MACH-ZEHNDER MODULATORS

Theory and Application

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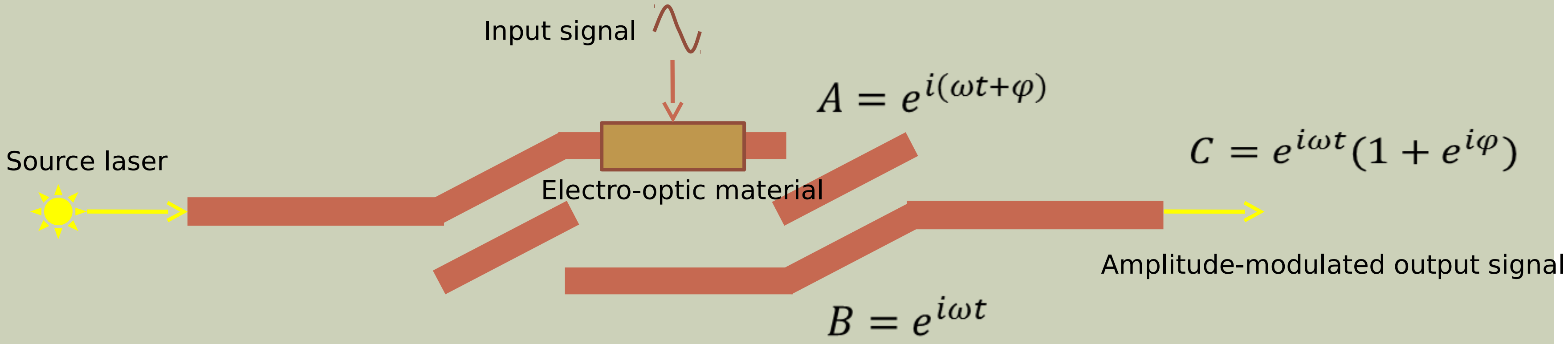
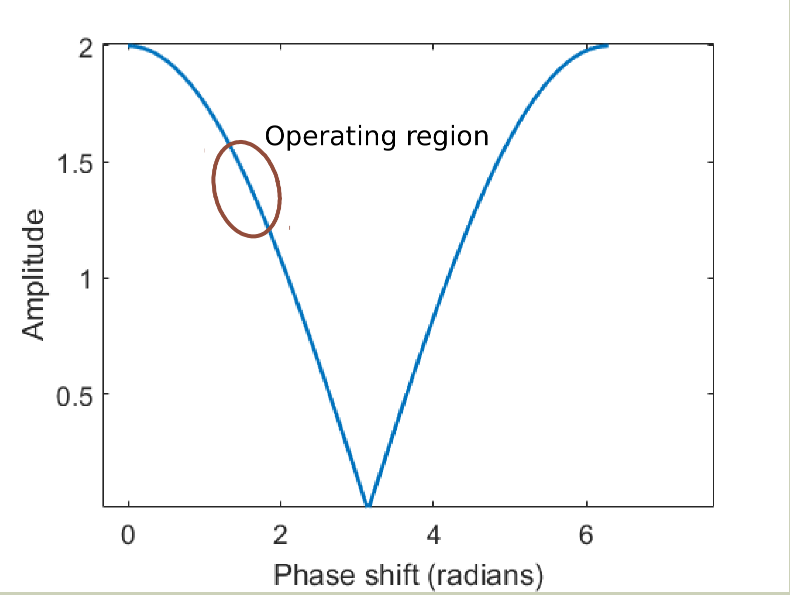
MACH-ZEHNDER MODULATORS

- Electro-optic modulators that impress a low-frequency (0-100 GHz) as an amplitude modulation on an optical carrier
- Commonly used in telecommunications industry for wideband data transfer over optical fiber
- Works on electro-optic effect: an applied field causes a change in the index of refraction of a material



MODULATED DATA

- Amplitude is the absolute value of $(1 + e^{i\varphi}) = \sqrt{2 + 2\cos\varphi}$
- Nonlinear mapping from source data to amplitude modulation
- Typically biased at quadrature point $(\pi/2)$and driven in small-signal regime for best linearity

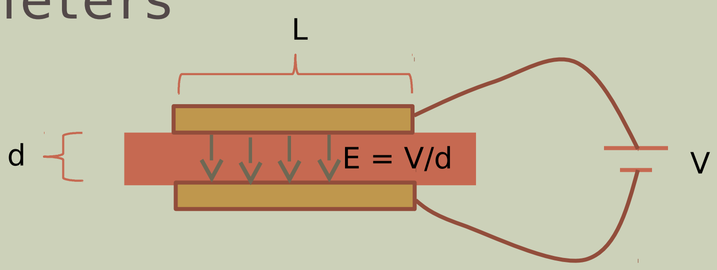


ELECTRO-OPTIC EFFECT (LINEAR)

- Pockels effect: index of refraction is <u>linear</u> in electric field
- Index of refraction/relative permittivity related to susceptibility of material

$$\epsilon = \epsilon_0(1+\chi)$$

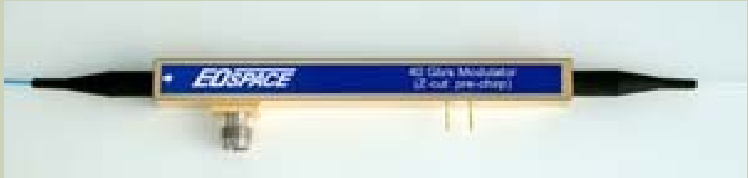
- Total phase shift is a function of index of refraction and length of path
- Various tradeoffs between L, d and V determine operating parameters



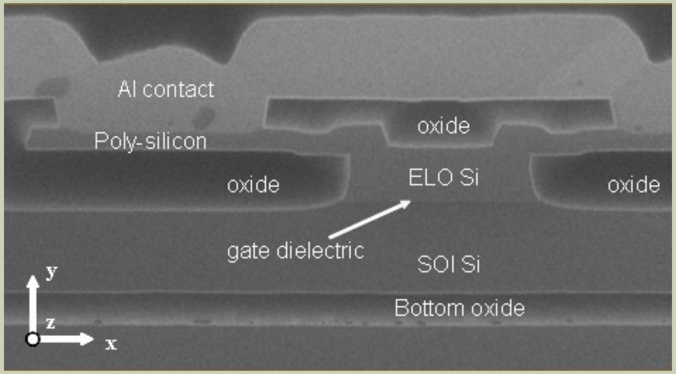
$$C = \varepsilon A/d$$

MODULATOR TYPES

- Discrete: LiNbO3 is the dominant material, >100 GHz bandwidth possible
- Integrated: demonstrated on silicon with lower bandwidth and performance (~10 GHz)



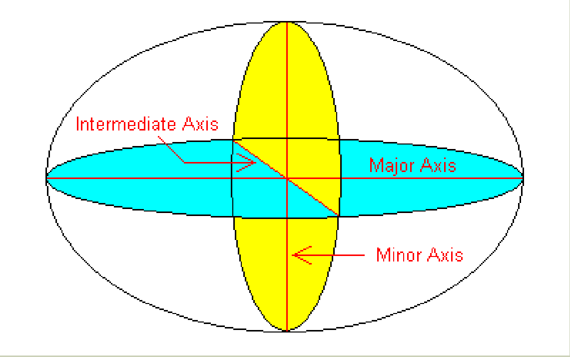
Discrete modulator from EOSpace



“High speed silicon Mach-Zehnder modulator”, L. Liao, D. Samara-Rubio, M. Morse, A. Liu, D. Hodge, Optics Express Vol. 13 No. 8, 18 April 2005

INDICATRIX

- For general anisotropic media ε depends on E-field orientation ε(x,y,z)
- Specific crystal structure and symmetries give rise to ε(x,y,z)
- A 3D plot of refractive index against electric field direction creates an ellipsoid called the <u>indicatrix,</u> parameterized by major, minor and intermediate axes
- Any ellipsoid has at least one direction with a circular cross section, defining an optical axis (propagation is isotropic in that direction)



INDICATRIX

- Electro-optic effect described by the electro-optic tensor: $\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j$

- Applied electric field changes the indicatrix shape

LITHIUM NIOBATE STRUCTURE

- Lacks inversion symmetry (not centrally symmetric), otherwise the field due to nearby molecules would be 0 (Jackson pp 160-161)
- Symmetry class 3M (three-fold rotational symmetry) leads to electro-optic tensor of the form:

$$r = \begin{bmatrix} 0 & -r_{22} & r_{13} \\ 0 & r_{22} & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{51} & 0 \\ r_{51} & 0 & 0 \\ -r_{22} & 0 & 0 \end{bmatrix}$$

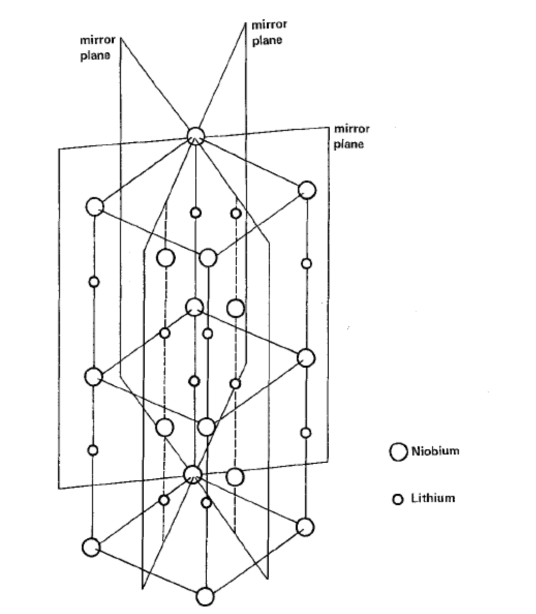
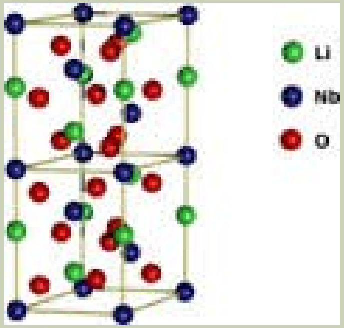
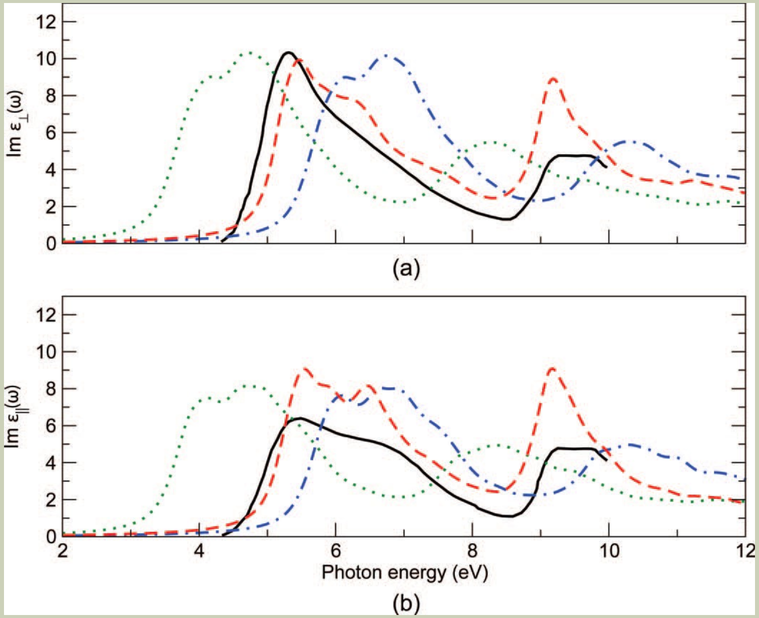


Fig. 3. Three mirror plane symmetry elements associated with lithium niobate (3*m* crystal class)



DETERMINING ELECTRO-OPTIC PROPERTIES OF MATERIALS

- Material characterization is largely experimental
- Some recent work using density functional theory to determine band structure and optical properties



The imaginary part of from experimental measurements (solid black line) and increasingly accurate calculations (dashed lines) for optical frequencies

“Linear and Nonlinear Optical Response of LiNbO3 Calculated From First Principles”, A. Riefer, S. Sanna, A. Gavrilenko, W. Schmidt, IEEE TRANSACTIONS ON ULTRASONICS, FERROELECTRICS, AND FREQUENCY CONTROL, VOL. 59, NO. 9, SEPTEMBER 2012