Silicon photonic devices and integrated circuits

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김창훈

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2. WDM transmitter & receivers
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4. Summary

btn BROADBAND TRANSMISSION NETWORK

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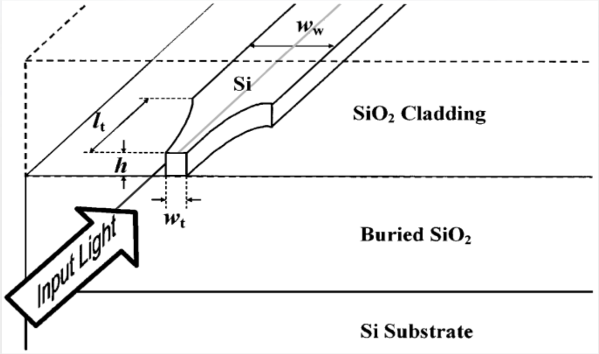
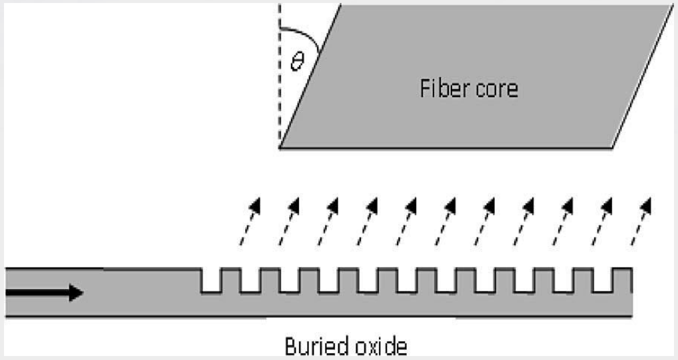
Introduction

❖ **Definition of Silicon Photonic devices in this paper**

1. **Using silicon-core waveguide**
   - ✓ **High index contrast (≈ 2) with silicon oxide as a cladding**
   - ✓ **High density integration (sub-micrometer)**
   - ✓ **High coupling efficiency between silicon waveguide and optical fiber**



< Inverse taper >



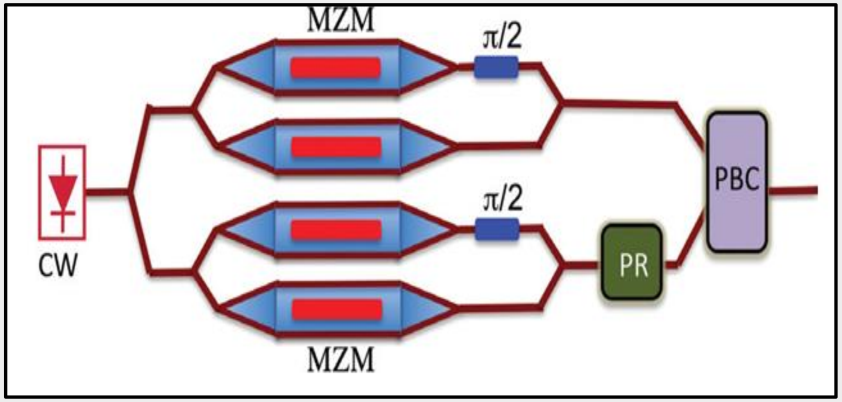
< Grating >

2. **Whole-wafer processing based on CMOS fabrication**
   - ✓ **Large-scale & low-cost manufacturability.**
   - ✓ **Monolithic integration of silicon PICs with CMOS drivers**
   - ✓ **Solve interconnect bottlenecks of modern electronic ICs**

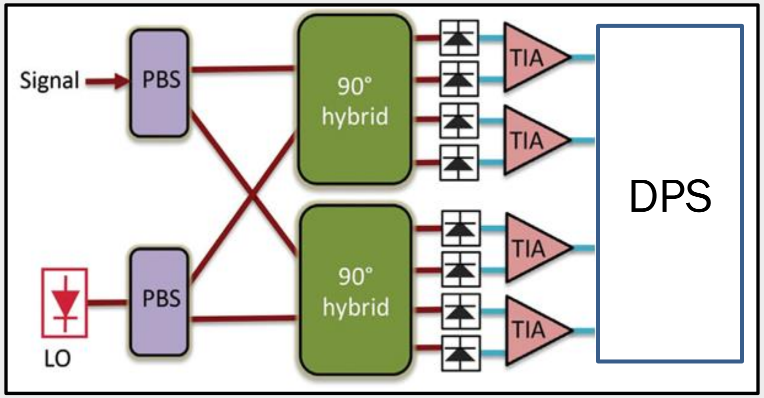
Introduction

❖ **Applications**

1. **Long-haul/metro coherent optical networks**
   - **High-order modulation (QAM, OFDM) and coherent detection**
   - **Maximize channel capacity up to 100 Gb/s, 400 Gb/s, 1 Tb/s**
   - **Integration of complex photonic circuit and CMOS electronics**



< Optical coherent transmitter >



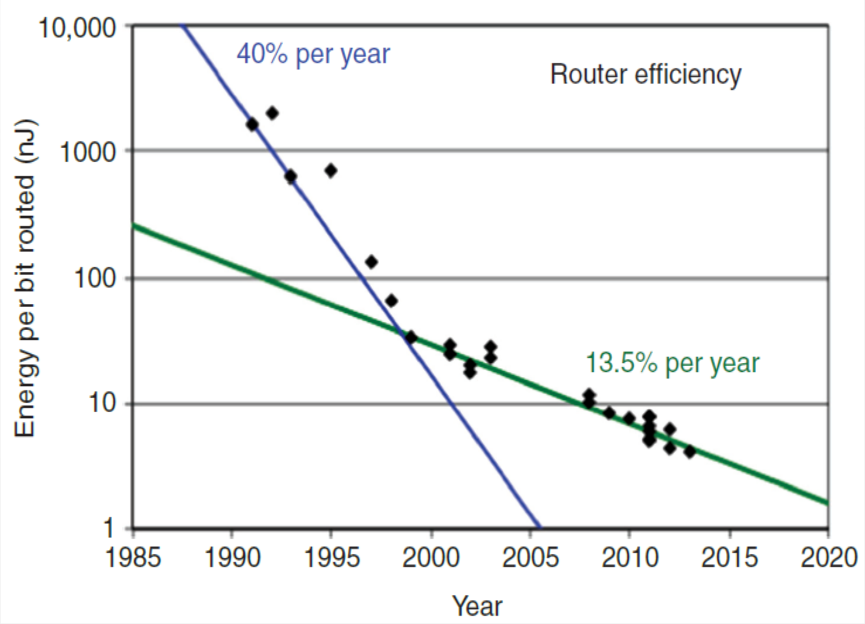
< Optical coherent receiver >

Introduction

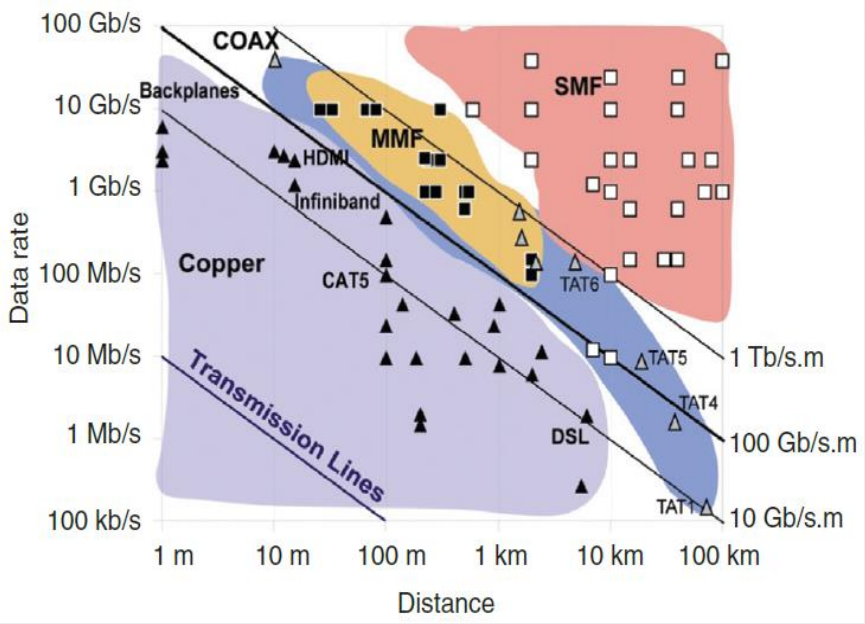
❖ **Applications**

2. **Optical interconnects for routers and switches**
3. **Datacenters and supercomputers**

✓ **Low power consumption & Co-integration of electronics and photonics**



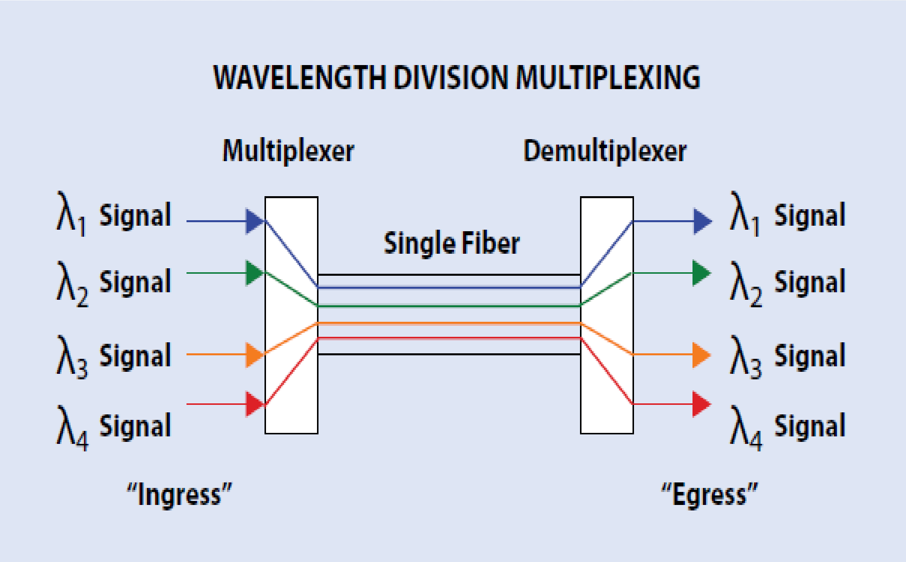
< Energy per bit routed for routers >



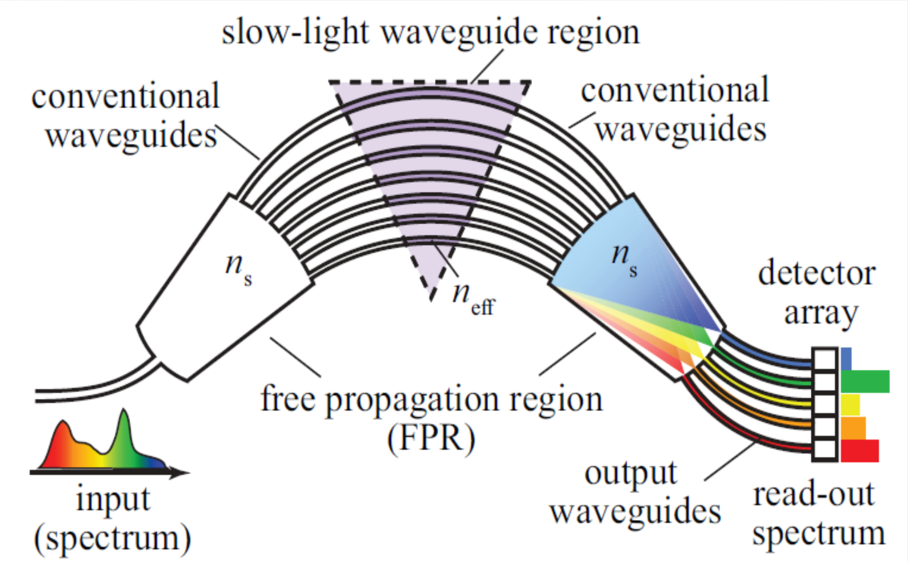
< Commercial interconnects >

WDM transmitters & receivers

❖ **WDM (Wavelength Division Multiplexing)**



< Basic WDM technology diagram >



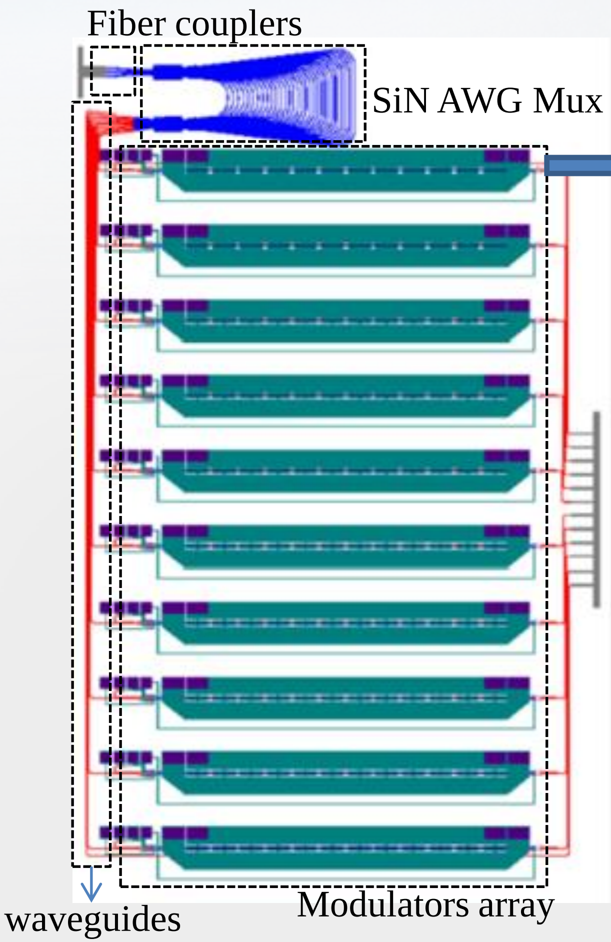
< AWG (Arrayed Waveguide Gratings) >

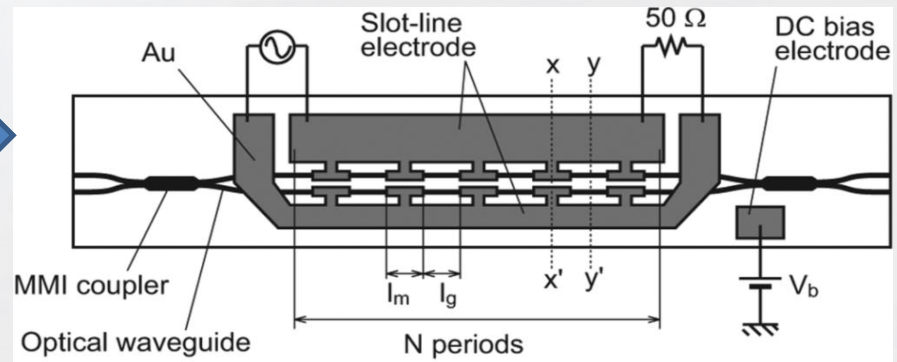
- Multi-channel system
- Transport multiple wavelengths over a fiber
- Use wavelength Mux/Demux

- Widely used for optical MUX/DeMUX
- Composed of two couplers and waveguides array
- Use phase shift and optical interference

WDM transmitters & receivers

❖ **WDM transmitter (100 GHz spacing, 25 Gbps/wavelength, 5x8 mm^2 footprint)**





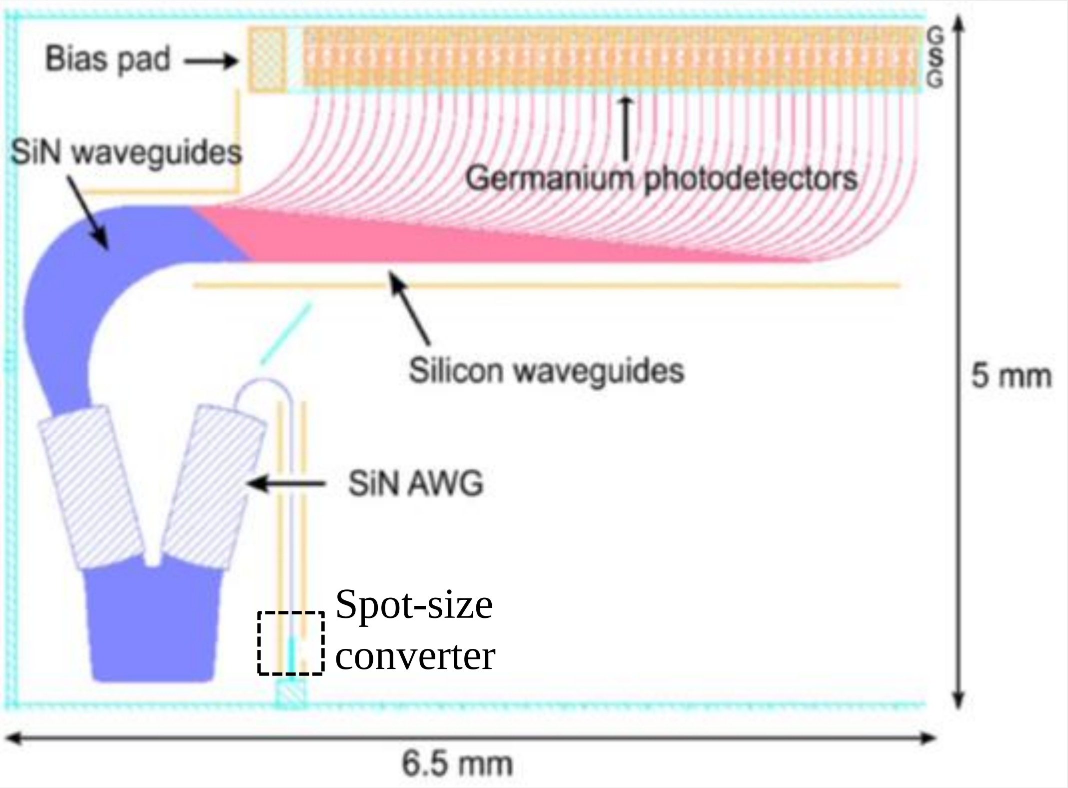
- Carrier depletion based MZM
- Use capacitively loaded traveling-wave electrodes
- Low capacitance, high speed operation

Component	Waveguide	Reason
Fiber couplers	Silica	Low index contrast
AWG	Si_3N_4	Fabrication tolerance
Waveguides	Silicon	Low loss
Modulators	Silicon	p-n junctions

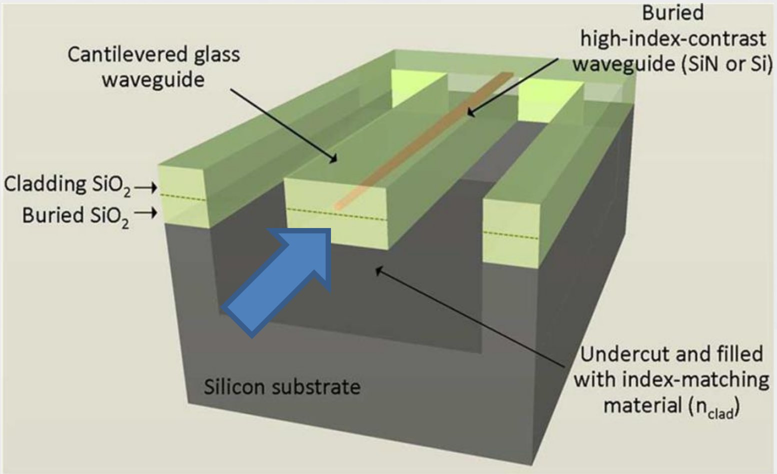
WDM transmitters & receivers

❖ **WDM receiver (0.2 A/W, 200 GHz spacing, 40 channels)**

- ➢ **Monolithically integrated WDM receiver**



< Integrated WDM receiver >

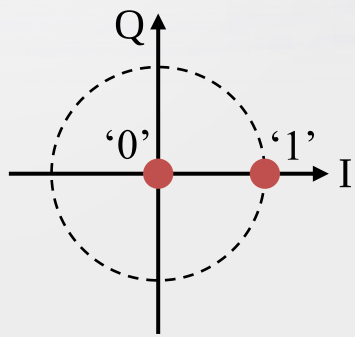
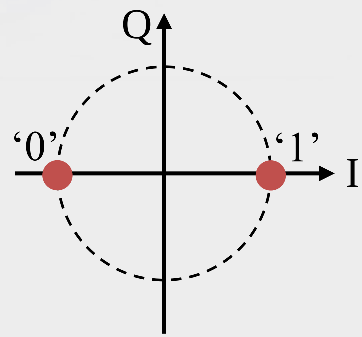
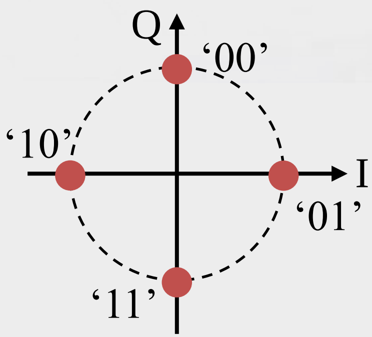
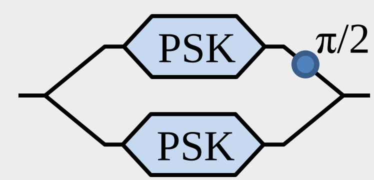


< cantilever based spot-size converter >

Component	Waveguide	Reason
Spot-size converter	Si_3N_4	Low coupling loss
AWG	Si_3N_4	Fabrication tolerance
Waveguides	Silicon	Low loss
Ge-PD	Silicon	p-n junctions

Coherent transmitters & receivers

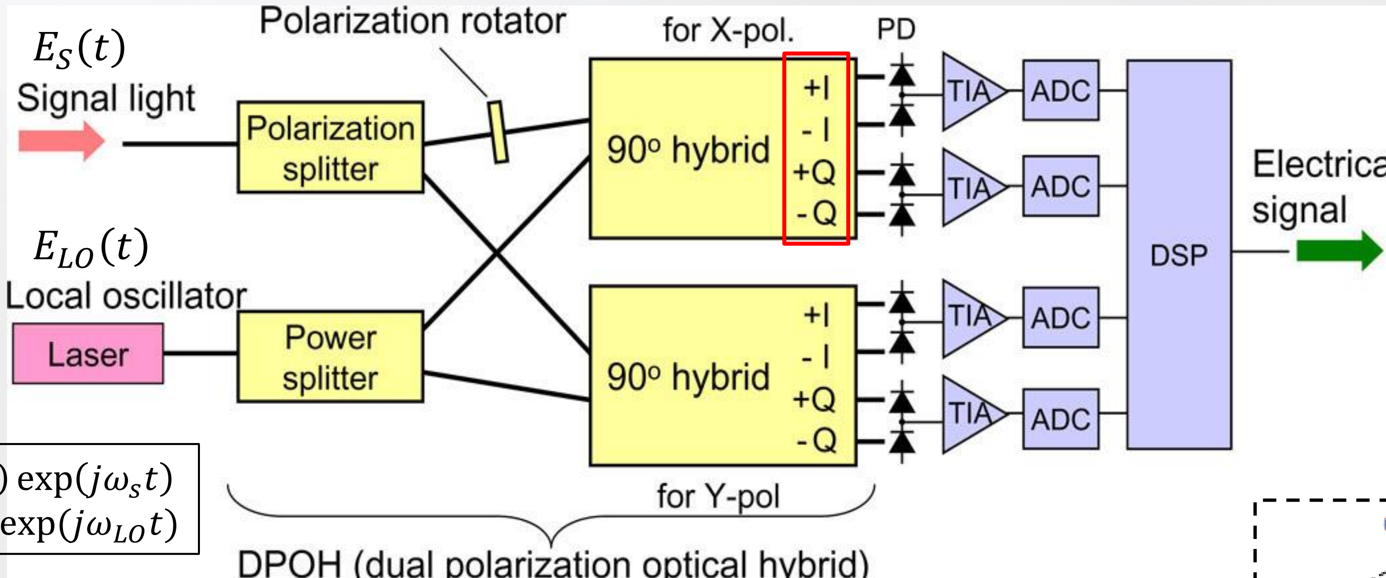
- **Optical coherent system**
  - High spectral efficiency: High-order modulation (QAM, OFDM)
  - High receiver sensitivity: optical beating between signal and local oscillator

Modulation formats	OOK	BPSK	QPSK (4-QAM)
Constellation			
Efficiency	1 bit/symbol	1 bit/symbol	2 bits/symbol
Modulator configuration			

Coherent transmitters & receivers

❖ **Optical coherent system**

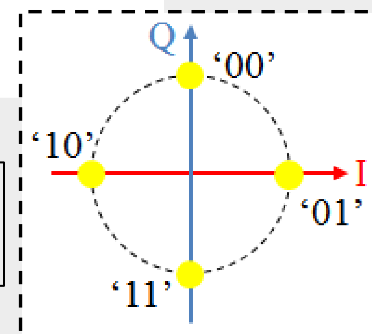
- High spectral efficiency: High-order modulation (QAM, OFDM)
- High receiver sensitivity: optical beating between signal and local oscillator



$$E_S(t) = A_S(t)\exp(j\omega_s t)$$
$$E_{LO}(t) = A_{LO}\exp(j\omega_{LO} t)$$

$$+I = \frac{1}{\sqrt{2}}(E_S + E_{LO}), -I = \frac{1}{\sqrt{2}}(E_S - E_{LO})$$
$$+Q = \frac{1}{\sqrt{2}}(E_S - jE_{LO}), -Q = \frac{1}{\sqrt{2}}(E_S + jE_{LO})$$

$$(+I)^2 - (-I)^2 = 2Re\{E_S E_{LO}^*\}$$
$$(+Q)^2 - (-Q)^2 = 2Im\{E_S E_{LO}^*\}$$



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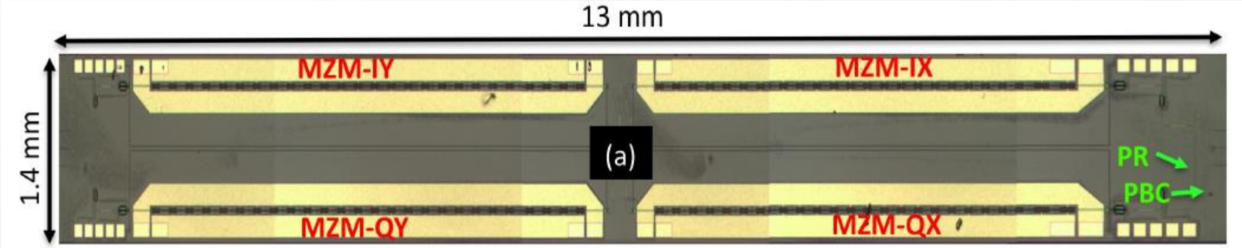
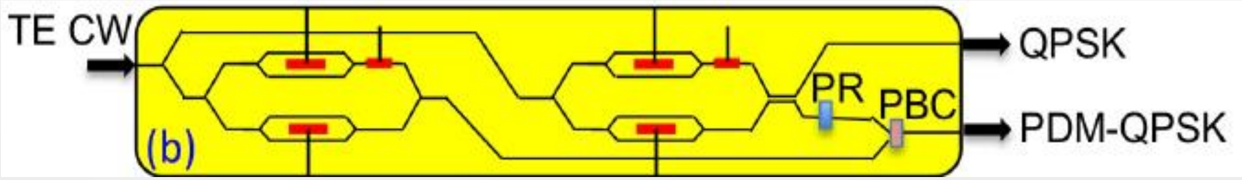
Coherent transmitters & receivers

❖ **Coherent transmitter**

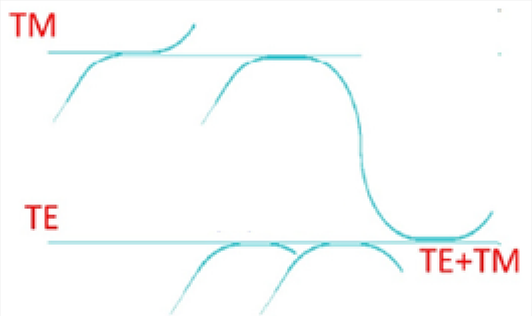
➢ **MZM based dual-polarization coherent transmitter (PDM-IQ modulator)**





➢ **Components**

- ✓ **Four MZMs**
- ✓ **Phase shifters**
- ✓ **Polarization rotator (PR)**
- ✓ **Polarization beam coupler (PBC)**

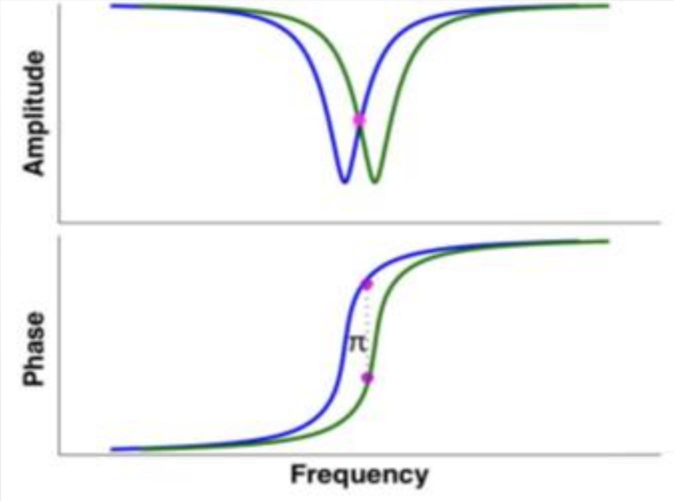


< directional coupler based PBC >

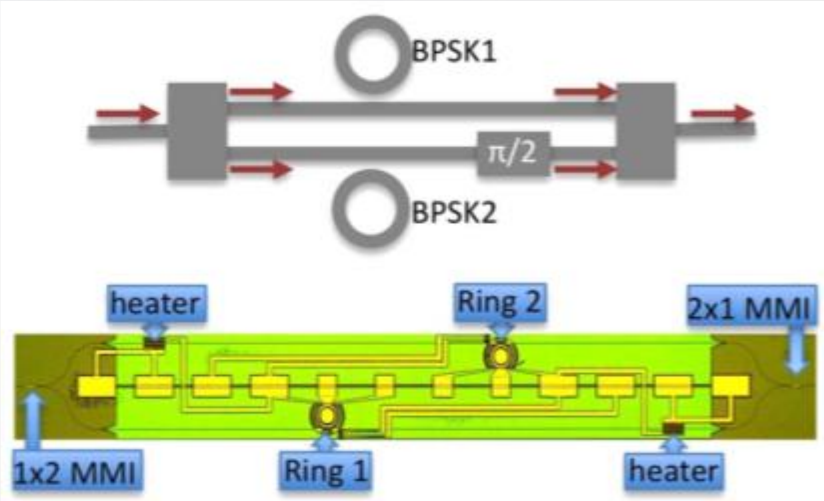
Coherent transmitters & receivers

❖ **Coherent transmitter**

➢ **Ring modulator based coherent transmitter**



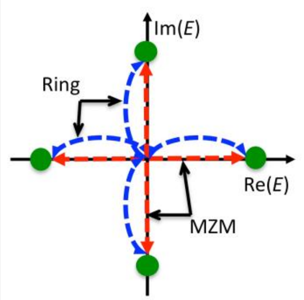
< BPSK modulation in ring modulator >



< QPSK modulator based on ring modulator >

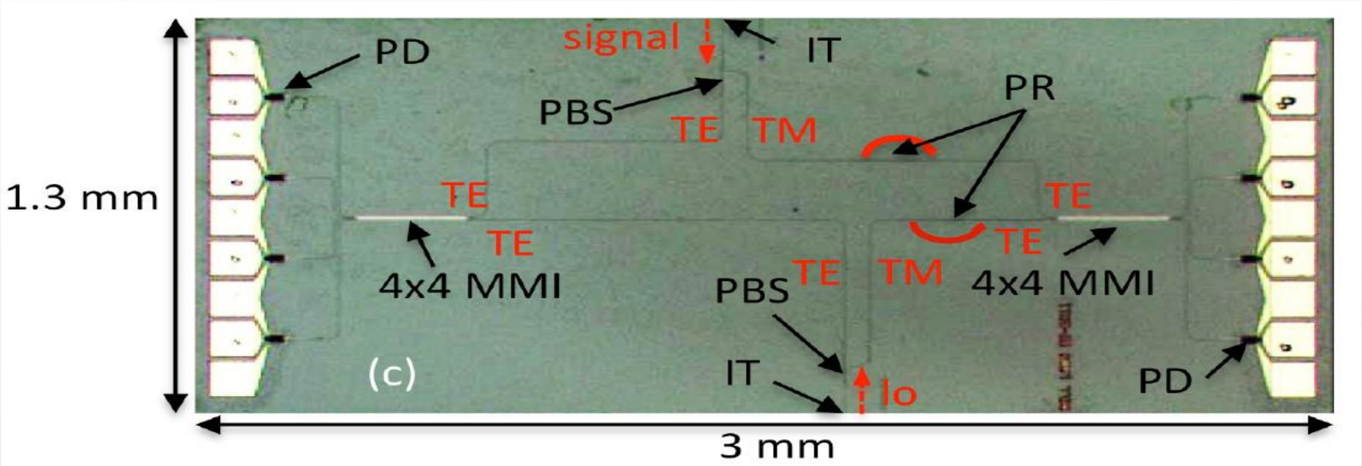
➢ **BPSK modulation using overdrive of ring modulator**

➢ **BPSK modulator x 2 + phase shift = QPSK modulator**



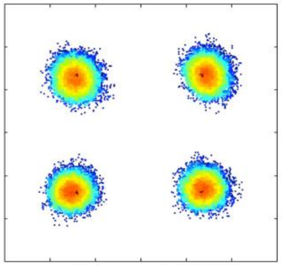
Coherent transmitters & receivers

- **Coherent receiver**
  - **Dual-polarization coherent receiver (PDM-coherent receiver)**

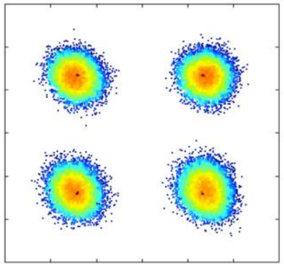


IT: inverse taper, **LO**: local oscillator, **PBS**: polarization beam splitter,
MMI: multimode interference coupler (90 degree hybrid)

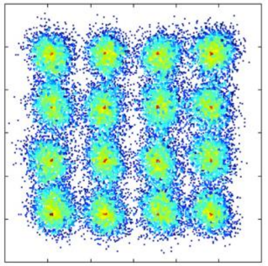
- **Components**
  - ✓ **Two PBSs**
  - ✓ **Two ITs**
  - ✓ **Two PRs**
  - ✓ **Two MMIs**
  - ✓ **Eight PDs**



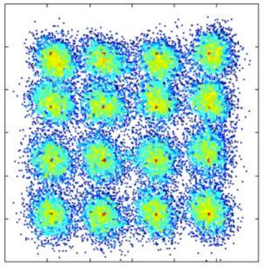
(b) x-pol QPSK



(c) y-pol QPSK



(d) x-pol 16-QAM



(e) y-pol 16-QAM

Summary

- Silicon Photonic devices
  - Using silicon-core waveguide
  - Whole-wafer processing based on CMOS fabrication
  - Applications
    - ✓ Long-haul/metro coherent optical networks
    - ✓ Optical interconnects for routers and switches
    - ✓ Datacenters and supercomputers
  - PICs
    - ✓ WDM transmitter/receiver
      - Integration of AWG and modulators array/PDs array
    - ✓ Coherent transmitter & receiver
      - MZM based PDM-IQ modulator
      - Micro-ring modulator based Coherent transmitter
      - PDM-coherent receiver