PIC notes (not completed)

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Chapter 1: Photonic ICs

- The overall benefits of (wafer-scale) integration
- The typical optical functions (active and passive) on a chip
- The two aspects that make silicon photonics a unique technology platform
- PICs need electronics and packaging to become a system

Chapter 2: Circuit Design Flow

What is a design flow, and its purpose?
Separation of design into 'front-end' and 'back-end'
The steps and tools for schematic design ('Front-end')
The most common techniques for optical circuit simulation
Difference between circuit layout and component layout
What is schematic driven design?
What happens during 'design rule checking'? Give examples
What is 'Layout versus Schematic'?
Use of hierarchy in circuit design.
What is a PDK?
Advantages/disadvantages of designing in Code / GUI

The purpose of a design flow is to translate an idea into a working chip.

1.1 idea/concept

- focus on the specifications (规格)

1.2 design & simulate function

- including underlying equations, behavioural models and flow of information. (底层的控制方程，行为模式，信息流).
- Note the hierarchy(层次), atomic cells contain a circuit model, while hierarchical cells contain another netlist. 底层单元包含一个电路模型，而顶层单元包含另一个网络结构。
- The optimization should be an iterative process. 优化是一个迭代过程
- Due to the linear nature of matrix multiplication, the scattering matrix method can only be used to model linear, time-invariant systems.

1.3 Layout

- A layout is the patterns used for fabricating a chip, organized in reusable cells with parameters about placement, transformations, etc.
- ''Hier'archy(层次，等级制度): Cells contain other cells.
- Routing(布线) stands for optical connectivity with waveguides, electrical connectivity with metal wiring, avoiding crossings, shorts and disconnections. (避免交叉，短接和断接)
- Schmatic driven layout (SDL): 简单地说 SDL 是一种在集成电路设计中使用的方法，通过电路原理图直接驱动布局设计，提高了设计效率和一致性。In SDL process, people derive the physical layout from the schematic, steps include generating the layout cells, place the layout cells and connect the layout cells together.
- However, there always will be some photonic-specific constrains (约束), for example optical length and phase control, minimal bend radius, waveguide spacing, matching

port direction and single routing layer! 布线只有一个图层！

1.4 Check design rules

- Violations (违规行为): edge, spacing, width, encapsulation(封装), ……
- Design rule check (DRC): obtuse angle(钝角) sharp/acute angle(锐角)
- Pattern densities (图案密度): refers to the proportion of the area occupied by patterns within a specific region. Pattern densities should be sufficiently uniform to avoid unequal etching rate & CMP dishing (化学机械抛光中的凹陷现象)
- Tiles should be added to keep the pattern densities uniform.

1.5 Verify design funtion / functional verification

- Check connectivity and functionality. Note that sometimes we need engineered crossing, but not connected. (LVS, layout versus shematic)
- We also need to resimulate the circuit based on the actual layout including lengths, crossings, reflections, etc.

1.6 Fabricate device

- Each step with imperfections and variability.
- Some imperfections may behave like a spatial low-pass filter, which means that there will be a minimum feature size can be fabricated such as 290nm for a Bragg grating. Otherwise, there wll be pattern rounding (图案的圆化)
- To avoid pattern rounding, we add optical proximity connections (光学临近矫正，OPC), which add serifs(衬线) and cutouts(切口?) to improve the accuracy of actual lithographic patterns.

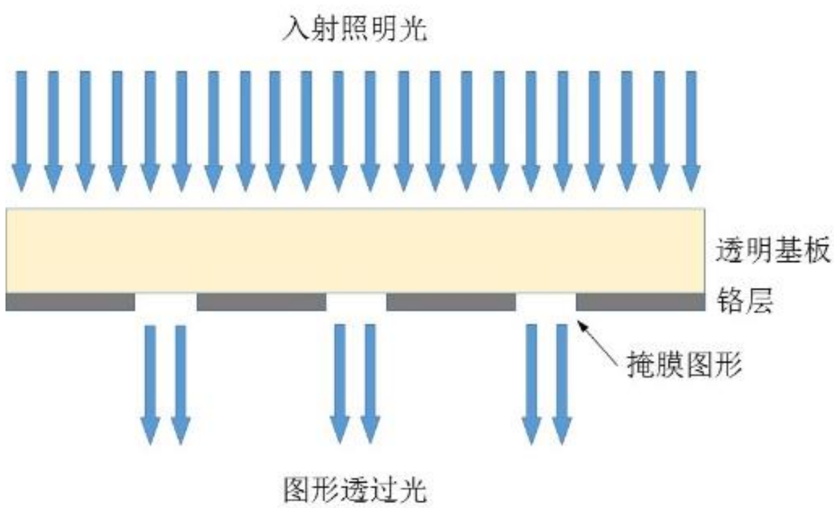
1.7 Test

- Implement wafer-scale testing using grating couplers.
- PDK: component libraries documentation support scripts.

Chapter 3: Mask Layout & PCells

Understand how a layout relates to the fabrication process
What is a reticle? Dark-field and Light-field
Use of mask layers, e.g. for defining waveguides.
High-level understanding of the GDSII structure, primitives and use of hierarchy
GDSII transformations and how they can cause DRC errors.
Common DRC errors, their causes and how to fix them.
The concept of a PCell (views, properties and evaluators)
Different views in a PCell

- Pcells: Parametric cells (参数化单元)
- A symbol view is an abstract representation of a component, while a netlist view describes the internal connectivity of a (sub)circuit.
- A schematic view equals to a netlist+ graphical information, while a layout view is a hierarchical description of polygons(多边形) on layers.
- Pcell is a python class documentation, including views, properties and layout evaluator.
- Fabrication is to imprint a pattern into the substrate, including imprinting the pattern in a sensitive polymer (lithography), transfer the pattern into the Silicon (etching) and remove the resist.
- A reticle (掩膜) is a Chrome(铬) layer on a glass plate. 光刻工艺中的掩模版，设计时有明场和暗场之分。Dark field means that during the lithography and etching process, the background is blocked and the features are transparent. “write the trench”, while light field means that a lot of light will go through the reticle and only the lines will remain raised on the substrate.(much easier using core and cladding structure than using dark field method)



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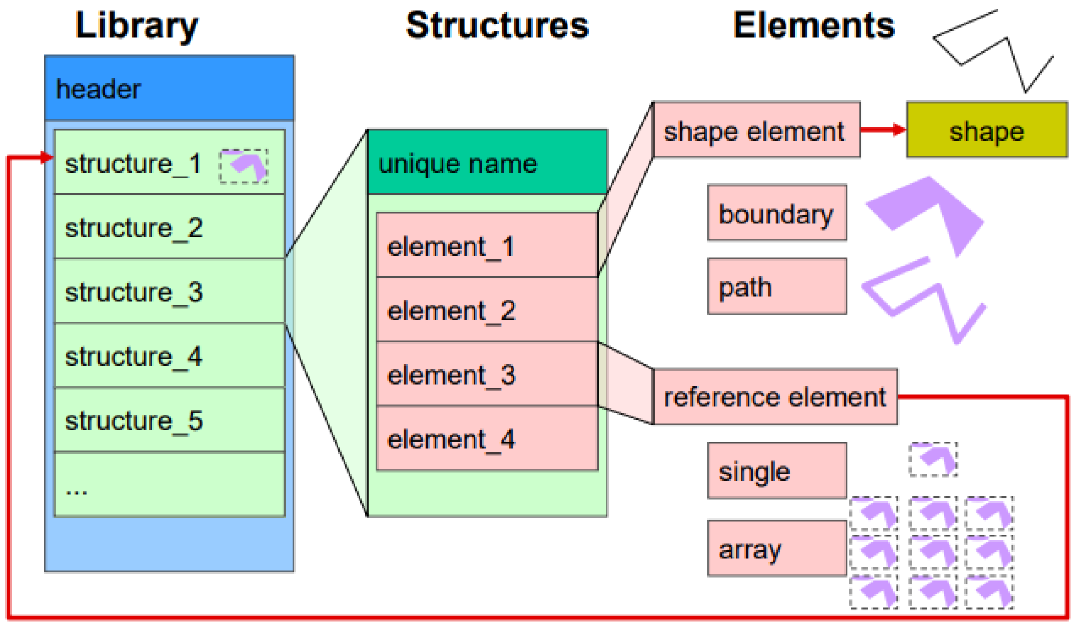
- GDSII is a graphics design system/standard binary database file format. The design in separated in cells ("Structure"), which contain polygons and references to other cells.



- Mask files are encoded on a grid. 掩膜文件通常编码在一个网格上; Snapping happen when someone wants to export the file. Snapping includes shape coordinated and references, happening in the frame of each sell, but the final layout is flattened to polygons. 从内部设计导出到 GDSII 文件时，坐标会对齐到最接近的网格点上，对其的对象包括形状坐标和引用（包括原点、周期等等）。每个单元的坐标会独立对其到各自的网格（造成了一些 misalignment），同时被展平成多边形以适应光刻工艺的要求。
- Thus, after some transformations e.g., rotations, it can give rise to small gaps on export. That's why we should avoid ports at non-orthogonal angles and non-orthogonal transformations.
- When processing DRC, these are not allowed:
  1. sharp angles, e.g., sharp corners where waveguides separate
  2. nanomter gaps, e.g., waveguide ports are not matching well, the solution is to snap to grid and flatten. 解决方法是对齐到网格并展平。（这时候小数转化成整数坐标）

Chapter 4: The Design Project

> Understand the fabrication process used for the project
>
> Understand the essential difference between
>
> - waveguides as connections (PlaceAndAutoRoute)
> - waveguides as components (PlaceAndConnect)

- What is a PDK? (again)
  A PDK is a set of tools, like component libraries, documentation, support scripts, etc.
  A PDK is fabrication and process-dependent.
- The process of E-Beam lithography (see PPT slides. P15-24)
- Tolerant directional couplers are more robust than the conventional ones against the fabrication variances, but longer and more wavelength dependent.

Chapter 5.1: Waveguides

The basic operational principle of an optical waveguide
The concept of (guided) modes
The difference between effective index and group index
The factors that determine the number of guided modes in a waveguide
Polarization of optical modes. Concept of TE and TM.
Effect of the index contrast
Effect of bend losses in optical waveguides
Effect of dispersion in optical waveguides
Loss mechanisms in optical waveguides

- 大部分都学过，只在这里简写
- The nature of light is electromagnetic wave, which propagates at the speed of light, with electrical and magnetic oscillations, wavelength and optical frequency.
- In a specific material, the wavelength of light becomes n times shorter for the same frequency, i.e., frequency remains the same while the wavelength and speed change, because the frequency characterises the oscillation of the source.
- Dispersion indicates the refractive index n is not the same for all frequencies.
  1. Group velocity is the velocity of a wave packet (pulse) consisting of a range of frequencies, determining the information's time delay. 群速度是波包的传播速度
  2. Phase velocity is the velocity of the phase fronts of a wave with a single frequency. 相速度是波前传播速度。（单一频率。有波包，傅里叶变换之后必然是有很多频率）
- 计算群速度：

GROUP INDEX AND GROUP VELOCITY

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Monochromatic wave:

— Propagation constant β

— Phase velocity $v_{ph} = \left(\frac{\beta}{\omega}\right)^{-1}$

— effective refractive index $n_{eff} = \frac{\beta}{k} = \frac{c}{v_{ph}}$

A perturbation of this wave will propagate

with the velocity $v_g = \left(\frac{\partial\beta}{\partial\omega}\right)^{-1}$

with the group index $n_g = \frac{c}{v_g} = c\frac{\partial\beta}{\partial\omega}$

$$n_g = c\frac{\partial}{\partial\omega}\left(\frac{\omega n_{eff}}{c}\right) = n_{eff} + \omega\frac{\partial n_{eff}}{\partial\omega} = n_{eff} - \lambda\frac{\partial n_{eff}}{\partial\lambda}$$

Propagation delay:

$$\Delta t = \frac{L}{v_g} = L\frac{\partial\beta}{\partial\omega} = \frac{L}{c}n_g = \frac{L}{c}\left(n_{eff} - \lambda\frac{\partial n_{eff}}{\partial\lambda}\right)$$

-

可以看出有效折射率是和相速度联系在一起的。群速度和相速度的关系可以通过和 propagation constant 联系在一起的定义推导出来。

- TE 波和 TM 波：自由空间中只能传播 TEM 波，即电场、磁场和波矢三者两两垂直。然而，在波导介质中可以传播 TE、TM，此时 E、H、k 不再两两相互垂直。

5.1.1 金属波导 metallic waveguide

- perfect metallic mirror: with pi shift and all light is reflected
- plane wave between 2 metallic mirrors is self-consistent if second reflection is in phase with the original one.
- 用几何光学的角度描述金属波导，就是光线入射角 $\sin\theta = m\lambda/2d$，边界条件是正弦值等于 0~等于 1

5.1.2 电介质波导 dielectric waveguide

- Guiding by total internal reflection, the number of guided modes is proportional to the numerical aperture (NA) square, which characterises the refractive index contrast of the waveguide.

5.1.3 dispersion

- Dispersion introduces chrip (temporal broadening).
- Normal dispersion: red travels faster than blue; anomalous dispersion: blue travels faster than red.

5.1.4 Losses

- Propagation losses in a waveguide include:
  1. Material absorption – nonlinear absorption is proportional to the optical intensity;
  2. Imperfect guiding (radiation)
  3. Imperfrctions of the waveguide (scattering)
- Notice that the refractive index contrast is not just the material. A silicon wire has high contrast in all directions, making sharp bends possible. However, a silicon rib has a lower contrast in the plane.

5.1.5 Bends

- Light is no longer fully confined. (可以用保角变换 conformal transformation 分析)
- Wavefront revolves around center, but the group velocity of wavefront cannot exceed c/n, causing radiation losses increasing with smaller bend radii. → however, smaller radius is needed for larger-scale integration ()
- The refractive index in the outside bend is larger. When mode mostly guided in region with the largest index, it can cause mode to shift outward and mismatch losses at transition between straight and bent waveguide. → no guiding by inner interface → whispering gallery modes. 耳语回廊模式
- Solution: low-loss spline(样条) bends, use rib in straight sections and circular wire section for bends, use Euler bend (羊角螺线)

chapter 5.2: PIC Platforoms

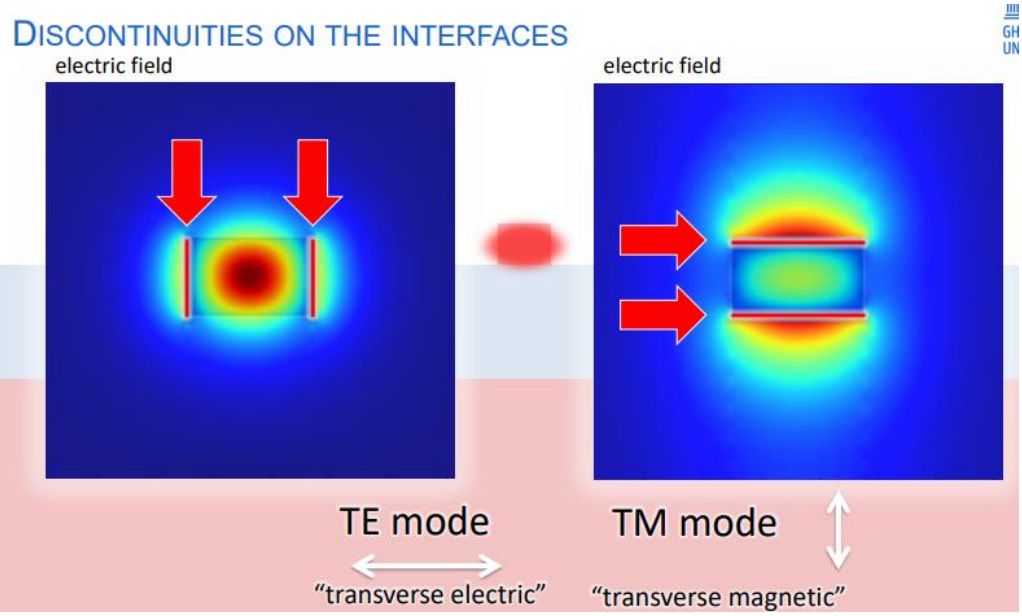
Material systems for PICs,
with their strengths and weaknesses.

Suitability for active functions/passive functions

Importance of refractive index contrast

Being able to motivate why a material system would be (un)suited for an application

- Photonic integration is a process which uses a mix of materials. To decide which materials to choose, one should take into account the following criteria including Wavelength range, waveguide loss, waveguide density, tunability, availability of active components (是否可以制造有源器件)......
- <u>**Material platforms:**</u>
  1. <u>Passive components 无源器件</u>(可以理解为波导材料)
     Silica on silicon: 硅基二氧化硅
     Polymer：（柔性）聚合物
     Silicon Nitride-based：氮化硅，这种材料在消光系数和非线性方面可调范围比较大
  2. <u>Active components 有源器件</u>
     III-V semiconductors: 3-5 族半导体，如砷化镓 GaAs，适用于高效光发射和探测
     Silicon photonics: 硅基光子学
     Lithium niobate: 铌酸锂
  3. 一般的 glass waveguide，index contrast 只有约 0.1%，三五族半导体可以达到 10%，silicon wire 可以达到 200%
  4. COMS: complementary metal-oxide-semiconductor. The implementation of high density photonic integrated circuits by means of (借助于) CMOS process technology in a CMOS fab.
  5. SOI waveguides (Slicon on isolator): A thin layer of silicon is isolated by an isolating material, typically silicon dioxide (glass, n=1.45).



5.2.1 Passive PIC Platforms

- **Silica on Silicon 硅基二氧化硅**

  Include glass-like materials, which have very low losses and are easy for fiber coupling (because the refractive index matches). The fabrication process often includes diffusion(扩散, exchanging ions in galss) and deposition(沉积, deposit layers onto a substrate) on a silicon carrier. (需要在硅基载体上进行，通常是 silicon wafer 晶圆, 所以叫硅基二氧化硅).

- **Polymers 聚合物**

  The functionality of polymers includes EO effects, non-linearities, etc. they are useful for assembly techniques (即指将光子器件与激光器等的组装、封装过程).

- **Silicon Nitride 氮化硅**

  1. High contrast (refractive index 1.41, 2.4. 注意之前 ppt 写 silica on slicon 的时候波导芯层用的是 doped SiOxNy, 所以在这里说氮化硅平台有更高的 refractive index contrast)
  2. Wavelength transparency: 400→2000nm
  3. Can be fabricated with silicon process technologies.

- **Thick SOI (厚硅基绝缘体波导)**

  Large waveguide cross sections enable almost 100% mode confinement.

  Tight bends are not so easy tho.

5.2.2 Active PIC Platforms

- **III-V semiconductors**

  (注：三五族半导体：three-five compound semiconductors; compound: 化合物)

  They have epitaxially grown layer structures with direct bandgaps and high refractive index. The epitaxy substrate determines the wavelength range. The fabrication process uses semiconductor processes on 75mm-1500 wafers.

  1. InGaAsP / InP

     Indium gallium arsenide phosphide, 铟镓砷磷

     Indium phosphide，磷化铟

     Monolithic integration of active and passive elements can be achieved. 可单片集成。

     Low losses at 1.3um&1.55um (telecommunication)

     High refractive index contrast leads to compact waveguides (1um) and difficulties when coupling to fiber.

  2. GaAlAs / GaAs

     GaAlAs: Aluminium gallium arsenide, 铝砷化镓

     Also can achieve monolithic integration. Are used for short wavelengths (800nm). Aslo high refractive index contrast.

  3. Lithium niobate

     Has strong EO effect(can be used to fab high-speed modulators) & non-linearities, low losses, wide transparency range. But difficult to process.

WAVELENGTH TRANSPARENCY WINDOWS

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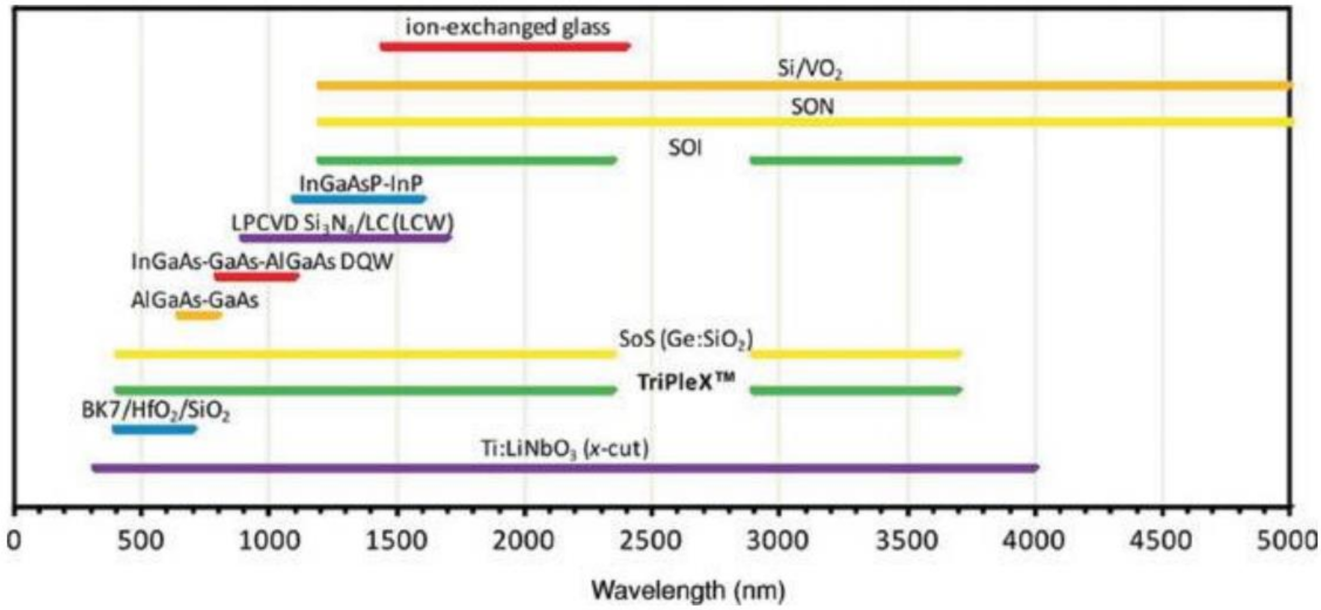

PLANAR WAVEGUIDE MATERIALS

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	InGaAs/InP	AlGaAs/ GaAs	SiO_x on Si	TF $LiNbO_3$	Polymers	SiN	Silicon/Ge
Light Sources	Yes	Yes	No	No	No	No	No
Detectors	Yes	Yes	No	No	No	No	Yes
Modulators	Yes	Yes	No	Yes	Yes	No	Yes
Passive optics	**Yes**	Yes	Yes	Yes	Yes	Yes	Yes
Wavelength	1.5	1.3-1.5	0.45-1.6	0.4-2.6	0.5-...	0.45 – 2.0	1.2-2.0
Coupling loss [dB]	> 2	> 2	0.4	< 1	< 0.5	~1	~1
Propagation loss [dB/cm]	2	2	< 0.01	< 0.3	0.1 – 1.5	0.05	1.0
Temperatures dn/dT [10^{-4}/K]	2	2	< 0.1	< 0.1	0.1 – 1.5	0.2	1.8
Anisotropy $\|n_{TE}-n_{TM}\|$ [10^{-4}]	0.1-10	2-10	0.1-0.5	400	2-50	1-1000	10-20000
Stability	Good	Good	Good	Good	Decent	Good	Good
Wafer size	2-3”	3-6”	4-8”	3”	≥8”	6-12”	6-12”

Chapter 6: Components & Building Blocks

Distinction between active and passive building blocks
Operational principles of the directional coupler
Understand the working of the Multi-Mode interferometer
Different wavelength filters
Optical fiber coupling mechanisms (mostly for silicon)
Understand the working of the grating coupler
Electro-optic modulation and tuning techniques
Photodetection techniques
Gain mechanisms (for lasers and amplifiers)
Integration strategies with electronics

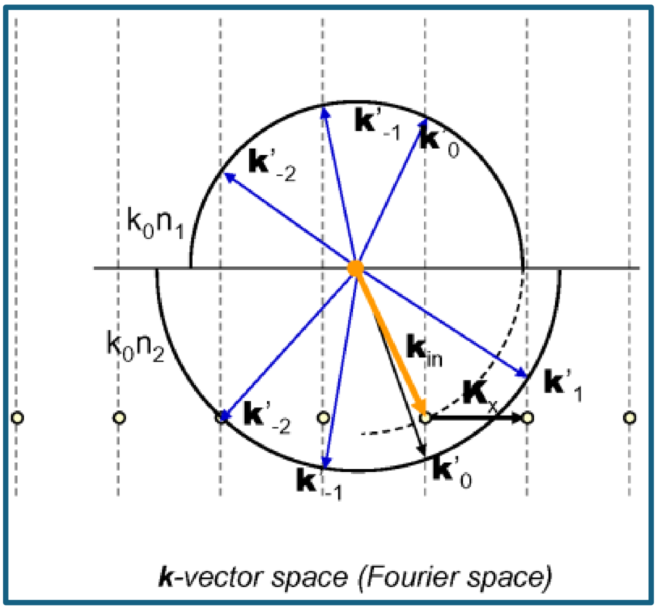
- Components include passive/active ones. Note that passive components can be described using S-matrix while active components including modulators, detectors, amplifiers, and lasers, can not.
- Coupling between waveguides=coupling between modes

6.1 Passive building blocks

- **coupling: reciprocal**
  回忆：波导模式数量与 v number 有关，v number 与 d、index contrast 成正比。Index contrast 越大、芯径越大，模式数量越多。
- **Splitter as combiner**
  Satisfy reciprocal condition. 3dB splitter→coupler with 3dB loss.
- Directional coupler
  Incoming wave excites even and odd supermodes equally.
  Even and odd propagate at different phase velocities
  Depending on the length, the modes in the output waveguides are excited
- **MMI (multimode interferometer)**
  multiple modes are excited. After propagation, constructive or destructive interference occurs.
  Constructive interference at multiples of $L_\pi = \frac{\pi}{\beta_0-\beta_1}$
- **Coupling between waveguides**: taper; or in-plane lenses
- **Coupling to fiber**
  e.g. inverted tape (can be understood using the concept of reciprocity)
- **Polarization in waveguides**
  We would like to process light which is in only one polarization on-chip.
  We could use directional coupler, taper, mode evolution or mode interference, etc.

- **Grating couplers**

  Bragg consition



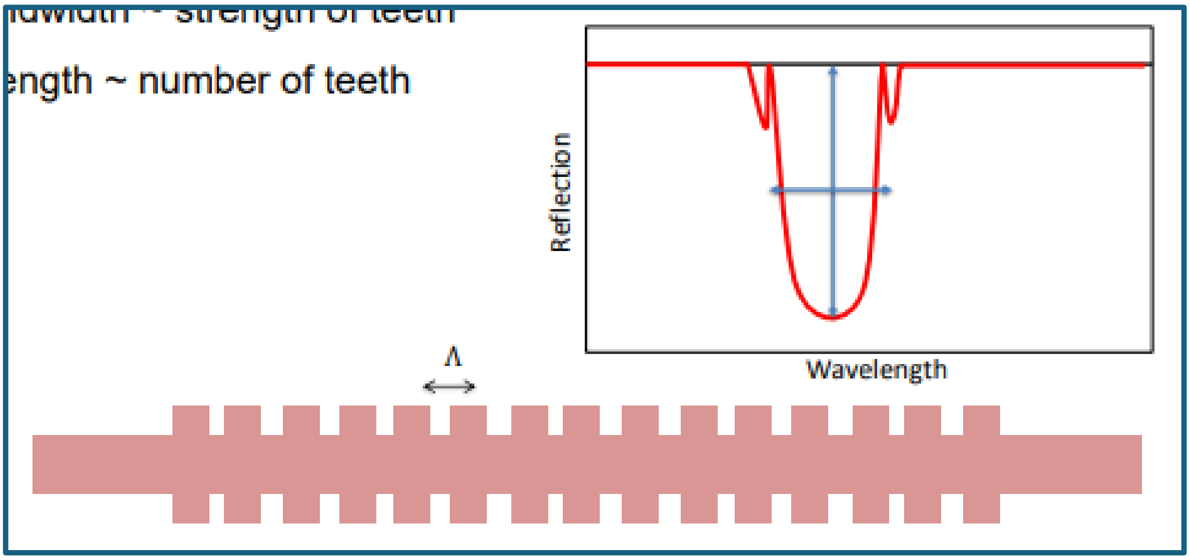
  Different diffraction orders going up and down with a coupling angle (in order to reduce second-order back reflection, which is strong under vertical coupling? → can also add some bragg mirrors, but relatively hard to fabricate).

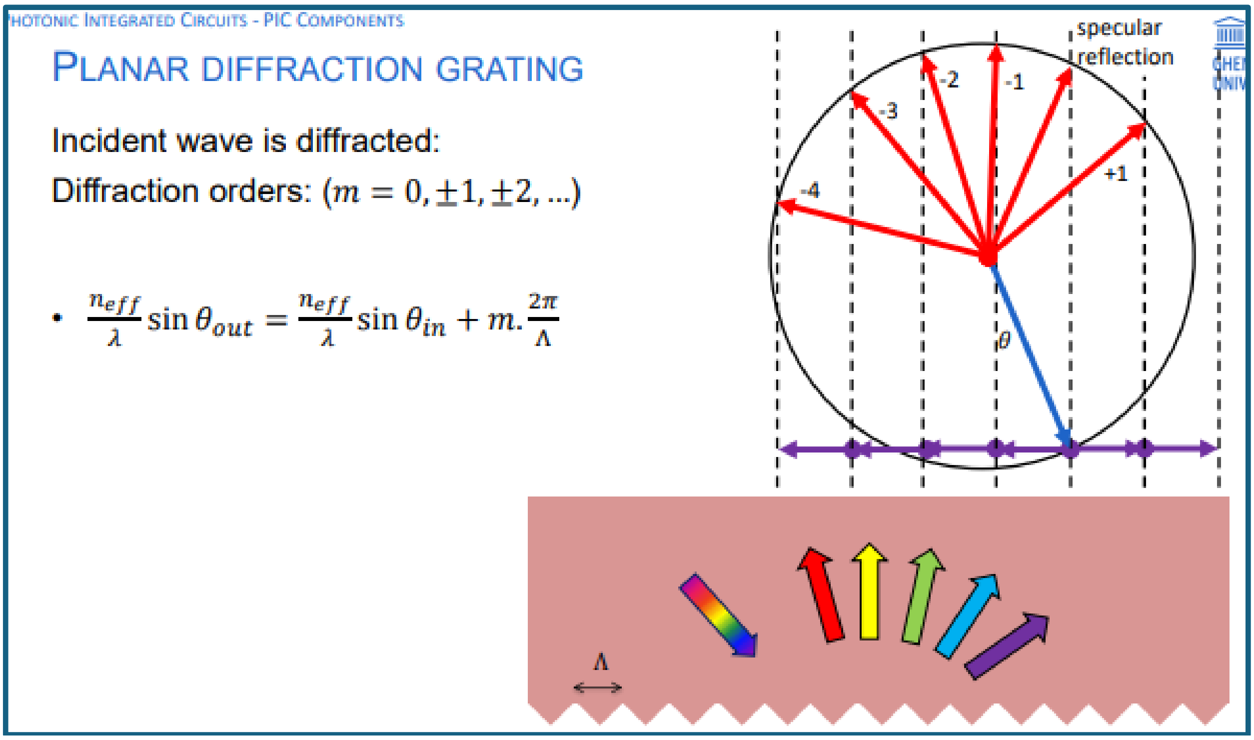
- **Polarization splitting**

  Grating couplers are polarization sensitive, in order to control the polarization effect, we use 2D grating couplers. → due to different coupling efficiency.(如何分析 grating coupler 对不同偏振模式的响应？→对于 TE 模式，电场在光栅平面内振荡，主要受光栅槽的横向结构影响。对于 TM 模式，电场垂直于光栅平面振荡，主要受光栅槽的深度和垂直结构影响。)

- **Wavelength filtering**

- Absorption, MZI, AWG, waveguide gratings, planar diffraction grating, ring resonators…





6.2 Active building blocks

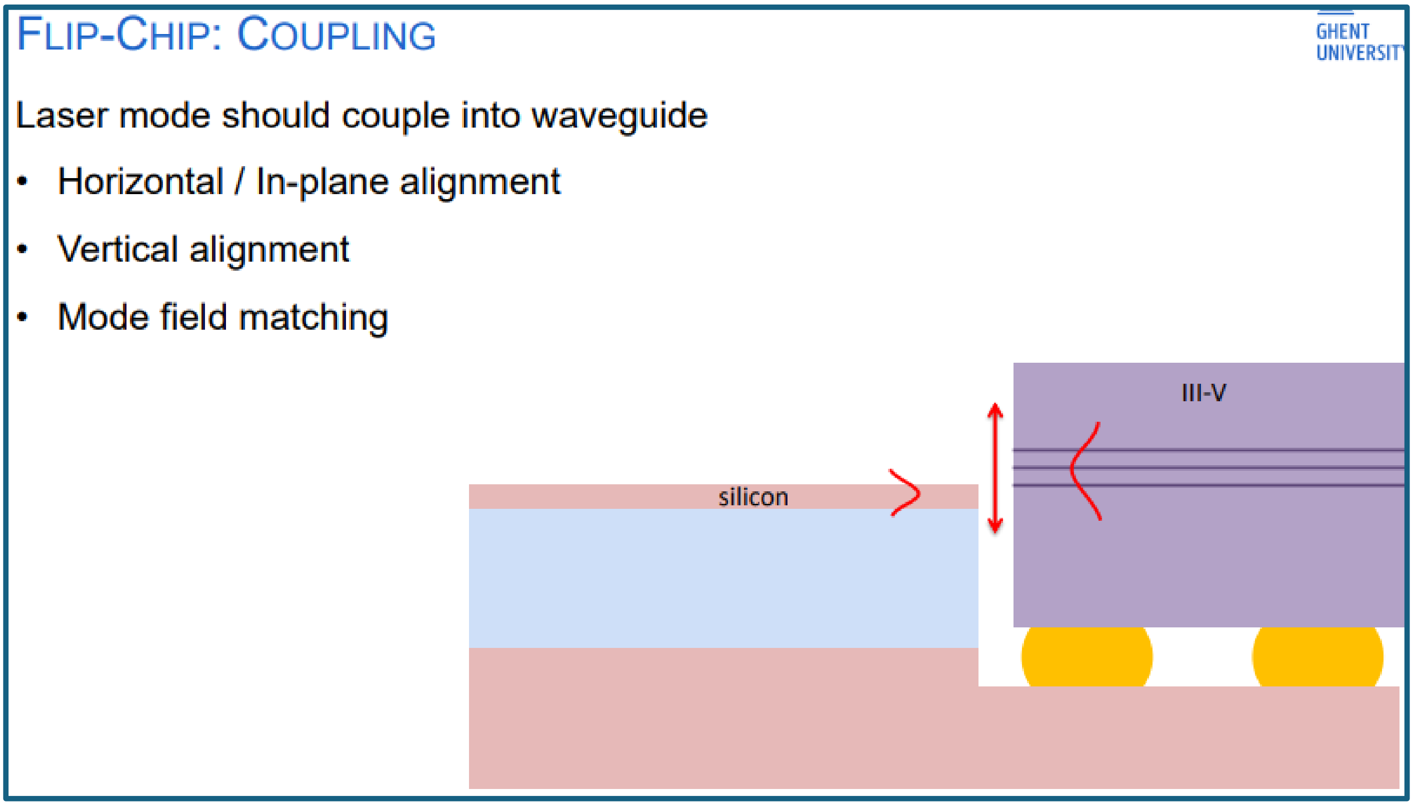
- **Modulators**
  1. EO modulation
  2. Amplitude modulation (absorption modulation, phase modulation);
     e.g. The basic optical phase shifter: a heater
  3. Tuning techniques: mechanical
  4. Acoustic modulation: require long acoustic propagation length and piezo-electric material. （压电材料
  5. Carrier-based modulation: add doped junction to silicon waveguide to mudulate refractive index.

MODULATION MECHANISMS: IMPLEMENTATION

	InGaAs InP	AlGaAs GaAs	SiO_x on Si	$LiNbO_3$	Polymers	SiN	Silicon Ge	BTO PZT
Mechanical (MEMS)	+	++	-	-	-	++	+++	++
Thermal (heaters)	++	++	+	o	o	++	+++	O
Acoustics (SAW)	++	++	-	+++	-	-	+	++
Carriers	+++	+++	-	-	-	-	+++	-
Franz-Keldysh	+++	+++	-	-	-	-	+++	-
Pockels	+	+	-	+++	+++	-	o	+++

*Franz-Keldysh effect: 在施加电场后，半导体材料的光吸收谱(band gap)发生变化

- **Photo detectors**
  1. <u>Photodiodes</u>: absorb photons and create electron-hole pair. →requires low RC for fast response.
  2. <u>Photoconduction</u>(光导探测器): defect mediated 由缺陷介导的; 光子能量小于带隙的情况下，defects can absorb photons with hv<Eg. Usually slower (higher RC), can be combined with diode for collection.
  3. <u>Bolometers(辐射热计):</u> When there is no direct way to generate current, we can implement the following steps: a) absorb light; b) materials heats up; c)measure temperature.
- **Gain and Lasers: how to introduce optical gain on a PIC?**



6.3 Electronics integration

- Integration of photonics and electronics: co-packaging (wire-bonding, flip-chipping, interposers) 第一种主要集成方法：共封装；包括线键合、芯片倒置安装、中阶层等；
- 3D stacking; 3D 堆叠；
- Monolithic: 单片集成；using identical semiconductor materials to fabricate photonics and electronics, then connect them together. Have to consider issues like
  1. Material compatibility: 材料兼容性
  2. Temperature compatibility
  3. Codesign considerations, like density rules.

Chapter 7.1: Component design& Simulation

Difference between component design and circuit design
What can affect a component's performance?
Explain how photonic components require Multiphysics
Understand timescales for modelling components
Difference between active and passive components
Linear components, S-parameters, waveguide ports
Reciprocity (and when is it possible to have nonreciprocity)

- Q1: Circuits are only an abstraction, there is real object (components) behind the symbol and reality always differs from the model, so when you design circuits, you should still be aware of the components.
- Q2: A component's performance (including propagation, modulation, filtering, detection, and emission) can be affected by its geometry, materials, environment, fabrication process, neighbours, etc.
- Q3: When designing and simulating PIC components, it is necessary to consider the interactions of various physical phenomena.
  e.g. silicon phase modulator: self-heating, junction design, thermo-optical response…
  e.g. waveguide biosensor: microfluidic control, thermal noise, diffusion, …
- Q4: time scales:
  1. Photonic oscillatons: fs
  2. Nonlinear effects: <ps
  3. Laser dynamic: <ns
  4. Thermal effects: us-ms;
- Q6: Linear systems can be described by Scatter parameters, which are linear coupling between ports. Notice that linearity means superposition, and ports are just **orthogonal states**.
- Q7: Most linear photonic components are reciprocal. 即散射矩阵是对称矩阵（转置和自身相同）If a circuit is made out of materials with symmetrical constitutive parameters, the circuit is called reciprocal. This is the case for almost all materials, except for magnetic materials in the presence of a magnetic field (e.g. optical isolators), non-linearities, and time-varying systems.

Chapter 7.2: Simulation Techniques

Understand the basic concepts of different Maxwell solvers

- FDTD
- Hz finite elements
- beam propagation
- eigenmode expansion
- plane-wave expansion

in terms of

- performance and scaling
- approximations and limitations
- problems where they can be used

S-parameter extraction (using FDTD): what is the process?

(defining geometry, waveguide ports, modal overlaps, …)

Choosing which simulator to use for a problem (+ motivation why)

7.2.1 Planer circuit geometries

- Has limitations, e.g. solutions are pure TE/TM, bad approximations on the corner, bad approximations for high index contrast.

7.2.2 Finite difference time domain (FDTD)

- Descretisation E/H field (Yee cell). When you ask for the field in a position, you get an interpolation. 蛙跳算法：leapfrogging
- Scaling (可扩展性，规模化处理能力): the smaller the cell, the smaller the time step. Accuracy improves with more cells.
- Locall subgriding can improve the resolution, but only do this for areas of interest. However, this could lead to reflections, impedance(阻抗) mismatch, etc
- Boundary conditions: PEC/PMC 完美电磁导体条件, assume all the filed doesn't go through the boundaries. They are numerically efficient, but they reflect! → **okay to use when there is no light nearby (e.g. waveguide simulations)**
- Boundary condition: perfectly matched layers (完美匹配层): increase the simulation size by adding extra layer, which absorbs perpendicular incidence and guides parallel waves.

7.2.3 Finite elements

- Discretisation of Maxwell eqs (in the spatial domain)
- **Can handle 2 types of problems:**
  1. **Eigenmode solutions (no sourse): often used for waveguide mode solving;**

2. Source-driven: response to an excitation.

- Required fewer cells. The mesh is nonuniform with triangles or ‘tetra’’hedrons. Can better conform to (符合) curved geometries.
- Boundary conditions: can introduce perfectly matched layer. No native boundary conditions.

7.2.4 Eigenmode expansion

- As analytically as possible. However, difficult to find all the eigenmodes especially with complex material.
- Scaling: simulation time~N^3 (number of modes)
- No need to calculate all the field.
- 详细见上学期数学书；

7.2.5 Beam propagation / BPM

- Base on the Helmholtz equation, assume the Δn is sufficiently small.
- FFT-BPM 这种算法不能仿真光的反射, FD-BPM, FD-BiBPM……

光束传输法最初是用来模拟激光在大气中的传播[32]，后来进一步将此方法运用到光纤研究中[5]，并逐渐发展出很多计算方法。光束传输方法是处理光波在非均匀介质中传播的重要方法之一，是目前光波导器件研究与设计领域最流行的方法，也是最适合开发通用光波导器件 CAD 软件的方法[33]。其基本思想是将入射光束沿传播方向，将所要传播的距离分成若干个步长 h，光在每个步长 h 中的传播都先看成是在均匀介质中的传播，通过第 l 步的场的分布 ϕ_l，得出第 l+1 步的场的分布 ϕ_{l+1}，如图 2-1 所示。步长可以等长，也可以根据实际要求进行变步长的模拟计算。

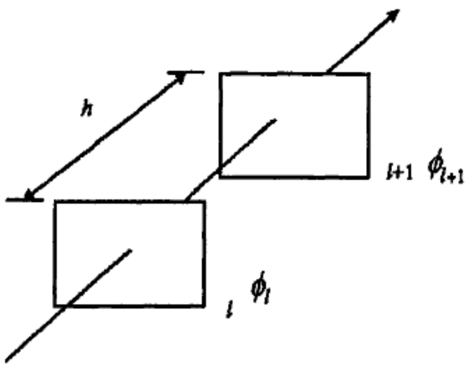
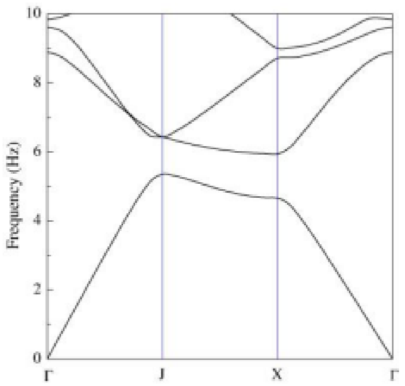


图 2-1 光束传输法的基本原理

光束传输法从标量或矢量波方程出发，可以通过如快速傅立叶变换、有限元、有限差分法等多种方法给出数值计算模型。与其他光波导仿真方法不同的是，光束传播法同时处理波导模和辐射模，描述的是整个介质上(包括波导区和非波导区)的场分布。本章将从光束传播法理论来源入手，推导出有限差分光束传播法并予以实现。

7.2.6 Plane-wave expansion



Plane wave expansion

Describe the field as a superposition of plane waves

Calculate coupling between the waves by scatterers

Solving for eigenvalues (e.g. band diagrams) or excitation-driven

Easy far-field calculations

Strengths:

- simple base set
- Standard fourier transform

Weaknesses:

- Many waves needed
- Difficult to describe discontinuities

- Easy to calculate, but difficult to describe field discontinuities.（方波的傅里叶需要无数个平面波）就是使用大量的平面波+傅里叶变换描述场，结构中的散射体决定了平面波相互之间的耦合系数。

1. What are the pros & cons of the different numerical methods for photonics? In what circumstances would you use them?

① finite difference method

applying this to frequency domain results in a linear system

applying this to time domain results the famous FDTD.

→ may introduce discretisation error

→ apply when we only have information about the solution at discrete points.

② finite elements

transform the problem into a minimize procedure.

has advantages when it comes to e.g. sensitivity to rounding errors.

③ Eigenmode expansion

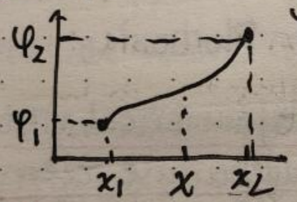
are used in layered photonic structures, in which the fields can be expanded in the basis set formed by the eigenmodes of each layer.

3. How does the finite-element method distinguish itself from other methods?

Finite element method doesn't directly solve a differential equation. instead, the recipe is,

① subdivide the structure.

② approximate the unknow function.



$$\varphi_l(x) = \frac{x_2 - x}{x_2 - x_1}\varphi_1 + \frac{x - x_1}{x_2 - x_1}\varphi_2$$

for $\varphi_l(x,y) = \sum_{i=1}^{M} \overset{\text{coeft.}}{u_{i,l}} \cdot \overset{\text{basis}}{b_{i,l}(x,y)}$

③ Join the elements. (with connection matrix)

④ Write down an expression for J (to minimize)

e.g. time-averaged stored energy. $\mathcal{E} = \frac{1}{2}\int \left(\frac{1}{\omega^2\varepsilon}\left|\frac{dH}{dx}\right|^2 - \mu|H|^2\right)dx$

$\longrightarrow J = \int\left[\left(\frac{dH}{dx}\right)^2 - k^2H^2\right]dx.$

J can be calculated in terms of the unknown nodal values φ_i.

$J = \sum_l J_l$

⑤ Minimise J : Rayleigh-Ritz method.

6. For what problems is eigenmode expansion best used?

For specific structures that consist of a number of layers where the refractive index profile doesn't change in the propagation direction.

The eigenmodes form a complete set, so that they can be used to expand any arbitrary field in the layer.

Chapter 8: Circuit Simulation

The difference between white-box and black-box models
The difference between *scattering wave* and *effort-flow*
The difference between Waveguide Ports and Electrical Terms
The correspondence between transmission lines and waveguides
Optical signals (power, phase, modes, wavelengths)
Different time-domain modeling schemes (e.g. ODE)
Options for Photonic-electronic cosimulation
Effect of the time step in time-domain circuit simulations

- Q1: white-box knows the circuit inside allowing people to capture the physics, while black-box has internals unknown, we can only apply a mathematical fit for it.
- Q2: 这其实是在比较电路分析中的功率流动形式 和光学电路分析中的波散射形式的不同。Effort-flow nets with a voltage potential, people look at the current flowing through terms and can be solved using SPICE (simulation program with integrated circuit emphasis,集成电路通用模拟程序); However, wave scattering formalism focus on the ports which represent the input and output of the light and links with a travelling wave. The beam propagation is bi-directional and can be solved with a signal propagator or wave scattering formalism.
- Q3: 对电路来说，基尔霍夫定律

  Term is the contact point for an electrical wire → 接触点/焊点？

  Net is all locations connected at the same electrical potential → 等电势点

  对光路来说，

  Port is the interface for propagating waves. (一个 port 相当于两个 terms/输入输出)

  Link is the 0-length transmission line over which a wave propagates (bidirectional).
- Q4：在 PIC 中，波导用于引导光波的传播，类似于电气电路中的传输线引导电信号的传播。可以类比计算波导的阻抗 Z=E/H；
- **Time domain models for linear circuits**
  1. Use the scattering matrix method, consider coupling between all ports.
  2. Q5：思路是，调整散射矩阵中的每个矩阵元素，使其为时间的函数。傅里叶空间中，矩阵元素就为调制频率ω_0的函数；注意 a 是输入场；接着可以：
     - 引入 delay(memory) 近似系统的冲激响应（finite impulse response model）

$$b_j(t) = \sum\sum S_{ji,m}(\omega_0)a_j(t - T_m)$$

     - 引入 derivatives 用于控制

$$b_i(t) = \sum S_{ji}a_j(t) + \sum P_{ji}\frac{\partial a_j}{\partial t}(t)$$

- State-space model 状态空间模型
  Suppose the system have internal states, use partial differential equations to describe the coupling between incoming singals&states, time&states, states&outgoing signals. → ABCD matrix

$$\frac{dx_i}{dt}(t) = \sum A_{ji} x_j(t) + \sum B_{ji} a_j(t)$$

$$b(t) = \sum C_{ji} x_j(t) + \sum D_{ji} a_j(t)$$

- Vector fitting for creating State-space model 矢量拟合法
  思路是从测量到的散射矩阵元出发，转换到拉普拉斯域，再用 vector fitting 矢量拟合的放大，将 S 表示为极点 poles 和残差 residues(留数？)的和，再转换成 ABCD 矩阵的形式。→ 推导比较数学，基本是把传递函数写成带有零点、极点、线性项和常数项的形式，定义未知函数通过求解线性问题（零点）来识别极点，迭代后 f(s)收敛(converge) (具体参看 ppt chap.8)

$$\overbrace{\left(\sum_{m=1}^{N} \frac{\tilde{r}_m}{s-\bar{a}_m} + 1\right)}^{\sigma(s)} \cdot f(s) = \sum_{m=1}^{N} \frac{r_m}{s-\bar{a}_m} + d + sh$$

- Q8: circuit elements have a delay of at least 1 time step. 描述电路元件对时间的响应至少需要延迟一个时间步长。Smaller time steps → more accurate → longer simulation

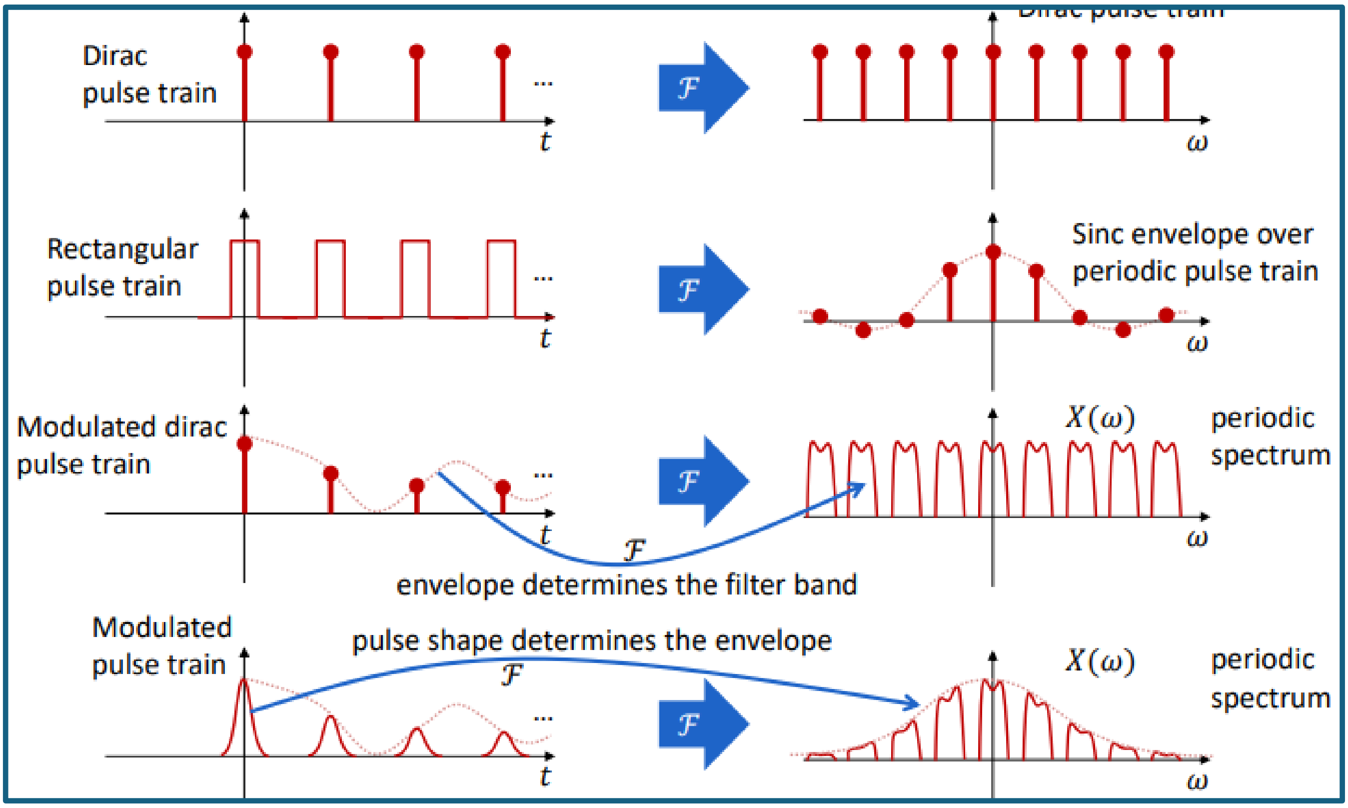
3. Q6: Optical signals consists of directions (是否包含反射？), intensity & phase, wavelength range (monochromatic or polychromatic?) and polarizations (modes).
4. In conclusion, photonics and electronics use different formalisms, and we use effort-flow/SPICE to simulate electrical circuits and Scattering waves to simulate optical circuits.
5. Q7: co-simulation: 可以 simulate everything in electrical simulator (SPICE-MNA), 也可以 simulate everything in a photonics simulator. Also, we can co-simulate with waveform exchange, executed sequentially (顺序执行) and in parallel, exchange data at each step.

Chapter 9: Wavelength Filters

Basic operational principle of a wavelength filter
Performance metrics of a filter (insertion loss, ER, …)
Difference between FIR and IIR filters
Basic concept of an MZI and lattice filter
All-pass and add-drop Ring resonators: linewidth, Q-factor
    Finesse, critical coupling, decay time, …
Basic concept of an AWG
Basic concept of an Echelle grating
Effect of imaging and overlap in an AWG/Echelle
How to make a flat-top transmission in an AWG
Different parameters of an AWG and how to choose them
Effect of phase errors in Lattice filters and AWGs

9.1 Introduction

- Q2: Performance metrics of a filter: insertion loss, crosstalk(相邻波导或不同模式之间的串扰), ripple(intra-band & out-of-band), rolloff.
- 一些有用的傅里叶变换对：



- 在一个类似 AWG 的结构中, time delay means the output is a contribution of delayed inputs, which can be transformed into Fourier domain. 实际信号的 response 是 δ 函数和输入方波的卷积；傅里叶空间同理。（注意：time delay，FSR 要用群折射率来算）

- The Z transform for discrete-time filters: Z 变换
  A filter response in time domain is a linear combination of the response of different delay times. Z transformation convert y(t) into a polynomial as a function of time step multiplied by the input series X(z(t)). 单位圆上的 Z 变换就是 DFT，单位圆内/外的 Z 变换表征了信号的瞬态响应/反因果（anticausal）行为

Filter response in time domain

$$y(t) = b_0x(t) + b_1x(t-\Delta t) + b_2x(t-2\Delta t) + \cdots + b_Mx(t-\mathrm{M}\Delta t)$$

Fourier transformation: $y(t) \to Y(\omega) = \int_{-\infty}^{+\infty} y(t)e^{-j\omega t}dt$

$$Y(\omega) = \left(b_0 + b_1e^{-j\omega\Delta t} + b_2e^{-j2\omega\Delta t} + \cdots + b_Me^{-jM\omega\Delta t}\right)\cdot X(\omega) = H_\omega(\omega)X(\omega)$$

Laplace transformation: $y(t) \to Y(s) = \int_{0}^{+\infty} y(t)e^{-st}dt$ with $s = \sigma + j\omega$

$$Y(s) = \left(b_0 + b_1e^{-s\Delta t} + b_2e^{-2s\Delta t} + \cdots + b_Me^{-Ms\Delta t}\right)\cdot X(s) = H_s(s)X(s)$$

Z-transformation: $y[t] \to Y(z)$ with $z = e^{s\Delta t}$ (Discrete time)

$$Y(z) = (b_0 + b_1z^{-1} + b_2z^{-2} + \cdots + b_Mz^{-M})\cdot X(z) = H_z(z)X(z)$$

- What can impact filter performance?
  1. Overall losses
  2. Waveguide dispersion
  3. Coupler dispersion
  4. Phase errors

9.2 MZI filters

- Power transmission 是 transfer function H(z) 幅度值的平方 → only full transmission for \kappa=0.5 (3dB coupler)
- In reality, couplers are wavelength dependent, & phase delay, which could shift the spectrum a bit.
- Q3: **FIR filter**: A finite impulse response filter whose impulse response is of finite duration, because it settles to zero in finite time.
  IIR filter: Feedback filters, these filters involve feedback, the value of the output sample value at a given point is dependent on previous values of the output, as well as the present value of the input. → infinite response
- **Q4: MZI lattice filters:**
  Consists of concatenated 2*1 MZI filters, can generate a set of different delays (L, 2L, 3L...) (略，见考试例题)

9.3 Ring resonator filters

- Notice: Never measure FWHM on a dB scale!! (always measure in a linear scale), 假设 Tman-Tmin<3dB, 那么就无法测量 3dB 带宽了。
- Linewidth: FWHM， Q factor: f_res/FWHM， 品质因数越高线宽越窄
- Finesse: FSR/FWHM， Critical coupling: all light that is pumped in the ring is also dissipated. 临界耦合时消光比最大
- **Decay time**

9.4 Waveguide Grating

-
-

Chapter 10: Programmable Photonics

- How does a 2x2 photonic gate works? Implementations
- Forward only meshes and linear transformations
- Recirculating meshes: how to implement filtering
- Layers in the technology stack
- Effect of parasitics

-

- Photonic circuits that can me programmed using software.
-

Chapter 11: Design & Manufacturability

- Understand basic semiconductor fabrication processes
- How fabrication processes introduce variability (different contributions)
- Effect of variability in the geometry of (silicon) waveguides
- Effect of pattern density on variability
- Different levels of variability (process conditions -> circuit functionality)
- Different scales of variability (local, die, wafer, lot)
- The need for statistical process monitoring
- Random variations versus deterministic/correlated variations
- Parasitic reflections in waveguide and circuits
- Methods to reduce parasitic reflections
- Methods to reduce circuit sensitivity

Chapter 12: After Fabrication

Understand the measurement process
How the measurements can be affected by variability
Why effective index is hard to measure and how to do it
Parameter extraction: Semi-analytical / Curve fitting / global optimization

Chapter 13: Applications

Basic knowledge of different application fields

Communications: principles of WDM, coherent communication

Sensing: different mechanisms (index, spectroscopy)

Principle of OCT, LDV, LiDAR

Microwave filtering

Economics of wafer-scale processing and generic chips