VLSI Photonic Circuits and Devices

Henghua DENG

infinera®

NRC·CNRC

University of Waterloo

PEKING UNIVERSITY 1898

August 25, 2009

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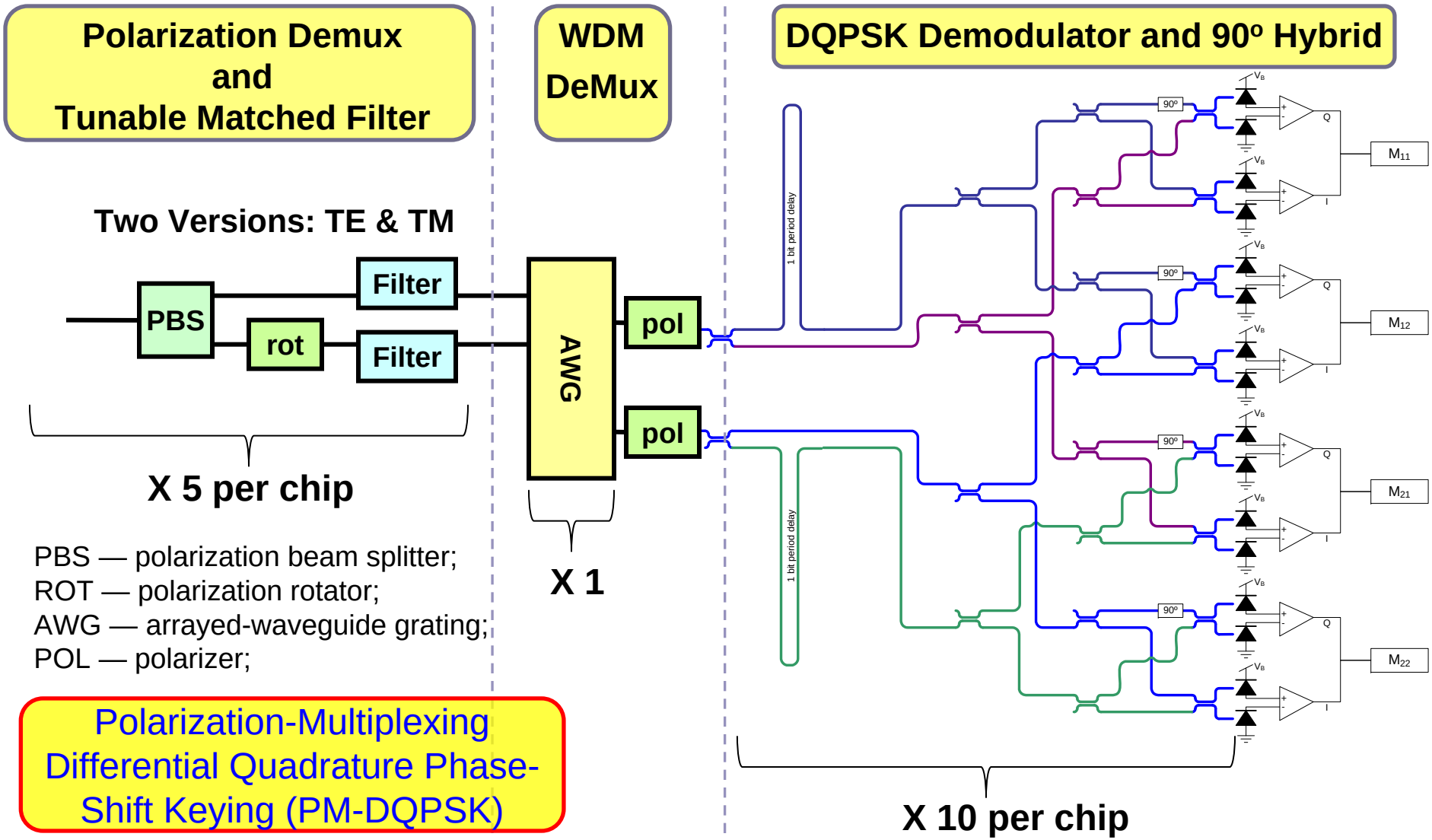
http://www.linkedin.com/in/denghenghua

Overview

- **Planar Lightwave Circuit (PLC)**
  - PM-DQPSK Demodulator
  - AWG and OADM
- **Integrated Photonic Device**
  - Polarization Controller (SOI, Hydex™, InP)
  - Numerical Simulation (FEM, BPM) and Software
- **More Experience**
  - Optical Telecom Network
  - Nanophotonics, Microfabrication and Measurement
  - Electronic Design Automation
- **Summary**

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PLC PM-DQPSK Demodulator

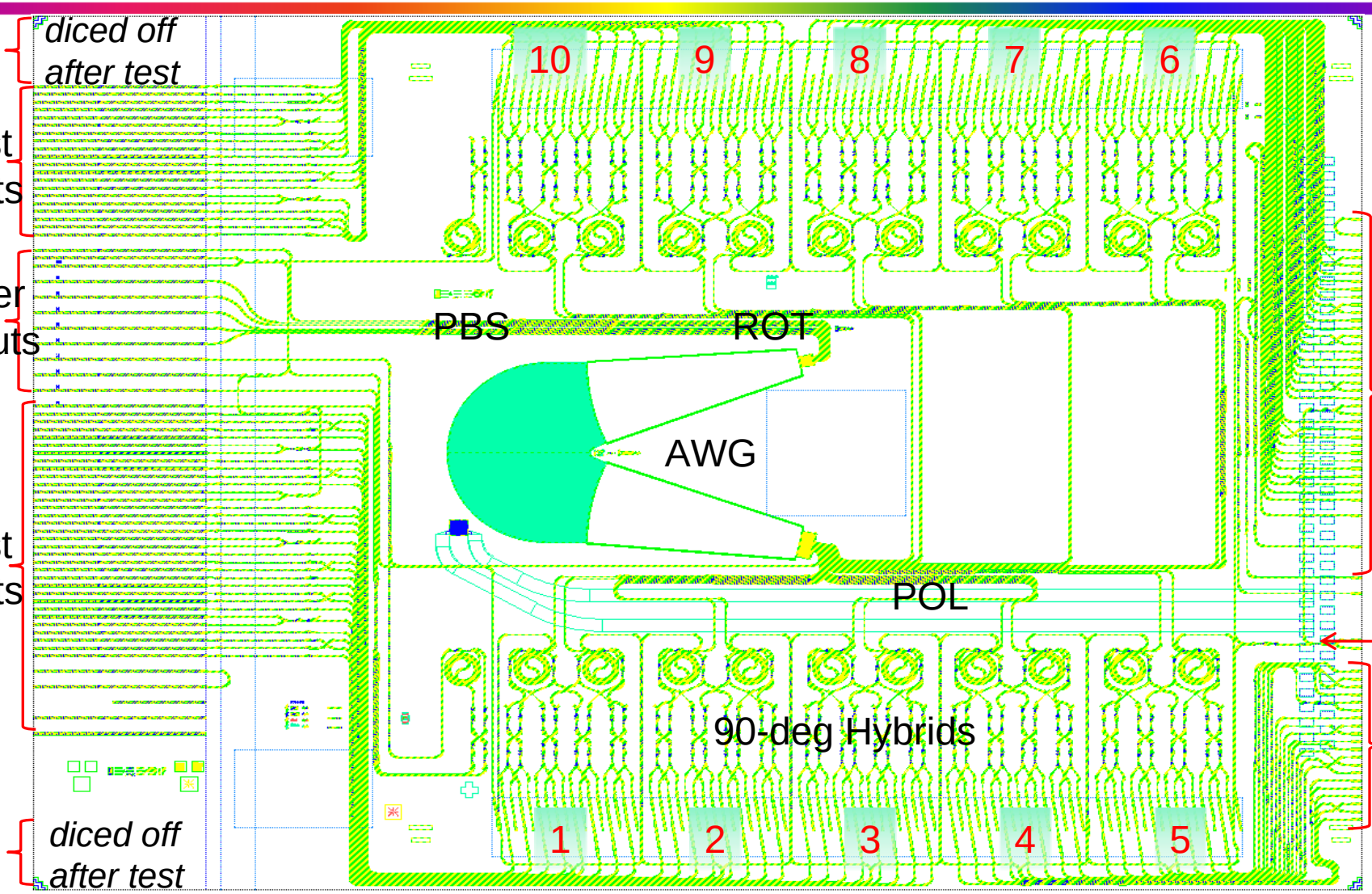


PBS — polarization beam splitter;
ROT — polarization rotator;
AWG — arrayed-waveguide grating;
POL — polarizer;

Polarization-Multiplexing Differential Quadrature Phase-Shift Keying (PM-DQPSK)

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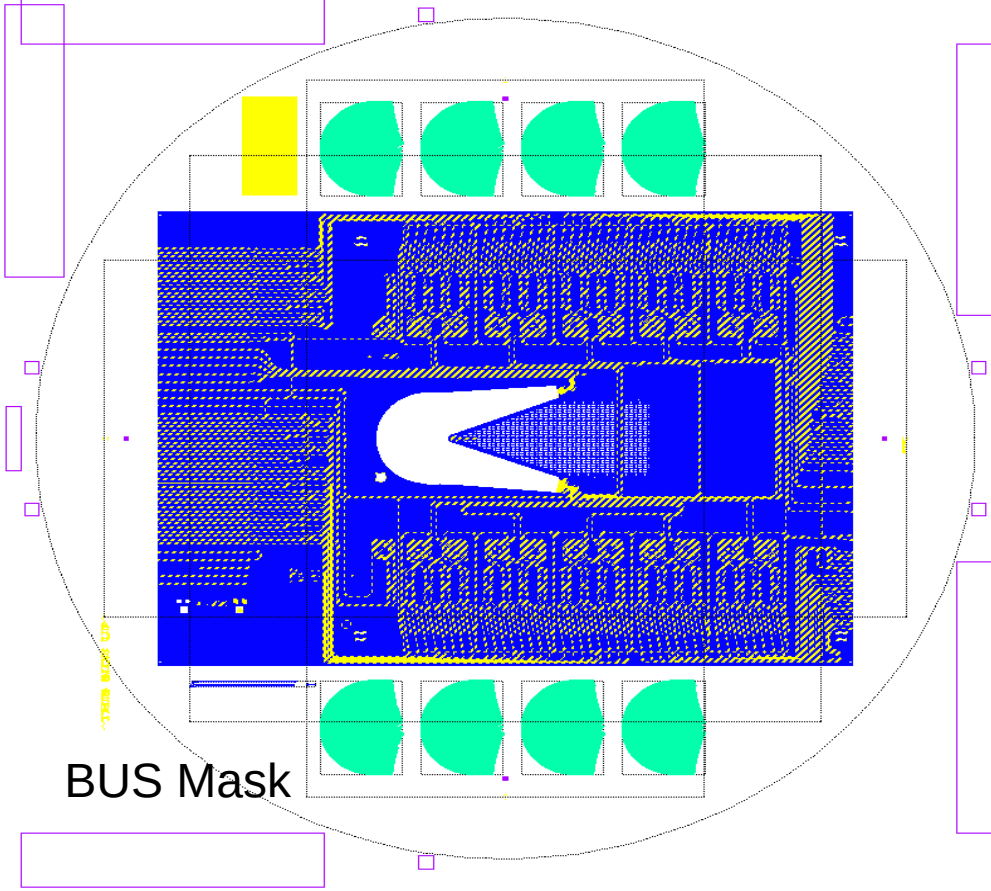
PM-DQPSK Rx Layout

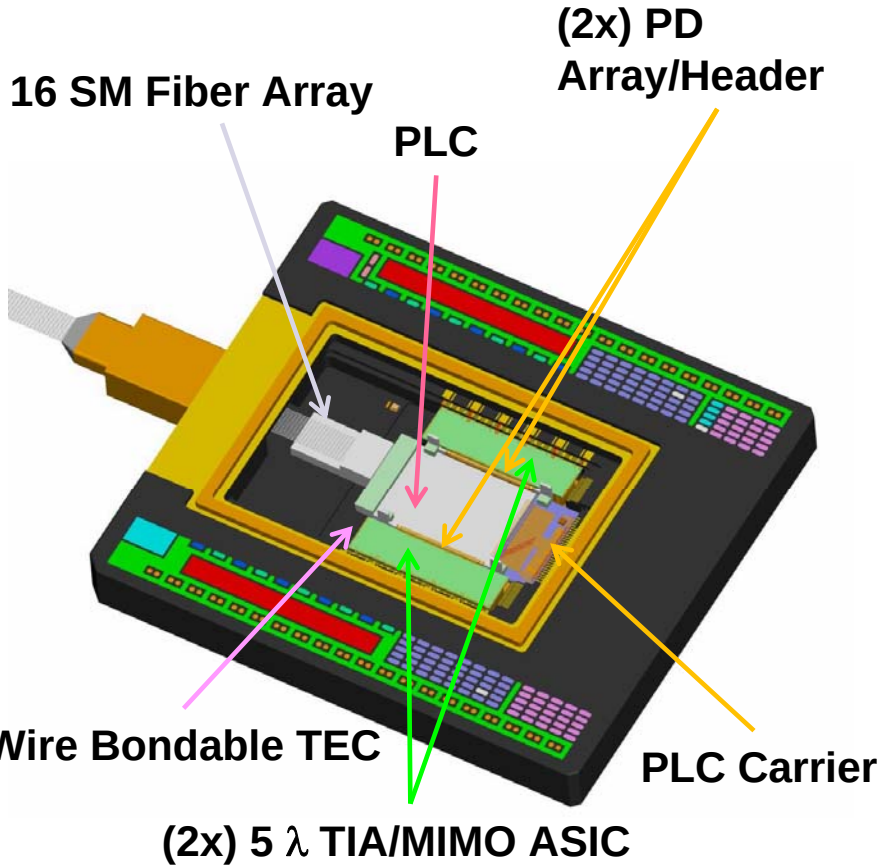


Size: **19mm x (12+2)mm;** Hundreds of Elements;

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Reticle and Packaging





- **Stitching AWG**
  - ❖ **To determine best phase-error compensation**
  - ❖ **Density compensation for best fabrication precision**

- ➢ **Stacked-ceramic package with LGA interface for 40ch x 10G output**
- ➢ **PLC chip 10λ for PM-DQPSK**
- ➢ **160 Photodiode interconnect at 10G**
- ➢ **Integrated TIA/AGC/MIMO ASIC w/ Fanout.**

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AWG Parameters

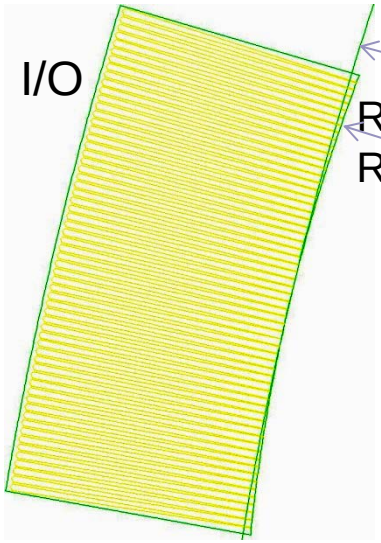
Parameter	Value for TE mode	Value for TM mode
f0 (λ0)	194.00THz (1545.32nm)	194.00THz (1545.32nm)
δf ($\delta\lambda$)	100GHz (0.80nm)	100GHz (0.80nm)
Δf_{FSR} (Target)	6800GHz	6800GHz
(Din, Dout, Darr)	(6.5, 6.5, 6.5) um	(6.5, 6.5, 6.5) um
(Nc, nc, ns) (#1)	(1.7660, 1.6050, 1.6610)	(1.7680, 1.6060, 1.6550)
m (#2)	26	26
Δf_{FSR} (#3) ($\Delta\lambda_{FSR}$)	6781.30GHz (54.03nm)	6777.85GHz (54.01nm)
dL (#4)	25.0333um	25.0177um
Lf (#5)	3079.5699um	3066.8842um
θ (#6a)	16.40 degree ($1.5\theta^{(\#6b)}$=24.60)	16.46 degree ($1.5\theta^{(\#6b)}$=24.69)
Narr (#7a)	136(204(#7b))	136(204(#7b))
Lu (#8) (1000/1200/2000G)	0.26/0.38/1.05dB	0.26/0.38/1.05dB

Narr = 201; Minimum radius > 90um; Four Orientations;

(#1). (group, array-waevguide, slab) index; (#2). diffraction order; (#3). free spectrum range;
(#4). adjacent length difference; (#5). Free propagation region length (Rowland Circle Radius);
(#6). power confining angle (full horn); (#7). Number of arrayed-waveguide; (#8). Loss imbalance;

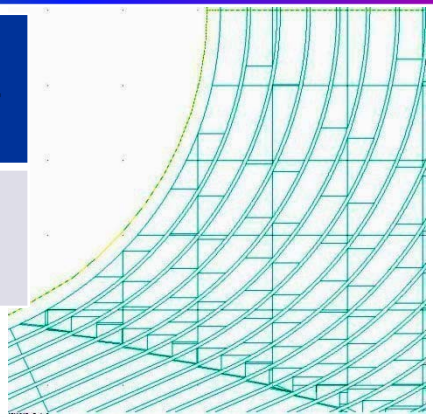
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AWG Layout Details

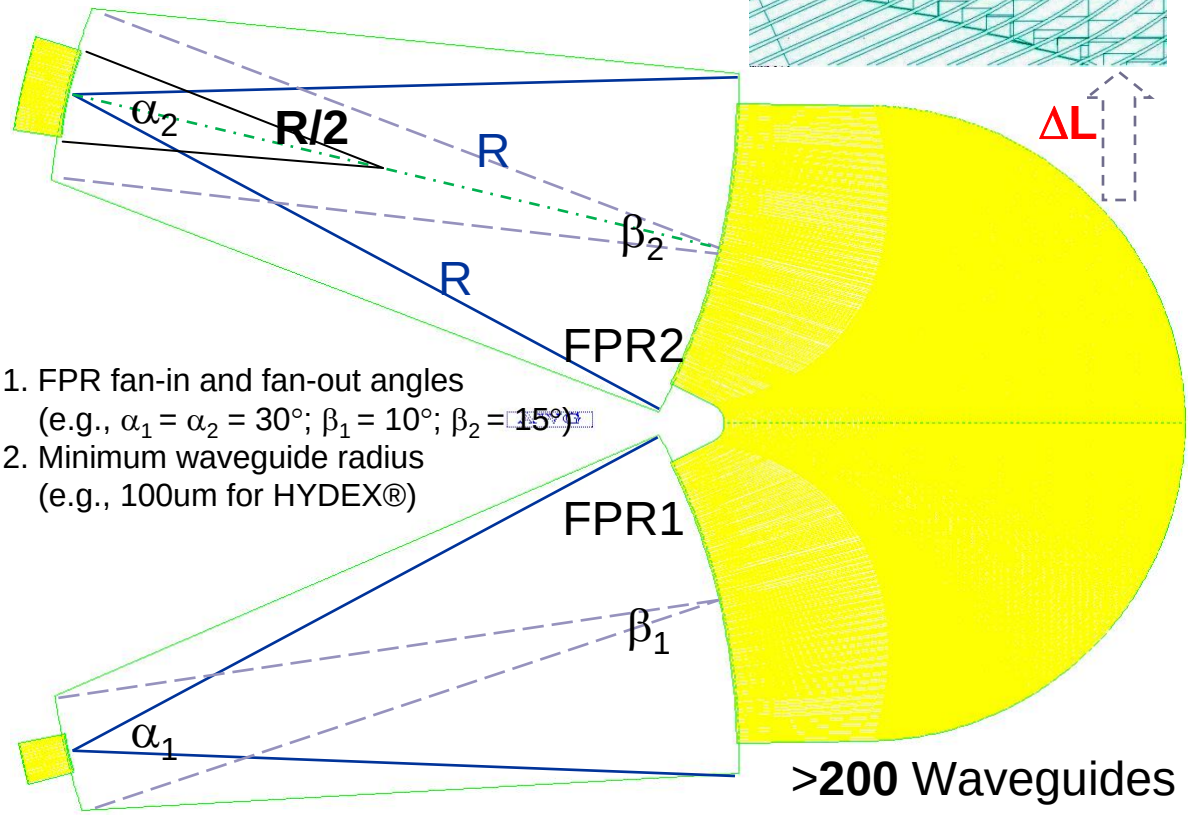


Array pattern exactly aligned on both Stepper and MASK GRIDs – geometric info without distortion

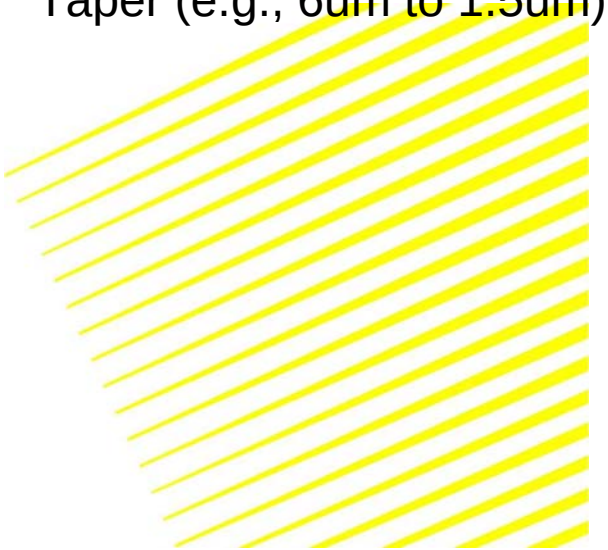
e.g., AWG trace dL(25.0563um) error: (max, min, mean, std) = (2.0685, -1.0910, 0.3595, 0.5654) nm.







Taper (e.g., 6um to 1.5um)



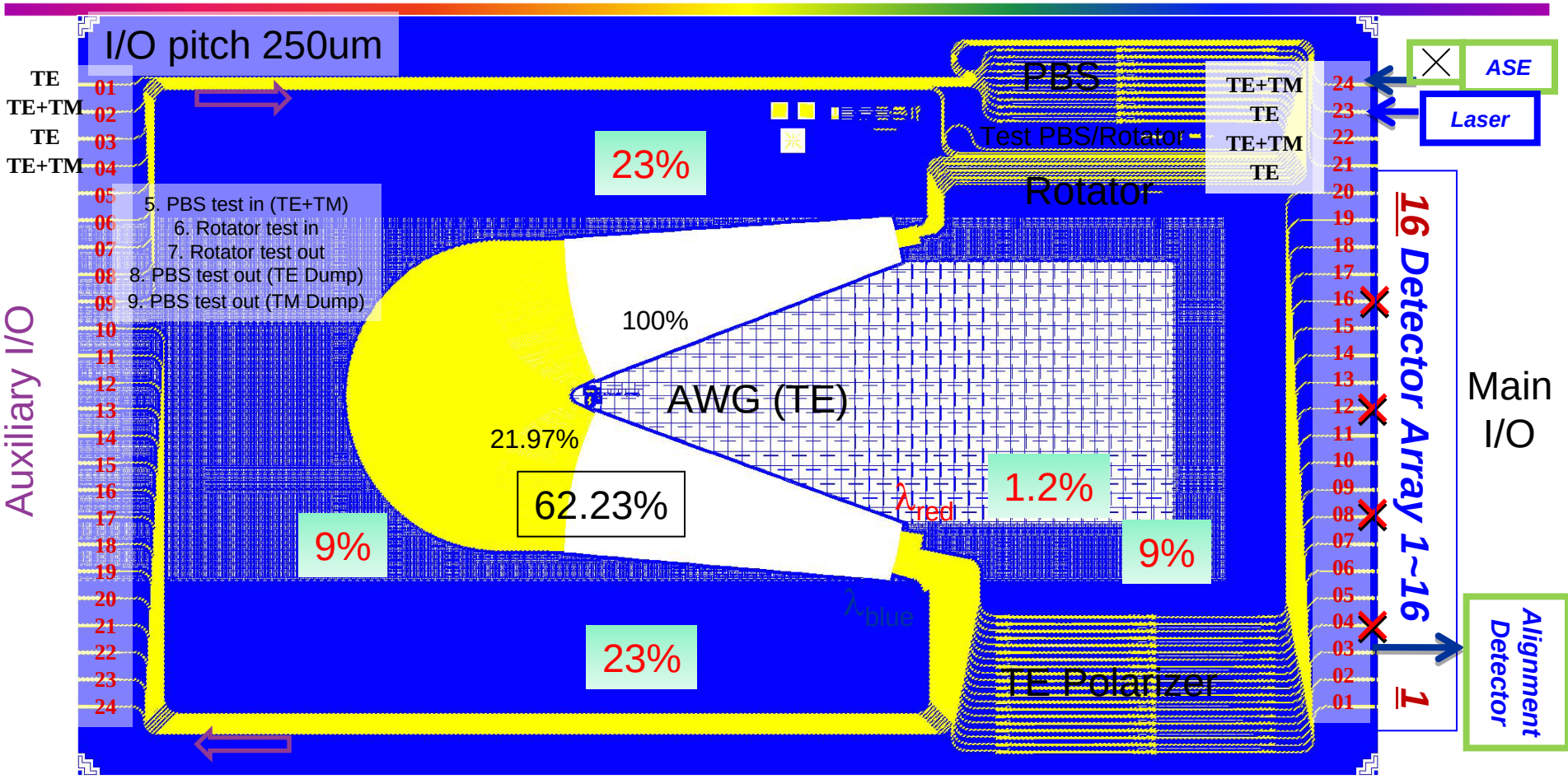
1. FPR fan-in and fan-out angles (e.g., $\alpha_1 = \alpha_2 = 30°$; $\beta_1 = 10°$; $\beta_2 = 15°$)
2. Minimum waveguide radius (e.g., 100um for HYDEX®)

>**200** Waveguides

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5.35x3.65 = 19.5 mm^2

AWG Density and Test Map

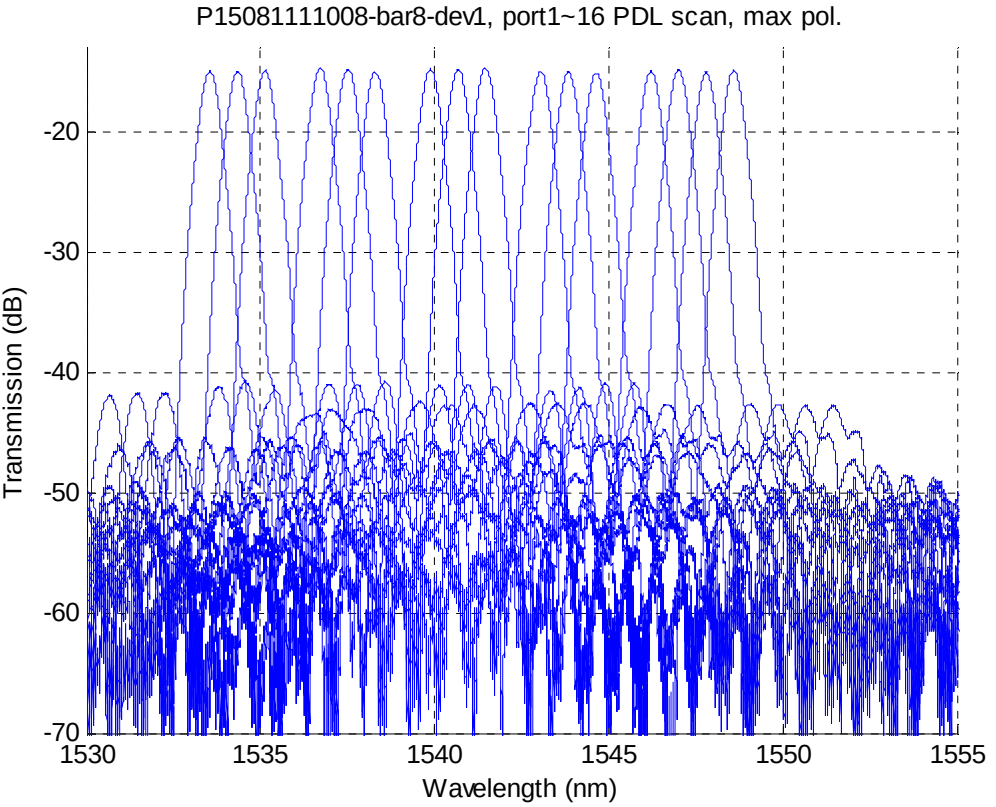


Size: **12mm*7mm** m=26; dL=25.0177um; FSR=6777.85GHz; Narr=201; R0=90um;

- **AWG Density Compensation**
  - **For balancing global and local densities**
  - **For best fabrication precision**

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AWG Performance

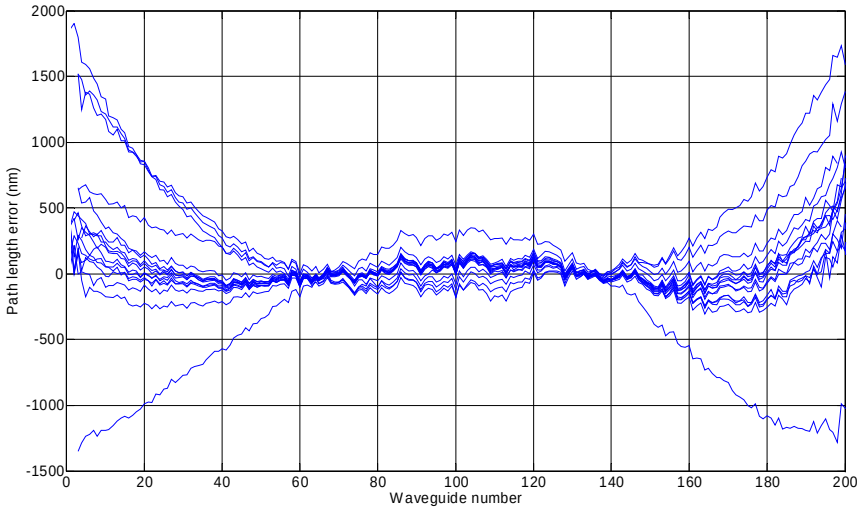


AWG Spectrum

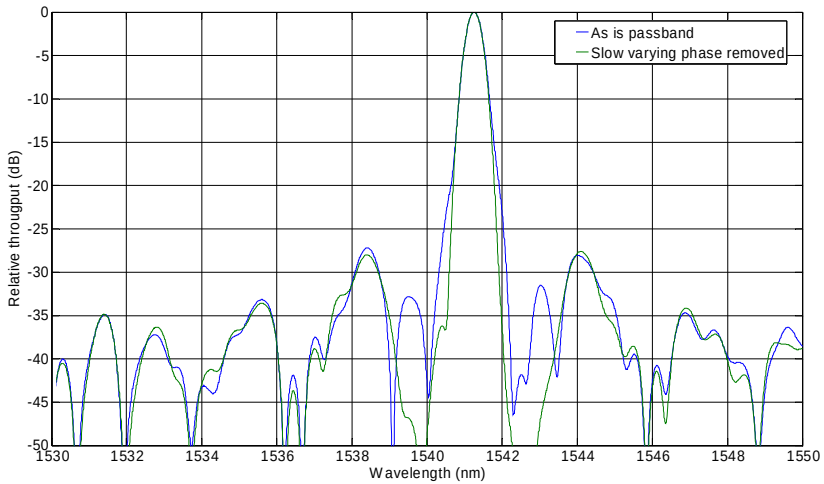
(A). Value includes fiber coupling losses of ~12dB.

(B). Skipped four outputs

(C). Performance
AWG size 3mm x 5mm; 100GHz Spacing; FSR 6800GHz; Insertion Loss <2.5dB; Loss uniformity <1dB; 3dB bandwidth 60GHz; Crosstalk >25dB (adjacent) and >35 dB (non-adjacent);



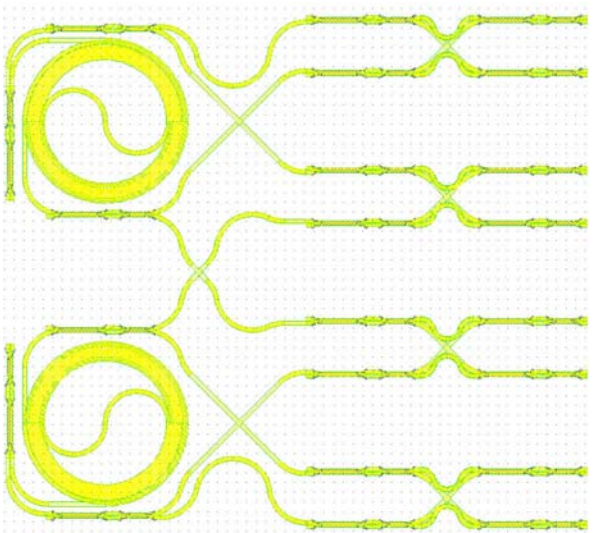
Slow-Varying Path Length Errors

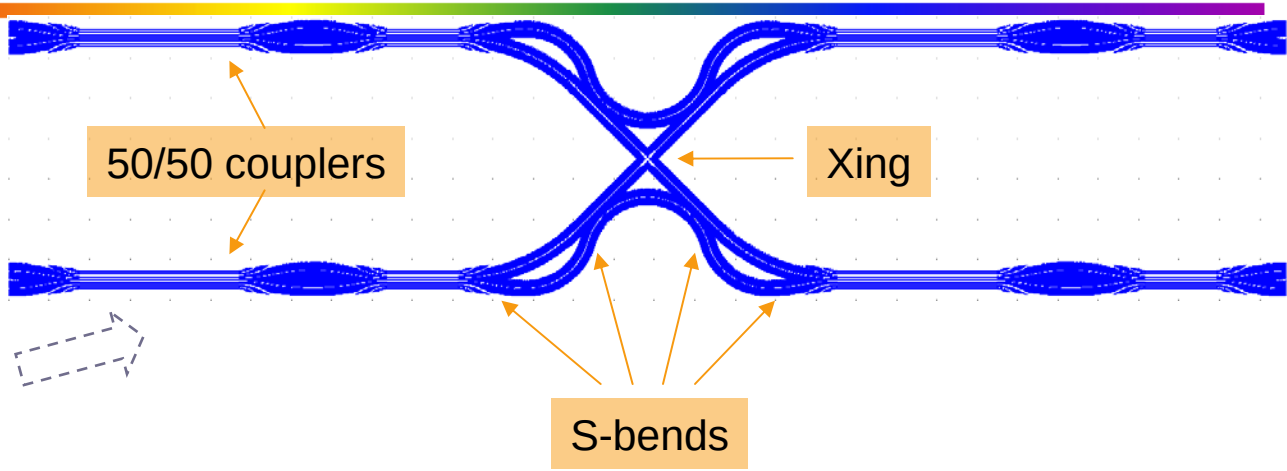


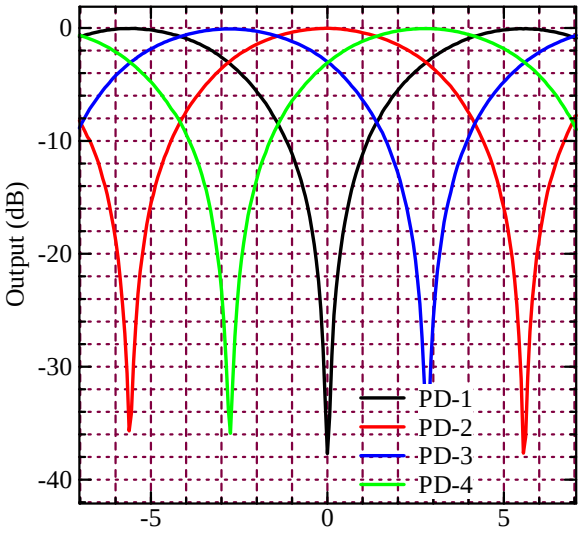
Phase-Error Compensation

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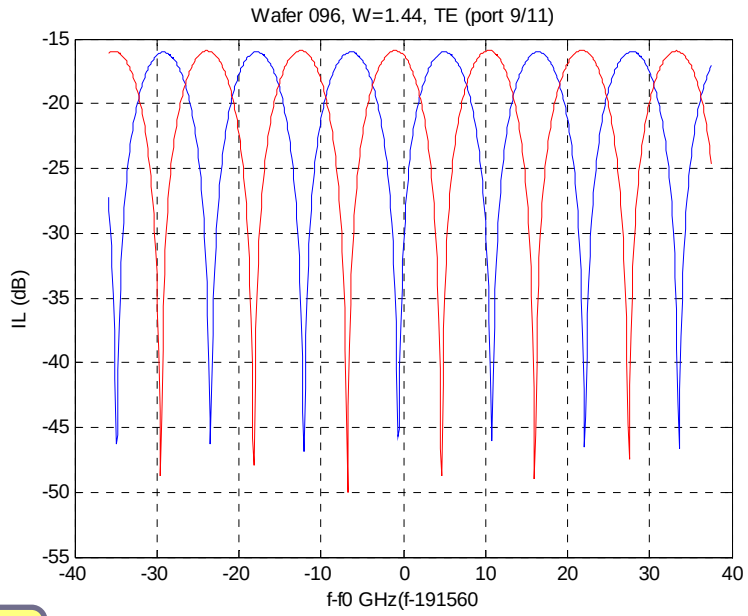
PM-DQPSK 90-deg Hybrid







Simulation

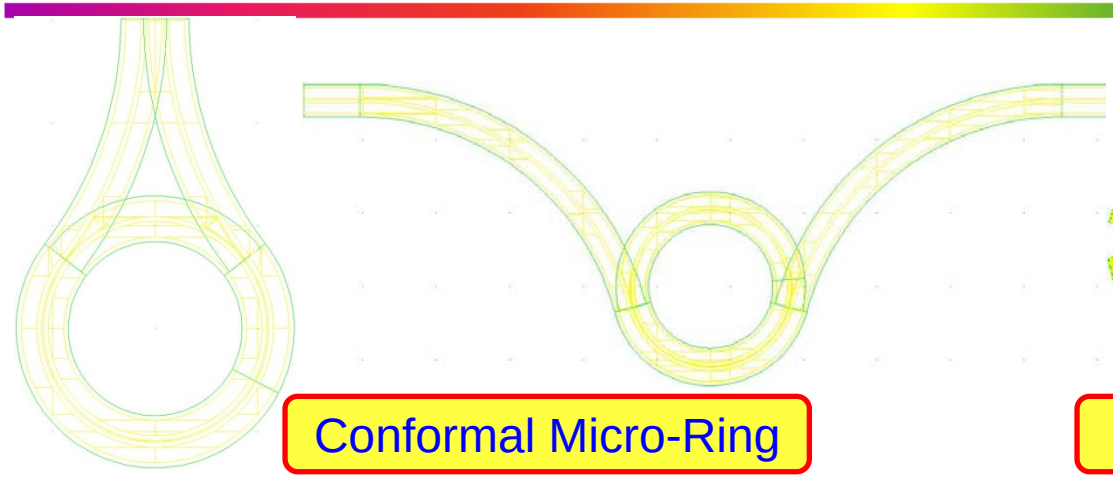


Measurement

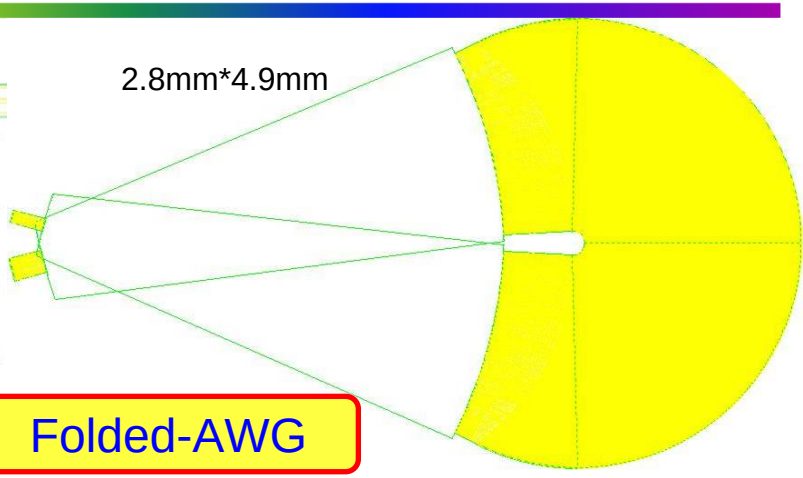
> 30 dB Extinction

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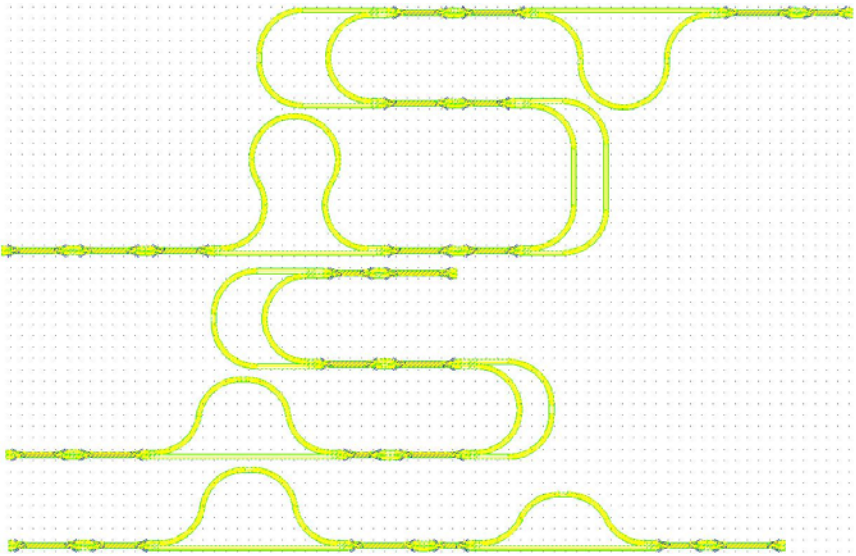
More PLC Devices …



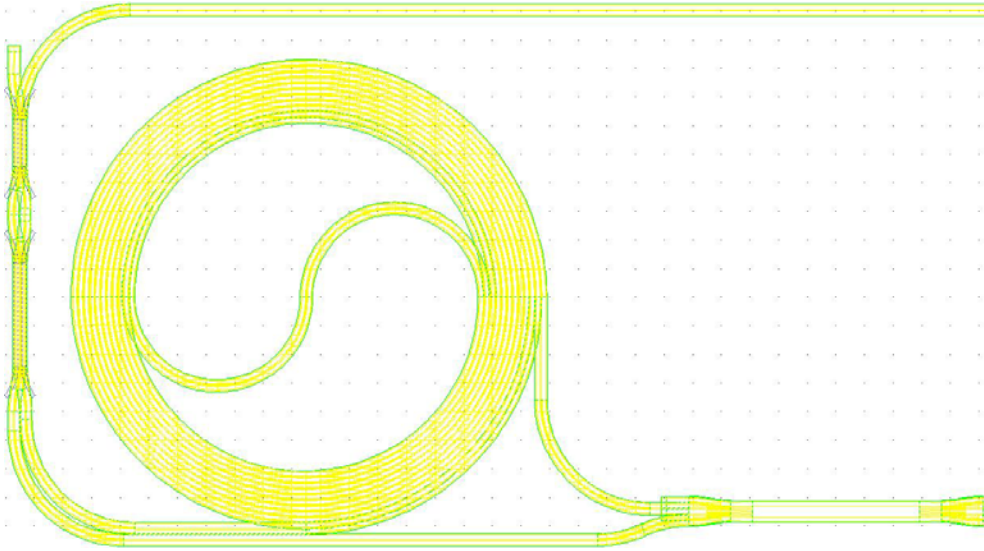
Conformal Micro-Ring



Folded-AWG



Multi-Stage Filters



MMI DQPSK Hybrid

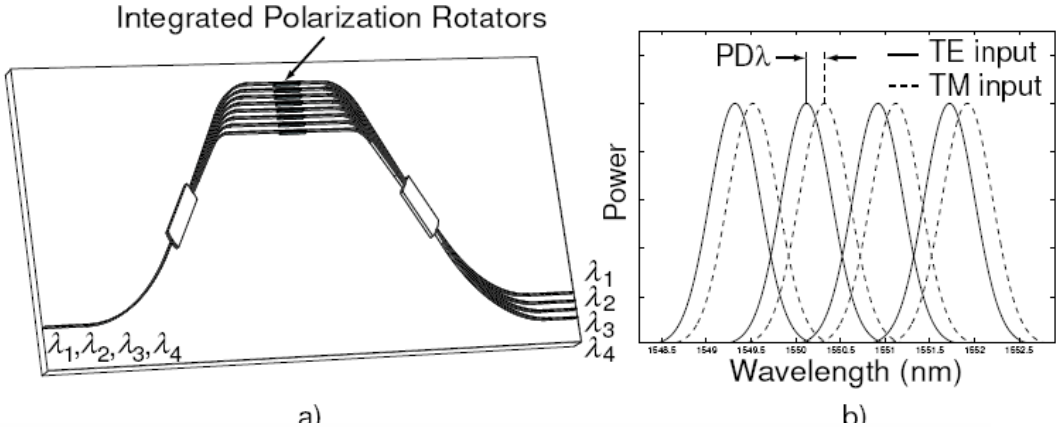
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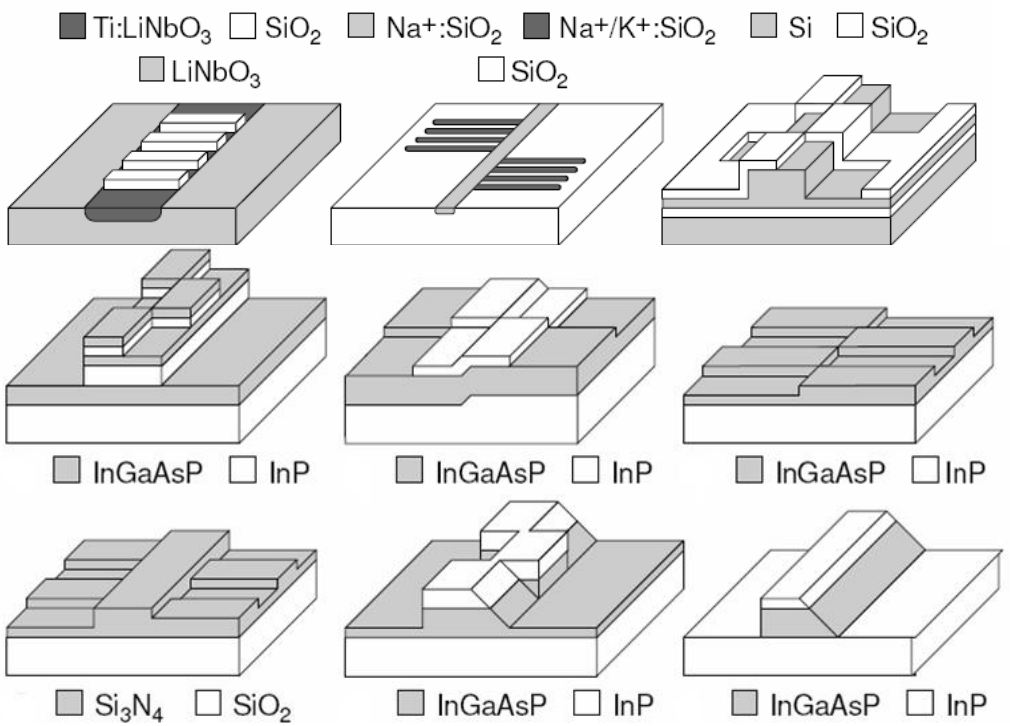
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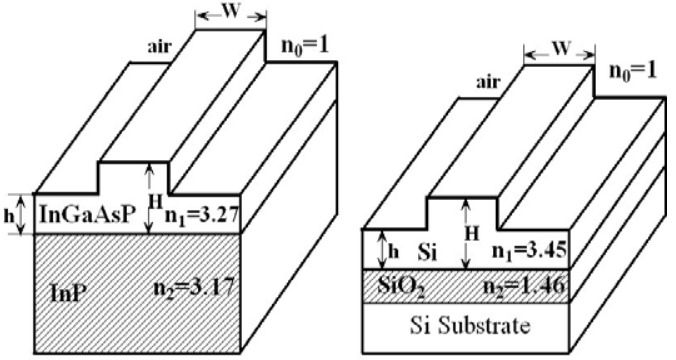
Integrated Polarization Controller





Previous Polarization Rotators

- **Polarization controller**
  - **Birefringence causes PMD and PDL**
    - **Signal distortion and loss**
    - **Bit rate and bandwidth limitation**
  - **Polarization beam splitter (PBS)**
  - **Polarization rotator (PR)**
- **Realization**
  - ***Active***
    - **Electro-optic and thermal-strain effects**
    - **Voltage-controlled electrode → Difficulties**
  - ***Passive***
    - **Anisotropic material**
    - **Asymmetric geometry**
- **Material**
  - **III-V (AlGaAs/GaAs, InGaAsP/InP)**
  - **Silica**
  - **Silicon-on-Insulator (SOI)**
    - **Main platform for *Silicon Photonics***
    - **Compatible with VLSI CMOS electronics (low cost OEIC)**
    - **Strong optical confinement (Compact and low loss)**

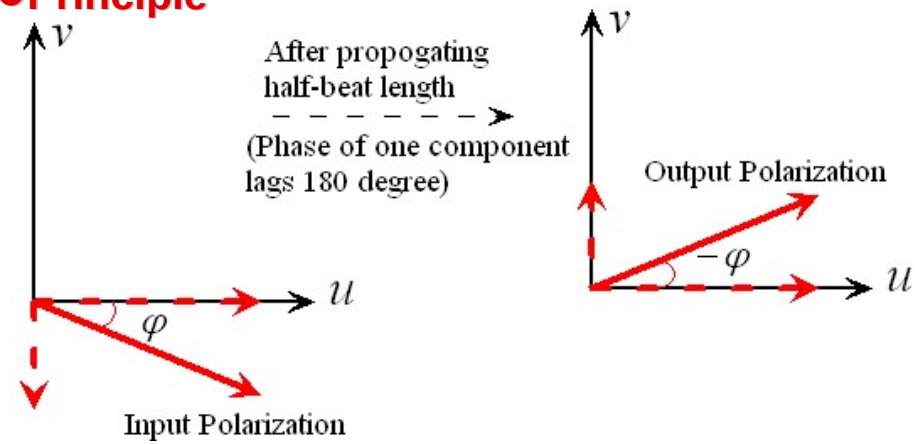


Single-Section SOI Polarization Rotator

Advantage

- Strongly-hybridized modes.
- Easy fabrication. Compact size. Low loss.

Principle

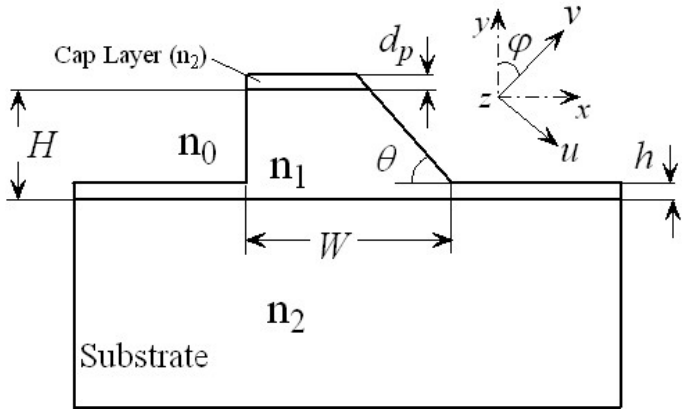


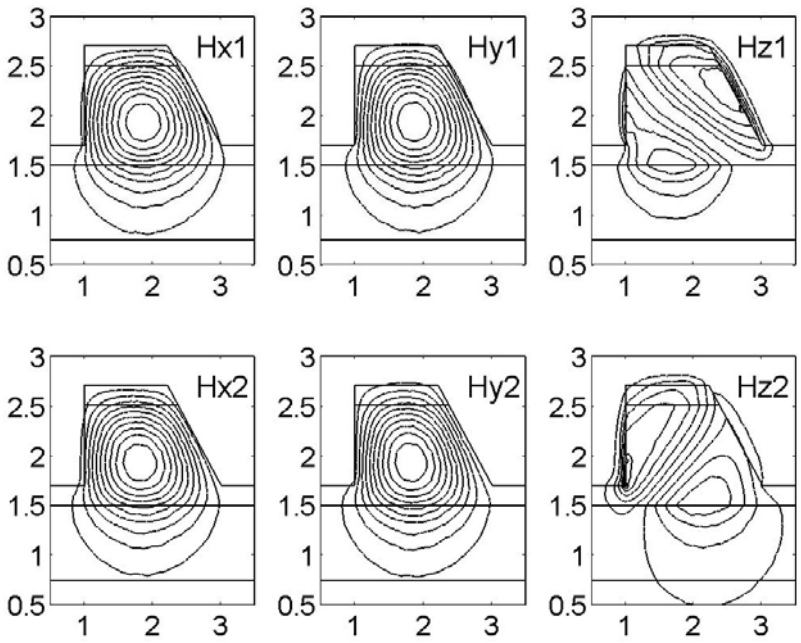
Optical-Axis Rotation

- Rotation Parameter

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

- Rotation Angle
  - *R*>>1 (*φ* > 45°) → *x*-polarized;
  - *R*<<1 (*φ* < 45°) → *y*-polarized;
  - *R*=1 (*φ* = 45°) → *PR* (Single Section)





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Full-Vectorial Finite Element Method (FV-FEM) and Beam Propagation Method (FE-BPM)

●FEM Mode Solver

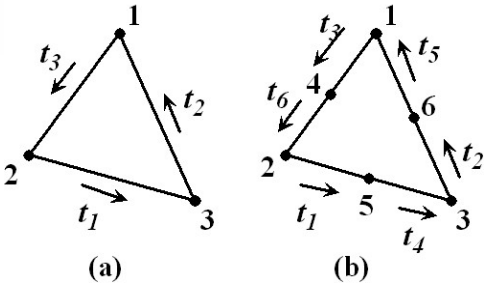
- ❖ **Obtain functional → Divide problem region → Derive elementary matrix → Assemble global system → Solve eigenvalue equation**

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

- ❖ **FEM Eigenvalue Equation**

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

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



Mixed elements
(Avoid spurious modes)

●FE-BPM Iteration $[A]_k\{\phi\}_{k+1} = [B]_k\{\phi\}_k$

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

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

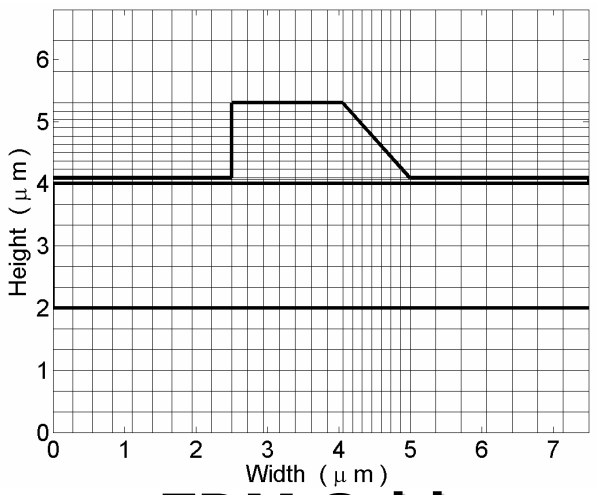
- ❖ **Fresnel and Wide-Angle; Adaptive reference index n_0; Imaginary-Distance BPM as Mode Solver; Anisotropic Perfectly-Matched-Layer (PML) Boundary Condition**

●Advantages

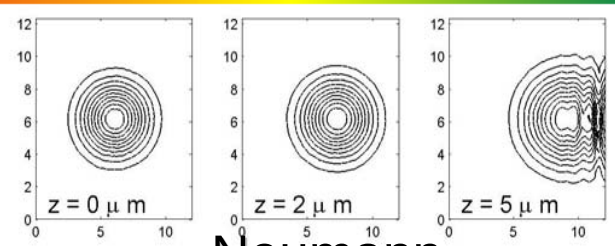
- ❖ **Accurate, efficient, and versatile (*Arbitrary-shape, anisotropic, inhomogeneous, lossy*)**
- ❖ **Non-uniform unstructured mesh & Adaptive Mesh (FDM limited by rectangular grids)**

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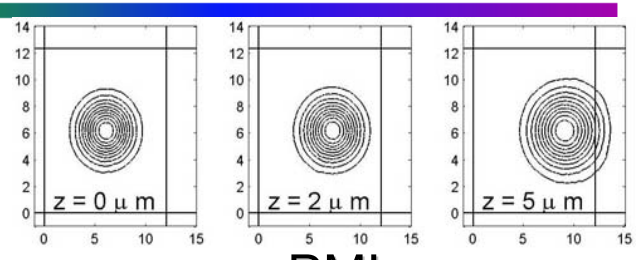
FEM Mesh and BPM Boundary Condition



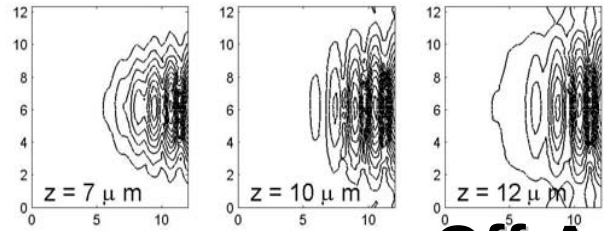
FDM Grids

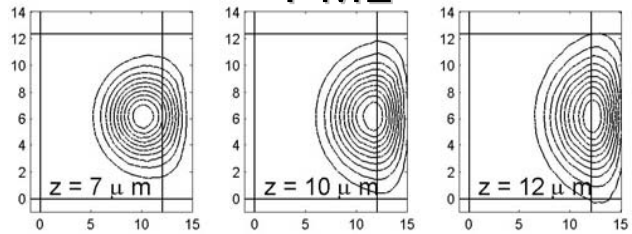


Neumann

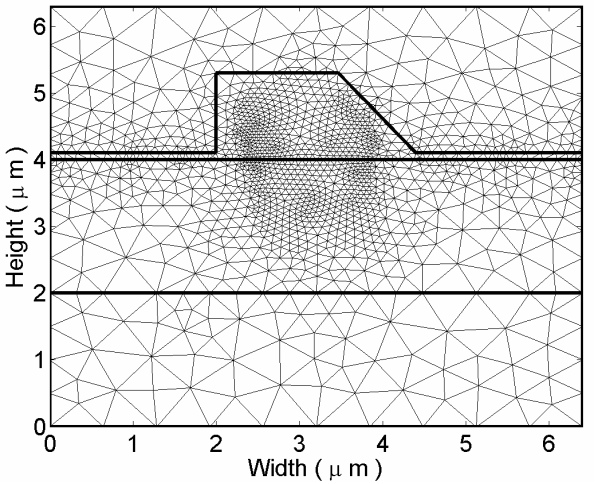


PML

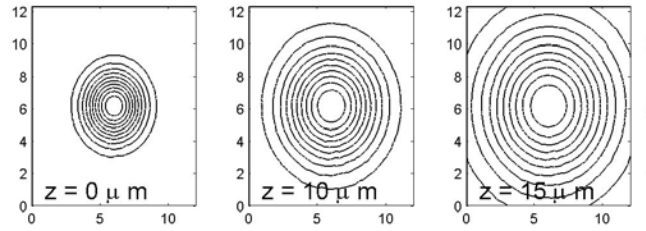




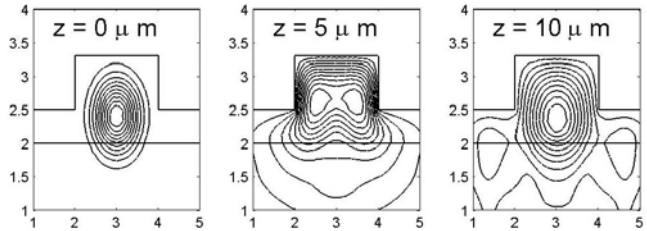
Off-Axis BPM



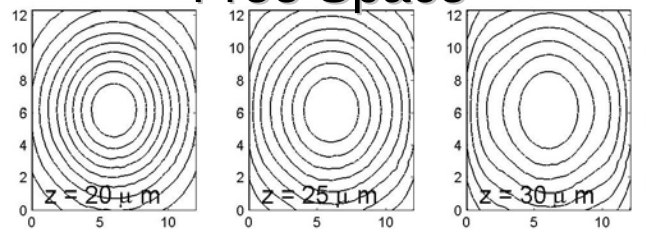
Adaptive Mesh

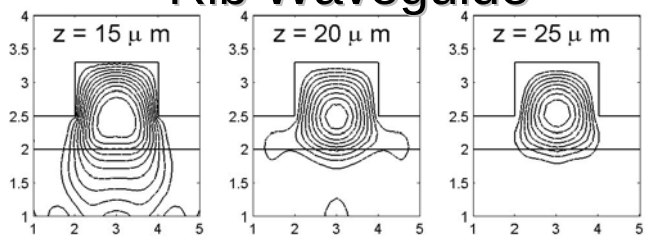


Free Space



Rib Waveguide

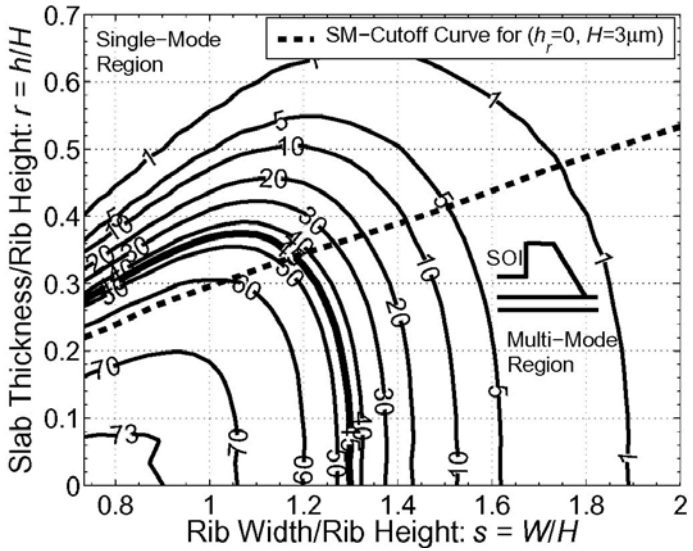


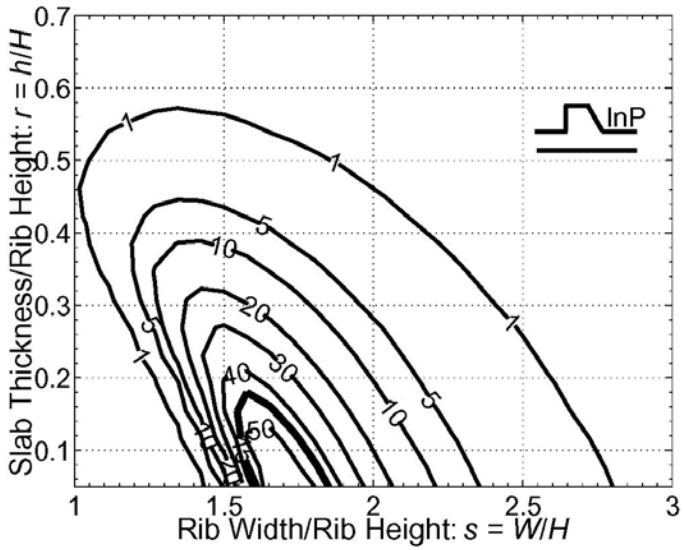


On-Axis BPM

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Design and Characterization





●SOI PR

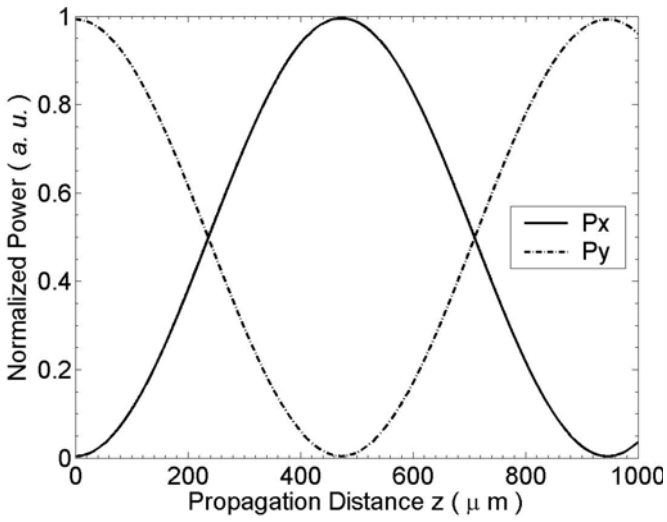
(1). Single-mode from $1 \le H \le 10\mu m$

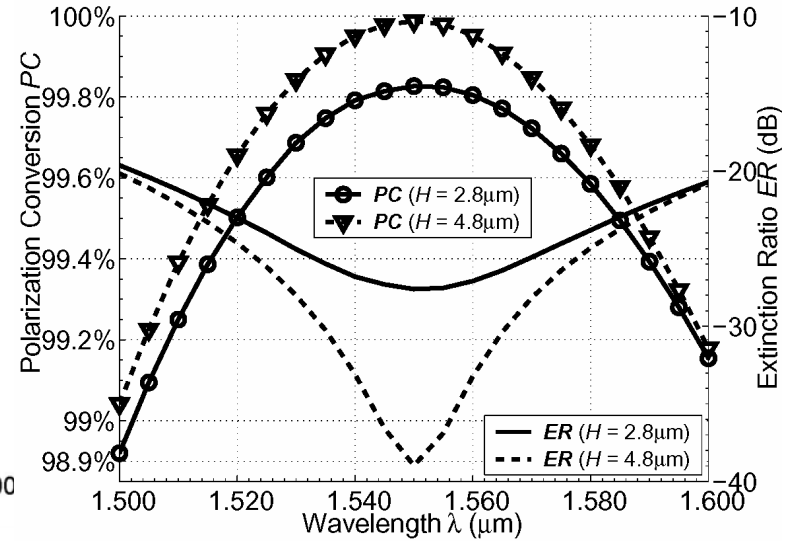
(2). Normalized Charts for various H

●III-V PR

Small cross-section H for single-mode

(due to weak optical confinement)





●Power Exchange

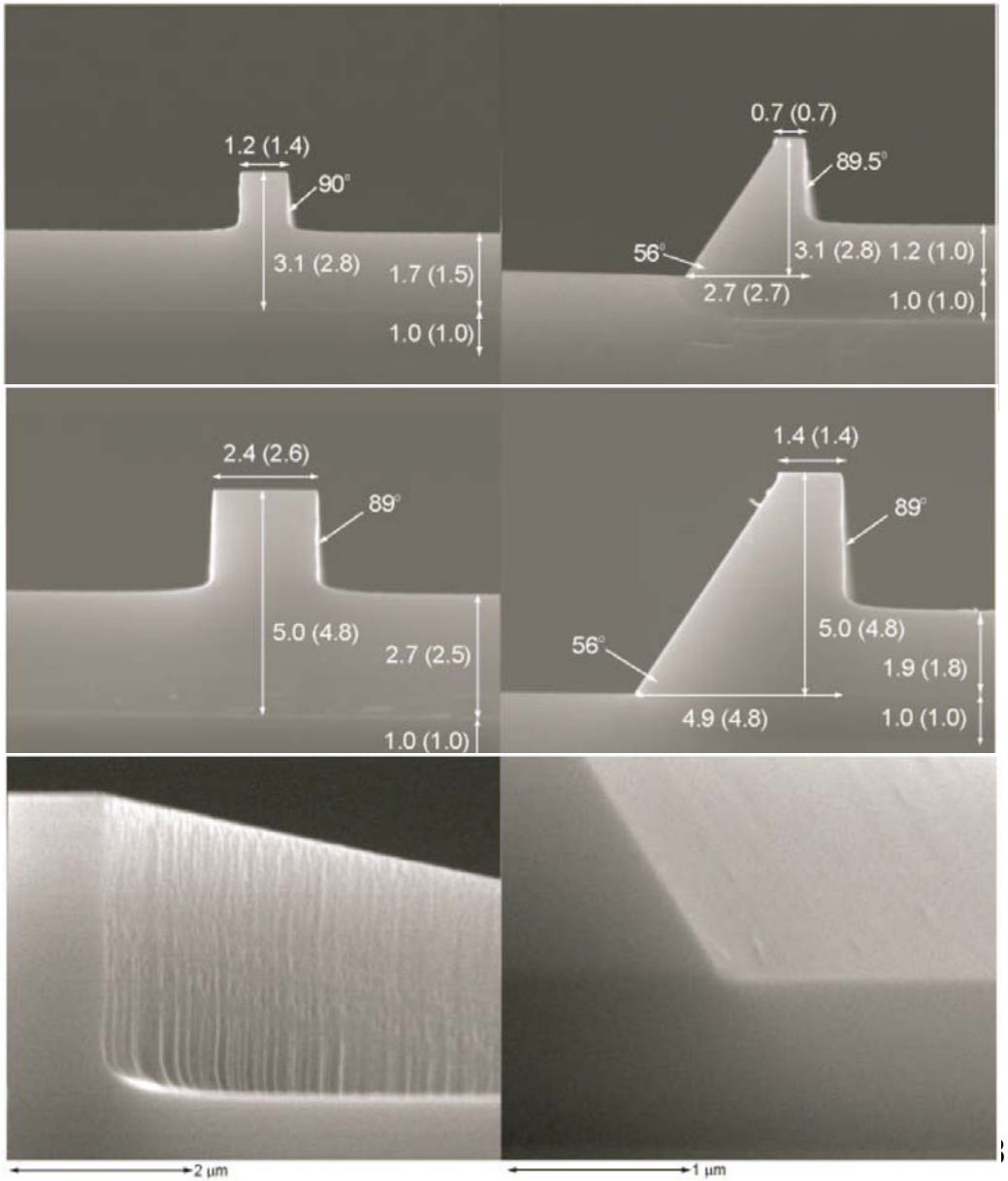
- **BPM Verifies Analytical Formula**
- ***PC* = 99.60% (99.61%) for TE- (TM-) input**

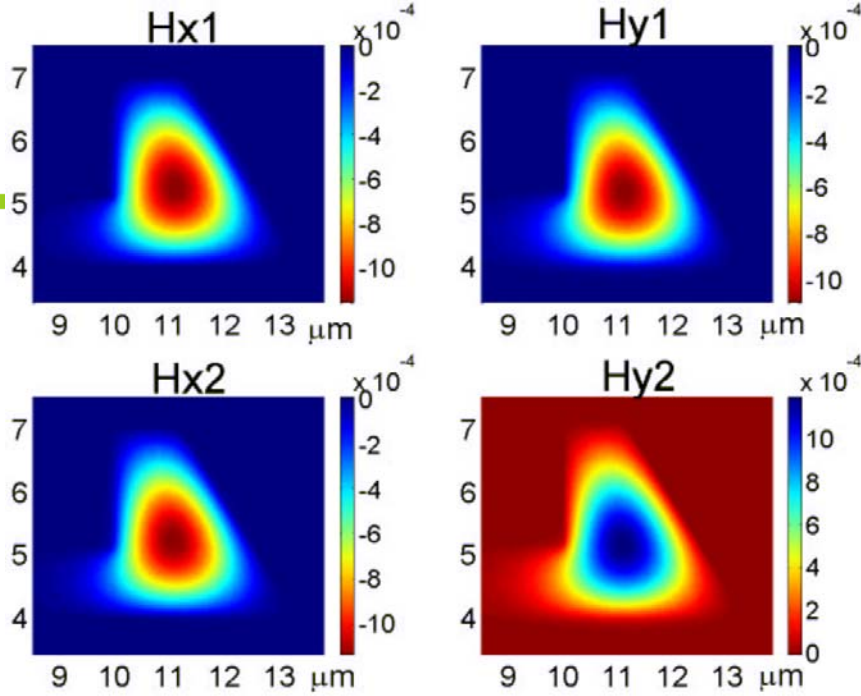
●Spectral Property

- **PC > 99.7% in *C*-band**
- **–25dB (–30dB) crosstalk for 3μm (5μm) device**
- **Suitable for DWDM**

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Fabricated Device



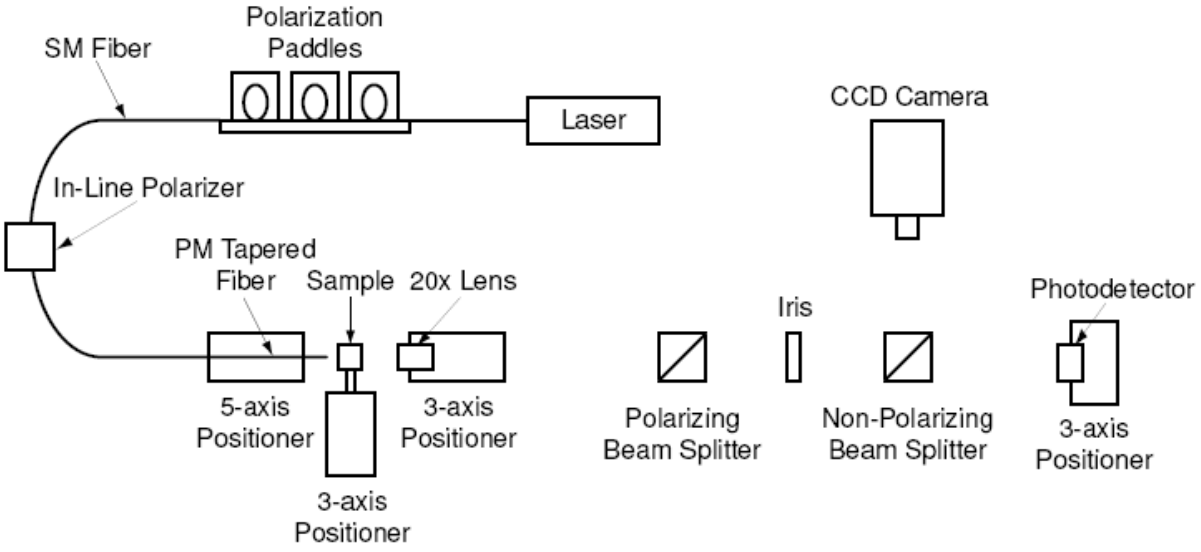


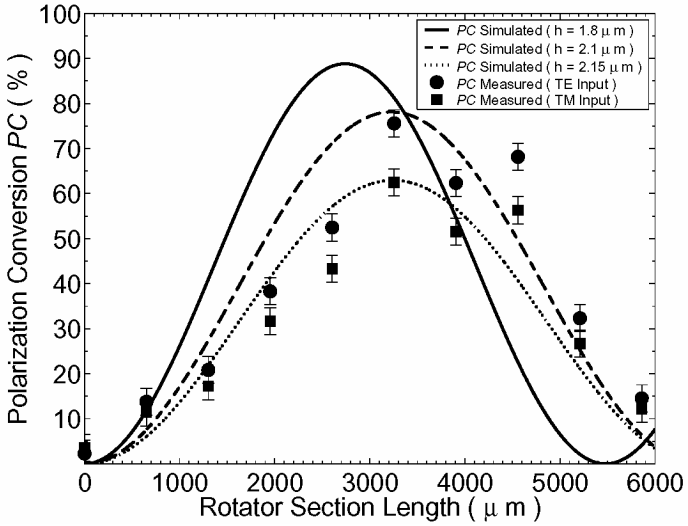
Identical TE and TM fields;

Confined in guiding region.

- **Procedure**
  - **BE-SOI — wafer**
  - **RIE — vertical wall**
  - **TMAH — slanted wall.**
- **Quality**
  - **smooth slanted-facet**
- **SEM Precision**
  - **0.1μm — height /width**
  - **1° — angles**

Testing and Measurement

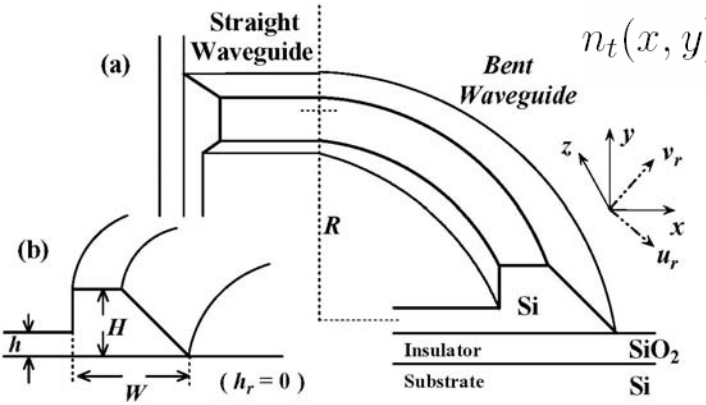




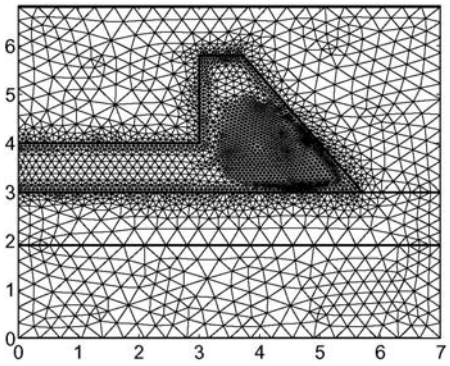
- **Fabrication Variation**
  - **Optimal:** (*H, W, h, hr*) =(4.8, 4.8, 1.8, 0)μm, *R*=1.01, L_π=2572 μm, *PC*= 99.98%
  - **Actual:** (*H, W, h, hr*) =(5.0, 4.9, 1.9, 0)μm, θ_{slant}=56˚, $\theta_{vertical}$=89˚, *R*=1.122, *Lπ* = 2940 μm
    - **Simulated: PC = 88 % (Maximum theoretical)**
    - **Measured: $PC_{TE\rightarrow TM}$ = 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***

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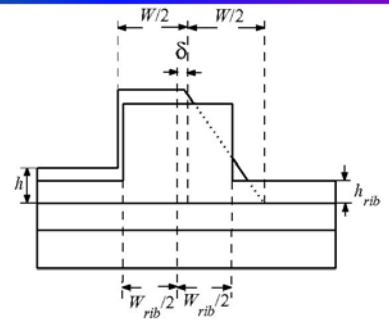
Bending and Coupling



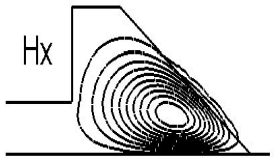
$$n_t(x,y) = n(x,y)(1 + \frac{x}{R_c})$$



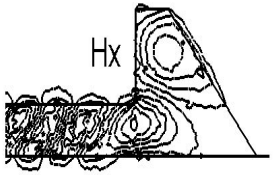
Adaptive Mesh



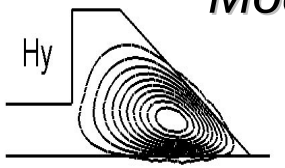
Outer Facet Slanted (R = 50 μ m)

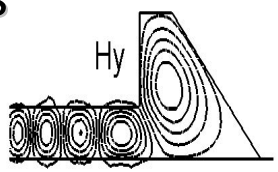


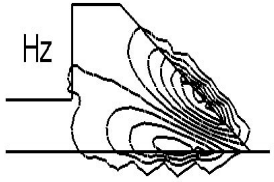
Outer Facet Vertical (R = 50 μ m)

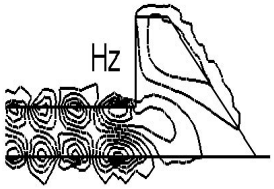


Modes

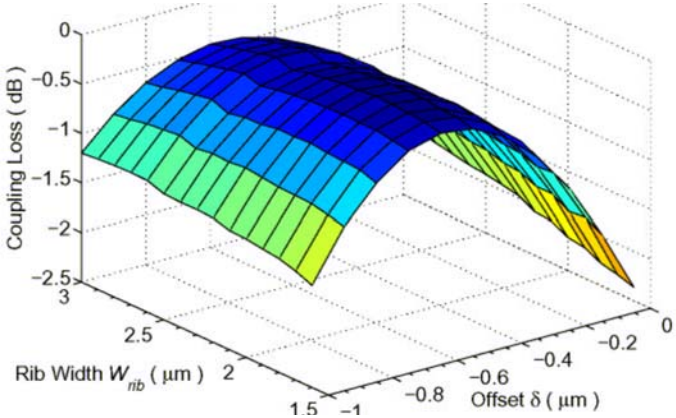


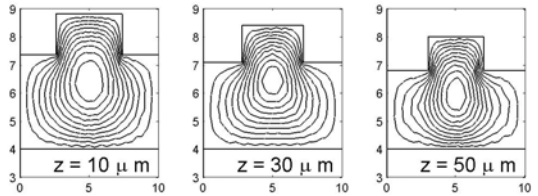


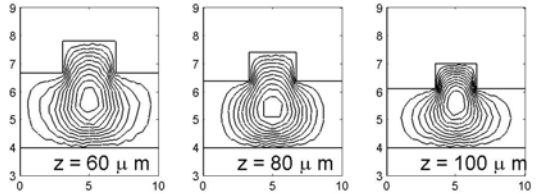




- **Bending Analysis**
  - **Asymmetric behavior**
  - **Change both light direction and polarization**
- **Butt-Coupling**
  - **Optimize offset**
- **Taper**
  - **Improves coupling**





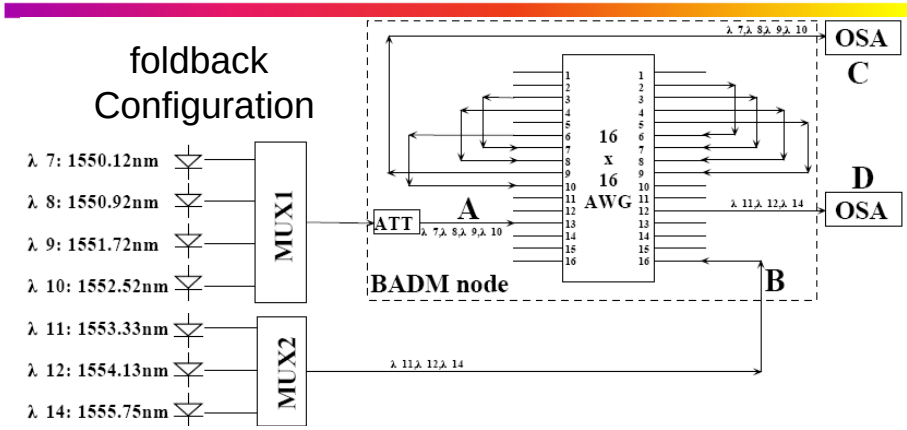


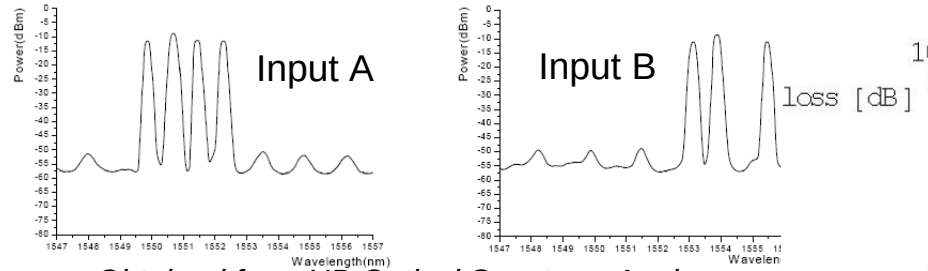
Overview

- **Planar Lightwave Circuit (PLC)**
  - PM-DQPSK Demodulator
  - AWG and OADM
- **Integrated Photonic Device**
  - Polarization Controller (SOI, Hydex®, InP)
  - Numerical Simulation (FEM, BPM) and Software
- **More Experience**
  - Optical Telecom Network
  - Nanophotonics, Microfabrication and Measurement
  - Electronic Design Automation
- **Summary**

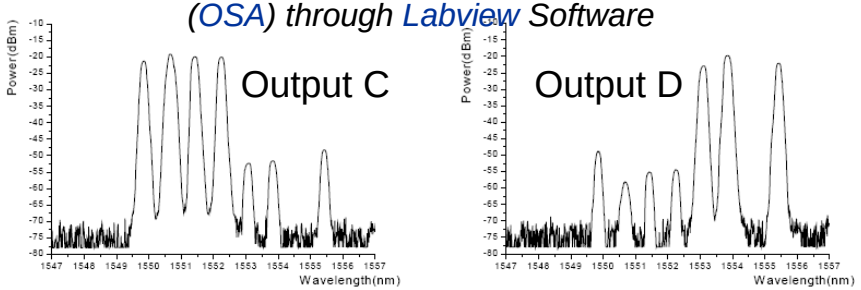
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AWG-based OADM



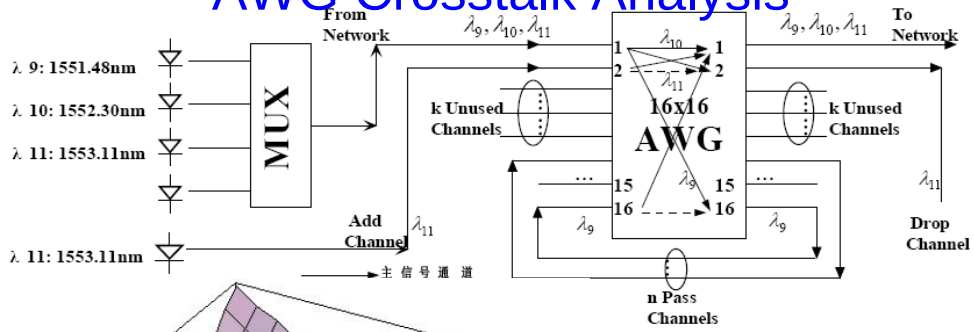


Obtained from HP Optical Spectrum Analyzer (OSA) through Labview Software

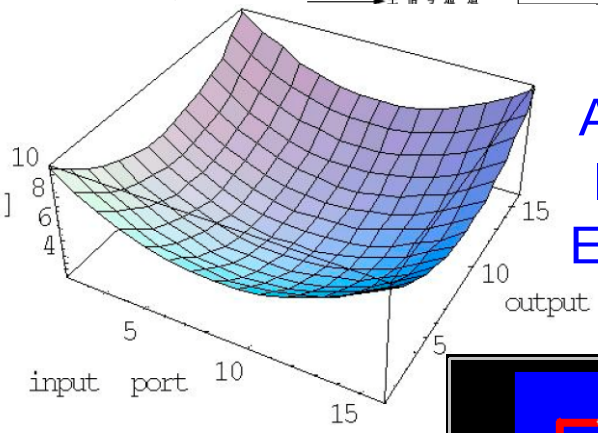


Bidirectional OADM Experiment (Optical Spectrum)

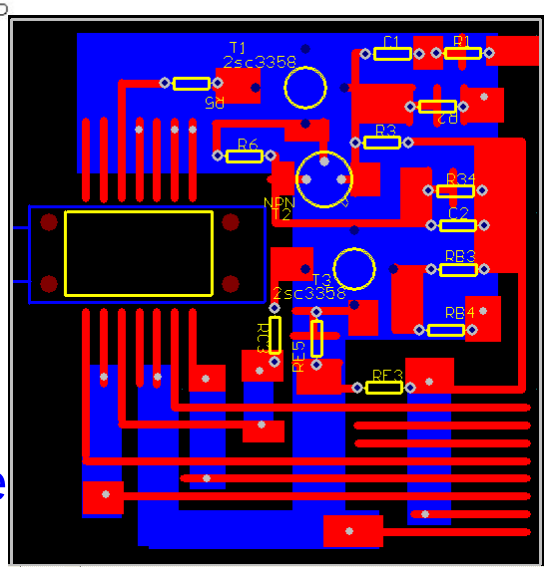
AWG Crosstalk Analysis



AWG Loss-Imbalance Equalization

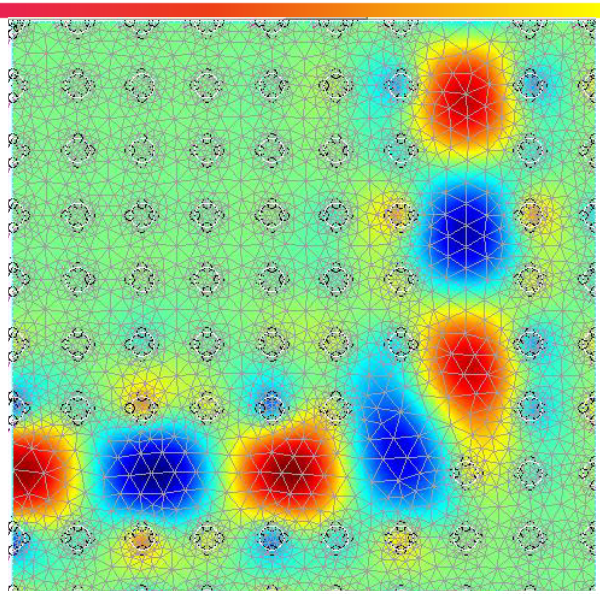


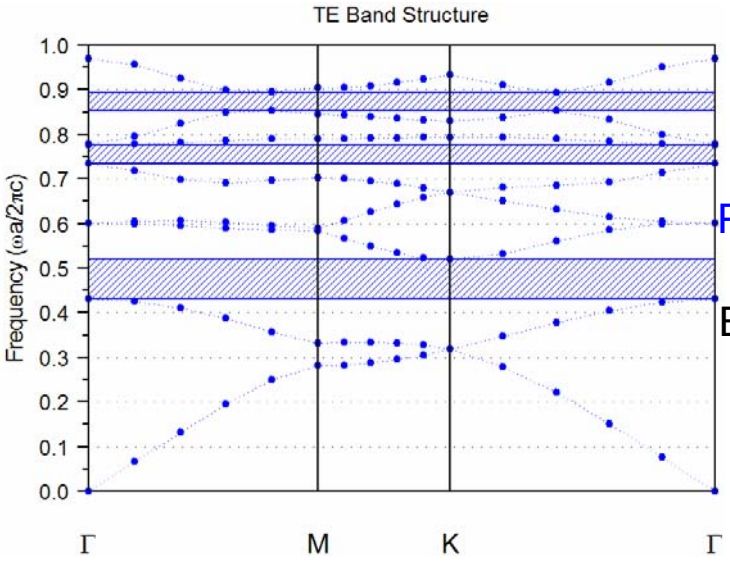
Electronic Circuit for Laser Temperature Control



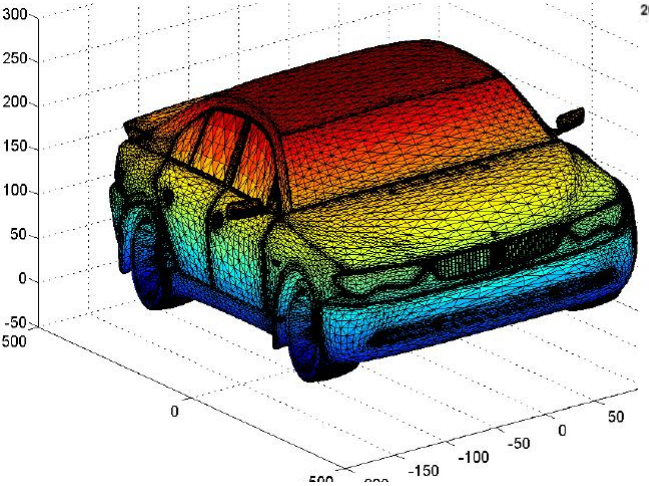
Electronic Design Automation

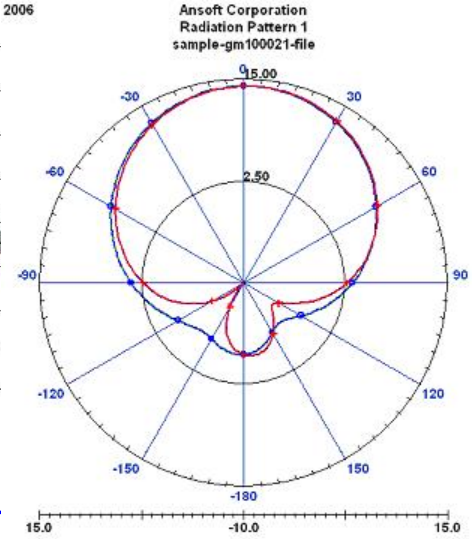
Photonic Bandgap (PBG) Bend (FEMLAB /Comsol Multiphysics)



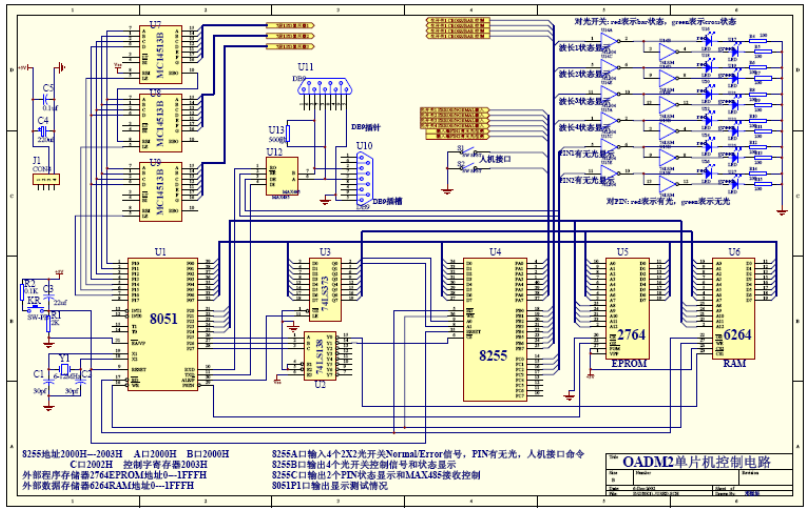


Photonic Crystal Fiber (PCF) (RSoft BandSolve)





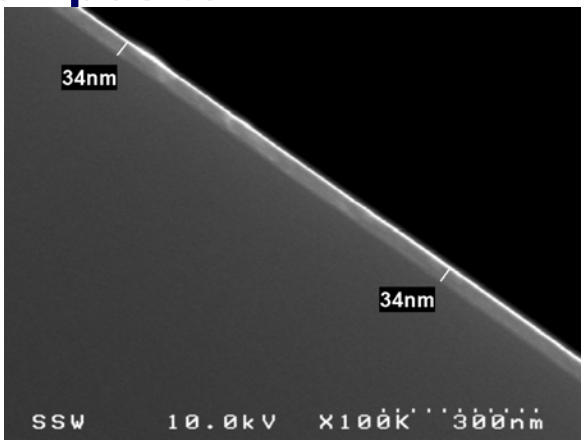
Tiny Antenna in Big Car (AutoCAD – Geometry, MATLAB – Mesh, Ansoft HFSS and FEKO – Far Field)



Microprocessor Circuit for OADM Power and Switching Control

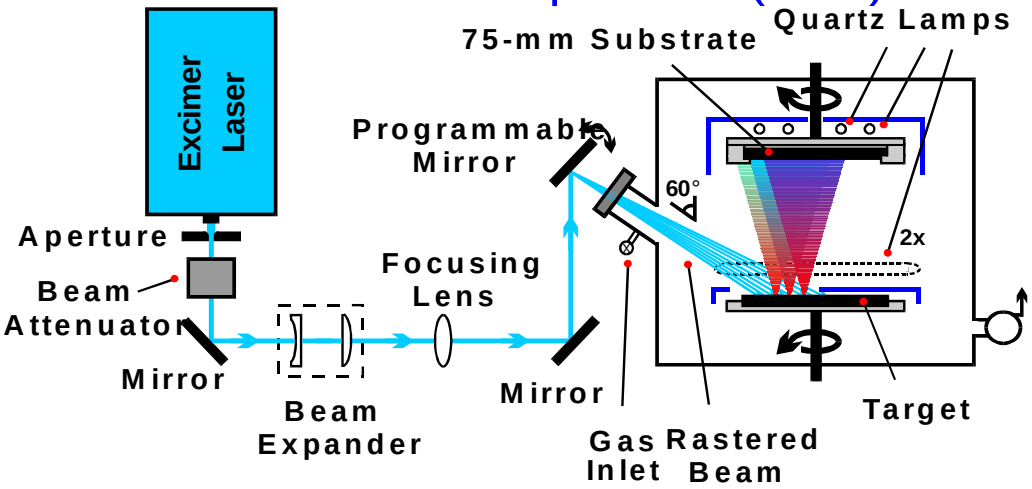
NRC·CNRC
From Discovery to Innovation...

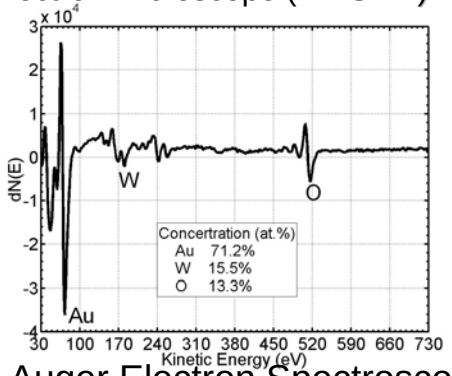
Suface Plasmon Resonance Sensor with Nanocomposite Thin-Film



Field-Emission Scanning Electron Microscope (FE-SEM)

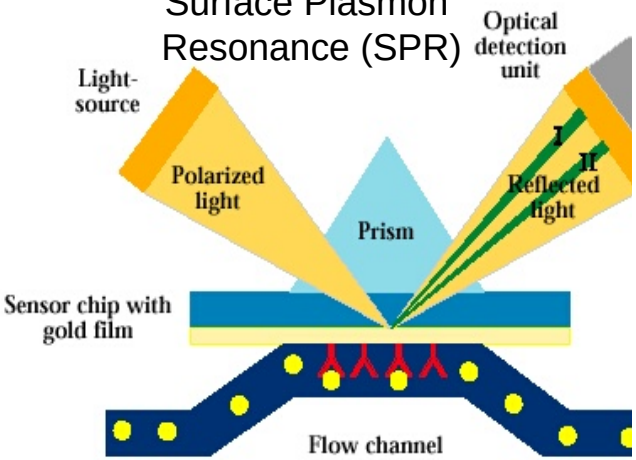
Pulsed Laser Deposition (PLD)



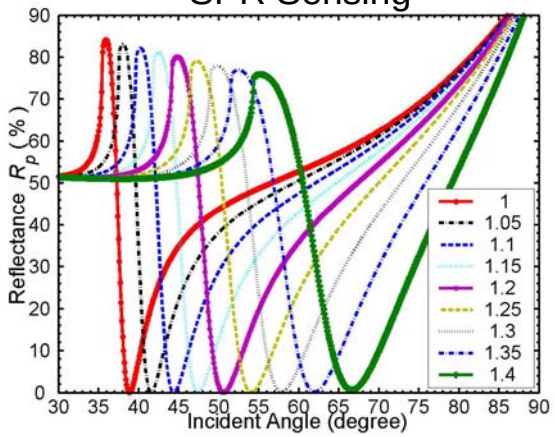


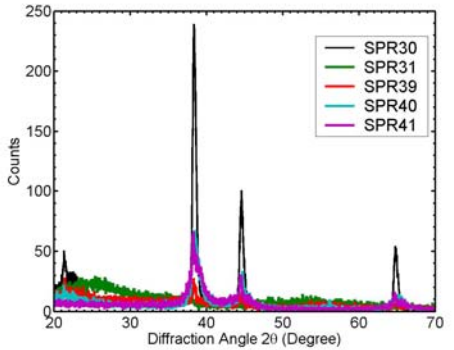
Auger Electron Spectroscopy

Surface Plasmon Resonance (SPR)



SPR Sensing





X-Ray Diffraction (XRD)

Summary of Qualification

- **Photonic Device and Optical Network**
  - ❖ AWG, OADM, OXC, DWDM, DQPSK, PBG, SOI, Hydex™, …
  - ❖ MMI, MZI, Coupler, PBS, Crossing, Bend, Taper, Micro-Ring, …
- **Simulation, Fabrication, and Measurement**
  - ❖ FEM, FDM, BPM, FDTD, CMT, …
  - ❖ OSA, PVD, SEM, XRD, AES, SCI, Profilometer, …
- **Hardware and Software**
  - ❖ Electronic Circuit (SCH&PCB), FPGA, C, VB, IC Editors, …
  - ❖ RSoft, Apollo, Comsol/Femlab, Ansoft, AutoCAD, Matlab, ...
- **Personality**
  - ❖ Collaborative, Innovative, Creative, Productive, Competitive, …

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Acknowledgement

- Dr. **Brent Little**, Dr. **Wei Chen**, Dr. **Sai Chu**, Dr. **John Hryniewicz**, **…** (Infinera)
- Prof. **David O. Yevick** and Prof. **Sujeet K. Chaudhuri** (Waterloo)
- Prof. **Paul E. Jessop** and Mr. **Chris Brooks** (McMaster)
- 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** (Peking Univ.)

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Thank You



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