Electro-optic effect

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Nonlinear polarisation

❑ Constitutive relations

$$\mathbf{D} = \varepsilon\mathbf{E} = \varepsilon_o\mathbf{E} + \mathbf{P},$$

$$\mathbf{P} = \varepsilon_o\chi\mathbf{E}$$

❑ Origin of nonlinear response

Related to anharmonic motion of bound electrons under the influence of an applied field.

$$\mathbf{P} = \varepsilon_o\chi\mathbf{E} = \varepsilon_o\left(\chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{EE} + \chi^{(3)}\mathbf{EEE} + \cdots\right)$$

Note: $\chi^{(2)}$ is non-zero only for media that lack an inversion symmetry (centrosymmetry).

Linear electro-optic effect

Also called ***Pockels*** effect: Refractive index change linearly proportional to the external electric field, i.e. $\Delta n \propto E_{ext}$.

Recall $\quad \boldsymbol{P} = \varepsilon_o \chi \boldsymbol{E} = \varepsilon_o \left(\chi^{(1)} \boldsymbol{E} + \chi^{(2)} \boldsymbol{EE} + \chi^{(3)} \boldsymbol{EEE} + \cdots \right)$

$$For \quad \Delta n = C_L E_{ext}, \quad C_L \sim 10^{-12} \text{ m/V}$$

Quadratic electro-optic effect

Also called ***Kerr*** effect: Refractive index change quadratically proportional to the external electric field, i.e. $\Delta n \propto E_{ext}^2$.

Recall $\boldsymbol{P} = \varepsilon_o \chi \boldsymbol{E} = \varepsilon_o \left(\chi^{(1)} \boldsymbol{E} + \chi^{(2)} \boldsymbol{EE} + \chi^{(3)} \boldsymbol{EEE} + \cdots \right)$

$$For \quad \Delta n = C_Q E_{ext}^2, \quad C_Q \sim 10^{-18}\ \mathrm{m^2/V^2}$$

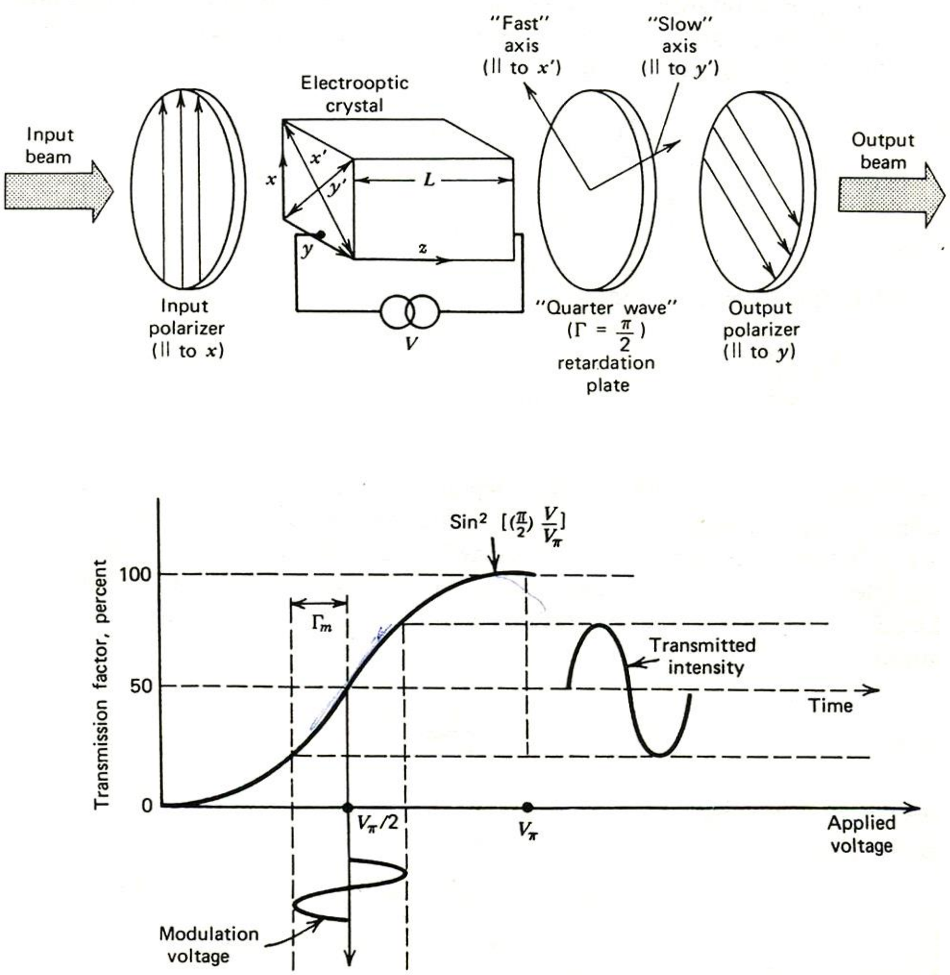
Kerr constant: $\Delta n = K \lambda E^2$

e.g. $K = 5.1 \times 10^{-14}$ m/V^2 for water

Intensity dependent refractive index: $\Delta n = n_2 I$, where $I = \frac{1}{2} \varepsilon_0 c n |E|^2$

e.g. $n_2 \sim 3 \times 10^{-20}$ m^2/W for silica glass

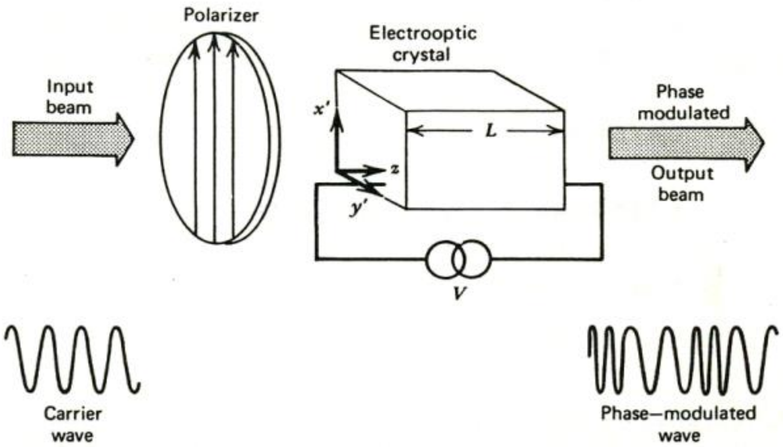
Electro-optic amplitude modulator



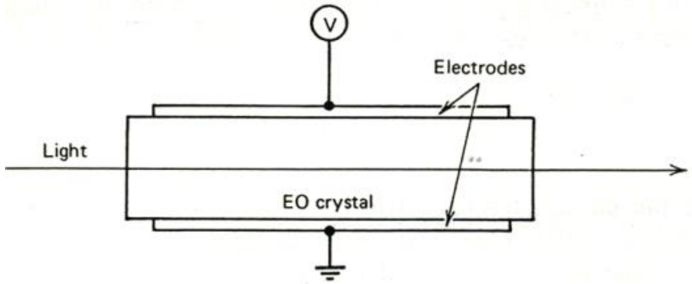
$$\Gamma = \frac{\pi}{2} + \Gamma_m \sin \omega_m t$$

Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic phase modulator

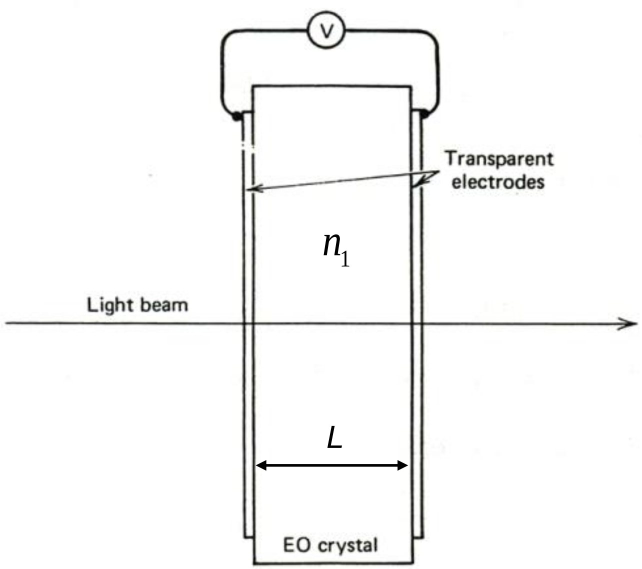


$$E_{out} = A\cos\left[\omega t - \frac{\omega}{c}\left(n_o + C_L E_m \sin \omega_{mt} t\right)L\right]$$

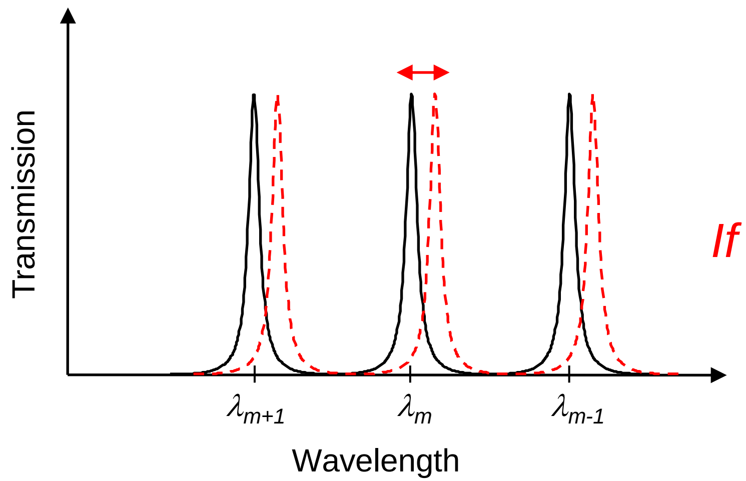


Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic modulator (Fabry-Perot filter)



Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh



For the maximum transmission:

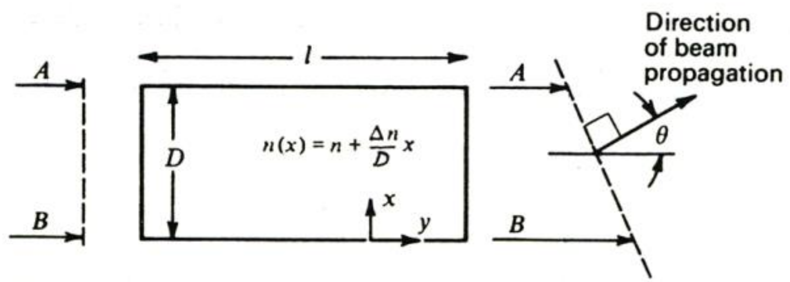
$$2kL = 2\frac{2\pi L}{\lambda}n_1 = 2m\pi, \ \ m = 1, 2, 3, \cdots$$

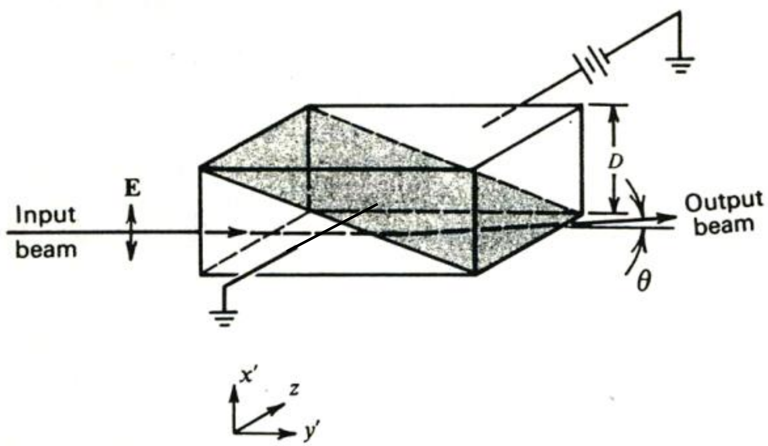
$$\lambda_m = \frac{2L}{m}n_1$$

If voltage applied:

$$\lambda_m = \frac{2L}{m}(n_1 + C_L E_{ext})$$

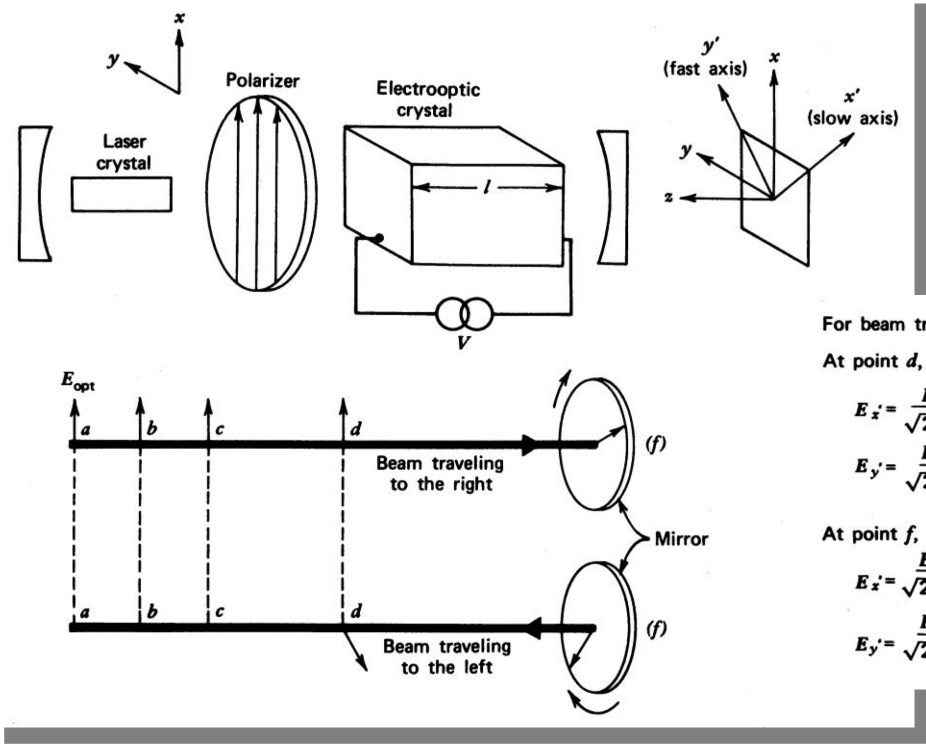
Electro-optic beam deflector





Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic Q-switch



For beam traveling to right:

At point d,

$$E_{x'} = \frac{E}{\sqrt{2}} \cos \omega t$$
$$E_{y'} = \frac{E}{\sqrt{2}} \cos \omega t$$

The optical field is linearly polarized with its electric field vector parallel to x

At point f,

$$E_{x'} = \frac{E}{\sqrt{2}} \cos \left(\omega t - kl - \frac{\pi}{2}\right)$$
$$E_{y'} = \frac{E}{\sqrt{2}} \cos (\omega t - kl)$$

Circularly polarized

For beam traveling to left:

At point f,

$$E_{x'} = -\frac{E}{\sqrt{2}} \cos \left(\omega t - kl - \frac{\pi}{2}\right)$$
$$E_{y'} = -\frac{E}{\sqrt{2}} \cos (\omega t - kl)$$

Circularly polarized

At point d,

$$E_{x'} = -\frac{E}{\sqrt{2}} \cos (\omega t - 2kl - \pi)$$
$$E_{y'} = -\frac{E}{\sqrt{2}} \cos (\omega t - 2kl)$$

Linearly polarized along y

Source: *Optical Waves in Crystals*, A. Yariv and P. Yeh

Electro-optic property of liquid crystal

- **Liquid crystals**
  - Liquid crystal phases: smectic, nematic, and cholesteric
  - Nematic LC: uniaxial dipole moment
    $\Rightarrow$ dynamic director alignment along the applied electric field
  - Switching time: ~msec
- **Twisted nematic LC in liquid crystal displays (LCD's)**

Nonlinear response of fiber gratings

■ Nonlinear Coupled-Mode Theory

$$\nabla \cdot (E' \times H_p^* + E_p^* \times H') = -i\omega E_p^* \cdot (\Delta\varepsilon_L + \Delta\varepsilon_{NL}) E', \quad (p = 1,2,\ldots)$$

$$\Delta\varepsilon_{NL(q)} = \varepsilon_o \frac{3}{4} \chi^{(3)}(r,\phi,z) \cdot \sum_s \alpha_{(q,s)} \left| E_s(t,z) \right|^2 \left| \hat{e}_s \right|^2, \ \alpha_{(q,s)} = \begin{cases} 1 & (q = s), \\ 2 & (q \neq s). \end{cases}$$

■ Efficiency of All-Optical Switching in Fiber Gratings

- Conditions for high efficiency:

Large nonlinear spectral shift & Rapid spectral modulation band

- Nonlinear spectral shift: $\dfrac{\Delta\lambda_s}{\lambda} \approx \dfrac{n_{2,eff} I_{eff}}{\Delta n_g}$

FBG: Steep spectral modulation slope but small spectral shift

LPFG: Large spectral shift but slow spectral modulation slope

$\Rightarrow$ Cascaded LPFG's