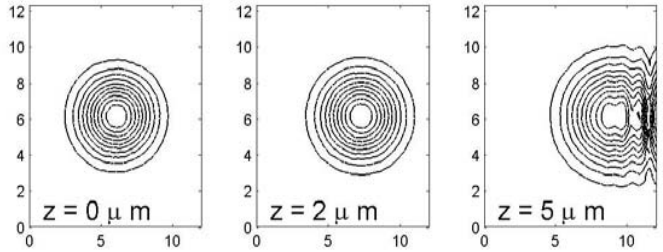
$$[A]_k = -2jk_0n_0[\widetilde{M}]_k + \alpha\Delta z\left([K]_k - k_0^2n_0^2[M]_k\right)$$

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

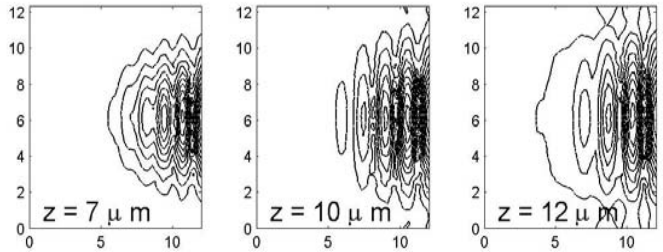
  - **Fresnel and Wide-Angle**
  - **Crank-Nicholson (CN) α = 0.5, Quasi-CN α = 0.5 + ε**
- **Adaptive reference index *n_0***
- **Imaginary-Distance BPM as Mode Solver**
- **Anisotropic Perfectly-Matched-Layer (PML) Boundary Condition (BC)**

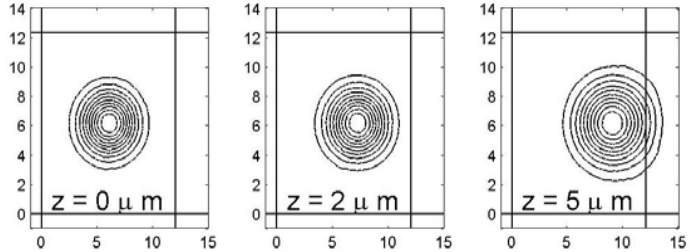
Perfectly Matched Layer (PML)

Off-Axis BPM

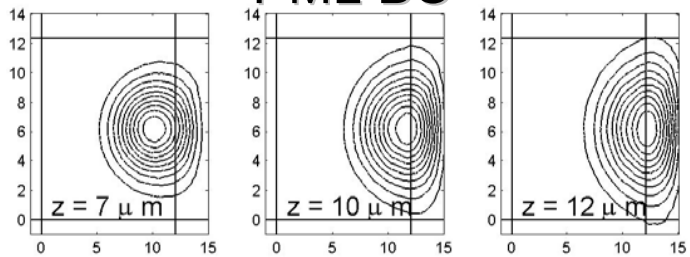


Neumann BC

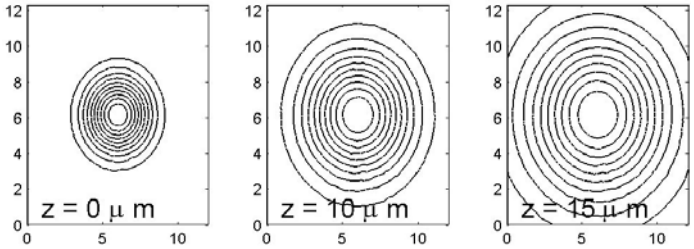




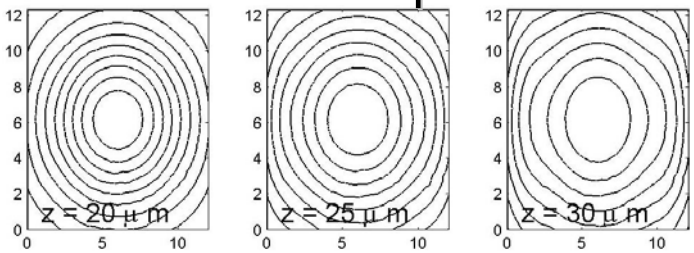
PML BC

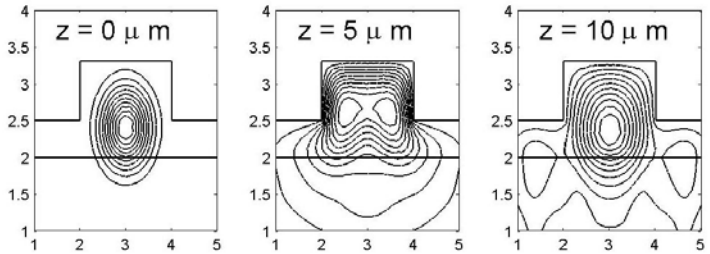


On-Axis BPM (PML)

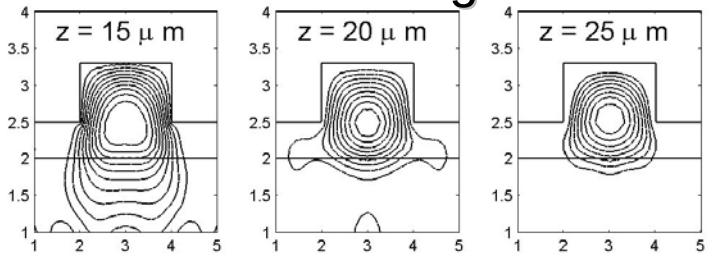


In Free Space

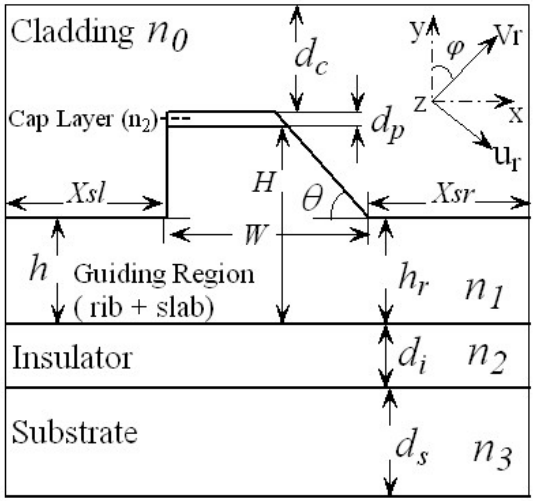


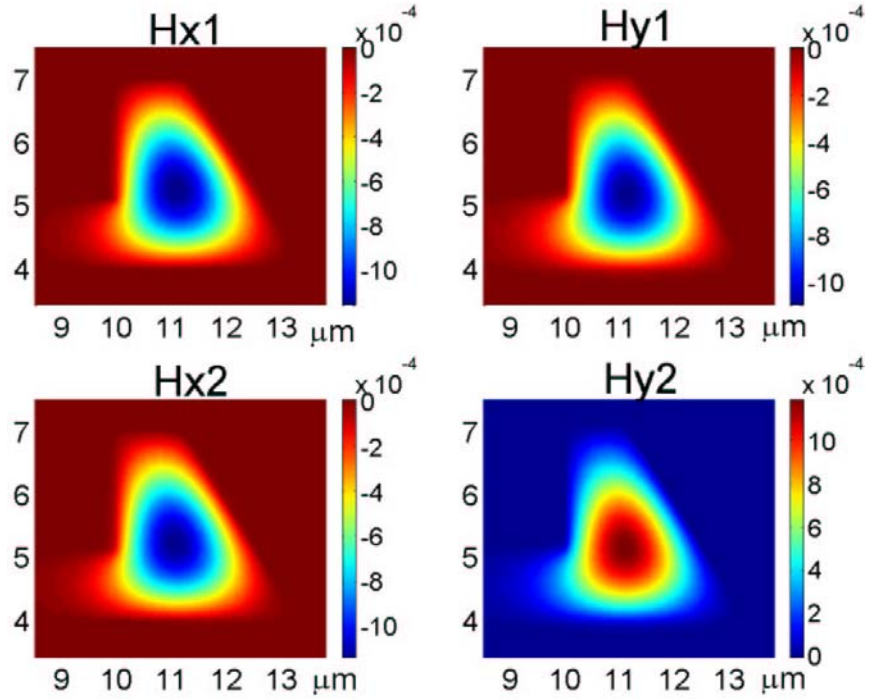


In Rib Waveguide



General Design Rules





- **Optical-Axis Rotation**
  - **Rotation Parameter**

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

  - **Rotation Angle** $\varphi = tan^{-1}(R)$
    - ***R*>>1 (*φ* > 45°) → *x*-polarized;**
    - ***R*<<1 (*φ* < 45°) → *y*-polarized;**
    - ***R*=1 (*φ* = 45°) → *PR* (Single Section)**

Identical TE and TM fields;

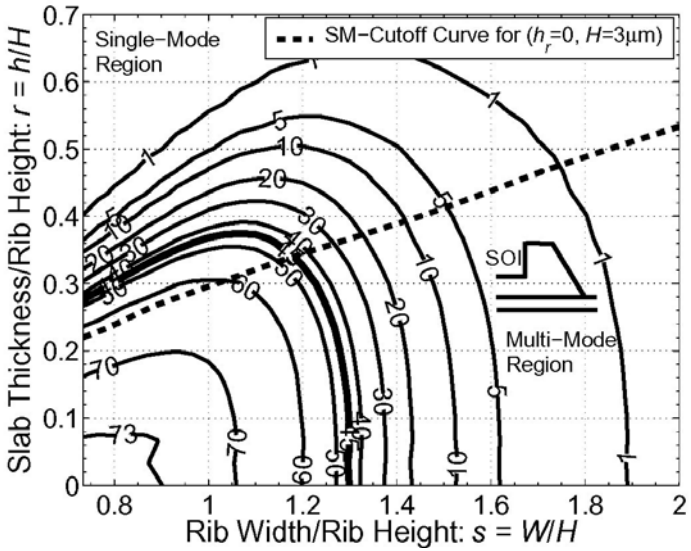
Confined in guiding region.

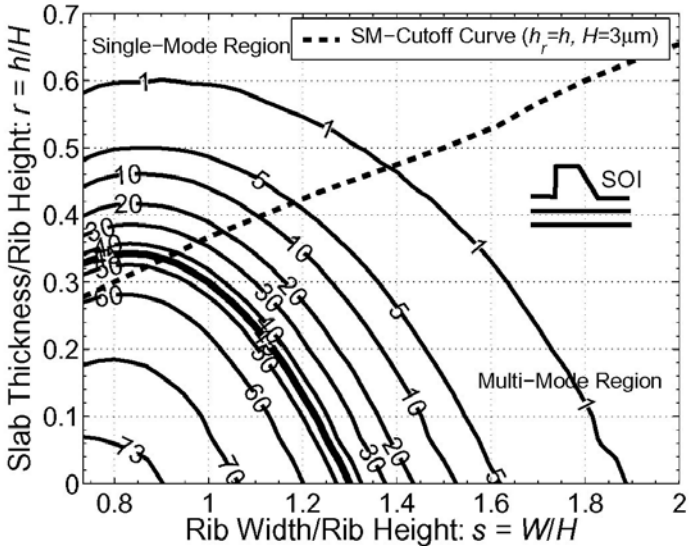
***A serial of designs*, e.g.:**

(1). H=3μm, W=3.3μm, h=1.1μm, hr=0, θ=54.736°, n1=3.48, n2=1.45

(2). H=2.8μm, W=2.7μm, h=1μm, hr=0, θ=54.736°, n1=3.48, n2=1.45

Normalized Design Charts





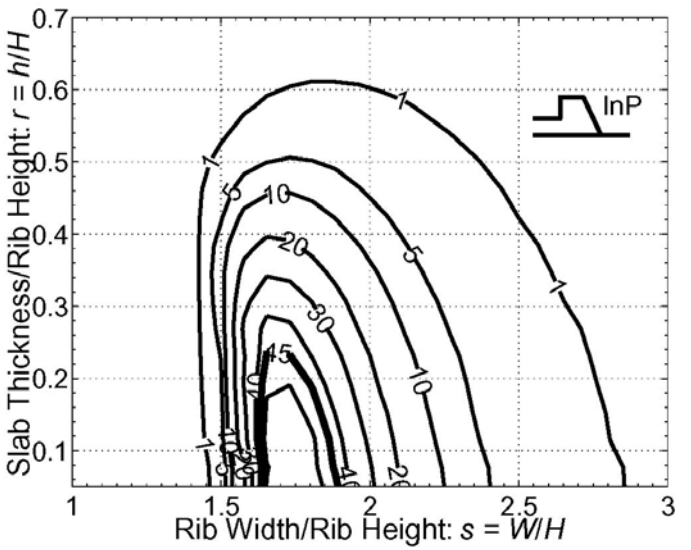
●SOI PR

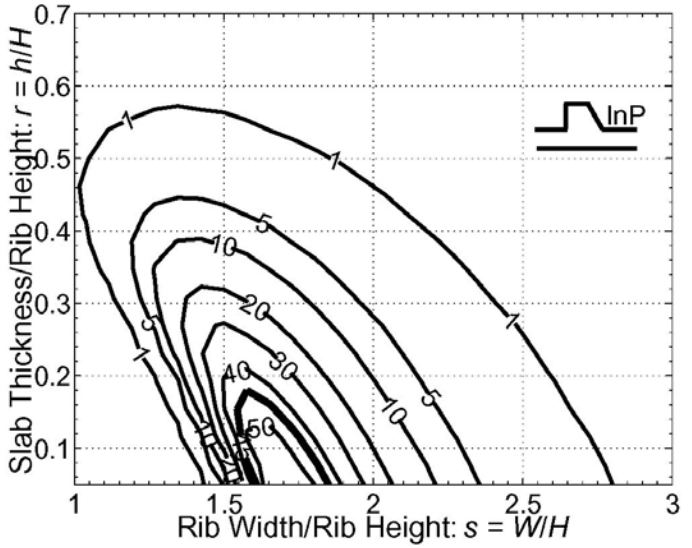
(1). Single-mode from $1 \le H \le 10\mu m$

(2). Similar Charts for Various *H*

(3). Empirical Formula

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

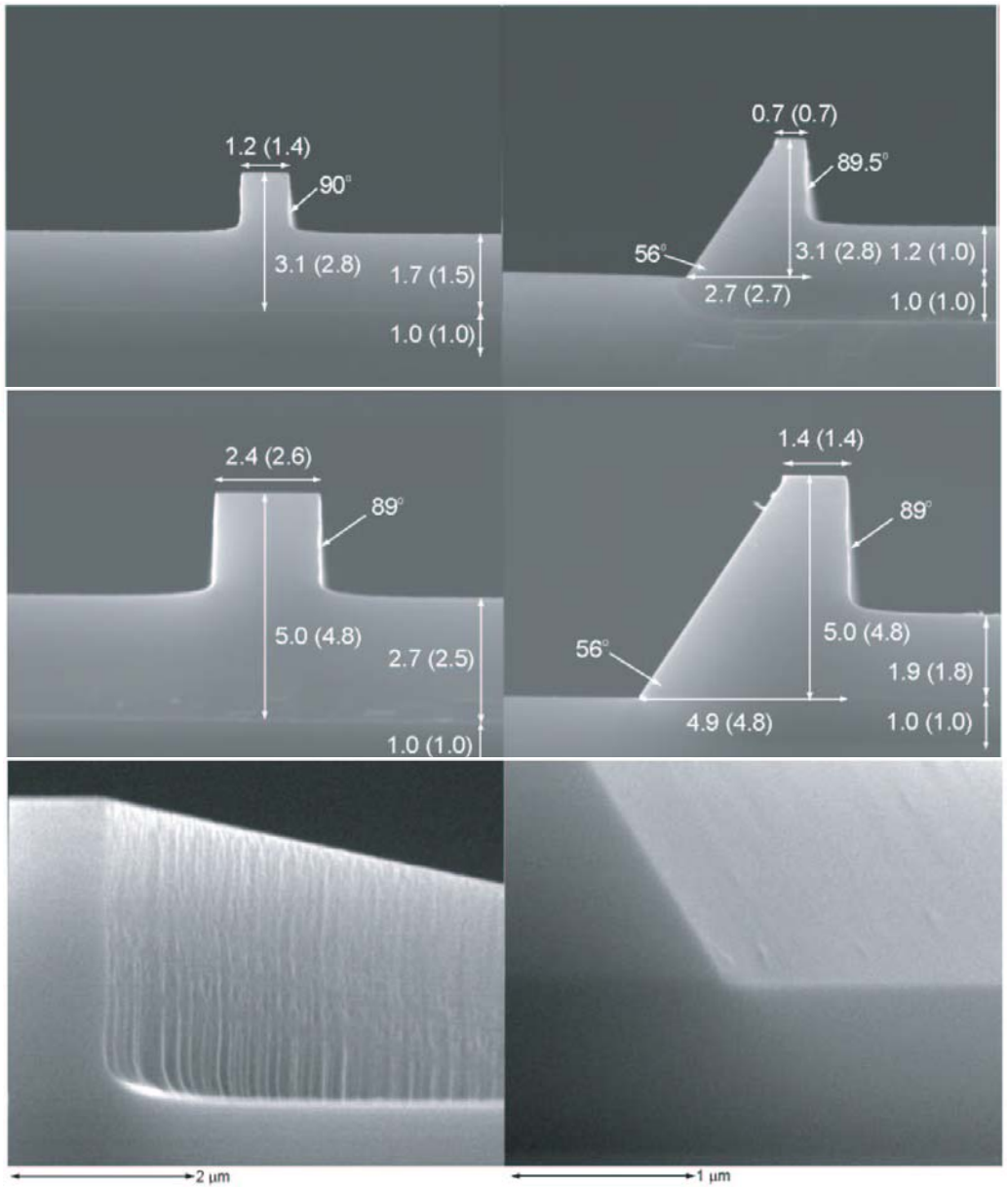




●III-V PR

Cross-section *H* has to be small for single-mode (due to weak optical confinement)

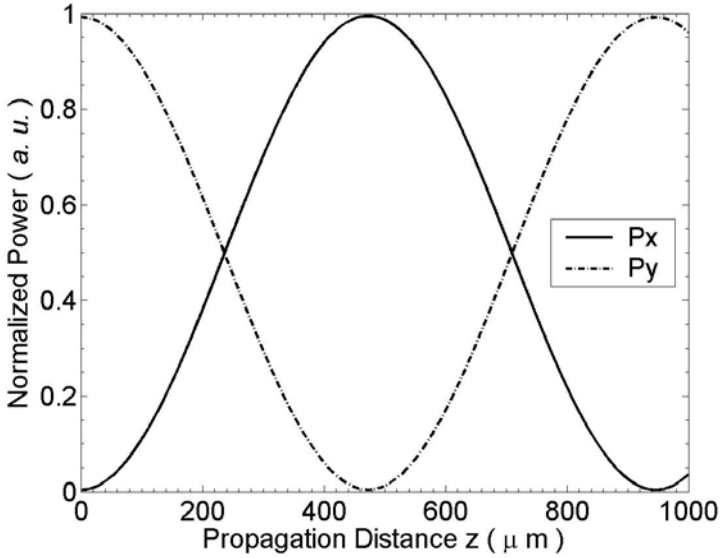
Fabricated Device



- **Procedure**
  - **BE-SOI — wafer**
  - **RIE — vertical wall**
  - **TMAH — slanted wall.**
- **Quality**
  - **smooth slanted-facet**
- **SEM Precision**
  - **0.1µm — height /width**
  - **1° — angles**
- **Target Optimal Device**
  - **3µm design —** (*H, W, h, hr*) =(2.8, 2.7, 1, 0)µm, *R*=1.04, *Lπ =502.4* µm
  - **5µm design —** (*H, W, h, hr*) =(4.8, 4.8, 1.8, 0)µm, *R*=1.01, *Lπ =2572* µm

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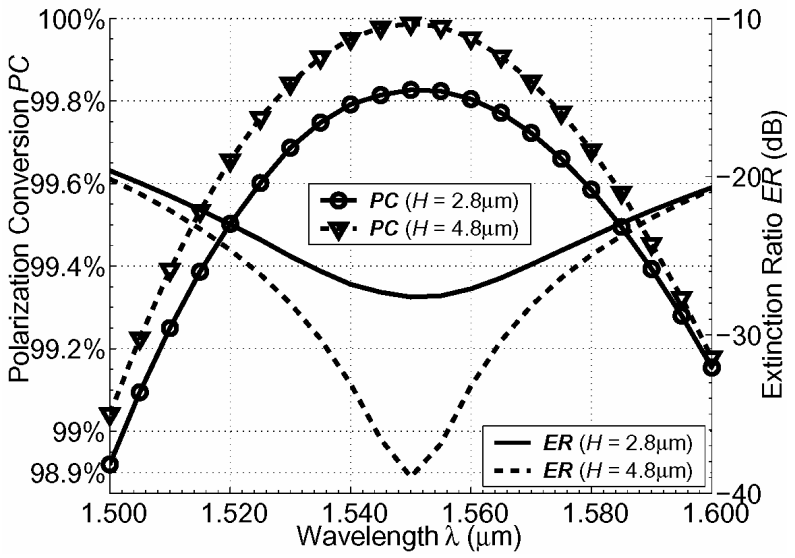
Power Exchange and Spectral Property



- **BPM Verifies Formula for Polarization Conversion**

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

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

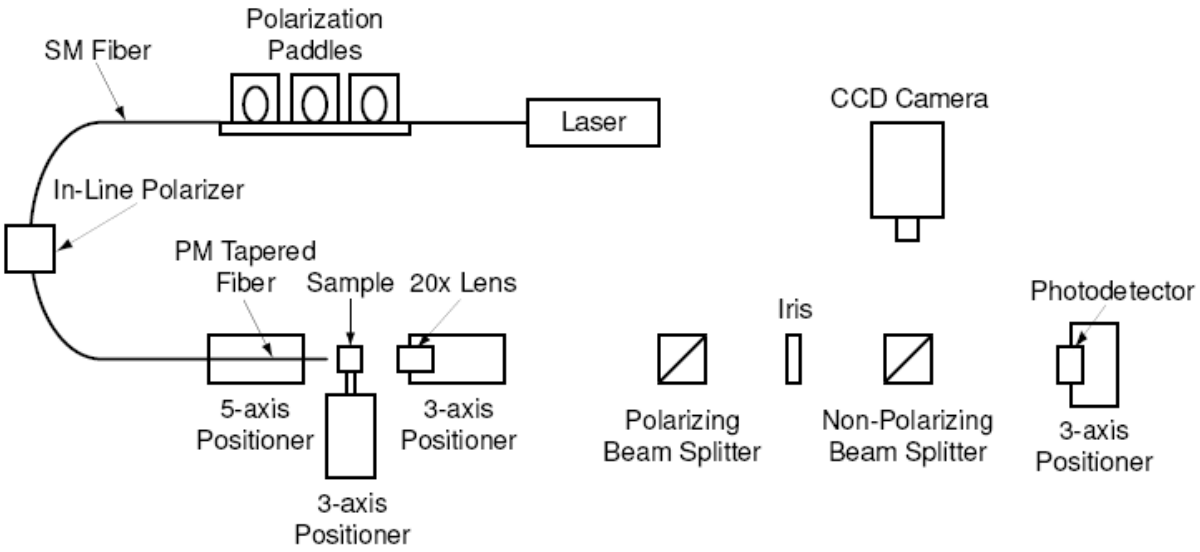


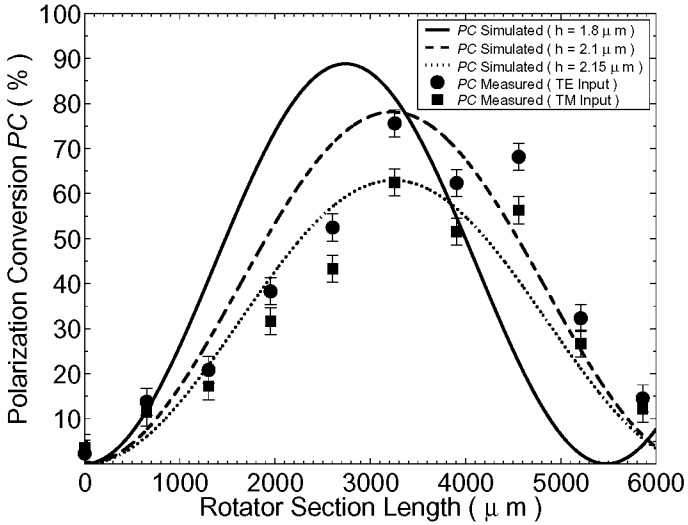
- **Stable in 1.50 < λ < 1.60 μm (covers C- and L-bands)**
  - **PC > 99.7% in ITU-T *C*-band**
  - **Polarization Crosstalk (Extinction Ratio)**

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

  - **–25dB (–30dB) crosstalk for 3μm (5μm) device**
- **Suitable for DWDM and PLC**

Optical Characterization

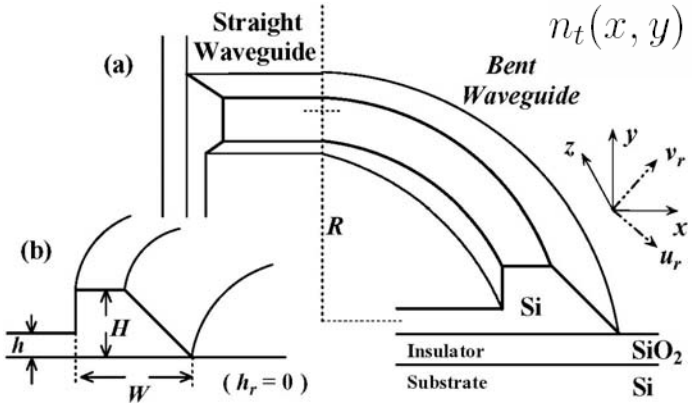


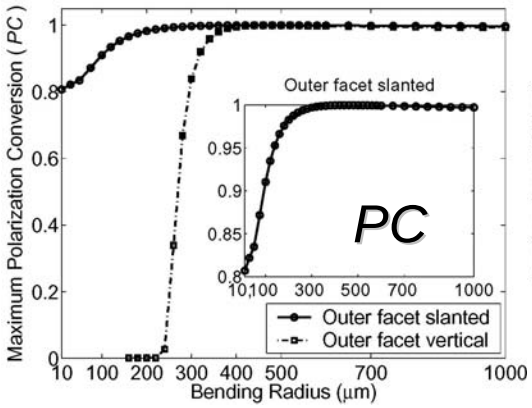


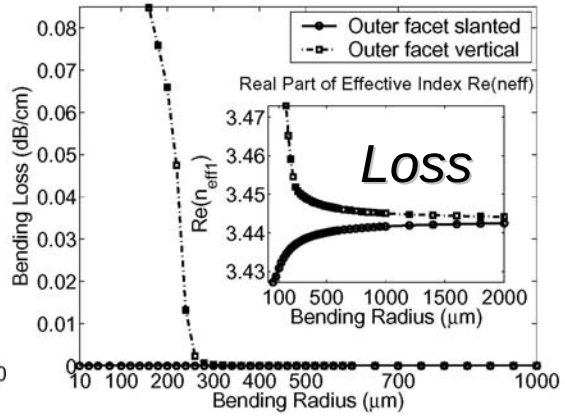
- **Fabrication Variation**
  - **Optimal:** (*H, W, h, hr*) =(4.8, 4.8, 1.8, 0)μm, *R*=1.01, L_π=2572 μm, *PC*= 99.98%
  - **Actual:** (*H, W, h, hr*) =(5.0, 4.9, 1.9, 0)μm, θ_{slant}=56°, $\theta_{vertical}$=89°, *R*=1.122, *Lπ* = 2940 μm
    - **Simulated: PC = 88 % (Maximum theoretical)**
    - **Measured: $PC_{TE\rightarrow TM}$ = 75% ± 3% and $PC_{TM\rightarrow TE}$ = 62% ± 3%**
      Loss 0.6 ± 0.1 dB/mm and 0.5 ± 0.1 dB/mm for TE- and TM-input, respectively.
- **Analysis**
  - **Variation of *h* is most important**
    - **Simulation with *h* = 2.1 μm fits well**
    - **Rounding of vertical sidewall corner → Effectively increases *h***

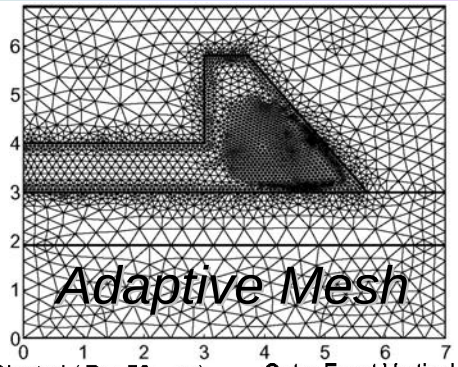
Bending Characteristics

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



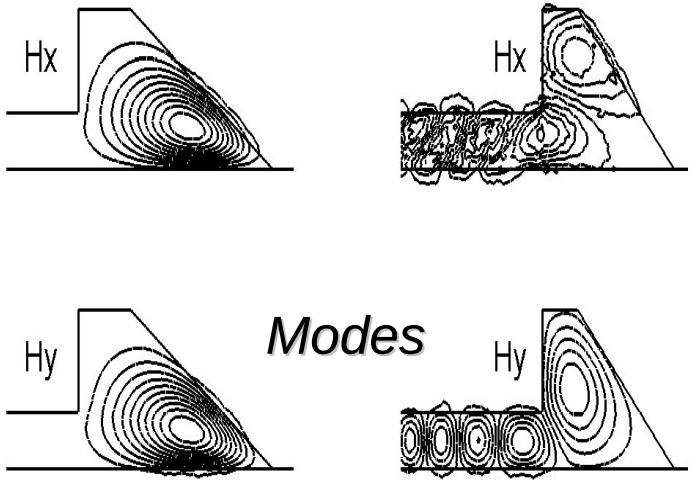






Outer Facet Slanted (R = 50 μ m)

Outer Facet Vertical (R = 50 μ m)

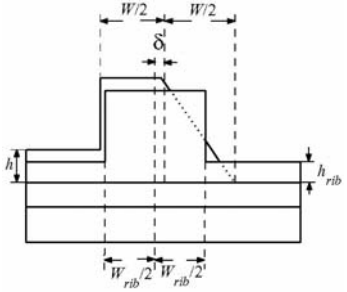


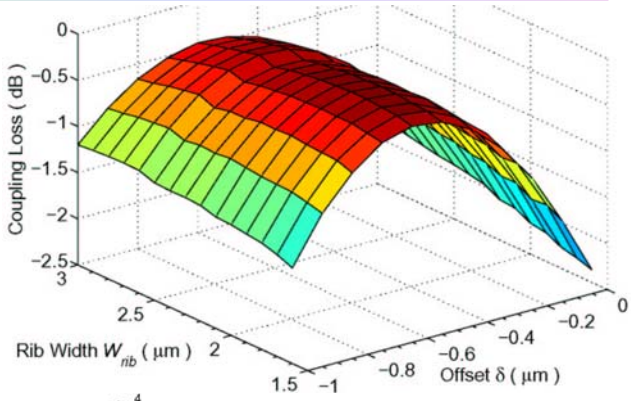
- **Asymmetric bending behavior**
- **Changes both light direction and polarization**
- **Advantages of Outer Facet Slanted (a)**
  - **Insensitive to bending radius**
  - **No radiation loss; Small transition loss**
  - **Polarization-Insensitive AWG**

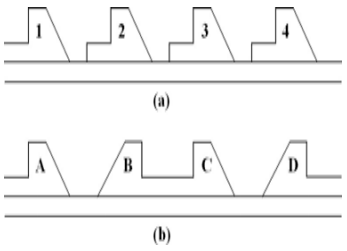
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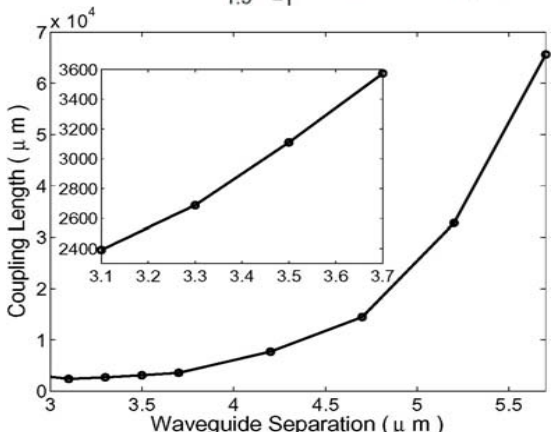
Coupling Loss

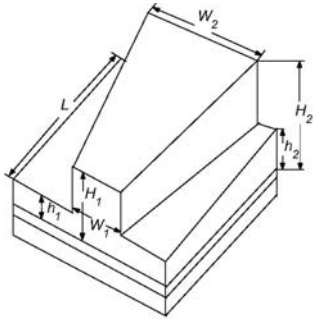
- **Butt-Coupling**
  - To Single-Mode Fibers (SMF)
    - Flexible cross-section enables low loss
  - To SOI Rib Waveguides
    - Good mode matching
    - Improve by position offset
    - Minimum –0.21dB (–0.19dB) for TE (TM) input
- **Parallel Coupling**
  - Compact Large-scale PIC
    - Separation 6μm
- **Taper Coupling**
  - Improves Coupling Efficiency
    - Convert mode shape & size
    - 1/50 slope → taper loss 9.6×10^{-3}dB/mm

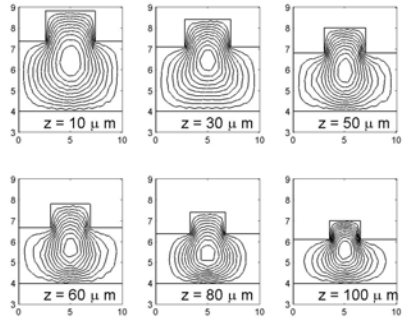












Conclusion — SOI PR

- **SOI Polarization Rotators**
  - **General design rules (for both SOI and III-V)**
  - **Novel asymmetric configuration**
  - **Conversion efficiency, crosstalk, bending, coupling, and loss**
  - **Fabrication and Measurement**
- **Numerical algorithms**
  - **FV-FEM mode solver and BPM**
  - **Perfectly Matched Layer (PML)**
  - **Adaptive Meshing**

More Photonics-Related Experience

- **WDM All Optical Network**

National Optical Communication Lab, Peking University (PKU), Bejing (MASc)

  - **Arrayed Waveguide Grating (AWG)**
  - **Optical Add-Drop Multiplexer (OADM)**

- **Nanophotonics and Nanofabrication**

National Research Council Canada (NRC), London, Ontario (NSERC Fellow)

  - **Photonic Bandgap Device (PBG)**
  - **Plasmonics — Surface Plasmon Resonance (SPR)**
  - **Physical Vapor Deposition (PVD)**

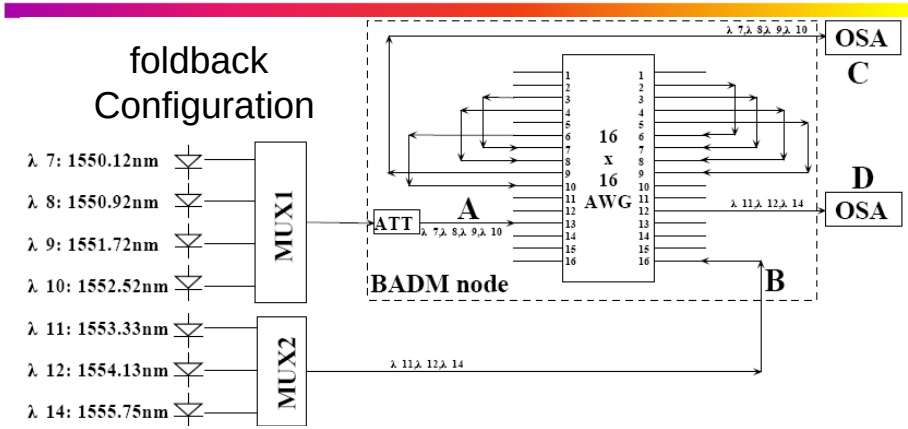
- **Electronic Design Automation — EDA**

  - **Electronic Circuit** (Microprocessor and Programmable Logic Device)
  - **Photonics Software** (RSoft, FEMLAB, Ansoft, FEKO)

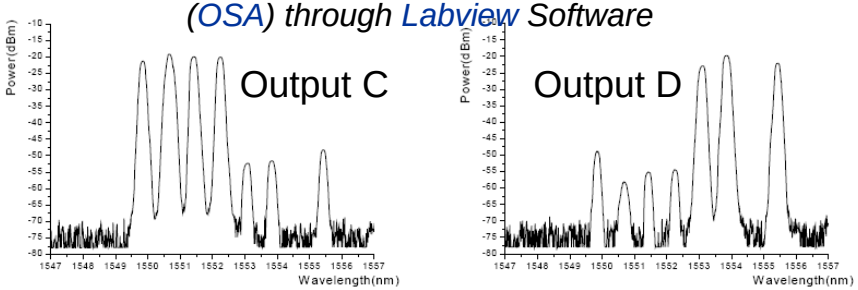
- **Microwave and Electromagnetics**

  - **Antenna and Wireless Communication**
  - **Terahertz photonics**

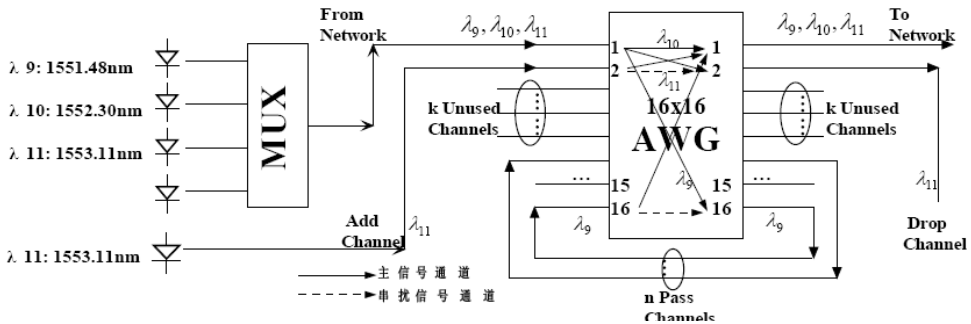
AWG-based OADM



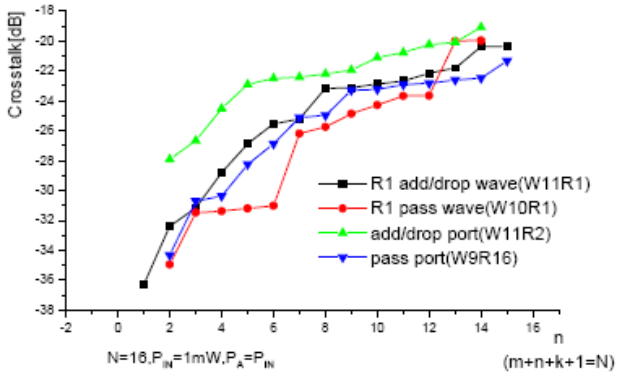
Obtained from HP Optical Spectrum Analyzer (OSA) through Labview Software

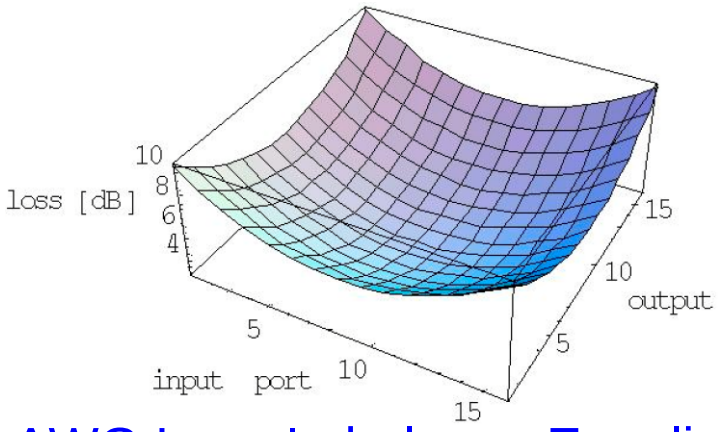


Bidirectional OADM Experiment (Optical Spectrum)



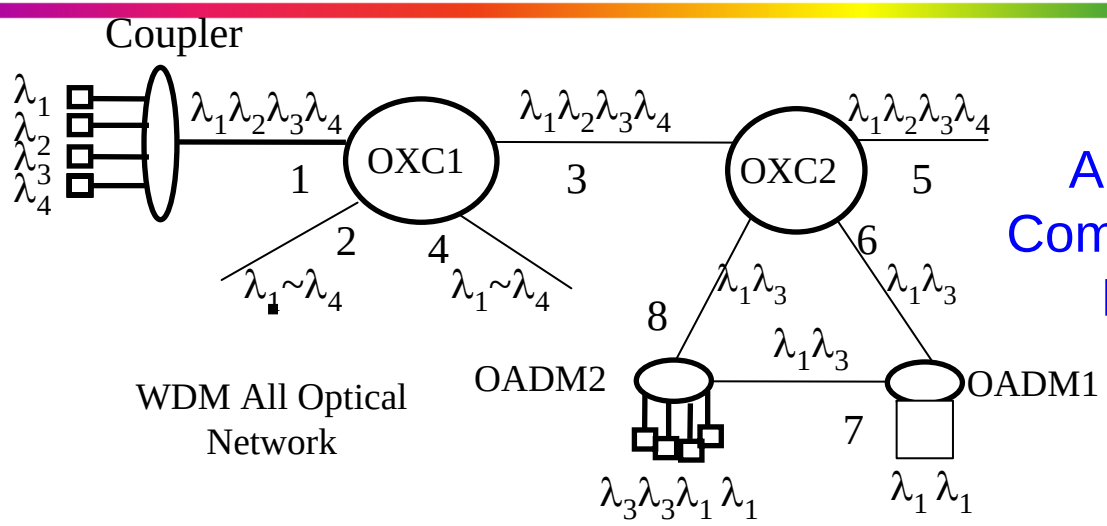
AWG Crosstalk Analysis





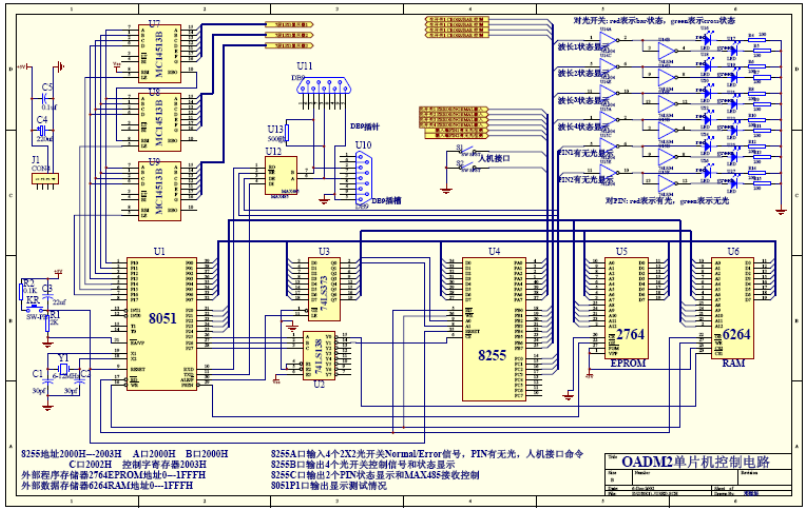
AWG Loss-Imbalance Equalization

WDM All Optical Network (AON)

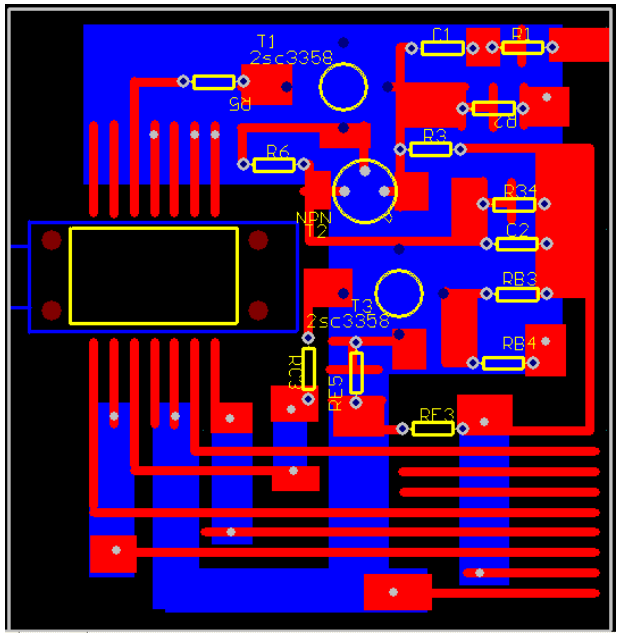


WDM All Optical Network

An Optical Communication Network

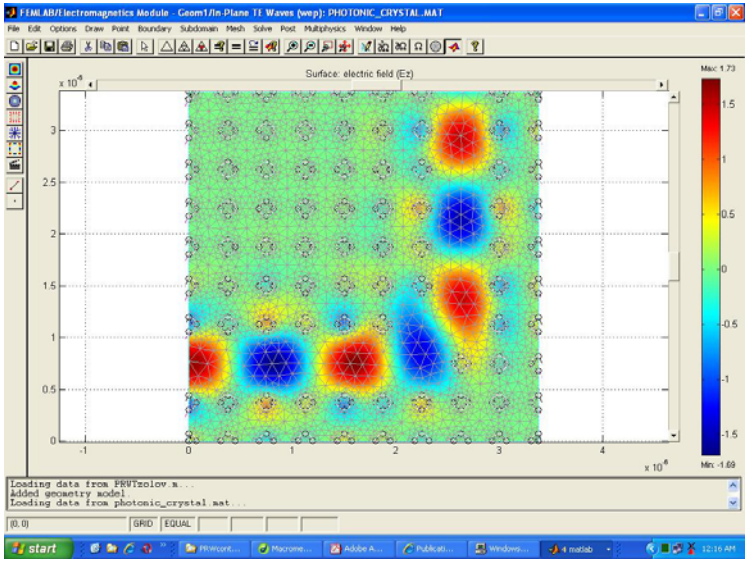


Microprocessor Circuit for OADM Power and Switching Control

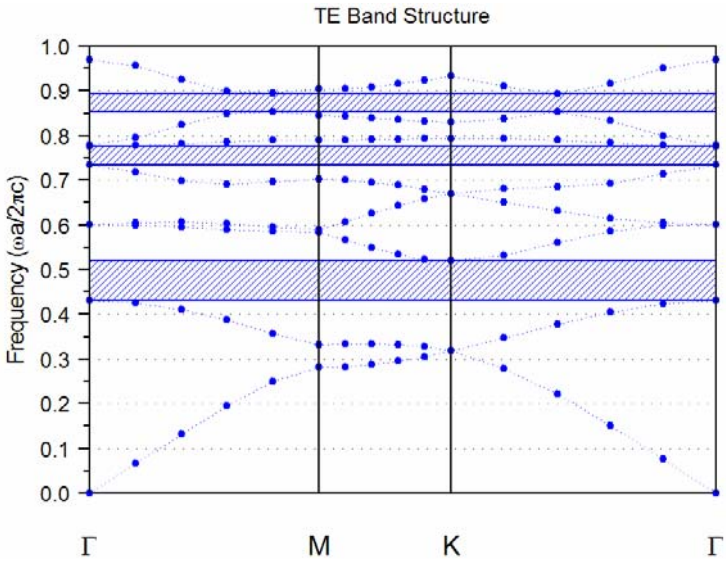


Electronic Circuit for Laser Temperature Control

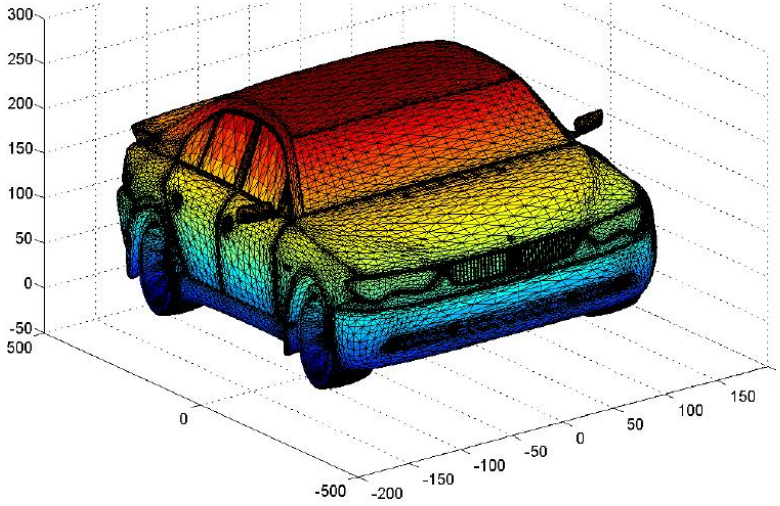
Photonics/Microwave Software

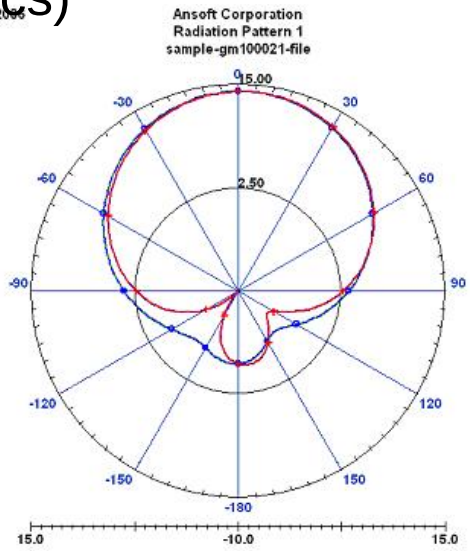


Photonic Bandgap (PBG) Bend
(FEMLAB/Comsol Multiphysics)



Photonic Crystal Fiber (PCF)
(RSoft BandSolve)



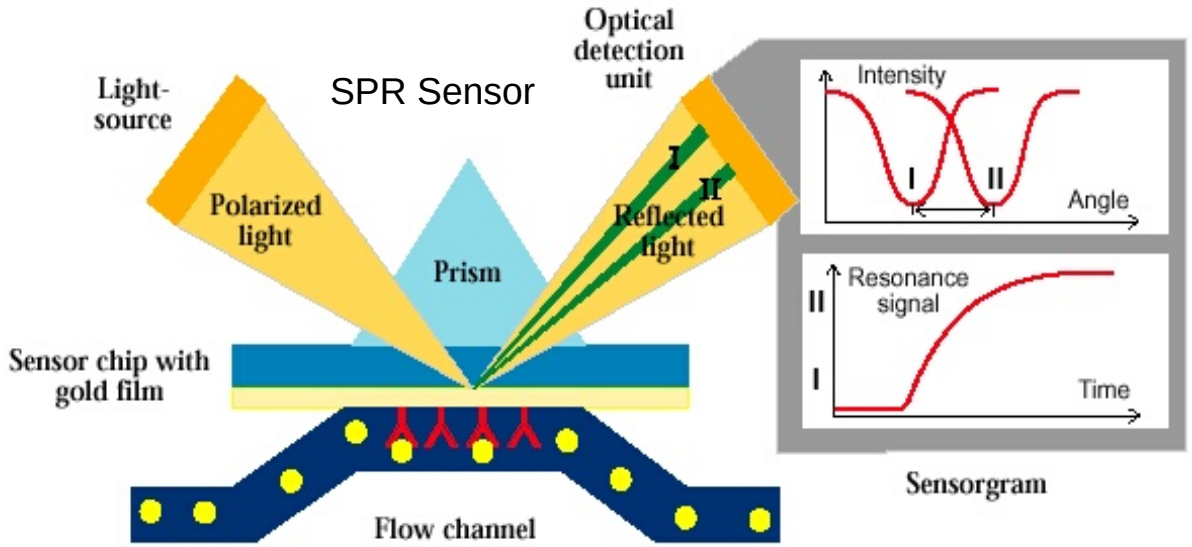


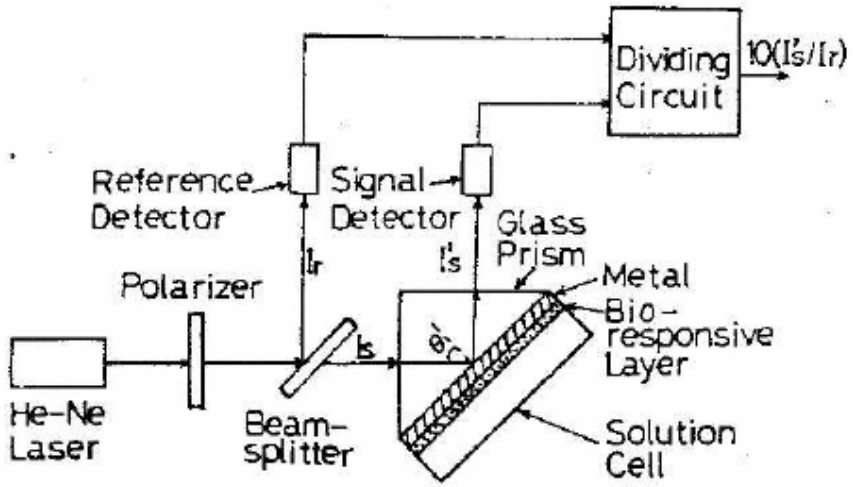
Tiny Antenna in Big Car
(AutoCAD – Geometry,
MATLAB – Mesh,
Ansoft HFSS and FEKO
– Far Field)

www.eng.uwaterloo.ca/~hdeng/

Plasmonics — Surface Plasmon Resonance (SPR)

- **Advantage**
  - **Real-time monitoring**
  - **High sensitivity**
  - **Non-labeling**
  - **Versatility**
  - **Parallel detection**
- **Principle**
  - **Metal-dielectric interface: Photo → Plasmon**
  - **Evanescent wave causes oscillation of free electrons**
  - **Surrounding ε variation causes reflection shifts**

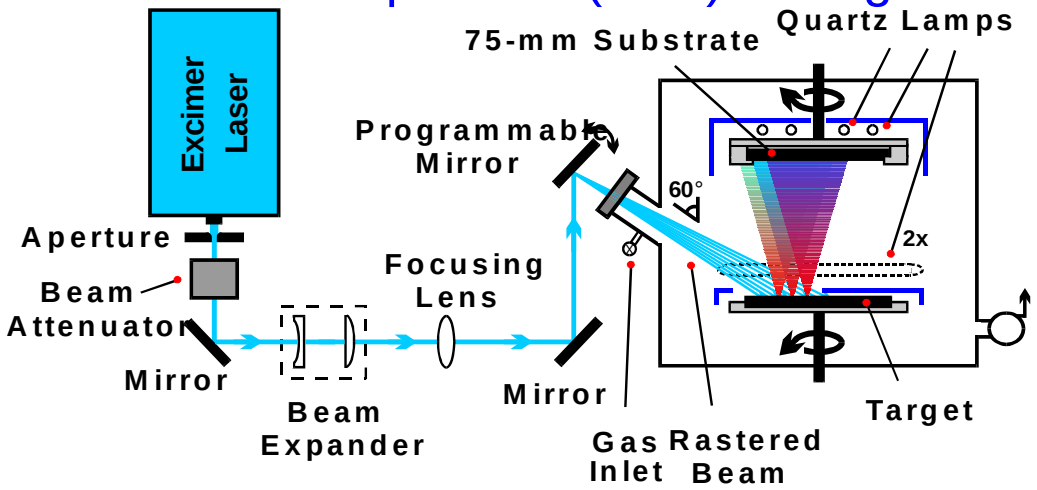


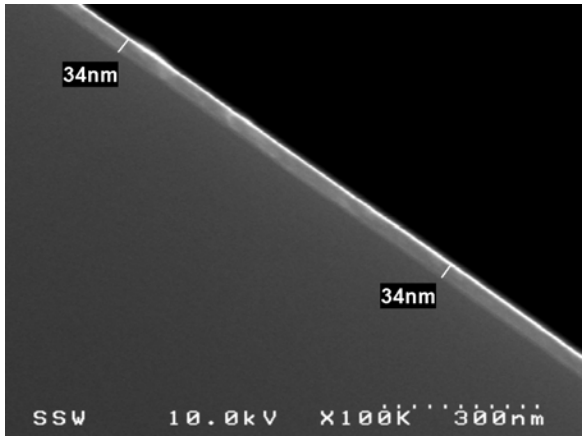


SPR Configuration

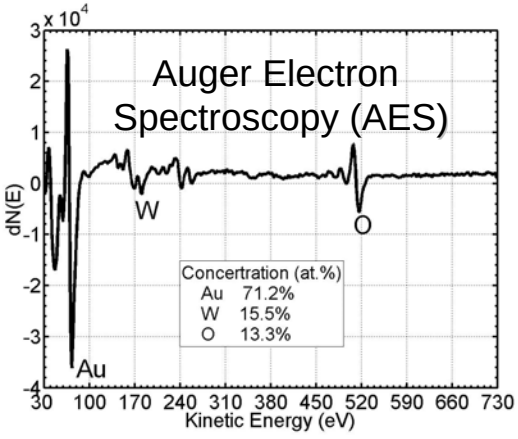
Physical Vapor Deposition (PVD) of Nanocomposite Film for SPR Sensor

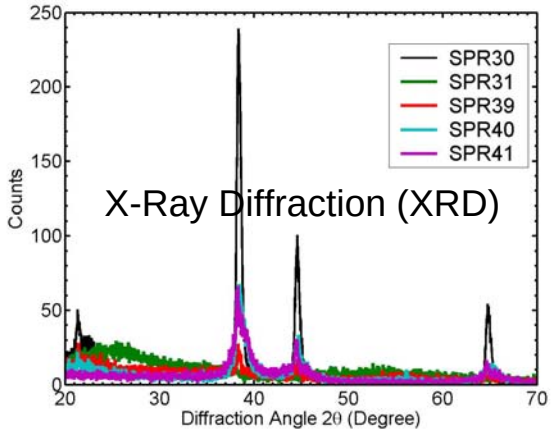
Pulsed Laser Deposition (PLD) Configuration



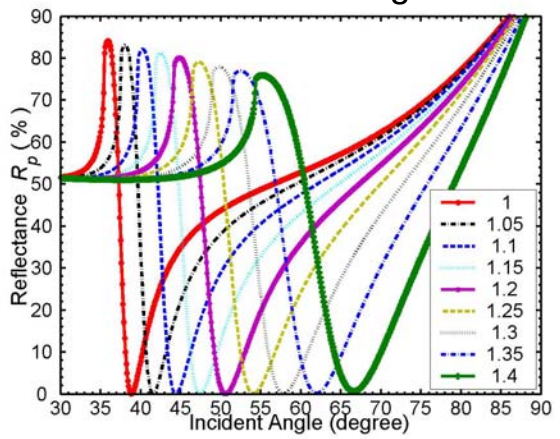


Field-Emission Scanning Electron Microscope (FE-SEM)





SPR Sensing



Summary of Qualification

- **Photonic Device and Optical Network**
  - AWG, OADM, OXC, WDM, PBG, PCF, SOI
  - Polarization Controller, Bent Waveguide, Taper
- **Numerical Simulation and Experiment**
  - FEM, FDM, BPM, FDTD
  - OSA, PVD, SEM, XRD, AES
- **Hardware and Software**
  - Electrionic Circuit, Protel SCH&PCB, C, VB
  - RSoft, Femlab/Comsol, Matlab, Ansoft, FEKO

Acknowledgement



- Prof. **David O. Yevick** and Prof. **Sujeet K. Chaudhuri** (Waterloo)
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- Prof. **Garry. Tarr** (Carleton)
- Dr. **Chenglin Xu** (Apollo, RSoft)
- Prof. **Anand Gopinath** (Minnesota)
- Dr. **Dongfang Yang** and Dr. **Bo Chen** (NRC)
- Prof. **Deming Wu** and Prof. **Anshi Xu** (Beijing Univ.)

Thank You

