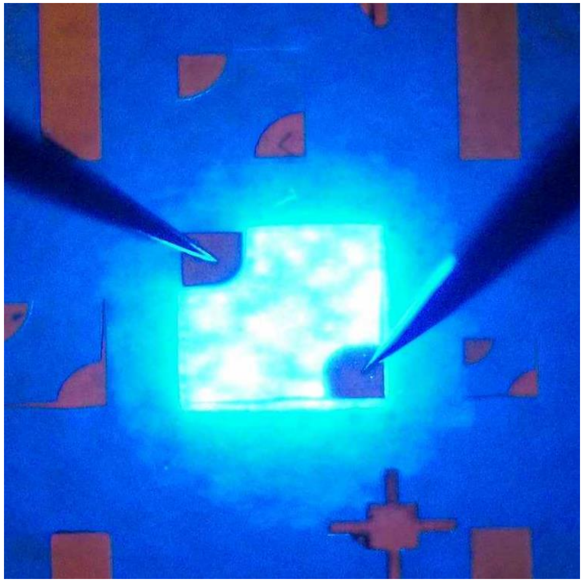
# Optoelectronics
# ELEC-E3210



## Lecture 7

Aalto University
School of Electrical
Engineering

# Outline

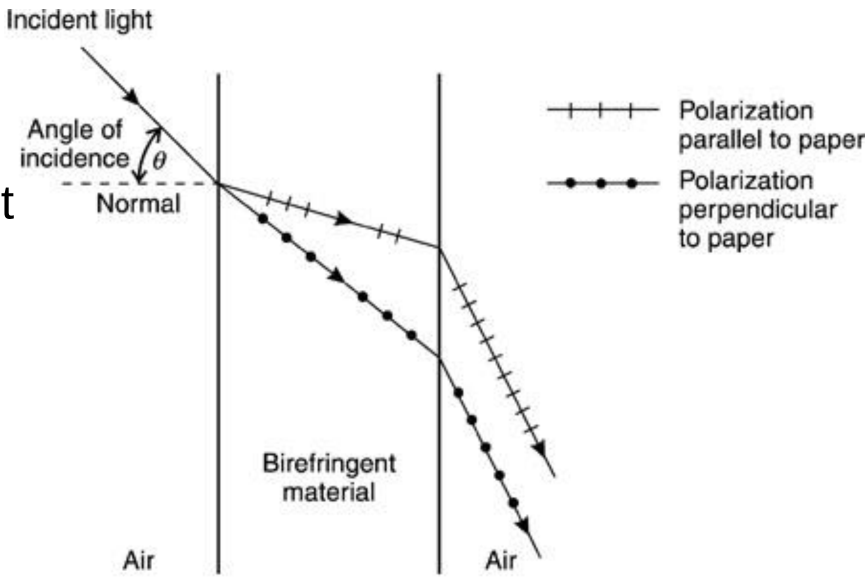
- Electro-optic modulators
- $LiNbO_3$ modulators
- Switching devices

*P. Bhattacharya: chapter 11*
*J. Singh: chapter 12*

# Birefringence

Electro-optic modulators rely on the phenomenon of **birefringence.**

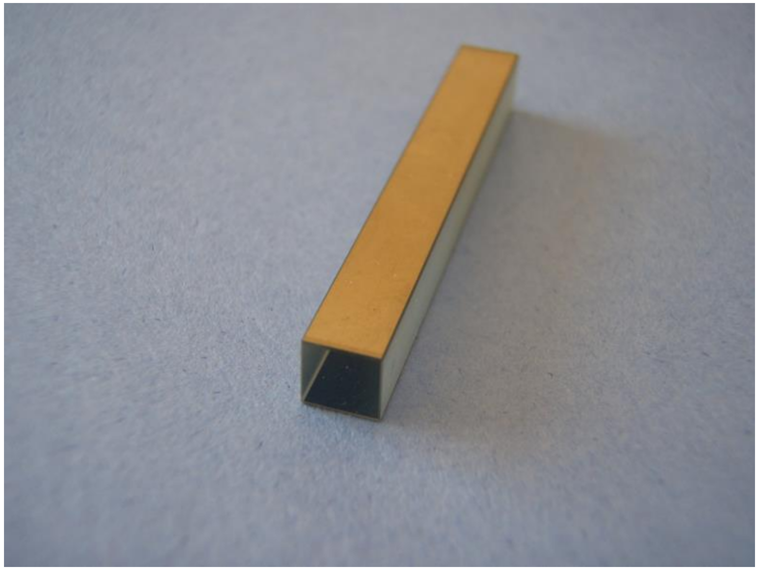
- In certain crystalline materials an incident light ray will separate into two rays that may travel in different directions
- The propagation direction depends on light polarization
- Many materials (quartz, calcite) exhibit birefringence naturally
- Number of nonlinear crystals (KDP, ADP, LiNb0$_3$, BBO, LiTaO$_3$ etc) exhibit birefringence under applied voltage → electro-optic effect



# Electro-optic crystals

**LiTaO3 crystal for EOM**

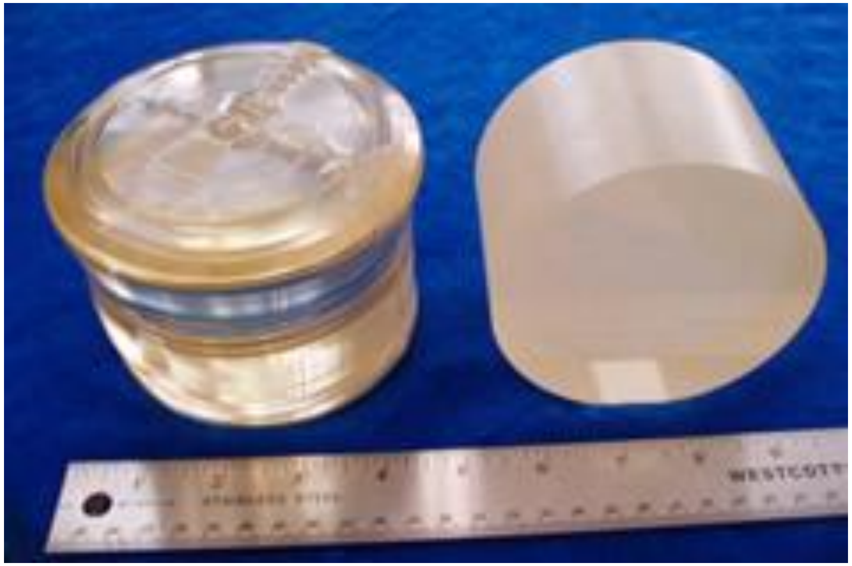
www.sciner.com



5 mm (X) x 5 mm (Z) x 40 mm (Y)
Sides 5x5 are polished 20/10 S/D and AR coated
Metal electrodes Au+Cr

**LiNbO3 crystal for EOM**

www.siccas.com



Size: Diameter 25-75 mm

# Refractive index

- In general, the refractive index of a crystal is not isotropic and is described in terms of an index ellipsoid:
- $n_{ri}$ are the principle refractive indices and $x_i$ are principle axis

$$\sum_{i=1}^{3} \frac{x_i^2}{n_{ri}^2} = 1$$

- *Because of anisotropy different refractive indices are affected differently by an applied electric field.*

The field-dependent change in the refractive index:

$$\Delta\left(\frac{1}{n_r^2}\right) = \boxed{r^l}\mathbf{E} + \boxed{s^q}\mathbf{E}^2$$

Linear electro-optic coefficient

Quadratic coefficient

If $r^l$ is large → Pockels effect

If $s^q$ is large → Kerr effect

# Pockels & Kerr

**Friedrich Pockels** (**1865–1913**) was first to describe the linear electro-optic effect in 1893.

**John Kerr** (**1824–1907**) discovered the quadratic electro-optic effect in 1875.

# Pockels effect

Pockels: $$\Delta\left(\frac{1}{n_r^2}\right)_i = \sum_{j=1}^{3} r_{ij}^{l} E_j$$

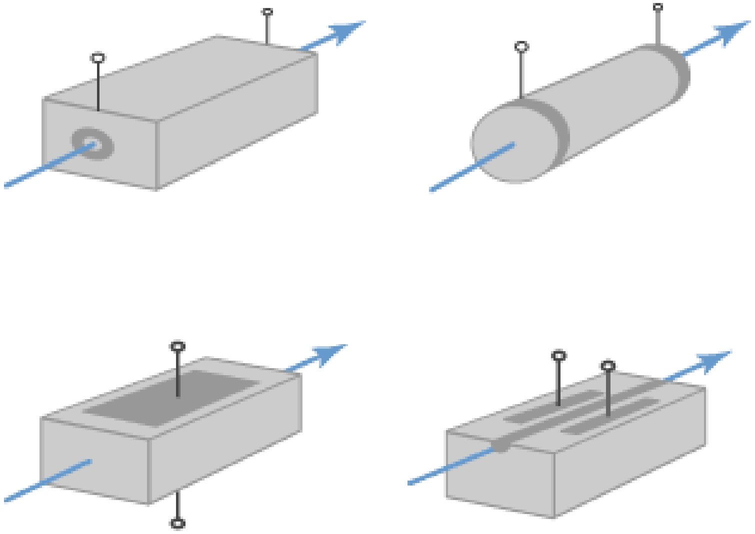
i(= 1-6) : six terms of the index ellipsoid
j(=1-3) : three cartesian coordinates
$r_{ij}$ : electro-optic tensor described by a (6 x 3) matrix

Symmetry considerations determine the zero or nonzero values of the electro-optic tensor. For example in zinc-blende materials there are only three and equal nonzero linear coefficients: $r_{41}^{l} = r_{52}^{l} = r_{63}^{l}$

| Material | $\lambda$ (μm) | $r_{ij}$ ($10^{-12}$ m/V) |
|---|---|---|
| GaAs | 0.8 -1.0 | $r_{41}$ = 1.2 |
| Quartz | 0.6 | $r_{41}$ = -0.2 |
| $LiNb0_3$ | 0.5 | $r_{42}$ = 30 |
| KDP | 0.5 | $r_{63}$ = 10.6 |

# Pockels cell

- Consists of a nonlinear cystal through which light can propagate
- A phase delay in the crystal can be modulated by applying a variable electrical voltage → the Pockels cell acts as a voltage-controlled waveplate



- **Longitudinal devices**
  - Electric field in the direction of the light beam, light passes through holes in the electrodes
  - Electrodes can be metallic rings or transparent layers on the end faces with metallic contacts
- **Transverse devices**
  - Electric field perpendicular to the light beam, field applied through electrodes at the sides of the crystal
  - Small apertures → lower switching voltages
  - Require often multiple crystals to counter birefringence or spatial walk-off

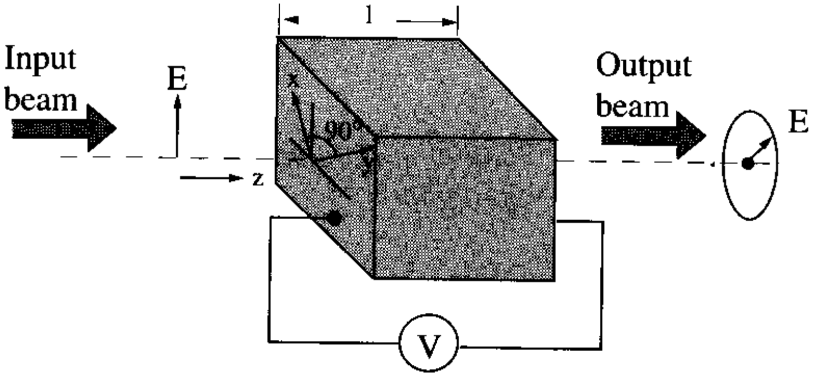
# Phase modulators

- Optical modulator used to control the phase of a laser beam

- Applications
  - wavelength tuning of a single-frequency laser
  - active mode locking
  - laser frequency stabilization schemes
  - data transmitters of optical fiber communications systems
  - interferometers
  - spectroscopic measurements

- Important properties
  - modulation bandwidth (typically many GHz for electro-optic modulators)
  - the amount of achievable phase delay
  - required drive voltage
  - device aperture (limits the beam radius of the modulated beam)
  - the outer device dimensions

# Electro-optic modulators: Phase modulation



Incident wave at z = 0: $E = A_0 e^{j\omega t}$

Polarized components:

$$E_x = E_y = \frac{1}{\sqrt{2}} A_0 e^{j\omega t}$$

Pockels: $\Delta\left(\frac{1}{n_r^2}\right) = -\frac{2\Delta n_r}{n_r^3} = r_{ij}^l E_z$ ← Applied field in z direction

Refractive indices:

$$n_{rx} = n_{r0} + \frac{n_{r0}^3}{2} r_{ij}^l E_z$$

$$n_{ry} = n_{r0} - \frac{n_{r0}^3}{2} r_{ij}^l E_z$$

$$n_{rz} = n_{rE}$$

applied bias
$V = E_z/l$

Phase difference at output: $\Delta\phi = \frac{2\pi}{\lambda}\left(n_{rx} - n_{ry}\right) l = \frac{2\pi}{\lambda} r_{ij}^l n_{r0}^3 V$

# Electro-optic modulators: Phase modulation

- The polarization of the input beam often has to be aligned with one optical axis of the crystal to avoid change of the polarization state
  - If the phase-shift between the two components at output is π/2, then the linearly polarized input wave is changed to a circularly polarized output wave
  - If the phase change is π, then the output is a linearly polarized wave with its polarization vector oriented at 90° with respect to the input wave

# Electro-optic phase modulator

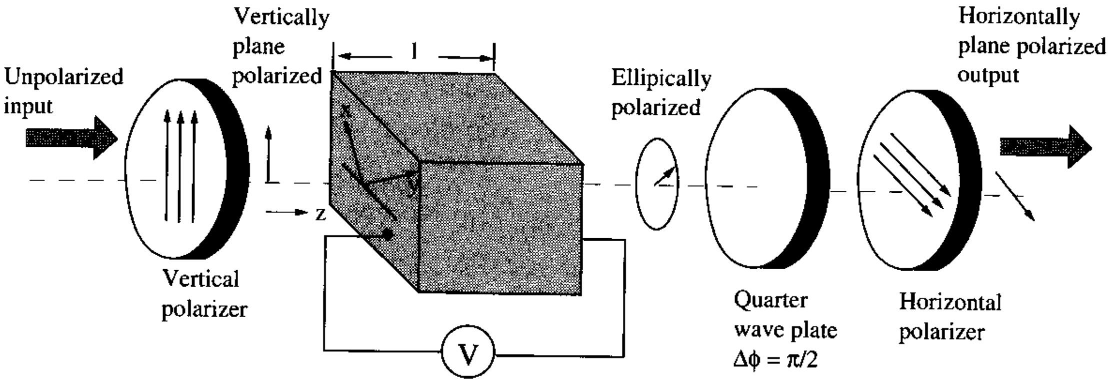
**Resonant Phase Modulator: PM50-100**

**50 MHz to 100 MHz**

By making the electro-optic crystal part of a tuned circuit, relatively low drive voltages can be used to achieve up to $\pi$ radians of phase modulation.

# Electro-optic modulators: Amplitude modulation

- Based on a Pockels cell for modifying the polarization state and a polarizer for subsequently converting this into a change of transmitted optical amplitude and power



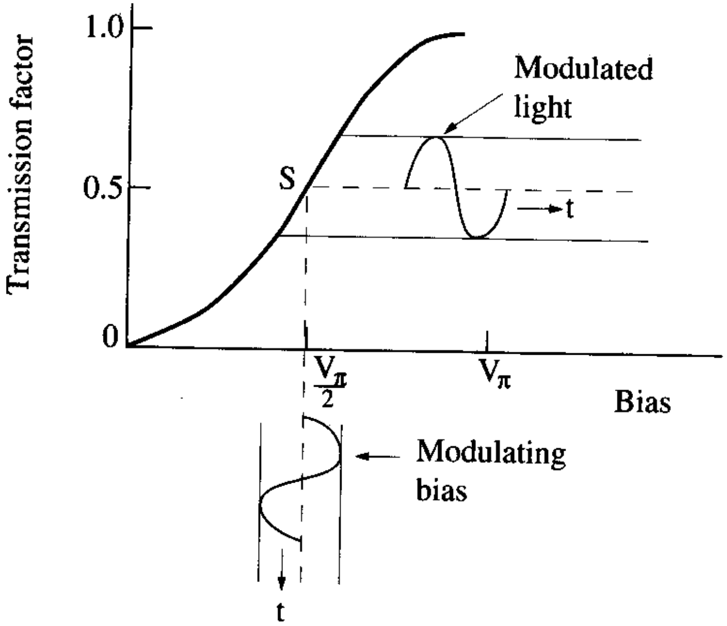
- Input wave is vertically polarized, output polarizer oriented at 90°
- Voltage V is adjusted such that Δϕ = π, then when
  - V = 0: Output is blocked off
  - $V = V_\pi$: Wave is fully transmitted

$$V_\pi = \frac{\lambda}{2 r_{ij}^{l} n_{r0}^{3}}$$

$$\frac{I_{out}}{I_{in}} = \sin^2\frac{\Delta\phi}{2} = \sin^2\left[\frac{\pi}{2}\frac{V}{V_\pi}\right]$$

# Electro-optic modulators: Amplitude modulation

- For small-signal modulation the modulator is usually biased at some point
- Bias point is typically fixed by inserting a quarter-wave plate at output



$$\Delta\phi_{total} = \frac{\pi}{2} + \Delta\phi$$

$$\frac{I_{out}}{I_{in}} = \sin^2\left[\frac{\pi}{4} + \frac{\pi}{2}\frac{V}{V_\pi}\right] = \frac{1}{2}\left[1 + \sin\frac{\pi V}{V_\pi}\right]$$

$$\frac{I_{out}}{I_{in}} = \frac{1}{2} + \frac{\pi V_0}{2V_\pi}\sin\omega t$$

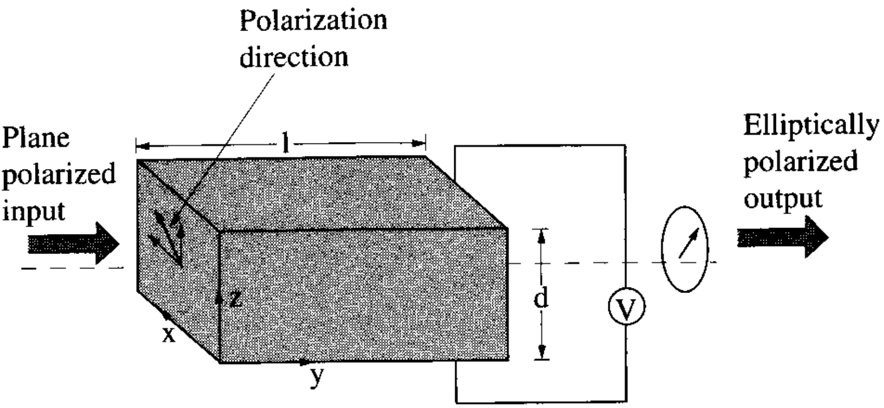
Where $\pi V_0 / V_\pi \ll 1$

# Transverse electro-optic modulators

- Longitudinal electro-optic modulators have some disadvantages
  - The electrodes at the ends must transmit light
  - Semitransparent electrodes result in nonuniform transmission and losses
- Practical modulators are therefore operated in transverse mode (electric field is applied normal to the propagation direction)

$$\Delta\phi = \phi_y - \phi_z$$

$$\Delta\phi = \frac{2\pi l}{\lambda}\left[\left(n_{r0} - n_{rE}\right) - \frac{n_{r0}^3}{2} r_{ij}^l \frac{V}{d}\right]$$



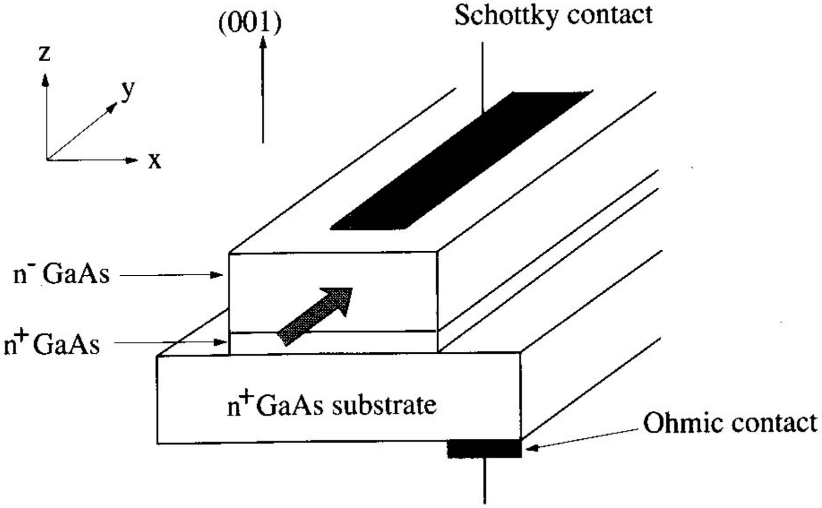
- $\Delta\phi$ or $n_r$ can be enhanced by increasing lenght l and decreasing thickness d
- Increasing device length will increase capacitance, degrade high-f modulation capability and increase losses

# GaAs waveguide modulator

- A typical GaAs electro-optic modulator is a ridge-waveguide structure
  - The bias is applied by means of a reverse-biased pn-junction or Schottky-diode along the growth (100) direction
  - The optical beam is coupled into the guide with its polarization at 45° to the edges of the guide to launch both TE and TM modes

- The electro-optic effect in zinc-blende crystals like GaAs is much smaller than e.g. in lithium niobate

- Phase shift in a crystal like GaAs depends on the crystallographic direction of the applied field



# Quantum well modulators

- Quadratic electro-optic effect will be pronounced in quantum wells
  - Quantum confined stark effect (transition energies, absorption coefficient and refractive indices vary quadratically with eletric field)
  - QCSE is an excitonic effect → the energy of the light to be modulated should be close to the e1 – hh1 transition energy
- In QW modulators there is also built-in birefringence due to the layer structure

$$\Delta\phi = \Delta n_r l\left(\frac{2\pi}{\lambda}\right) + \frac{\pi l}{\lambda} n_{r0}^{3}\left[r_{41}^{l} E_z + \left(s_{12}^{q} - s_{11}^{q}\right)E_z^{2}\right]$$

- Biaxial strain affects the electro-optic properties

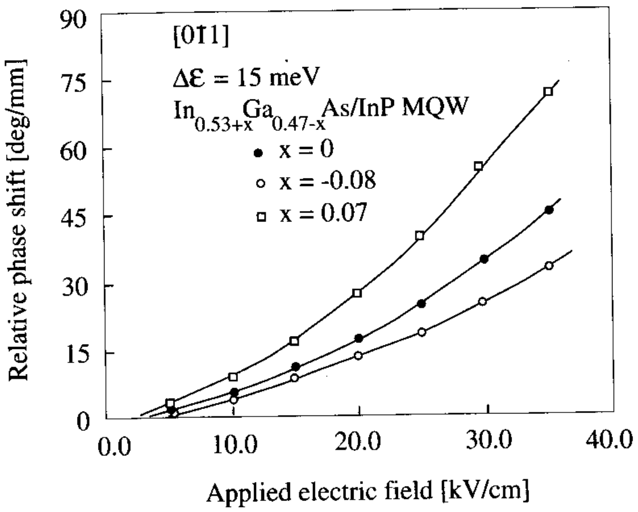


**Figure 11.13** Phase shift as a function of applied bias for lattice-matched and biaxially strained InGaAs/InP MQW electro-optic modulators measured by the author and co-workers (J. Pamulapati et al., *Journal of Applied Physics*, **69**, 4071, 1991).

# EA vs. EO modulators

- Electroabsorption modulators draw a photocurrent, while electro-optic modulators do not
- The photocurrent can represent a heat dissipation problem
- EA modulators operate near the semiconductor bandedge → higher absorption losses
- Quadractic electro-optic effect due to electro-absorption leads to chirping effects in modulation

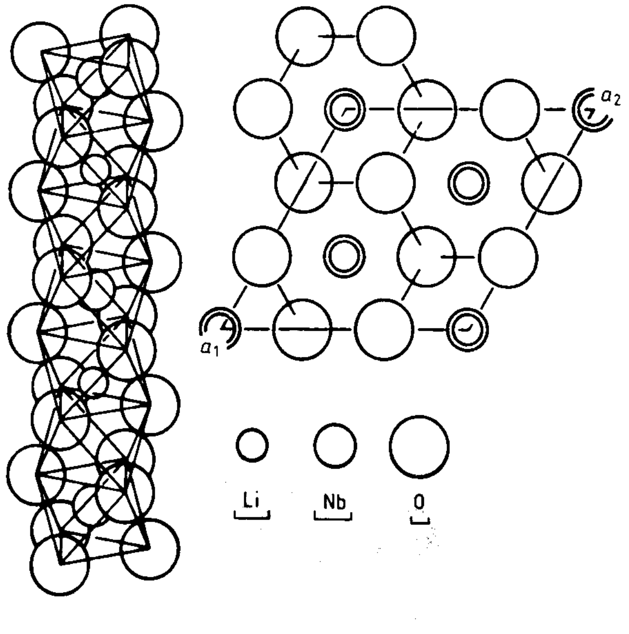
# Outline

- Electro-optic modulators
- $LiNbO_3$ modulators
- Switching devices

*P. Bhattacharya: chapter 11*
*J. Singh: chapter 12*

# $LiNbO_3$ crystal properties

- *Structure*



(*a*) (*b*)

**Figure 1.10.** Crystal structure of $LiNbO_3$ (Abrahams *et al* 1966a,b,c): (*a*) a succession of the distorted octahedrons along the polar *c* axis; (*b*) an idealized arrangement of the atoms in a unit cell along the *c* axis.

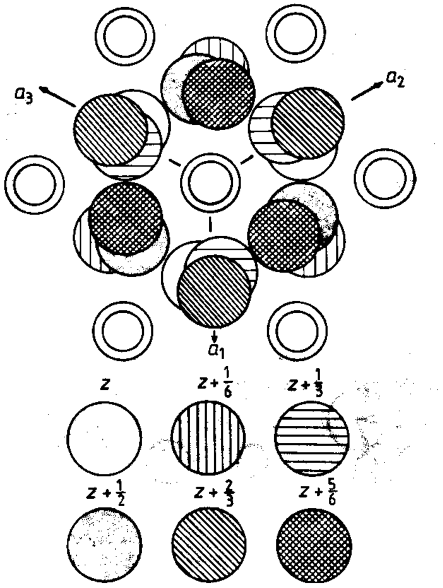


**Figure 1.9.** Projection of the $LiNbO_3$ crystal structure upon the plane of the (0001) basis (Abrahams *et al* 1966a,b,c). Differently shaded circles show oxygen ions at different levels relative to the plane of the drawing; light double circles stand for projections of positions of metal ions upon the drawing plane.

# $LiNbO_3$ crystal properties

- *Desirable Properties*
  - High electro-optic coefficients
  - High optical transparency near telecom transmission λ
  - High $T_C$
  - Mechanically and chemically stable
  - Manufacturing compatibility

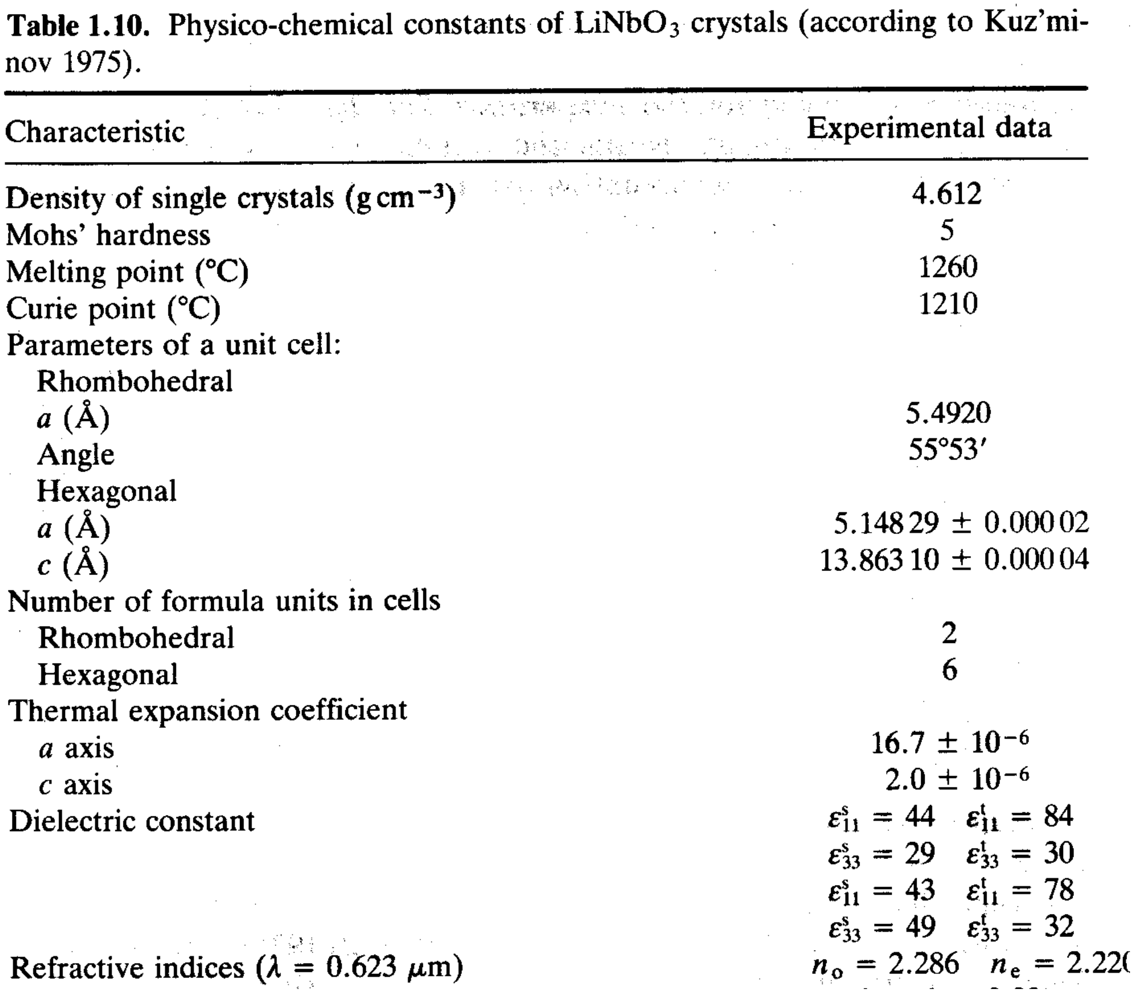
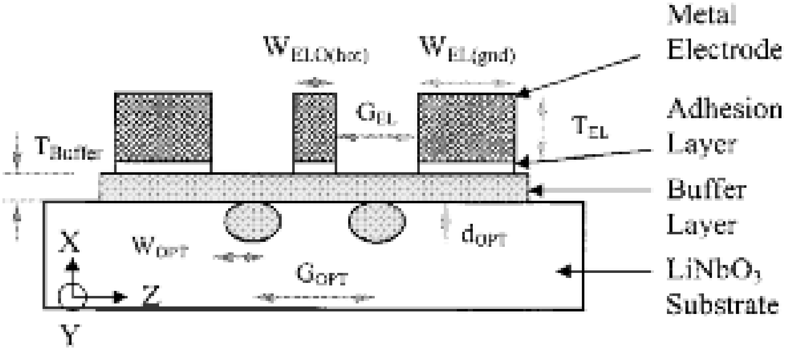


**Table 1.10.** Physico-chemical constants of $LiNbO_3$ crystals (according to Kuz'minov 1975).

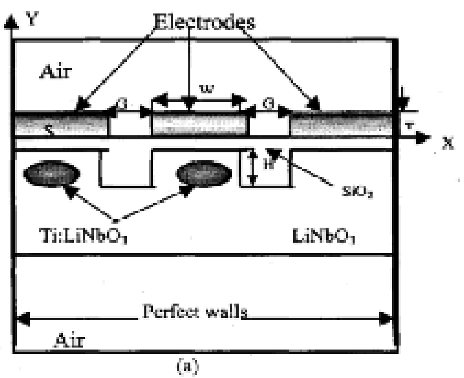
| Characteristic | Experimental data |
|---|---|
| Density of single crystals ($g\,cm^{-3}$) | 4.612 |
| Mohs' hardness | 5 |
| Melting point (°C) | 1260 |
| Curie point (°C) | 1210 |
| Parameters of a unit cell: | |
| Rhombohedral | |
| $a$ (Å) | 5.4920 |
| Angle | 55°53′ |
| Hexagonal | |
| $a$ (Å) | $5.14829 \pm 0.00002$ |
| $c$ (Å) | $13.86310 \pm 0.00004$ |
| Number of formula units in cells | |
| Rhombohedral | 2 |
| Hexagonal | 6 |
| Thermal expansion coefficient | |
| $a$ axis | $16.7 \pm 10^{-6}$ |
| $c$ axis | $2.0 \pm 10^{-6}$ |
| Dielectric constant | $\varepsilon^s_{11} = 44 \quad \varepsilon^t_{11} = 84$ |
| | $\varepsilon^s_{33} = 29 \quad \varepsilon^t_{33} = 30$ |
| | $\varepsilon^s_{11} = 43 \quad \varepsilon^t_{11} = 78$ |
| | $\varepsilon^s_{33} = 49 \quad \varepsilon^t_{33} = 32$ |
| Refractive indices ($\lambda = 0.623\ \mu m$) | $n_o = 2.286 \quad n_e = 2.22$ |

# Fabrication of LiNbO3 modulators

- Waveguides
  - Ti diffusion
    - ~1000 oC.
    - Li out-diffusion must be minimized.
  - Annealed proton exchange (APE)
    - Acid bath
    - ~125-250 oC.



Cross section of x-cut coplanar-waveguide



Cross section of z-cut ridge-waveguide

# Fabrication of LiNbO3 modulators

- *Electrodes*
  - Electroplated.
  - Typically Au.
  - Deposited directly on $LiNbO_3$ or on optically transparent buffer layer.
  - ~3-15 μm thick.

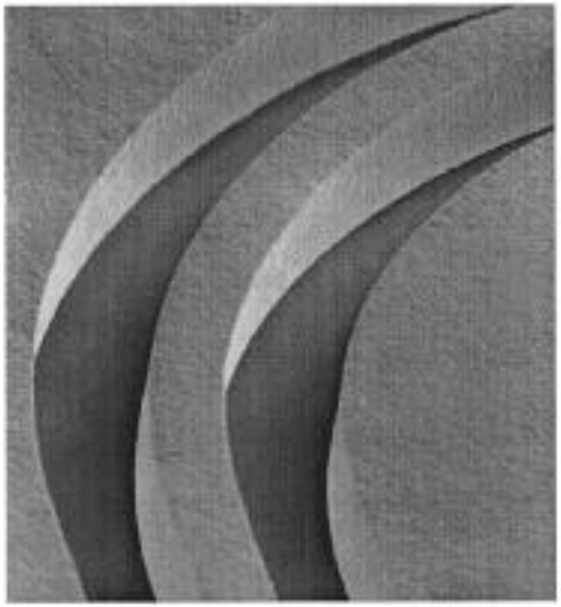


Fig. 2. SEM picture of 18-μm-thick gold-plated CPW electrodes at a region where the electrodes are making a bend.

# Fabrication of LiNbO3 modulators

- *Dicing & Polishing*
  - $LiNbO_3$ crystals do not cleave like GaAs or InP
    - Diamond saw cutting
  - Crystal ends cut at an angle to waveguide to reduce reflections.
  - Both ends are polished to an optical finish.
  - Must be free from debris and polishing compounds.

# Fabrication of LiNbO3 modulators

- *Pigtailing & Packaging*
  - subassemblies
    - Integrated-optic chip
      - The “waveguide”
    - Optical-fiber assemblies
      - Input (polarization maintained) and output (single-mode) fibers
    - Electrical or RF interconnects and housing
      - Package to modulator housing.

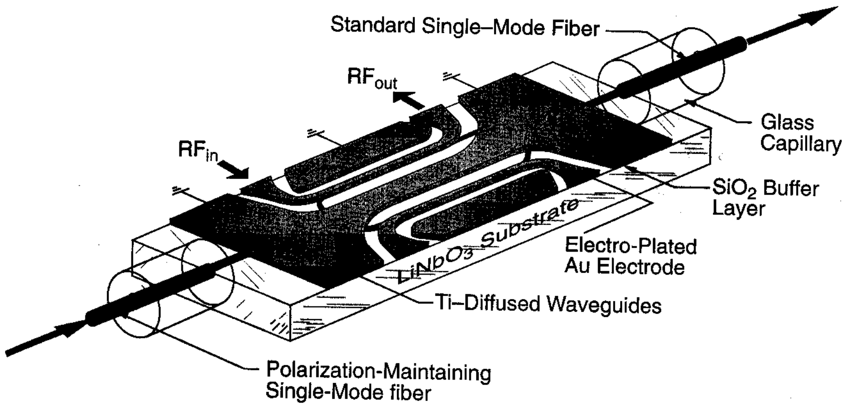
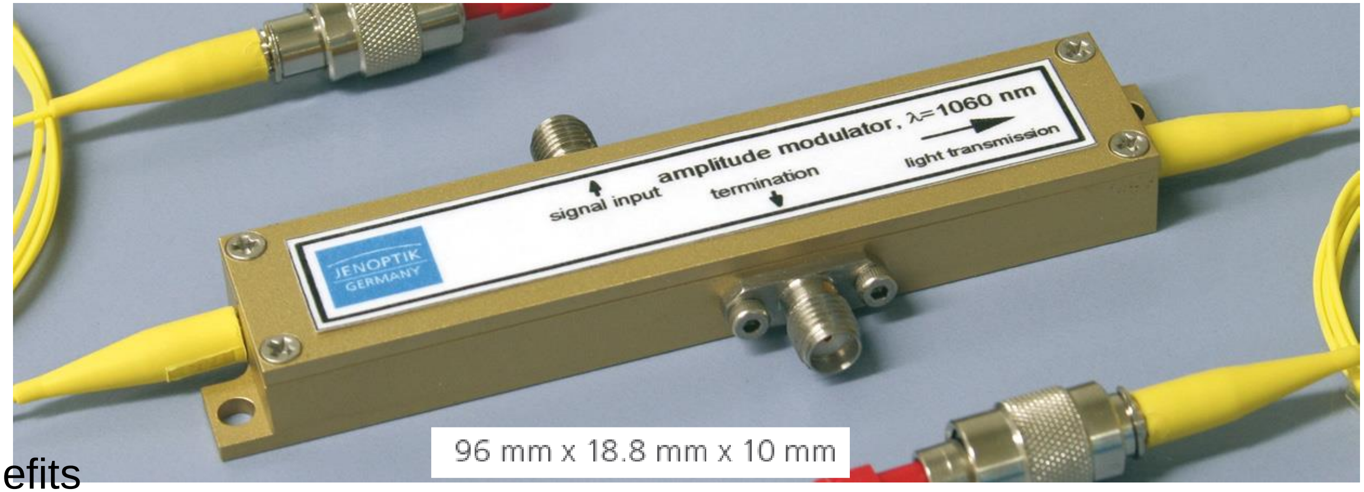


**Fig. 9.11** Schematic of a dual-drive Ti : $LiNbO_3$ Y-branch Mach–Zehnder modulator.

# Integrated Optical Amplitude Modulator

## Fiber-coupled electro-optical light-modulator



96 mm x 18.8 mm x 10 mm

Benefits

- Application in the VIS or IR spectrum
- High modulation frequencies
- Single mode fiber-coupling
- Low modulation voltage

Applications

- Analog modulation with high dynamic
- Digital modulation
- Short laser pulse generation
- Photo finishing, laser scanning microscopy
- Interferometric metrology

The Integrated Optical Amplitude Modulator is a compact fiber-coupled electro-optical modulator that works based on MgO:LiNbO3 and LiNbO3 crystals. Providing fast electro-optical response, it allows amplitude modulation frequencies as high as the Gigahertz range. Available modulators can handle wavelengths in the visible and the infrared spectral range.

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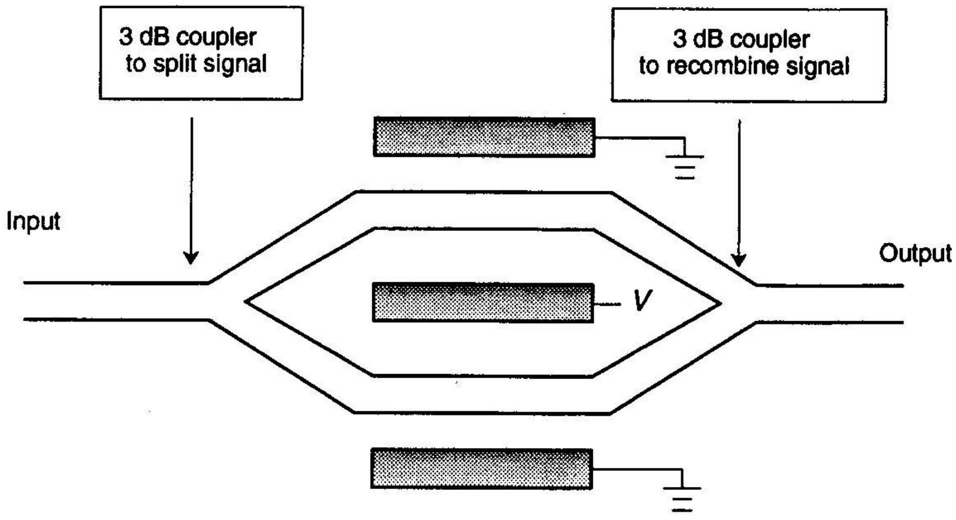
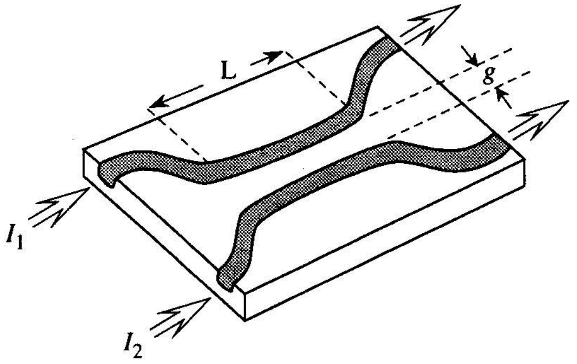
# Mach-Zehnder Interferometer



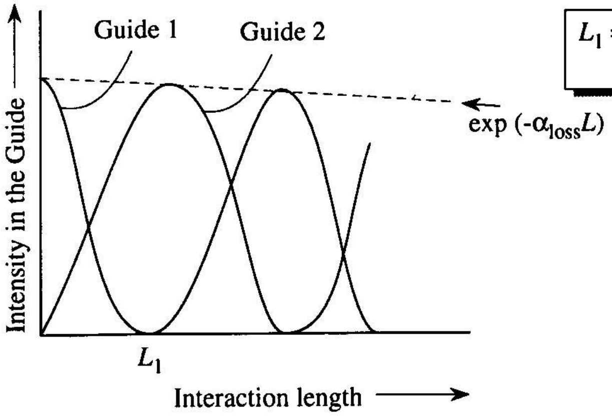
- Mach-Zehnder Interferometer
  - Light is split into two isolated (non-interacting) waveguides
  - BW as high as 75 GHz
  - Uses electro-optic effect to vary refractive index
  - A variable interference when light combined at output
  - Bias voltage affects the phase difference between the two arms and therefore the output power can be controlled

# Directional Coupler



(a)

Guides 1 and 2 are close enough that the optical waves in each guide are coupled to the mode in the other guide

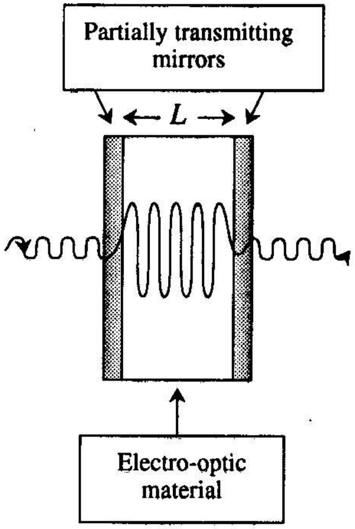


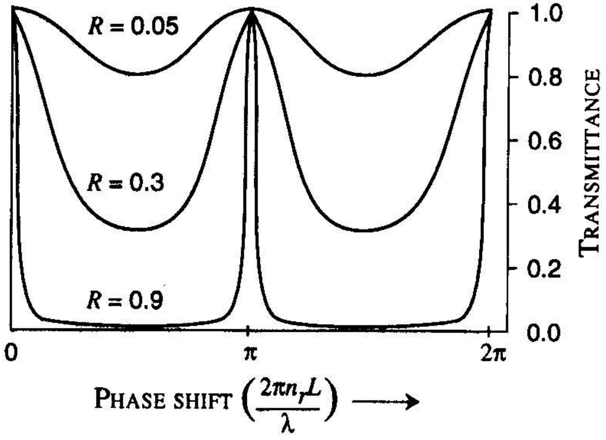
(b)

$L_1 = \frac{\pi}{2K}$ if $\beta_1 = \beta_2$

- Light is split into two or more coupled (interacting) modes
- Use reversed $\beta$-coupler
- Requires small waveguide separation for coupling
- A complete transfer of power occurs when the signal propagates a distance $L_1 = \pi/2K$
- K is a coupling coefficient due to overlap of modes of the two guides
- If the guides are not phase matched, the entire light is not coupled from one guide to another
- Difficult to design for high frequency → low speed modulators
- Small size and compact

# Fabry-Perot Modulator (Etalon)





$$T = \frac{1}{1 + \frac{4R}{(1-R)^2}\sin^2\left(\frac{2\pi n_r L}{\lambda}\right)}$$

- Two partially transmitting mirrors enclosing an electro-optic material
- Transmission maximum when $L = m\lambda/2n_r$
- If $n_r$ can be changed → the transmission will change
- FB modulators have been demonstrated to operate up to 10GHz

$$FSR = \frac{c}{2n_r L}$$

$$F = \frac{\pi (R_1 R_2)^{1/4}}{1-(R_1 R_2)^{1/2}}$$