Electro-Optic Modulators

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Introdution

- Electro-optic modulators use an electrical signal to modulate an optical signal (intensity, amplitude, frequency, phase, polarization).

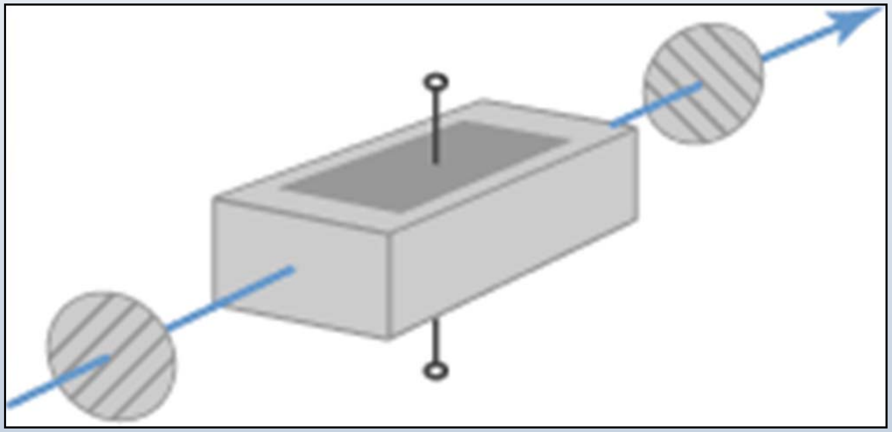


Image from http://www.rp-photonics.com/electro_optic_modulators.html

History

- During the 60's, 70's, and early 80's, direct modulation was the primary modulation scheme used.
  - Simple to implement
  - External modulators yielded high insertion losses
  - Problem: chirping at high frequencies.
- Improvements in semiconductor crystal growth and optical waveguides, along with the demand for increasingly higher bitrates, caused a resurgence of interest in external modulators in the late 80's.

Electro-Optic Effect

- For some materials, the refractive indices are functions of the applied electric field across the material.
  - Applied E-fields distort the crystal structure
- $\Delta n = -n_o^3(rE + sE^2)$
  - n_o = zero-field refractive index
  - **E** = magnitude of the applied electric field
  - **r, s =** components of the electro-optic tensor
    - r is on the order of 10^{-12} m/V
    - s is on the order of 10^{-20} $(m/V)^2$

Electro-Optic Effect

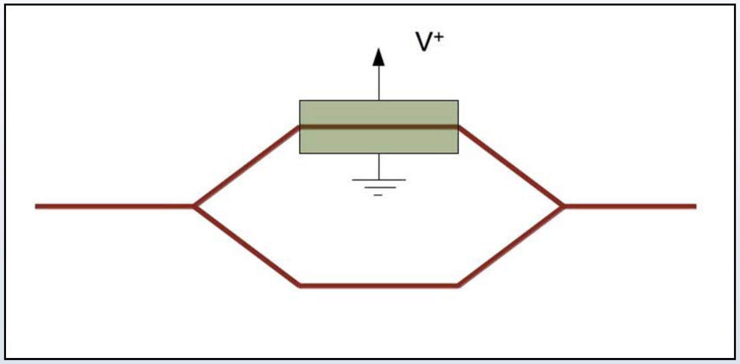
- **$\Delta n = -n_o^3(rE + sE^2)$**
- Linear relationship **= Pockels Effect**
  - Not present in materials whose crystals exhibit inversion symmetry.
- Quadratic relationship = **Kerr Effect**
  - Usually negligible compared to the Pockels Effect.

Modulation

- **Phase Modulation**
  - $\phi=(2\pi r n_0^3/(\lambda))*(EL)$
  - An applied electric field alters the speed at which the optical wave propagates through the device, resulting in a phase shift.
- **Polarization Modulation**
  - Possible because of anisotropy of refractive indices
  - Different components of the optical wave are delayed by different amounts, altering the polarization of the wave.

Modulation

- **Intensity Modulation**
  - **Mach-Zehnder Modulator**
  - Controls intensity of a laser through constructive/destructive interference
  - Useful for high-speed digital communications and switching applications.



Electroabsorption

- For some materials, an applied electric field alters the absorption coefficient of the material as well as the refractive index.
  - **Franz-Keldysh Effect**
  - An applied electric field effectively reduces the bandgap, leading to higher absorption.
  - **$E = E_0 \exp(-(1/2)\alpha z) * \exp(j(kz-\omega t))$**
  - Many materials exhibit both the electro-optic and Franz-Keldysh effects.

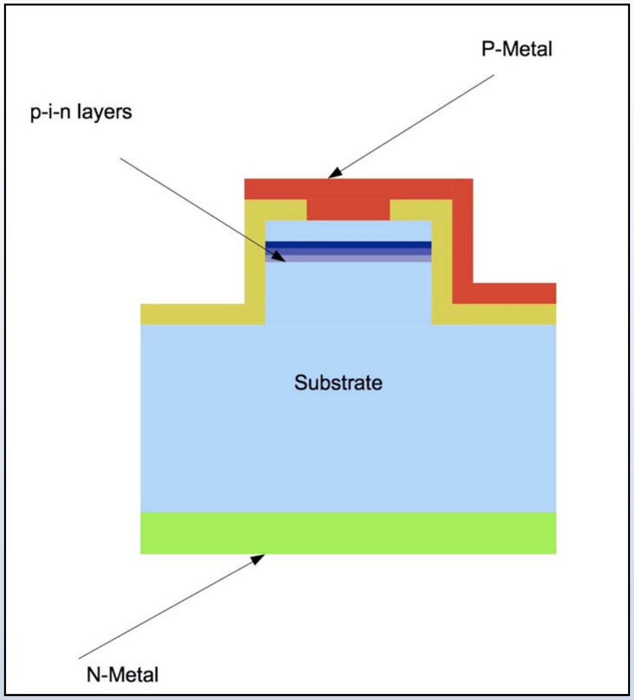
Fabrication

- Materials
  - Lithium Niobate ($LiNbO_3$)
    - Not a semiconductor (E_g = 4 eV).
    - High electro-optic coefficients.
    - Used in bulk modulators.
  - III-V Semiconductors
    - No inversion symmetry.
    - Used in OEICs.

Image from http://www.newport.com/store/genContent.aspx/Simply-Better-Optical-Modulators/977460/1033

Fabrication

- **Integrated Modulators**
  - III-V semiconductor substrate (GaAs, InP)
  - Bias voltage applied between the two metal contacts.
  - p-i-n layers form the optical waveguide. The optical signal propagates through the intrinsic layer.



Limitations

- **Low Electro-Optic Coefficients**
  - $\phi=(2\pi r n_0^3/(\lambda))*(EL)$
  - Requires large size and/or high voltages
    - For a GaAs modulator with L = 1 mm, a phase change of π/2 requires an electric field of 4.35 MV/m.
  - Multiple Quantum Wells
- **Sometimes incompatible with semiconductor technology**

Questions?

Sources

- Singh, Jasprit. *Optoelectronics: An Introduction to Materials and Devices*. McGraw-Hill, 1996. Print.
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- Zappe, Hans P. *Introduction to Semiconductor Integrated Optics*. Norwood, MA: Artech House, 1995. Print.