Hands-on class in Integrated Photonics

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Outline

1. Silicon photonics technology
2. The integrated photonic education kit
3. Some basics for the hands-on class
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Silicon Photonics

➢ **A disruptive technology:** integrate a large number of opto-electronic devices/optical functions into a low cost Si chip
➢ **The vision:** deliver optical connectivity everywhere, from network level to chip-to-chip
➢ **Today,** many optical function can be embedded at a Silicon chip level

- **Integration**
- **High volume/Low cost**
- **Low power consumption**
The basic building block: optical waveguide

Silicon On Insulator (SOI) wafer = optical planar waveguide

- high-index contrast (n_{Si}=3.5 – n_{SiO2}=1.5)
- Natural optical waveguide
- Strong light confinement
- Small footprint

Fabrication Process

Mode size \sim 0.1 \mu m^2
Propagation loss \sim 1 \text{ dB/cm}

Strip waveguide
Other building blocks

- Grating coupler
- Bragg structures
- Y-branch (beam splitter)
- Directional coupler
- Add-drop ring resonator
- Mach-Zehnder interferometer
Silicon photonics is growing fast and is a multibillion market!
However...

*Integrated Photonics remains unknown for a majority of undergrad/grad students, even in engineering fields*

- Today, only PhDs have the practical knowhow in integrated photonics

- As the technology matures the needs for highly specialized manpower gets less prominent

*Our job is to train and make you valuable to the market place by providing a practical introduction to Si Photonics*
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The Integrated Photonics Education Kit (IPEK)

We offer a hands-on tool to train future engineers in integrated photonics

- Standalone building blocks (rings, Bragg structures, MZI, etc...)
- Optical functionalities (Filtering, modulations, etc...)
- Includes resistive heating elements for tunable devices
- Easy to use and robust optical & electrical packaging
- Devices can be externally connected to each other
The Integrated Photonics Education Kit (IPEK)

A cost effective way of bringing Photonic Integrated Circuits to the classroom

Our research lab

Your hands-on class
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Goals of the lab class

Study a Mach-Zehnder interferometer integrated in the education kit:

• Familiarization with some lab tools (oscilloscope, photodiode, optical spectrum analyzer, laser, fibers etc.

• Measure the optical spectrum of the MZI, extract some characteristics of the device

• Electrical measurements

• Intensity modulation and measure the speed of the device
Optical communication link using Silicon Photonics

MZI is a key device in silicon photonics. For example, it can be used in optical communication links to encode data into optical waves. It enables:

- Intra-chip communications
- Inter-chip communications
- Data-com communications
Mach-Zehnder interferometer: device that converts phase modulation to intensity modulation using interferences.
Mach-Zehnder principle

\[ E_{1,2} = \frac{E_i}{\sqrt{2}} \]

\[ E_{o1} = E_1 e^{i\beta_1 L_1} \]

\[ E_{o2} = E_2 e^{i\beta_2 L_2} \]

- The propagation constant depends on \( n_{\text{eff}} \) and the wavelength

\[ \beta = kn_{\text{eff}} = \frac{2\pi}{\lambda} n_{\text{eff}} \]
The Mach-Zehnder principle

\[ E_{1,2} = \frac{E_i}{\sqrt{2}} \]

\[ E_{o1} = E_1 e^{i \beta_1 L_1} \]

\[ E_{o2} = E_2 e^{i \beta_2 L_2} \]

\[ I_o = \frac{I_i}{2} [1 + \cos(\beta_1 L_1 - \beta_2 L_2)] \]

- The propagation constant depends on \( n_{\text{eff}} \) and the wavelength
- The output of the interferometer is a sinusoidally varying function of wavelength for an imbalanced interferometer (\( L_1 \neq L_2 \))
- The intensity also varies sinusoidally with the waveguide effective index (\( n_{\text{eff}1} \) and \( n_{\text{eff}2} \))

\[ \beta = k n_{\text{eff}} = \frac{2\pi}{\lambda} n_{\text{eff}} \]
Mach-Zehnder principle

\[ E_{1,2} = \frac{E_i}{\sqrt{2}} \]
\[ E_{o1} = E_1 e^{i\beta_1 L_1} \]
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\[ I_o = \frac{I_i}{2} [1 + \cos(\beta_1 L_1 - \beta_2 L_2)] \]

Assignment:
1 - Derive this equation by yourself
2 – Plot the intensity as function of wavelength in C-band

Use this following parameter corresponding to the devices in the IPEK

- Arm 1 (Short Arm): 610 um
- Arm 2 (Long Arm): 710 um

\[ \beta = k n_{eff} = \frac{2\pi}{\lambda} n_{eff} \]
Mach-Zehnder principle

\[ E_{1,2} = \frac{E_i}{\sqrt{2}} \]

\[ E_{o1} = E_1 e^{i\beta_1 L_1} \]

\[ E_{o2} = E_2 e^{i\beta_2 L_2} \]

\[ \beta = k n_{\text{eff}} = \frac{2\pi}{\lambda} n_{\text{eff}} \]

\[ n_{\text{eff}} \approx 2.5 \quad n_g \approx 4 \]

\[ I_o = \frac{I_i}{2} \left[ 1 + \cos(\beta_1 L_1 - \beta_2 L_2) \right] \]

The period of oscillation is the free-spectral range (FSR)

\[ \Delta \lambda_{\text{FSR}} = \frac{\lambda^2}{n_g (L_1 - L_2)} \]

Assignment:
Derive that equation by yourself (hint derivate the phase w/ respect wavelength)
Mach-Zehnder principle

\[ I_o = \frac{I_i}{2} \left[ 1 + \cos \left( \frac{2\pi}{\lambda} (n_{eff1} L_1 - n_{eff2} L_2) \right) \right] \]

The intensity also varies sinusoidally with the waveguide effective index in the arm 1, which can be changed by:

- The thermo-optic effect (slow effect)
- The plasma dispersion effect (fast effect)
Mach-Zehnder principle

\[ I_o = \frac{I_i}{2} \left[ 1 + \cos \left( \frac{2\pi}{\lambda} (n_{eff1}L_1 - n_{eff2}L_2) \right) \right] \]

The intensity also varies sinusoidally with the waveguide effective index in the arm 1, which can be changed by:

- The thermo-optic effect (slow effect)
- The plasma dispersion effect (fast effect)
The thermo-optic effect on a waveguide

Thermo-optic effect: refractive index that changes with temperature

- The refractive index of silicon changes with temperature
- The thermo-optic coefficient of Si at room temperature is $\frac{dn_{Si}}{dT} \sim 1.8 \times 10^{-4} K^{-1}$
- The effective index experienced by the guided mode is $n_{eff}(\Delta T) \approx n_{eff} + \frac{dn_{eff}}{dT} \Delta T$

Apply a voltage on the resistive heater
Mach-Zehnder principle

**Arm 1**
- Heated section $L_H$
- Unheated section $\Delta L$
- Total length $L_1 = L_H + \Delta L$

**Arm 2**
- $L_2 = L_1 + \Delta L$

$\Delta T = 0 \text{ K}$

$$n_{eff1} \approx n_{eff2} = n_{eff}$$

$$\Delta \varphi = \frac{2\pi}{\lambda} n_{eff} (L_1 - L_2)$$

$\Delta T \neq 0 \text{ K}$

$$n_{eff}(\Delta T) \approx n_{eff} + \frac{dn_{eff}}{dT} \Delta T$$

$$\Delta \varphi = \frac{2\pi}{\lambda} \left( \frac{dn_{eff}}{dT} \Delta TL_H - n_{eff} \Delta L \right)$$
Assignment:

1- What is the temperature variation required for a $\pi$-phase shift?

2 - Plot the optical transmission spectrum at $\Delta T = 0$ K and $\Delta T = 10$ K, comment

3- Derive the output intensity when both arms are heated simultaneously, conclude.

4 - Plot the intensity versus $\Delta T$, compare with the a single heated arm case.
Any question?