Optoelectronic chip

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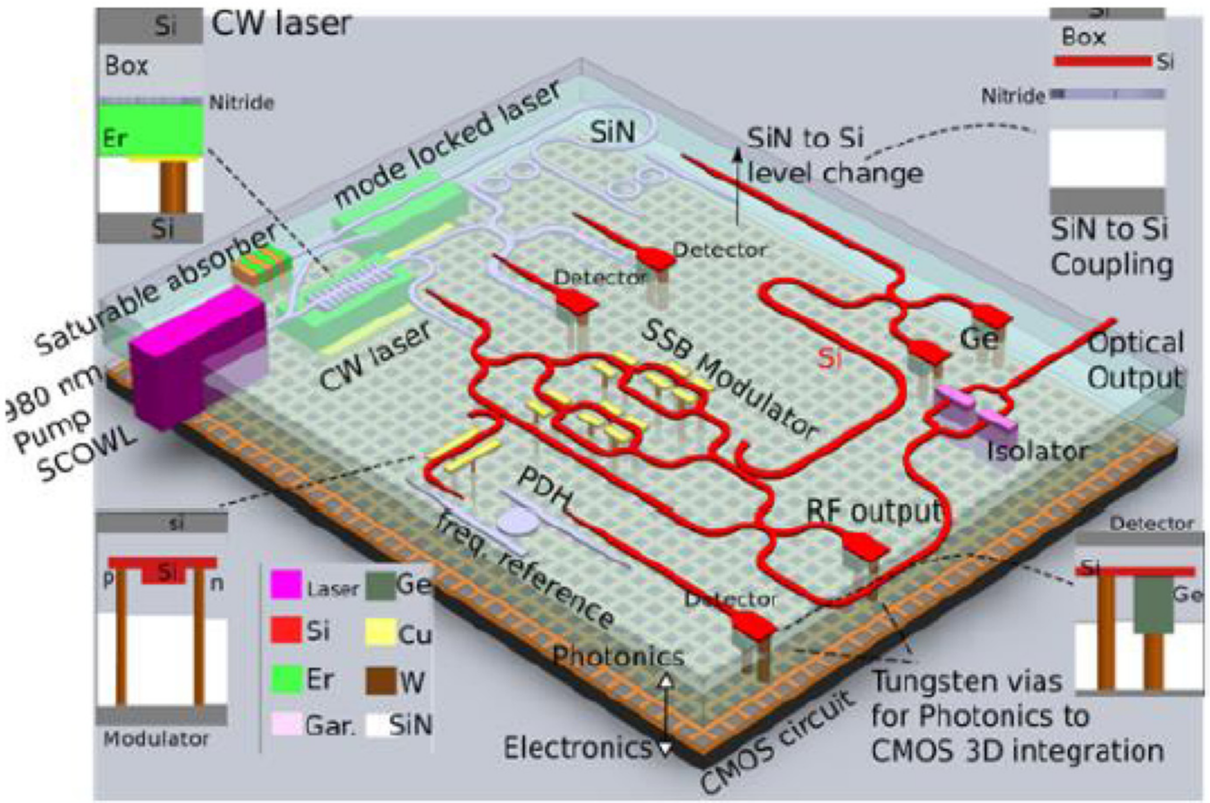
Course Overview

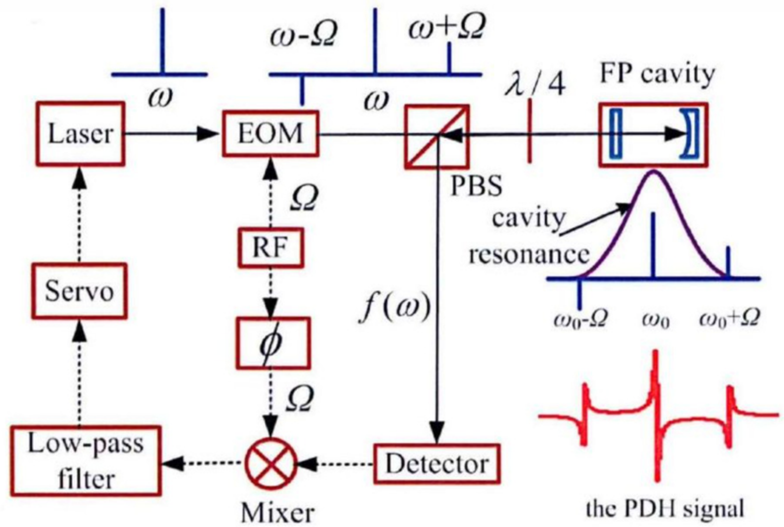
1. Basic Concepts of Optoelectronic Chips
2. Optical Waveguides, Couplers, and Filters
3. Coupled Mode Theory and Electro-Optic Modulators
4. Design Methods

Ref:
Robert G. Hunsperger, *Integrated Optics Theory and Technology*, Sixth Edition, Springer
Wim Bogaerts, *Introduction to Silicon Photonics Circuit Design*

1. Optoelectronic Integrated Circuits / Optoelectronic Chips

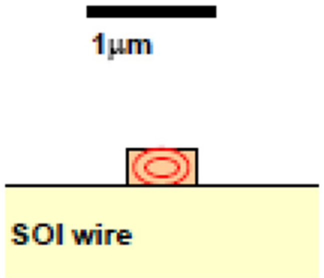
Integration of (many) optical functions on a chip





CW: continuous wave; SCOWL: slab-coupled optical waveguide laser
SSB: single side band;
PDH: Pound-Drever-Hall

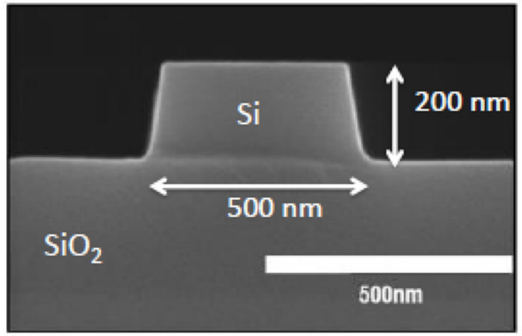
2. Optical Waveguides (1)

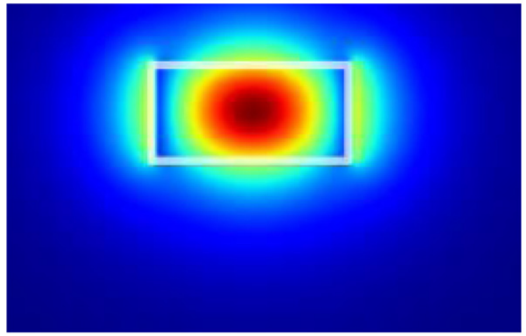


silicon wire:
index contrast ~ 200%

Why silicon photonics?

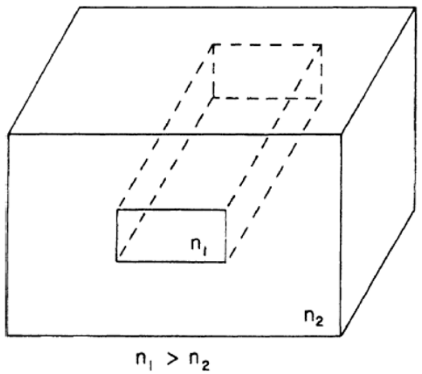
High index contrast
Submicrometer dimensions
small bend radius



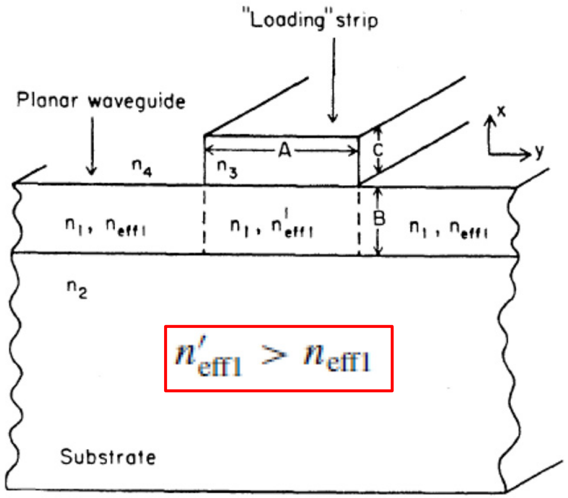


optical mode

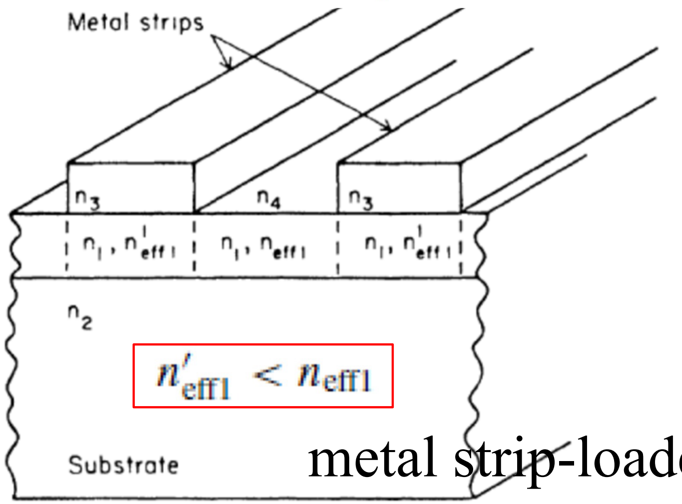
$n_1 > n_2 \geq n_3 > n_4$



channel waveguides



dielectric strip-loaded waveguides



metal strip-loaded waveguides

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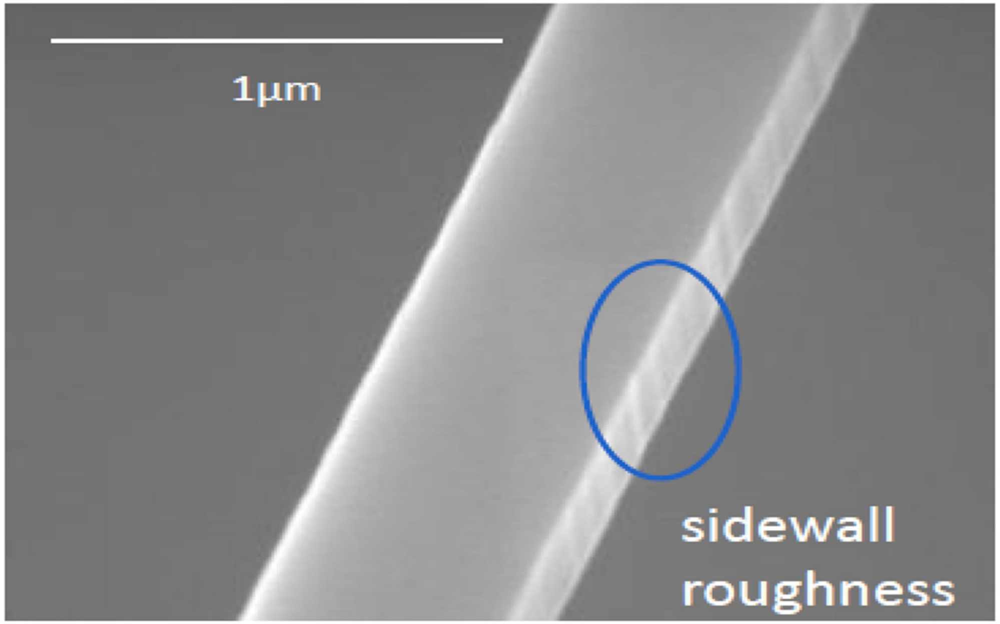
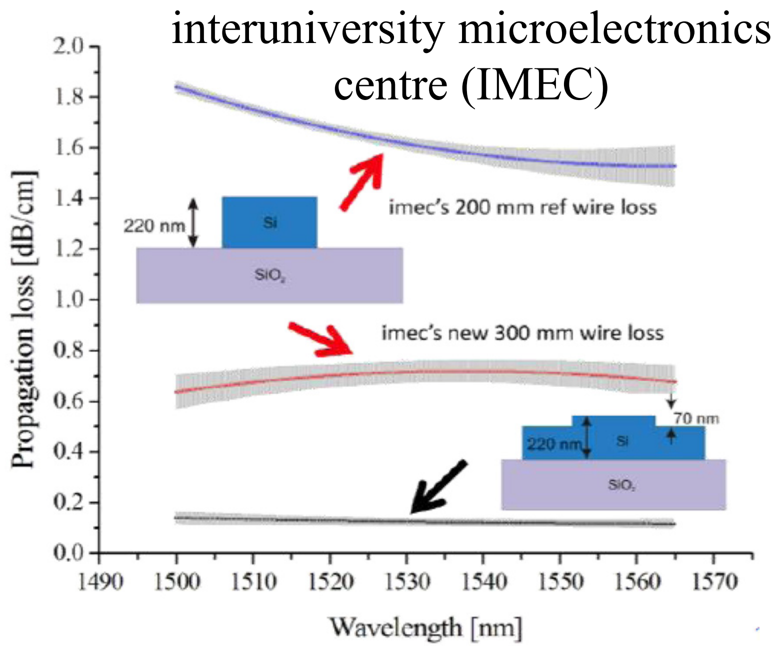
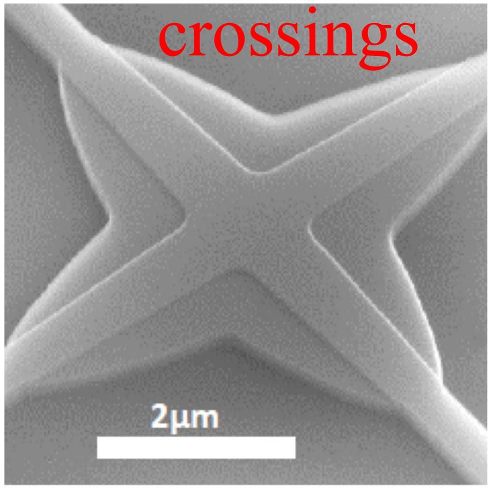
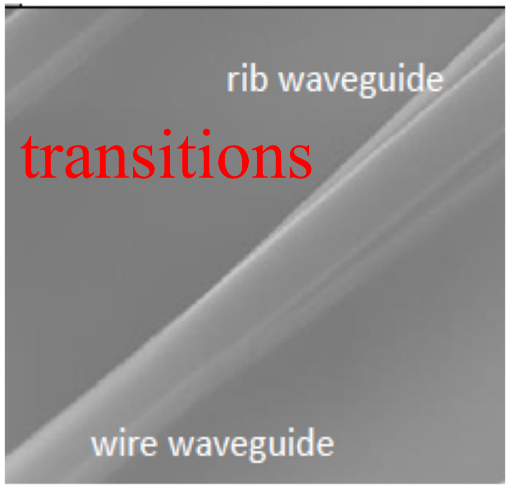
2. Optical Waveguides (2)

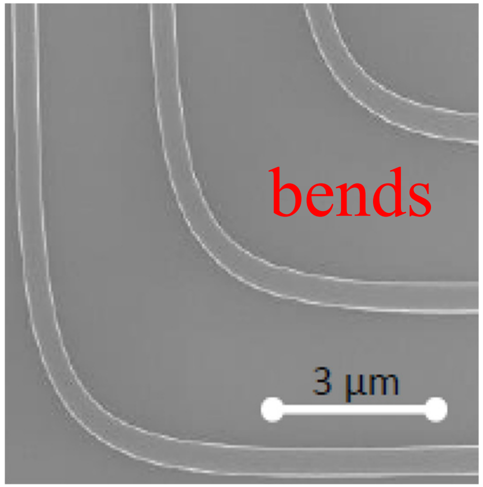
waveguide losses dominated by scattering.











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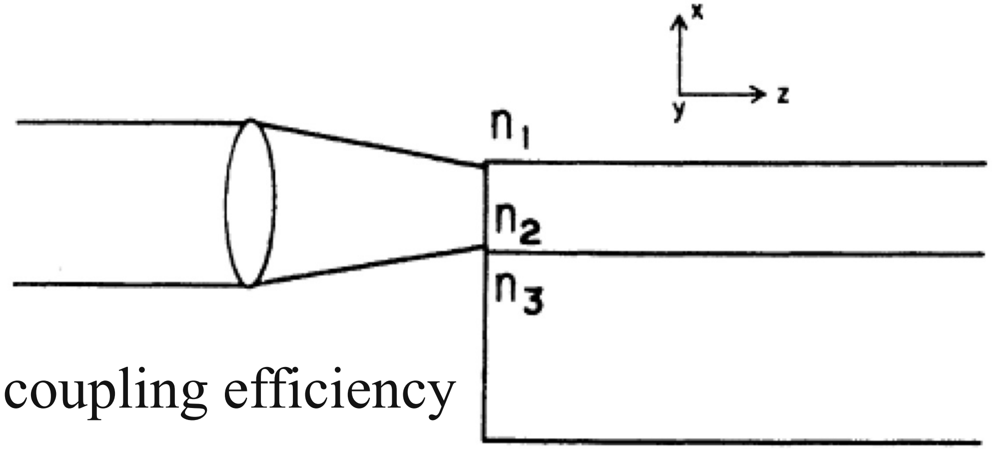
2. Optical Waveguide Couplers (3)

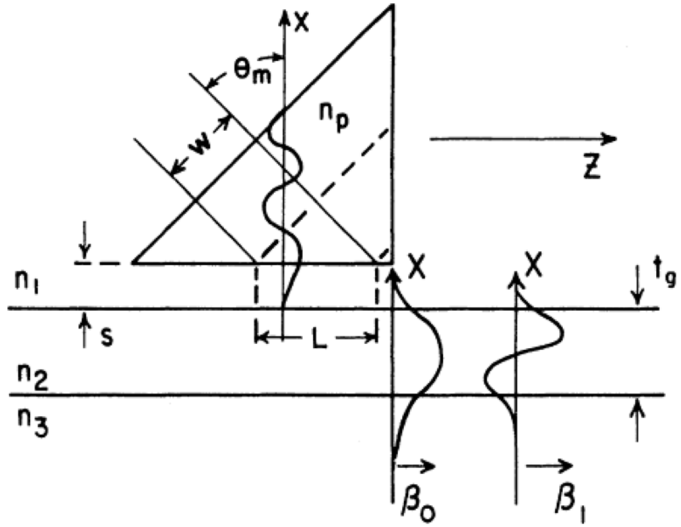
transverse coupling/ endfire coupling



coupling efficiency

$$\eta_{cm} = \frac{\left[\int A(x) B_m^*(x) \mathrm{d}x\right]^2}{\int A(x) A^*(x) \mathrm{d}x \int B_m(x) B_m^*(\dot{x}) \mathrm{d}x}$$

prism coupler

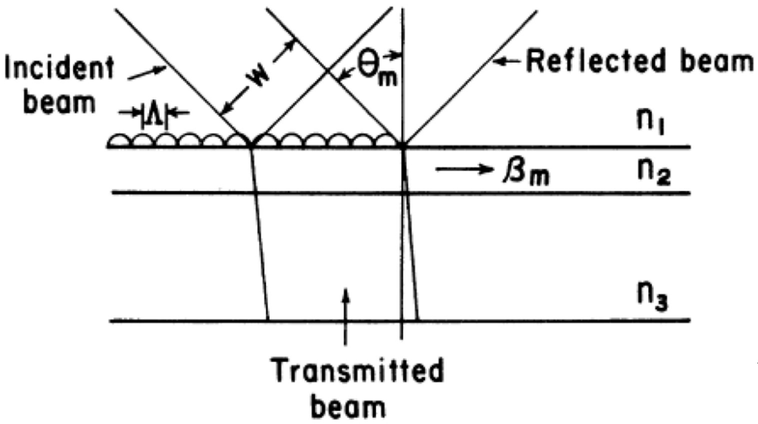


Why guided waves can be excited?

phase matching condition!

$$\beta_m = k_0 n_p \sin\theta_m$$

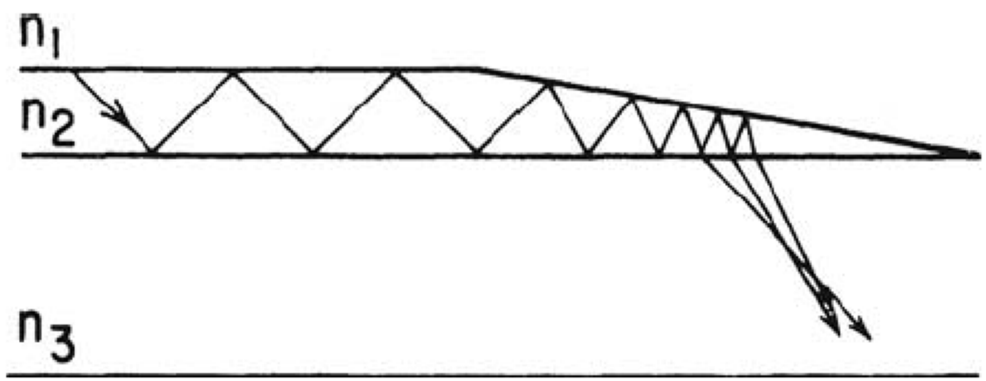
grating coupler



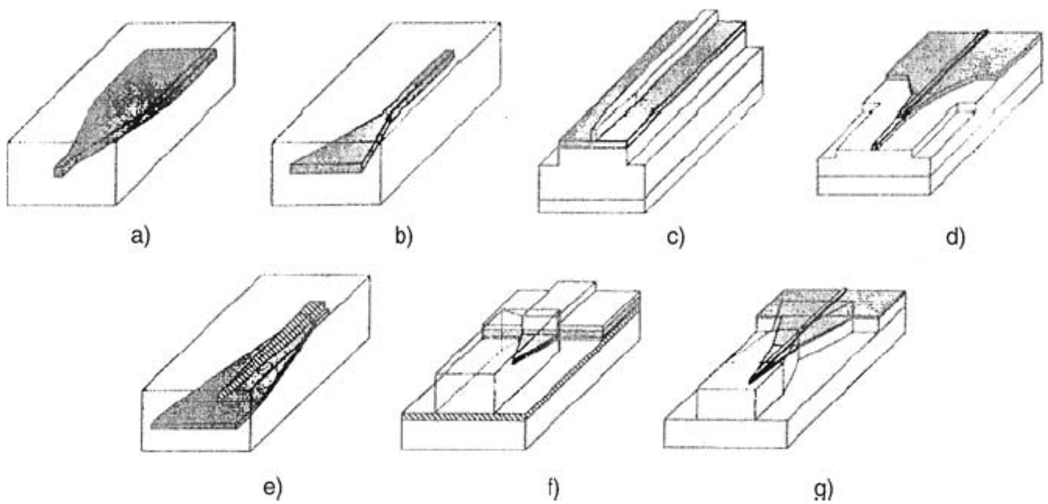
$$\beta_m = k_0 n_1 \sin\theta_m + \frac{2\pi}{\Lambda} m$$

2. Optical Waveguide Couplers (4)

tapered coupler



impedance matching!

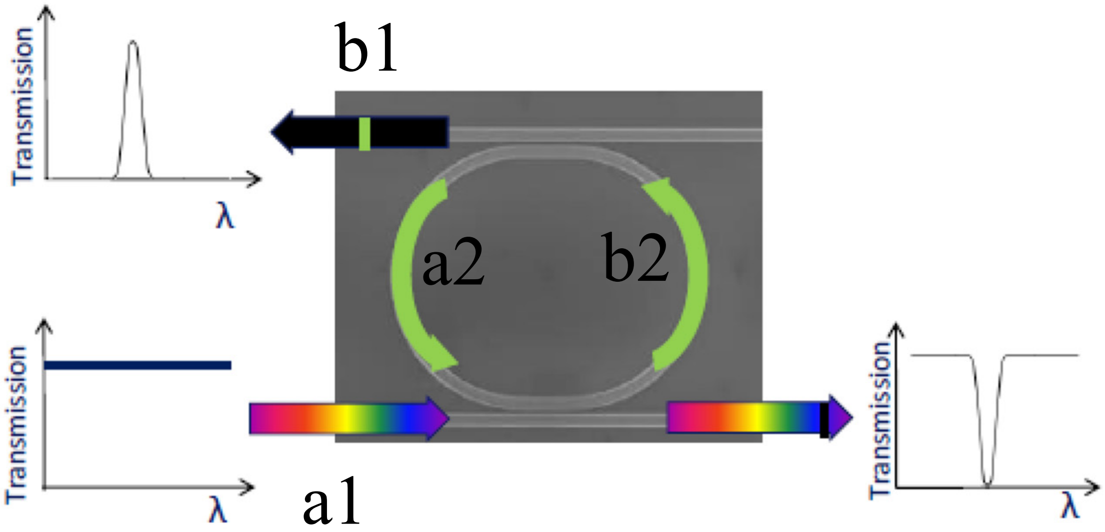


1. taper angle in the transition region is sufficiently small to prevent coupling of power from the fundamental mode into the higher order taper modes.

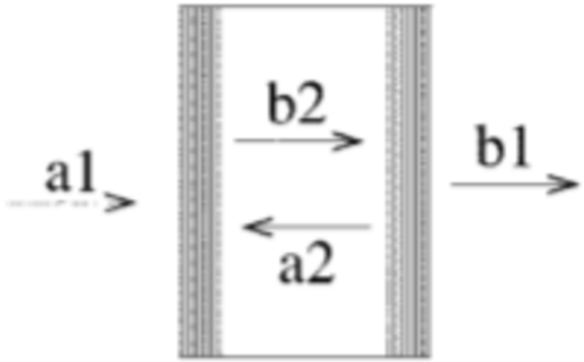
2. the minimum cross-sectional dimensions of the taper not be so small that the waveguide goes below cutoff, unless it is desired that optical energy be transferred to another waveguide as in the case of c.

2. Filters

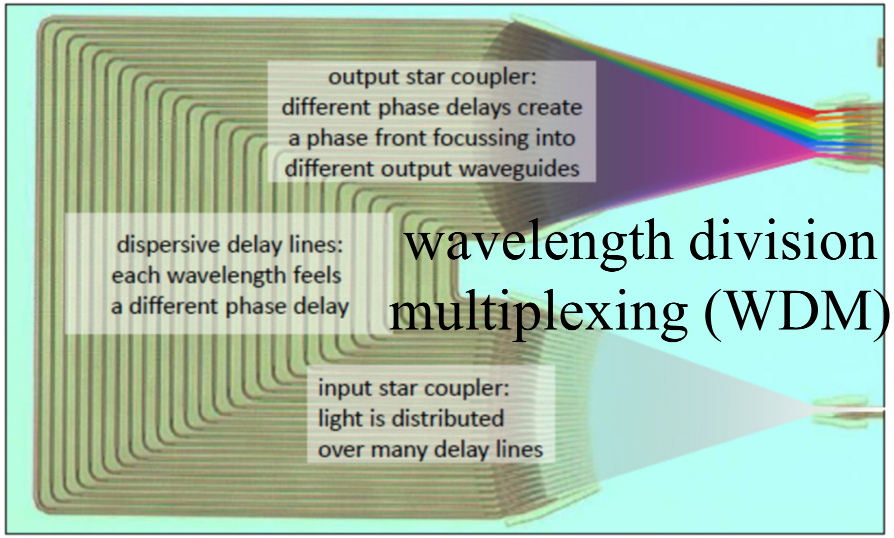
micro-ring resonator



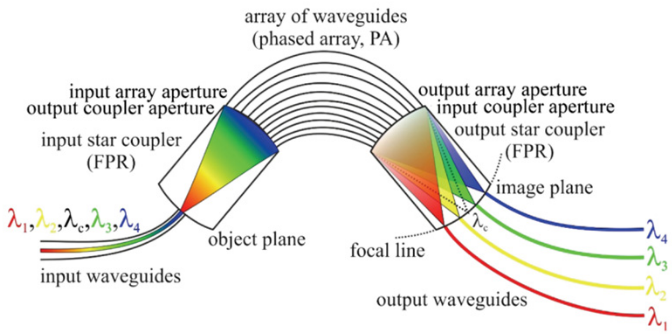
F-P resonator (analogy)

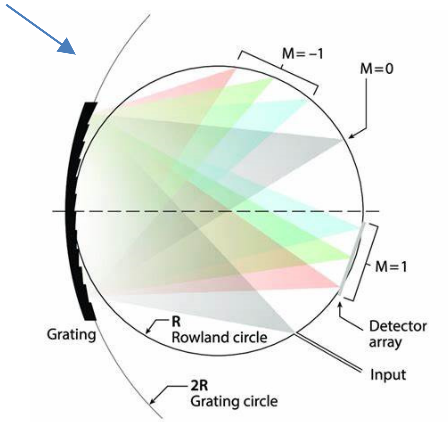


arrayed waveguide grating (AWG)



Rowland grating (analogy)





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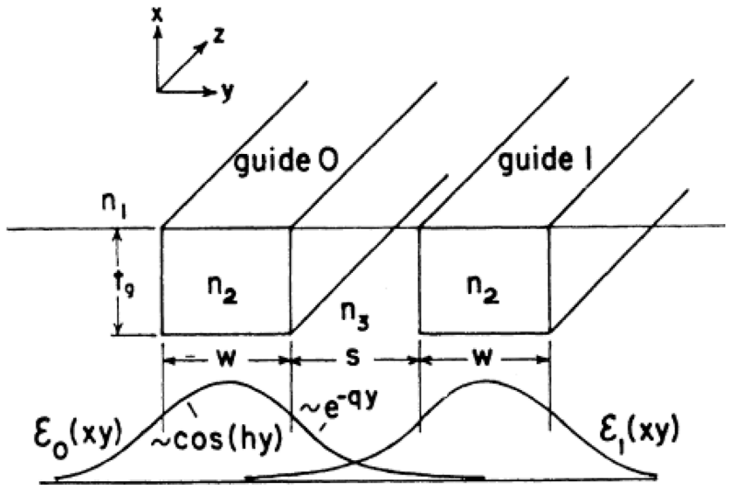
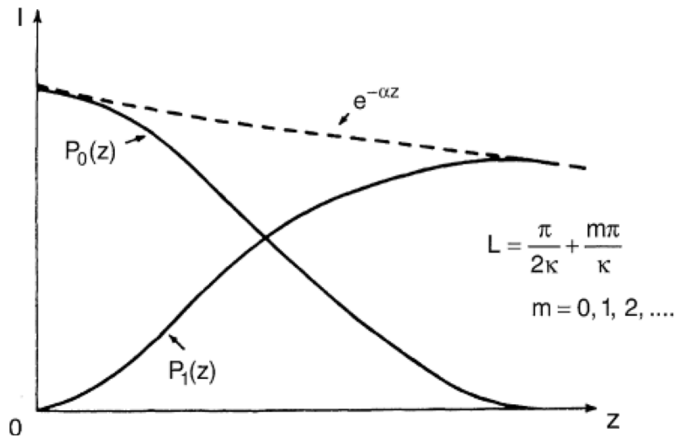
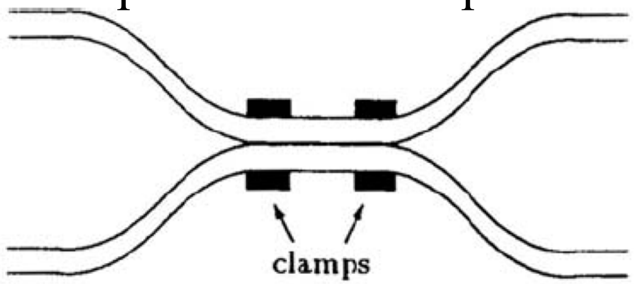
3. Coupled Mode Theory and Coupling between Waveguides





Optical Fiber Couplers



complex amplitude including exp(-$j\beta z$)

$$\bar{E}(x, y, z) = A(z)\bar{\mathcal{E}}(x, y)$$ → mode profile

coupled mode equation (same waveguides)

$$\frac{dA_0(z)}{dz} = -i\beta A_0(z) - i\kappa A_1(z)$$

$$\frac{dA_1(z)}{dz} = -i\beta A_1(z) - i\kappa A_0(z)$$

boundary condition

$A_0(0) = 1$ and $A_1(0) = 0,$

solution

$$A_0(z) = \cos(\kappa z)e^{-i\beta z}$$

$$A_1(z) = -i\sin(\kappa z)e^{-i\beta z}$$

3. Electro-Optic Modulators (1)

Electro-optic effect is **the change in index of refraction** produced by the **application of an electric field**. The effect is nonisotropic, and contains both linear (Pockels effect) and nonlinear (Kerr effect) components. The nonlinear (quadratic) Kerr electro-optic coefficient is relatively weak in commonly used waveguide materials. Typically, **Pockels effect** is to be used.

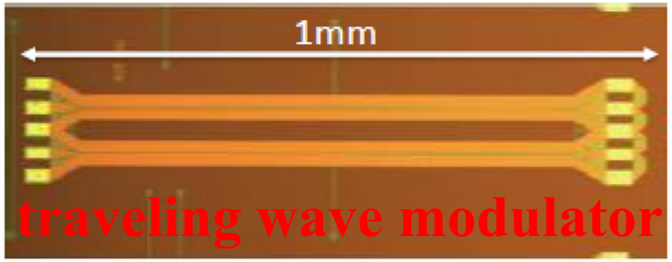
If coordinates are align to principal dielectric axes of the crystal, the index ellipsoid

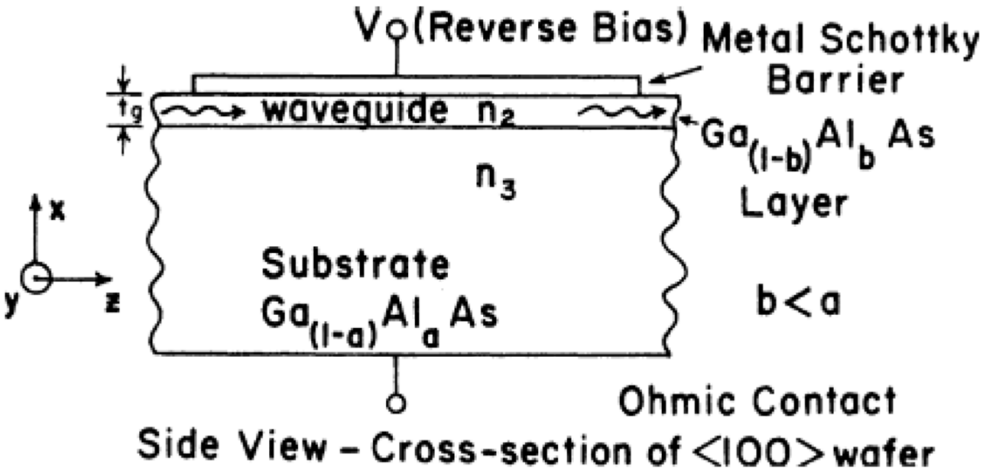
$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j$$

phase modulation

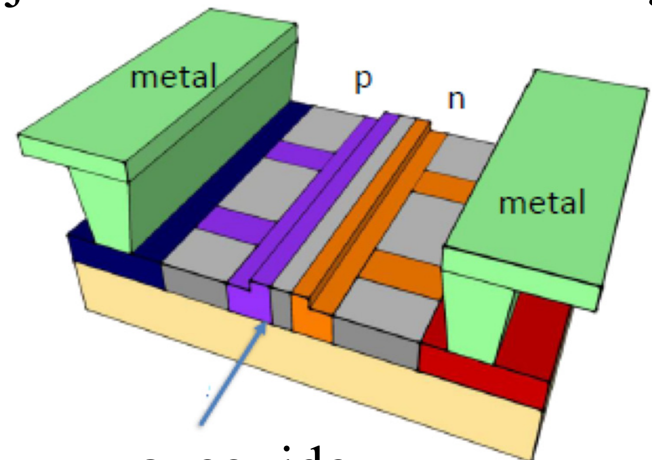
$$\Delta n = \Delta\beta / k$$

$$\Delta\varphi_{EO} = \Delta\beta L$$





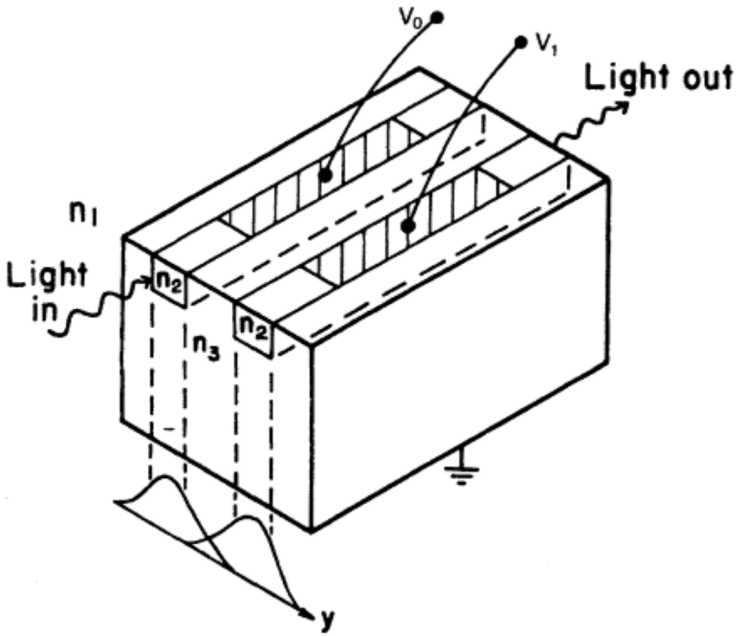
inject or extract carriers changes *n*



waveguide

3. Electro-Optic Modulators (2)

dual-channel waveguide electro-optic modulators



$$P_0(z) = \cos^2(gz)e^{-\alpha z} + \left(\frac{\Delta\beta}{2}\right)^2 \frac{\sin^2(gz)}{g^2} e^{-\alpha z}$$

$$P_1(z) = \frac{\kappa^2}{g^2}\sin^2(gz)e^{-\alpha z}$$

tunable directional coupler

coupled mode equation

$$\frac{dA_0(z)}{dz} = -i\beta_0 A_0(z) - i\kappa A_1(z)$$

$$\frac{dA_1(z)}{dz} = -i\beta_1 A_1(z) - i\kappa A_0(z)$$

phase modulation

$$\Delta\beta = \beta_0 - \beta_1$$

complex amplitude

$$A_0(z) = \left(\cos\, gz - i\frac{\Delta\beta}{2g}\sin\, gz\right)\exp\left[-i\left(\beta_0 - \frac{\Delta\beta}{2}\right)z\right]$$

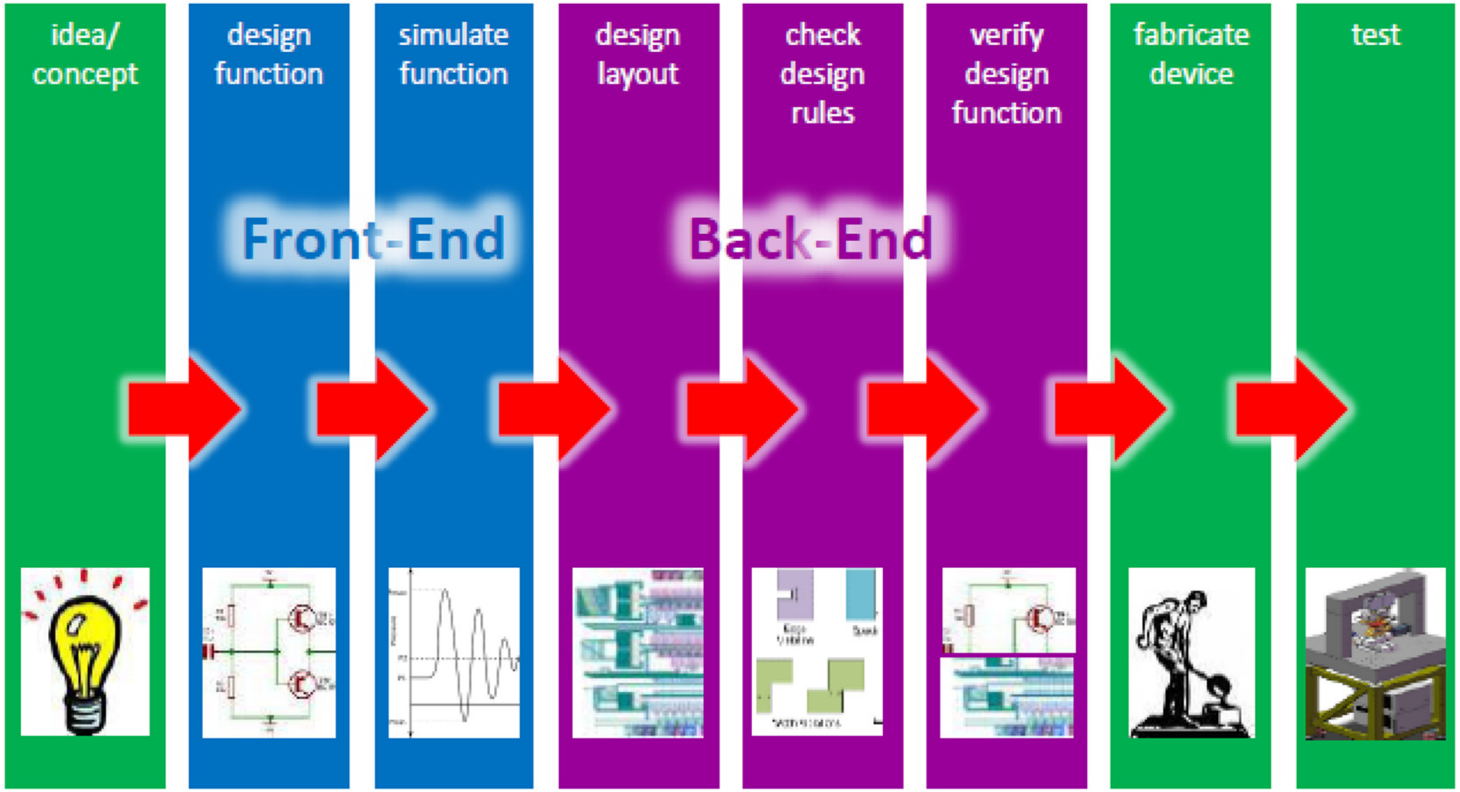
$$A_1(z) = -\left(\frac{-ik}{g}\sin\, gz\right)\exp\left[-i\left(\beta_1 + \frac{\Delta\beta}{2}\right)z\right]$$

$$g^2 \equiv k^2 + \left(\frac{\Delta\beta}{2}\right)^2$$

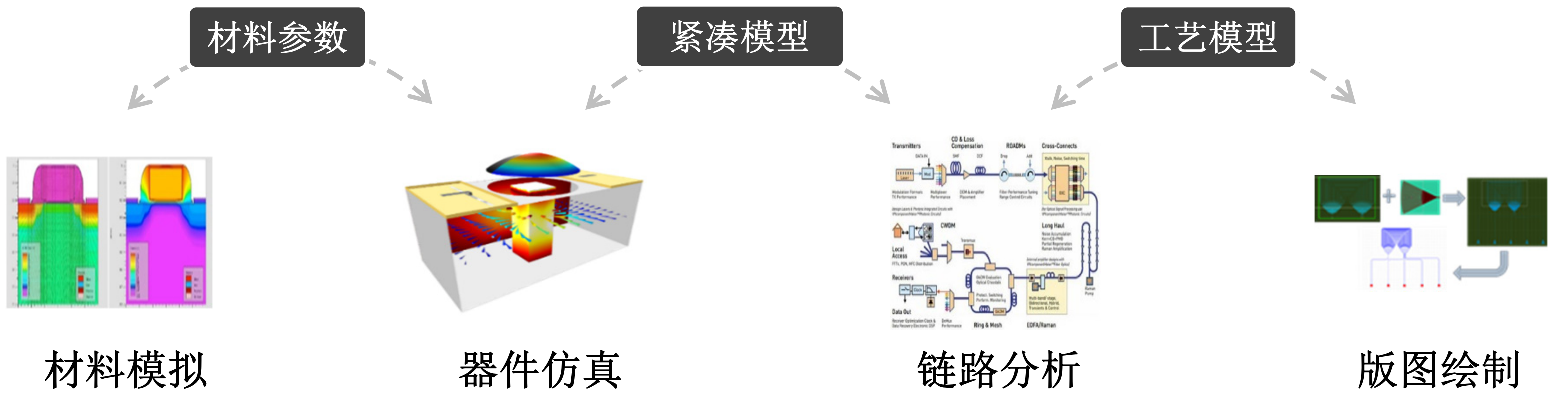
coupling is cancelled when

$$gL = \pi + m\pi, \quad \text{where} \quad m = 0, 1, 2, \ldots.$$

4. Design Methods (1)



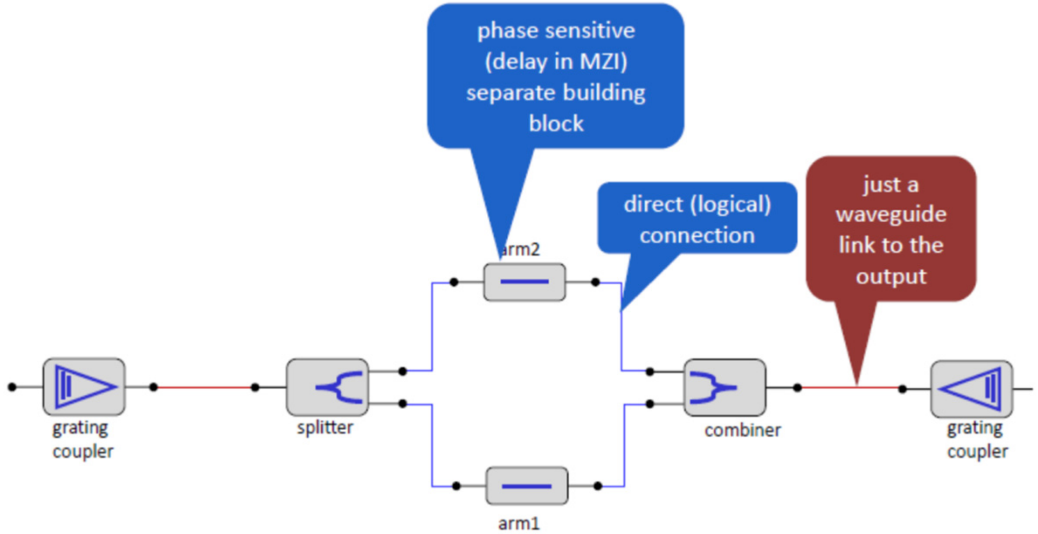
国家重点研发计划项目：光电芯片全流程联合仿真技术研发

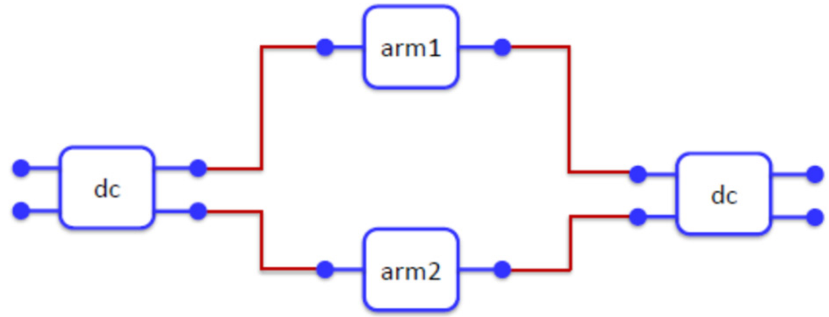


（工艺、材料）（光-电-热-量子、射频等）（器件库、原理图、拓扑）（布线、规则检查）

4. Design Methods (2)

Photonic integrated circuits (netlist or link analysis)



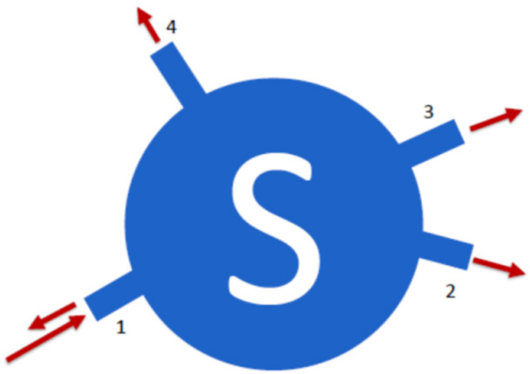


Mach Zehnder Interferometer

How to connect all passive photonic components?

Scattering matrix ! It is linear coupling between all 'ports'

frequency-dependent
bidirectional
complex amplitudes
multi-mode/polarization
multi-channel



S matrix can be cascaded!

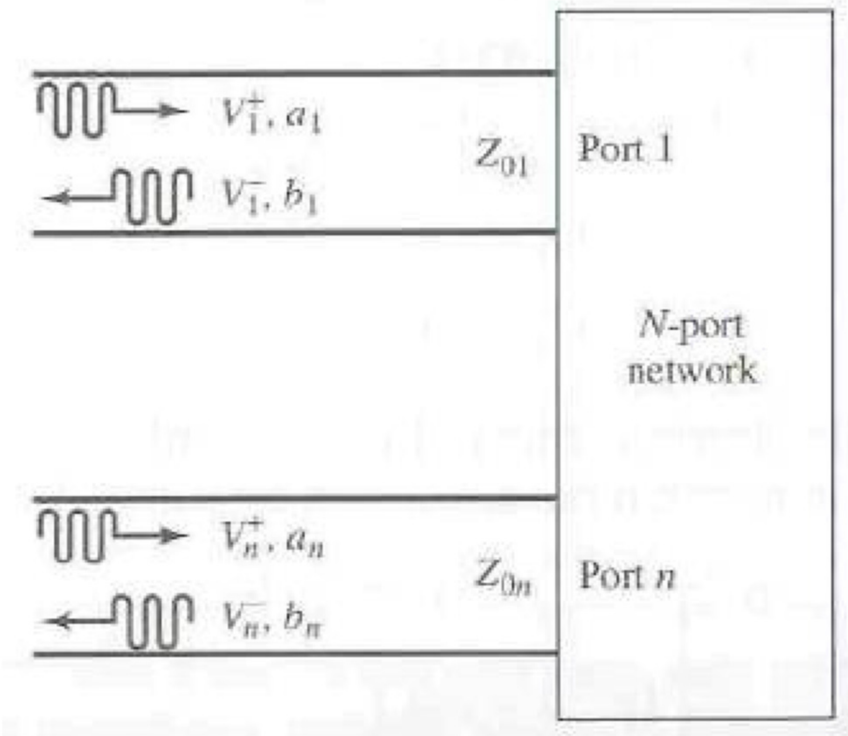
Generalized scattering matrix: A review

$$a_n = V_n^+ / \sqrt{Z_{0n}}, \quad b_n = V_n^- / \sqrt{Z_{0n}}$$

$$V_n = V_n^+ + V_n^- = \sqrt{Z_{0n}}(a_n + b_n)$$

$$I_n = \frac{1}{Z_{0n}}\left(V_n^+ - V_n^-\right) = \frac{1}{\sqrt{Z_{0n}}}(a_n - b_n)$$

$$P_n = \frac{1}{2}\mathrm{Re}\{V_n I_n^*\} = \frac{1}{2}|a_n|^2 - \frac{1}{2}|b_n|^2$$



$$[b] = [S][a] \qquad S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_k=0,\ k\neq j}$$

terminated in matched load

reciprocal $[S] = [S]^t$

lossless $[S]^{\dagger}[S] = [I]$

4. Design Methods (4)

Dense Wavelength Division Multiplexing (DWDM)

2 directions

2 components/phases (QAM)

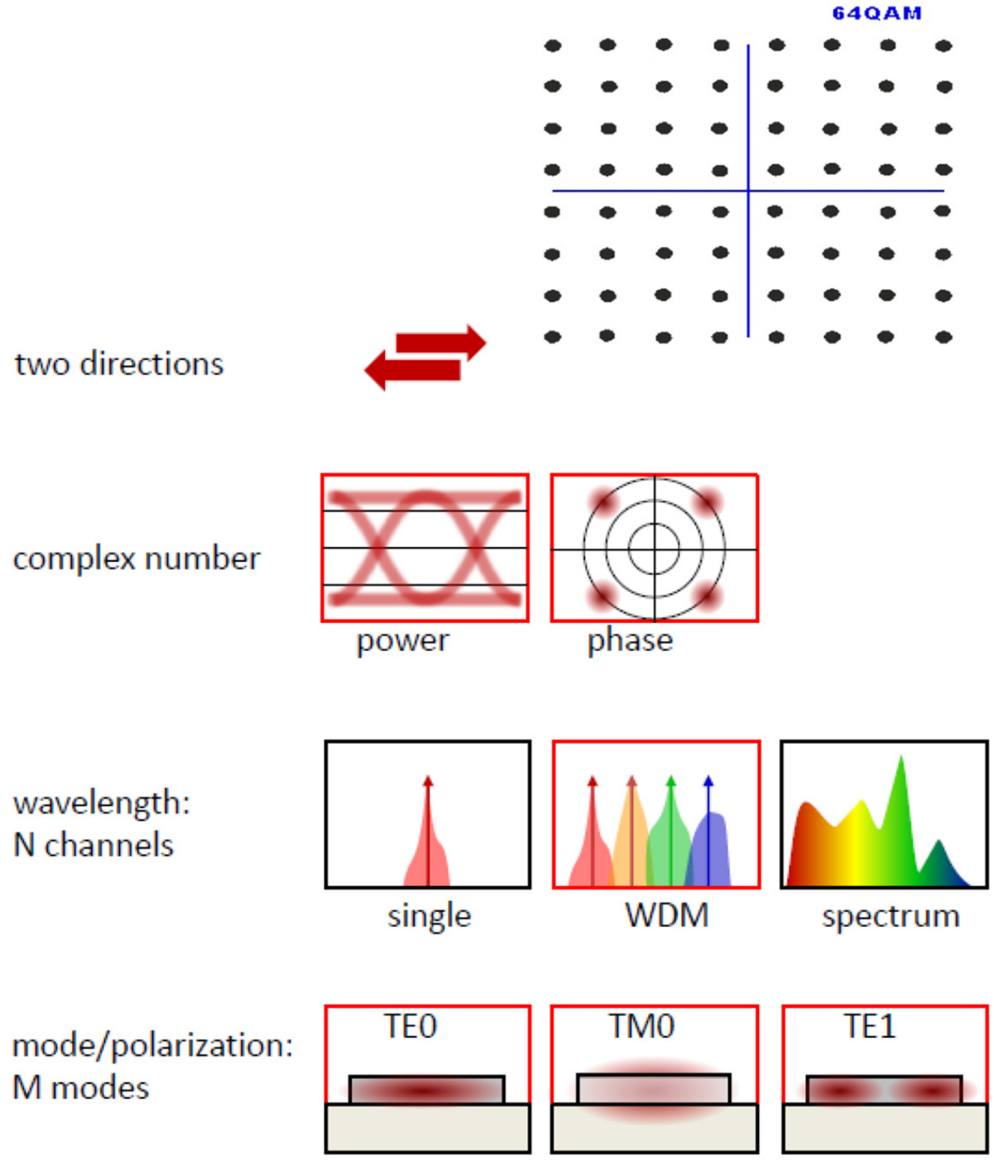
512 wavelength channels

4 modes

2×2×512×4

Quadrature amplitude modulation (QAM)

$$s_s(t) \triangleq \sin(2\pi f_c t) I(t) + \underbrace{\sin\left(2\pi f_c t + \frac{\pi}{2}\right)}_{\cos(2\pi f_c t)} Q(t)$$



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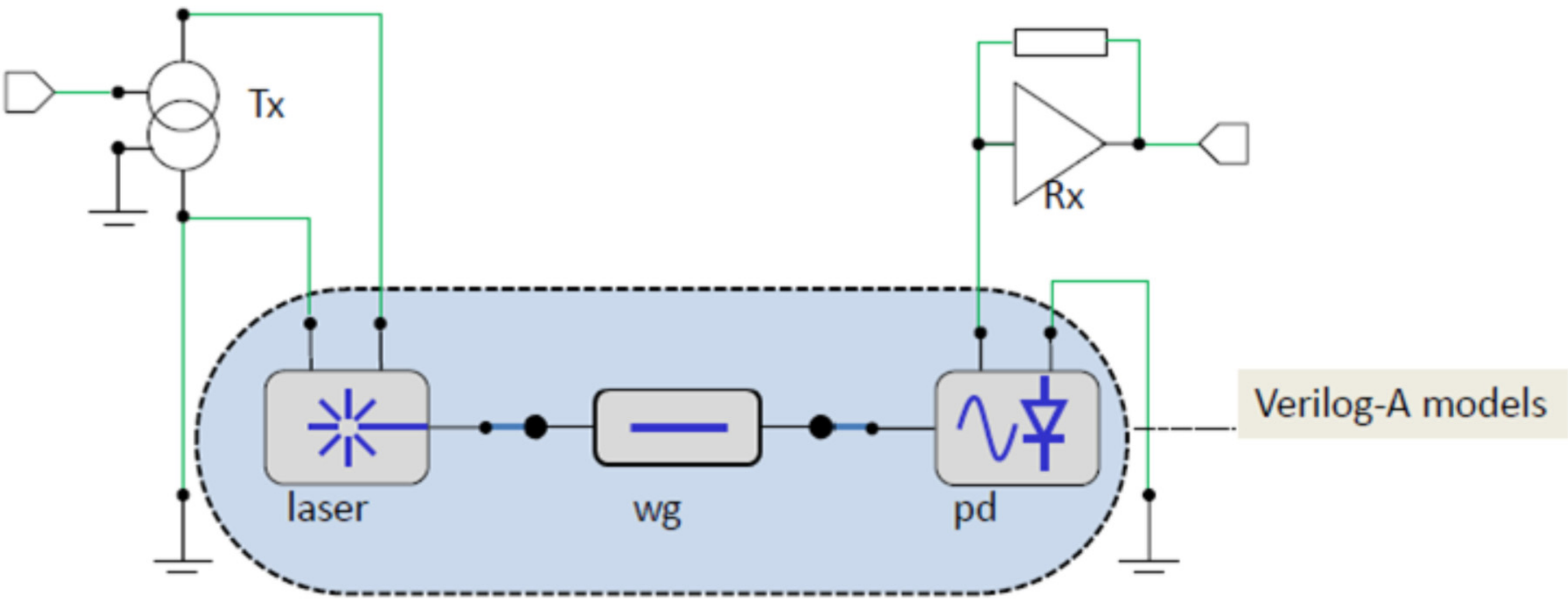
4. Design Methods (5)

Active + Passive or Photonics + Electronics

still not well developed …



Simulating all in electrical simulator (SPICE with modified nodal analysis)

1. Use native and verified model for electronics
2. Build Verilog-A (behavior) model or circuit model for photonics

4. Design Methods (6)

Verilog-A (behavior) model cases (simple)

single-mode waveguide

$$E_{out}(t) = e^{-\left(\alpha_A + j\beta(\omega_R)\right)L} \cdot E_{in}\left(t - \frac{n_g \cdot L}{c}\right)$$

continuous-wave laser

$$E_{out} = E_{amp}\angle(\phi_0 + 2\pi \int_0^t \Delta f \cdot d\tau)$$

waveguide coupler

$$\begin{bmatrix} E_{o1} \\ E_{o2} \end{bmatrix} = \begin{bmatrix} t & -j\kappa \\ -j\kappa & t \end{bmatrix} \begin{bmatrix} E_{i1} \\ E_{i2} \end{bmatrix}$$

waveguide splitter

$$\begin{bmatrix} E_{o1}(t) \\ E_{o2}(t) \end{bmatrix} = \begin{bmatrix} \sqrt{\alpha_s k_s} \\ \sqrt{\alpha_s(1-k_s)} \end{bmatrix} E_{in}(t - t_d)$$

optical phase shifter

$$\Delta n(x,y) = -8.8 \times 10^{-22} \Delta N_e(x,y) - 8.5 \times 10^{-18} \Delta N_h^{0.8}(x,y)$$
$$\Delta\alpha(x,y) = 8.5 \times 10^{-18} \Delta N_e(x,y) + 6 \times 10^{-18} \Delta N_h(x,y)$$

$$\Delta\phi(V,\lambda) = \frac{2\pi L}{\lambda}\left(\Delta n(V) + \frac{dn}{dT} \cdot (T - T_0)\right)$$

photodetector (Laplace transform)

$$i_{pd} = I_{dark} + \frac{\rho \cdot |E_{in}|^2}{1 + s\tau}$$

ρ: responsivity; τ: optical response time

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