Electroabsorption Modulators

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Optical Modulation

- Direct modulation
  - Output frequency shifts with drive signal
    - Carrier induced (chirp)
    - Temperature variation due to carrier modulation
  - Limited extinction ratio

- Indirect or External modulation
  - Electro-optic modulation
    - Change optical path length with applied electric field
  - Electroabsorption modulation
    - Change amount of light absorbed with applied electric field
  - Finite insertion loss (6-7 dB)
Advantages of EA modulator

- Zero biasing voltage
- Low driving voltage
- Low/negative chirp
- High speed
- Lesser polarization dependence
- Integration with DFB laser
- Allows a single optical power source to be used for large number of information carrying beams
Electroabsorption modulator

Mechanisms

- Franz-Keldysh effect
  - Observed in conventional bulk semiconductors
- Quantum-confined Stark effect (QCSE)
  - Quantum well structures

Both of these electroabsorption effects are prominent near the bandgap of semiconductors
Franz-Keldysh effect

Tunneling allows overlap of electron and hole wavefunctions for photon energy less than bandgap

\[
\phi = K(E')^{1/2} (8\phi_0^3 \exp \left[ \frac{4}{3} \phi_0^{3/2} \right]
\]

where,

\[
E' = \left( \frac{q^2 E^2 \hbar^2}{2m^*} \right)^{1/3}
\]

\[
\phi = \frac{\hbar \phi_0}{E'}
\]
Excitonic electroabsorption (Stark effect)

- Excitonic effects gives rise to a step-like rise in absorption spectra.
- Formation of excitons manifests themselves as a series of sharp resonances near the bandgap energy.
- Formed in very pure semiconductors at low temperatures.
- Excitons can be very easily field ionized.
Quantum Confined Stark Effect

- Quantum well increases the overlap of electron and hole wavefunctions
- Electric field reduces overlap and results in a corresponding reduction in absorption and luminescence
- Exciton absorption peak is not greatly broadened because of confinement
Device structure

- Primary materials for EA modulators are III-V semiconductors
- PIN structure
- Transmission type does not lead to high enough extinction ratio
- Waveguide type more commonly used - has higher optical confinement
Design considerations

- Operation principle
- Contrast ratio
- Insertion loss
- Modulation efficiency
- Chirp considerations and efficiency
- Packaging and integration
Extinction Ratio

\[ R_{on/\text{off}} = \frac{P_{out}(V_{on} = 0)}{P_{out}(V_{off} = V)} = \frac{e^{-a(0)L}}{e^{-a(V)L}} \]

\[ R_{on/\text{off}} (dB) = 10 \log(R_{on/\text{off}}) = 4.343 \cdot \left[ a(V) - a(0) \right] L \]

- BER directly effected by extinction ratio
- Contrast ratio can be made as large as possible by increasing the length of the modulator. But propagation loss then becomes an issue.
Insertion loss

- Absorptive loss
  - Longer the modulator, larger the insertion loss.
  - Trade-off with Extinction Ratio

\[
\text{Loss} = \frac{P_{in} P_{out}(V = 0)}{P_{in}} = 1 - e^{-\alpha L}
\]

- Single mode fiber coupling loss
  - Waveguide coupler can be used to reduce coupling loss
  - Can be as good as 1 dB
  - Typical numbers are 5-6 dB
Modulation efficiency

- Modulation efficiency quantifies how much voltage do we need to modulate the optical signal.

\[
\frac{R_{on/off}}{\pi V} = 4.343 \frac{\left[ \frac{\alpha(V)}{\alpha(0)} \right]_L}{\pi V} = 4.343 \frac{\alpha}{\pi F}
\]

- Smaller detuning will increase the modulation efficiency. However, it also results in a larger insertion loss.
Chirp

- Frequency sweep imposed as a result of power change

\[
\mathcal{E} = \frac{2\mathcal{E}}{c} \mathcal{E}_{n_r} = \frac{4\mathcal{E}}{c} \mathcal{E}_{g}
\]

- Imaginary part of refractive index is related to optical absorption coefficient by,

\[
\mathcal{E} = \frac{2\mathcal{E}}{c} k = \frac{4\mathcal{E}}{c} k
\]

- Kramers-Kronig relation

\[
\mathcal{E} n = \frac{hc}{\mathcal{E}} \left[ P_0 \mathcal{E}_{r} \mathcal{E}_{E} \left( \mathcal{E}_{h} \right)^2 dE \right]
\]
Chirp Engineering

Fig. 15. Illustration of index change due to QCSE. The absorption changes in area B contribute to positive $\Delta n$, while the absorption changes in areas A and C contribute to negative $\Delta n$.

\[
\Delta n = \frac{\hbar c}{\Delta} P \int_0^E \frac{1}{(\hbar c)^2} dE
\]

\[
\Delta f_{FWHM} = \frac{dI}{2I} \frac{dt}{dt}
\]
Integration

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