Physical Mechanisms for Optical Modulators

• Electro-optic modulators
  – Nonlinear crystals
  – LiNbO$_3$, GaAs, InP

• Franz-Keldysh effect
  – Sub-bandgap absorption induced by electric field
  – GaAs, InP

• Quantum confined Stark Effect (QCSE)
  – Absorption modulators in quantum wells
  – Mostly III-V, but also SiGe QWs

• Free carriers effect
  – Refractive index change due to electrons/holes
  – All semiconductors, including Si

• Thermo-optic effect
  – Refractive index change due to temperature
  – All semiconductors, including Si
Electro-Optic Effect (Pockels Effect)

\[
\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} + 2r_{63}F_{cz}xy = 1
\]

Table 12.1 A Few Electrooptic Materials With Their Parameters [1, 4, 6, 9]

<table>
<thead>
<tr>
<th>Point-Group</th>
<th>Symmetry</th>
<th>Material</th>
<th>Refractive Index</th>
<th>Wavelength (\lambda_d(\mu\text{m}))</th>
<th>Nonzero Electrooptic Coefficients (10^{-12} \text{ m/V})</th>
</tr>
</thead>
<tbody>
<tr>
<td>3m</td>
<td>3</td>
<td>LiNbO3</td>
<td>2.297, 2.208</td>
<td>0.633</td>
<td>(r_{12} = r_{23} = 8.6, r_{33} = 30.8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Quartz</td>
<td>1.544, 1.553</td>
<td>0.589</td>
<td>(r_{12} = r_{31} = -2r_{12} = -0.2)</td>
</tr>
<tr>
<td>42m</td>
<td>42</td>
<td>KCl(_2)PO4 (KDP)</td>
<td>1.5115, 1.4698</td>
<td>0.546</td>
<td>(r_{11} = r_{23} = 8.17, r_{33} = 10.3)</td>
</tr>
<tr>
<td>42m</td>
<td>42</td>
<td>NH(_4)(_2)PO4 (ADP)</td>
<td>1.5266, 1.4808</td>
<td>0.546</td>
<td>(r_{11} = r_{23} = 23.76, r_{33} = 8.56)</td>
</tr>
<tr>
<td>42m</td>
<td>42</td>
<td>KDP(_2)PO4 (KD(_2)P)</td>
<td>1.5079, 1.4683</td>
<td>0.546</td>
<td>(r_{11} = r_{23} = 3.41, r_{33} = 20.28)</td>
</tr>
<tr>
<td>43m</td>
<td>43</td>
<td>GaAs</td>
<td>3.60, 3.42, 3.34</td>
<td>0.9, 1.0, 1.0</td>
<td>(r_{11} = r_{23} = r_{33} = 1.1)</td>
</tr>
<tr>
<td>43m</td>
<td>43</td>
<td>InP</td>
<td>3.29, 3.20, 3.20</td>
<td>0.9, 1.35, 1.35</td>
<td>(r_{11} = r_{23} = r_{33} = 1.6)</td>
</tr>
<tr>
<td>43m</td>
<td>43</td>
<td>ZnSe</td>
<td>2.60, 2.60, 2.60</td>
<td>0.633</td>
<td>(r_{11} = r_{23} = r_{33} = 2.0)</td>
</tr>
<tr>
<td>43m</td>
<td>43</td>
<td>β-ZnS</td>
<td>2.36, 2.36, 2.36</td>
<td>0.6, 0.6, 0.6</td>
<td>(r_{11} = r_{23} = r_{33} = 1.1)</td>
</tr>
</tbody>
</table>

GaAs Electro-Optic Modulators

\[
r = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
r_{11} & 0 & 0 \\
r_{32} & 0 & 0 \\
0 & r_{33} & 0
\end{bmatrix}
\]

Apply electric field in z direction:

\[
x^2 + y^2 + z^2 + 2r_{63}F_{cz}xy = 1
\]

\[
r_{11} = n_o + \frac{1}{2}n_{633}^3F_z
\]

\[
r_{33} = n_o - \frac{1}{2}n_{633}^3F_z
\]

For GaAs at 1 \(\mu\text{m}\) wavelength

\[n_o = 3.42, \quad r_{11} = r_{32} = r_{33} = 1.5 \times 10^{-12} \text{ m/V}\]

For applied field of \(10^7 \text{ V/m}\)

\[
\Delta n = \frac{1}{2}n_{633}^3F_z = 3 \times 10^{-4}
\]

Note: Si is central symmetric and has no electro-optic effect.
Converting Index Change to Amplitude Change

\[ I_o = \left| E \right|^2 = \left| \frac{1}{2} E \cdot e^{j \frac{2\pi}{\lambda} (n_o + \Delta n) L} + \frac{1}{2} E \cdot e^{j \frac{2\pi}{\lambda} (n_o - \Delta n) L} \right|^2 \]

\[ = \left| E \right|^2 \left( 1 + \cos \left( \frac{4\pi n L}{\lambda} \right) \right) \]

\[ = \left| E \right|^2 \frac{1}{2} \left( 1 + \cos \left( \frac{4\pi n_o^3 F L}{\lambda} \right) \right) \]

\[ F = \frac{V}{d} \]

\[ V_p : \text{ voltage at } \pi \text{ phase shift} \]

\[ V_p L = \frac{d\lambda}{4n_o^3 F} \]

GaAs at 1\( \mu \)m, and assume d of 1\( \mu \)m

\[ V_p L \approx 4 \left[ V \cdot \text{mm} \right] \Rightarrow \text{Long devices} \]

Franz-Keldysh Effect

- Under electric field bias, energy bands of electrons are tilted
  - Slope = electric field
- Electron wave functions change from sinusoidal to “Airy” functions
- “Photon-assisted” tunneling
- Effective bandgap becomes smaller
  - Controllable by electric field (voltage)
- Absorption can be modulated by voltage
Absorption Modulator with Franz-Keldysh Effect

- Absorption edge shifts to lower energy with electric field in direct bandgap semiconductor (e.g., GaAs, InP)
- Absorption up to 1000 cm\(^{-1}\)
  - Short devices \(\sim 100\)μm

Quantum Confined Stark Effect (QCSE)

- Absorption edge shifts to lower energy with electric field in quantum wells
- Absorption up to 1000 cm\(^{-1}\)
  - Short devices \(\sim 100\)μm
Experimentally Measured Absorption in Quantum Wells

(i) No field
(ii) 60 kV/cm
(iii) 100 kV/cm
(iv) 150 kV/cm

Silicon Photonics

http://www.luxtera.com

• “Photonics on a silicon chip”
• High density integration
• CMOS process
  – Improved performance
  – Better process control

http://www.intel.com/pressroom
What is Silicon Photonics?

- Use Si to guide, process, and detect (Ge) light
- Leverage on CMOS fab
- Enable photonics to scale with Moore's Law
- Highly functional chip by integrating photonics with CMOS
- Enhance electronic as well as photonic performance

Most Common Platform: SOI

- SOI substrate
  - 220nm Si, 2um BOX
- Si waveguides
- Grating couplers
- Ge detectors
- Si modulators (usually p-i-n)
- Multiple level metals
- (Optional) CMOS

Moore’s Law on Lithography

Luxtera
- Founded in 2001 when lithographic feature size < ¼ wavelength (~ 100nm)
- First Si Photonics company

Properties of Si

+ Low loss (~ 0.2 to 2 dB/cm)
+ Tight optical confinement
  - Tiny waveguides (200x500nm²)
  - Sharp bends (radius ~ μm)
× Indirect bandgap → No Si laser
× Cubic crystal with inversion symmetry → No electro-optic effect

Optical modulation:
- Modulating carrier density
  \[ \Delta n = -8.8 \times 10^{-22} \Delta N_e \]
  
  \[ -8.5 \times 10^{-18} (\Delta N_e)^{0.8} \]
- Thermo-optic effect
  \[ \frac{dn}{dT} = 1.86 \times 10^{-4} \]
Free-Carrier Effect in Si

At 1.55\,\mu\text{m},
\[
\Delta n = -8.8 \times 10^{-22} \Delta N_e - 8.8 \times 10^{-18} \left( \Delta N_h \right)^{0.8} \\
\Delta \alpha = 8.5 \times 10^{-18} \Delta N_e + 6.0 \times 10^{-18} \Delta N_h
\]

For \( \Delta N_e = \Delta N_h = 10^{18} \text{ cm}^{-3} \)
\[
\Delta n = -0.003 \\
\Delta \alpha = 14.5 \text{ cm}^{-1}
\]

Si Mach-Zehnder Modulators

Table 1. Performance comparison of previously reported high-speed silicon MZMs (> 25 Gb/s) and devices in this work.

<table>
<thead>
<tr>
<th>Reference</th>
<th>[17]</th>
<th>[15]</th>
<th>[25]</th>
<th>[27]</th>
<th>[24]</th>
<th>L = 2 mm</th>
<th>L = 4 mm</th>
<th>L = 6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device length (mm)*</td>
<td>1</td>
<td>0.12</td>
<td>1.35</td>
<td>1</td>
<td>3.5</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Vpi-L (V-cm)</td>
<td>4</td>
<td>0.5</td>
<td>11</td>
<td>2.8</td>
<td>2.7</td>
<td>2.4</td>
<td>2.4</td>
<td>2.08</td>
</tr>
<tr>
<td>Vpi (V) *</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-8</td>
<td>10</td>
<td>12</td>
<td>5.2</td>
</tr>
<tr>
<td>Insertion loss (dB)*</td>
<td>4</td>
<td>2.5</td>
<td>15</td>
<td>3.7</td>
<td>15</td>
<td>4.3</td>
<td>4.1</td>
<td>6.6</td>
</tr>
<tr>
<td>Speed (Gb/s)</td>
<td>40</td>
<td>25</td>
<td>40</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

* Device length: the phase shifter length rather than the whole device length.
* Vpi under dc. NA represents that the phase shifter is too short and a π-phase shift may not be achievable before breakdown voltage.
* Insertion loss is defined as the on-chip loss for the wavelength at maximum transmission of the MZMs.

Microring Modulator

- Use resonance in microring to enhance the modulation
- Reduce modulator size from millimeters to tens of microns
- Enhanced modulation efficiency
- Reduced bandwidth
- Must match laser/resonator wavelengths


Basic Physics of Mirroring Resonator

Thermo-Optic Effect in Si

Experimentally measured data at 1.55µm:

\[
\frac{dn}{dT} = 9.48 \times 10^{-5} + 3.47 \times 10^{-7} T - 1.49 \times 10^{-10} T^2
\]

At 300K, \( \frac{dn}{dT} \approx 1.86 \times 10^{-4} \) K\(^{-1}\)

With ΔT of 270K, Δn = 0.05

Corresponding length for π phase shift is 15.5µm

- Index change due to (1) thermal expansion, (2) bandgap energy reduction with temperature
- Relatively strong compared with carrier effect
- Low optical loss introduced by heating
- Usually slow, limited by thermal RC time. Modulation time is on the order of milliseconds. For small structures, it could approach microsecond response time.
- Too slow for modulators, but often used in tunable filters, switches.
- High power consumption

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Thermo-Optic Effect in Silicon

- Si thermo-optic coefficient
  - \( \frac{dn}{dT} = 1.86 \times 10^{-4} \)
  - For ΔT ≈ 500 °C
    - Δn ≈ 3%, \( L_{\pi} \approx 10 \) um
- Steady power consumption
  - \( P_{\pi} \approx 10 \) mW

Fabry-Perot Resonator

\[ T = \frac{(1 - R)^2}{1 + R^2 - 2R \cos(\Delta \phi)} \]

\[ \Delta \phi = 2 \beta d = \frac{4 \pi n_e d}{\lambda} \]

Fig. 14.1. (a) Transmission of a light wave with electric field amplitude \( E_0 \) through a Fabry-Perot resonator. (b) Schematic illustration of allowed and disallowed optical modes in a Fabry-Perot cavity consisting of two unequal reflectors. Optical mode density for a resonator with (c) no mirror losses \( R_1 = R_2 = 100 \% \) and (d) mirror losses.

\[ T = \frac{(1 - R)^2}{1 + R^2 - 2R \cos(\Delta \phi)} \]

\[ \Delta \phi = 2 \beta d = \frac{4 \pi n_e d}{\lambda} \]