Modulation of light

- Direct modulation of sources
- Electro-absorption (EA) modulators
Why Modulation

- A communication link is established by transmission of information reliably
- Optical modulation is embedding the information on the optical carrier for this purpose
- The information can be digital (1,0) or analog (a continuous waveform)
- The bit error rate (BER) is the performance measure in digital systems
- The signal to noise ratio (SNR) is the performance measure in analog systems
Types of Optical Modulation

- **Direct modulation** is done by superimposing the modulating (message) signal on the driving current.
- **External modulation** is done after the light is generated; the laser is driven by a dc current and the modulation is done after that separately.
- Both these schemes can be done with either **digital** or **analog** modulating signals.
- In external modulation, the laser emits **continuous wave (CW)** light and the modulation is done in the fiber.
• Direct modulation of semiconductor lasers
  --- frequency response
  --- relaxation oscillation
  --- chirp
• external modulators:
  --- Electro-absorption modulators
  --- Mach-Zehnder interferometer
Important parameters used to characterize and compare different modulators

- **Modulation efficiency**: Defined differently depending on whether we modulate intensity, phase or frequency.
  
  For intensity it is defined as $(I_{\text{max}} - I_{\text{min}})/I_{\text{max}}$.

- **Modulation depth**: For intensity modulation it is defined in decibel by $10 \log (I_{\text{max}}/I_{\text{min}})$.

- **Modulation bandwidth**: Defined as the high frequency at which the efficiency has fallen by 3dB.

- **Power consumption**: Simply the power consumption per unit bandwidth needed for (intensity) modulation.
Direct Modulation

- The message signal (ac) is superimposed on the bias current (dc) which modulates the laser
- Robust and simple, hence widely used
- Issues: laser resonance frequency, chirp, turn on delay, clipping and laser nonlinearity
Direct Analog Modulation

**LED**

\[ P_t = I_B \]

**Laser**

\[ P_t = I_B - I_{th} \]

Modulation index (depth)

\[ m = \frac{\Delta I}{I_B} \]
Analog LED Modulation

Note:
No threshold current
→ No clipping
→ No turn on delay
Modulation of LED

- The frequency response of an LED depends on:
  1. Doping level in the active region
  2. Injected carrier lifetime in the recombination region, $\tau_i$.
  3. Parasitic capacitance of the LED

- If the drive current of an LED is modulated at a frequency of $\omega$ the output optical power of the device will vary as:

$$P(\omega) = \frac{P_0}{\sqrt{1 + (\omega \tau_i)^2}}$$

- Electrical current is directly proportional to the optical power, thus we can define electrical bandwidth and optical bandwidth, separately.

  Electrical BW = $10\log\left[\frac{p(\omega)}{p(0)}\right] = 20\log\left[\frac{I(\omega)}{I(0)}\right]$

  $p$: electrical power, $I$: electrical current
Optical BW = 10 \log \left( \frac{P(\omega)}{P(0)} \right) = 10 \log \left( \frac{I(\omega)}{I(0)} \right)
Modulation of Laser Diodes

- Internal Modulation: Simple but suffers from non-linear effects.
- External Modulation: for rates greater than 2 Gb/s, more complex, higher performance.
- Most fundamental limit for the modulation rate is set by the photon lifetime in the laser cavity:
  \[
  \frac{1}{\tau_{ph}} = \frac{c}{n} \left( \frac{1}{\alpha} + \frac{1}{2L} \ln \frac{1}{R_1 R_2} \right) = \frac{c}{n} g_{th}
  \]
- Another fundamental limit on modulation frequency is the relaxation oscillation frequency given by:
  \[
  f = \frac{1}{2\pi} \frac{1}{\sqrt{\tau_{sp} \tau_{ph}}} \left( \frac{I}{I_{th}} - 1 \right)^{1/2}
  \]
Laser Analog Modulation

Here $s(t)$ is the modulating signal, $P(t)$: output optical power
$P_t$: mean value

$$P(t) = P_t [1 + ms(t)]$$
Laser Digital Modulation

Optical Power $(P)$

Current $(I)$

$I_{th}$

$I_1$

$I_2$

$P(t)$

Current $(I)$

$t$
**Turn on Delay (lasers)**

- When the driving current suddenly jumps from low \((I_1 < I_{th})\) to high \((I_2 > I_{th})\), (step input), there is a finite time before the laser will turn on.
- This delay limits bit rate in *digital systems*.

\[
    t_d = \tau_{sp} \ln \left[ \frac{I_2 - I_1}{I_2 - I_{th}} \right]
\]
- **Input current**
  - Assume step input

- **Electron density**
  - steadily increases until threshold value is reached

- **Output optical power**
  - Starts to increase only after the electrons reach the threshold
Frequency Response of a Laser

Resonance Frequency ($f_r$) limits the highest possible modulation frequency.
The modulated spectrum

Twice the RF frequency

(3.6 GHz)

Two sidebands each separated by modulating frequency

Transfer function of the fiber

Modulation Depth ~ 0.2

Optical Carrier

RF Subcarrier

RF Bandwidth

$\lambda_0 = 1310$ nm
Linearity of Laser

Information carrying electrical signal $s(t)$

LED or Laser diode modulator

Optical output power:
$P(t) = P[1 + ms(t)]$
Nonlinearity

\[ x(t) = A \cos \omega t \]

\[ y(t) = A_0 + A_1 \cos \omega t + A_2 \cos 2\omega t + \ldots \]

Nth order harmonic distortion:

\[ 20 \log \left( \frac{A_n}{A_1} \right) \]
Intermodulation Distortion

\[ x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t \quad \Rightarrow \quad y(t) = \sum_{m,n} B_{mn} \cos(m \omega_1 + n \omega_2) t \quad m,n = 0, \pm 1, \pm 2, \ldots \]

Harmonics:

\[ n \omega_1, m \omega_2 \]

Intermodulated Terms:

\[ \omega_1 \pm \omega_2, 2\omega_1 \pm \omega_2, \omega_1 \pm 2\omega_2, \ldots \]
Laser Noise

- **Modal (speckle) Noise**: Fluctuations in the distribution of energy among various modes.
- **Mode partition Noise**: Intensity fluctuations in the longitudinal modes of a laser diode, main source of noise in single mode fiber systems.
- **Reflection Noise**: Light output gets reflected back from the fiber into the laser, couples with lasing modes, changing their phase, and generating noise peaks. Isolators & index matching fluids can eliminate these reflections.
Temperature variation of the threshold current

\[ I_{th}(T) = I_z e^{T / T_0} \]
Limitations of Direct Modulation

- **Turn on delay** and **resonance frequency** are the two major factors that limit the speed of digital laser modulation.
- **Saturation** and **clipping** introduces nonlinear distortion with analog modulation (especially in multi carrier systems).
- Nonlinear distortions introduce second and third order intermodulation products.
- **Chirp:** Laser output wavelength drifts with modulating current.
Chirp

In laser diode, the refractive index varies with carrier density.

Modulation $\rightarrow$ vary current $\rightarrow$ vary carrier density
$\rightarrow$ vary refractive index $\rightarrow$ index varies with time
$\rightarrow$ phase delay varies with time $\rightarrow$ induces new frequency

**frequency varies with time : chirp**

- chirp results in broadening of a laser linewidth
- chirp magnitude is $\sim 100\text{MHz} - \text{GHz/mA}$,
  $\sim 0.001\%$ of center frequency
A pulse can have a frequency that varies in time.

This pulse increases its frequency linearly in time (from red to blue).

In analogy to bird sounds, this pulse is called a "chirped" pulse.
Modulation and light generation are separated
- Offers much wider bandwidth ➔ up to 60 GHz
- More expensive and complex
- Used in high end systems
External Modulated Spectrum

- Typical spectrum is double side band
- However, single side band is possible which is useful at extreme RF frequencies
Mach-Zehnder modulator

Material with Constant Index of Refraction

Input Optical Signal

Phase Interference of Two Half-Signals

V = Applied Switching Signal

Material with Variable Index of Refraction

Output Optical Signal
Parameters to characterize performance of optical modulation

- modulation depth
- bandwidth
- insertion loss
- degree of isolation
- power handling
- induced chirp
Mach-Zehnder modulator

- Applying voltages to electrodes to change the refractive indices of light paths 1 & 2.
- The optical paths of 1 & 2 vary with the applied voltage.
- In phase → strong output light; out of phase → weak output.
- Output light is then modulated by voltage signal.
Light in

In phase
Constructive output

Out of phase

Light in

leakage
Destructive output
Characteristics of Mach-Zehnder modulator

- material: LiNbO$_3$
- modulation depth: better than 20 dB
- bandwidth: could be 60 GHz
- insertion loss: $\geq$ 4 dB
- power handling: 200 mW
- induced chirp: negligible
- $V_\pi$: a few volts, depending on bandwidth
Electroabsorption (EA) Modulator

- EA modulator is a semiconductor device with the same structure as the laser diode.

- In laser diodes, we inject large enough current to achieve stimulated emission. While in EA modulator, we apply electric field (reverse bias) to change the absorption spectrum. No carriers are injected into the active region. However, carriers are generated due to absorption of light.

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Schematics of an EA modulator

(a) Waveguide modulator

(b) Transverse transmission modulator

\[ P_{out}(V) = T(V) P_{in} \]
Physics behind EA Modulators

How absorption spectrum in semiconductors can be changed?

- Physical model: effective-mass equation
  - Single-particle representation
  - Two-particle representation
- Coulomb interaction between electrons and holes: Excitons
- Electric field effect: Franz-Keldysh effect (neglect Coulomb interaction)
- Coulomb+Electric field: DC Stark effect
  - Franz-Keldysh effect plus Coulomb interaction between electrons and holes (excitons).
- Coulomb+Electric field+QW: Quantum Confined Stark Effect (QCSE)
  - DC Stark Effect in quantum wells
  - Excitons been confined in quantum well. Stark effect enhanced.
Franz-Keldysh Shift of Energy Gap in an Electric Field (no excitons)


Franz-Keldysh Shift of Exciton Energy Gap in Electric Field

Quantum-Confined Stark Effect in Quantum Wells

\( P_{\text{out}}(V) = T(V) P_{\text{in}} \)

\[ \alpha(\hbar \omega) \]

\[ \alpha(V) \]

\[ \alpha(0) \]

\[ h \omega_0 \]

\[ V(t) \]

\[ P_{\text{out}}(V) \]

\[ P_{\text{in}} \]
Electro-absorption (EA) modulator

- When the P-N structure in LED is reverse-biased, it becomes light absorption.
- At zero-bias, absorption is weak. Under strong reverse-biased, absorption is strong.
- Light intensity is then modulated by the voltage signal.
Characteristics of EA modulator

- material: semiconductor QWs
- modulation depth: better than 10 dB
- bandwidth: could be 40 GHz
- insertion loss: almost zero
- power handling: 1 mW
- induced chirp: negligible
- operation voltage: 2 V
- integrable with LD
Advantages of EA modulators

- Zero biasing voltage
- Low driving voltage
- Low/negative chirp
- High bandwidth
- Integrated with DFB
Integration of EA modulator with LD

Laser diode (LD)

QW gain region

QW EA modulator
Integrated DFB-EA Transmitter

- 10Gb/s module, $I_{th} = 20mA$, $P_{max} = 4mW @80mA$, extinction ratio = 15dB for -2.5V.

Source: Alcatel Optronics
Intersubband electro-modulator

More sensitive technique
- Probe samples with less active charge
- Observe transitions from a smaller number of wells

Technological applications
- Optoelectronic switches

Device Structure

Optical coupling

Kyma Substrate
AlGaN/GaN Electro-modulator

30Å Al$_{0.55}$Ga$_{0.45}$N/27Å GaN

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Peak (meV)</th>
<th>FWHM (meV)</th>
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<tr>
<td>Electro-modulation</td>
<td>478</td>
<td>139</td>
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<tr>
<td>Absorption</td>
<td>487</td>
<td>208</td>
</tr>
<tr>
<td>Simulation</td>
<td>481</td>
<td>N/A</td>
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</tbody>
</table>

**Highlight:** dramatic reduction in linewidth, possibly due to charge modulation in a single well

Summary of Optical Modulation

- **Direct modulation on semiconductor lasers:**
  - Output frequency drifts
    - carrier induced (chirp)
    - temperature variation due to carrier modulation
  - Limited modulation depth (don’t want to turn off laser)

- **External modulation**
  - Electro-optical modulation (low efficiency)
  - Electroabsorption (EA) modulation (smaller modulation bandwidth)