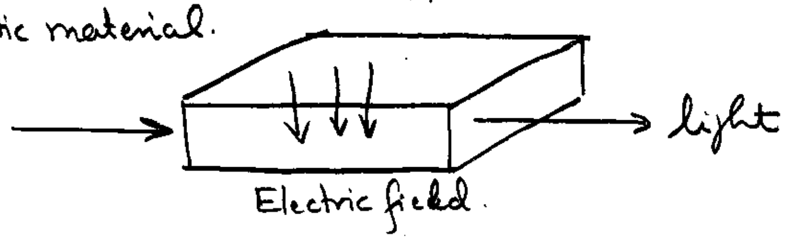
Read information in handouts - pages 218-234.
- You have the background to understand these.
- we can discuss them some time.

Electro-optics.

Electro-optic Effect.

Electro-optic material.



E-O effect is the change in the refractive index resulting from the application of a DC or low frequency electric field.
- A field applied to an anisotropic electro-optic material modifies its refractive index and thereby its effects on polarized light.

- Refractive index changes that are proportional to $\vec{E}_{applied}$ - linear electro-optic effect or the Pockels effect.

- Refractive index changes $\propto (\vec{E}_{applied})^2 \Rightarrow$ quadratic electro-optic effect or the Kerr Effect!

Suppose $\Delta n \sim 10^{-5}$ & we travel 10^5 wavelengths.

1 wavelength $\sim 1\,\mu m \quad \Rightarrow$

$$k_0 n d \rightarrow k(n+\Delta n) d.$$

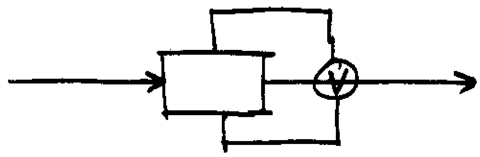
$$k_0 \Delta n d = \frac{2\pi \Delta n}{\lambda} d = 2\pi \Rightarrow \text{additional } 2\pi \text{ phase shift.}$$

Why interesting?

① Lens made of a material whose $n = n(E_{applied}) \Rightarrow$ controllable focal length

② Prism whose beam bending is controllable can be used for a scanning device.

③ Optical phase modulator.

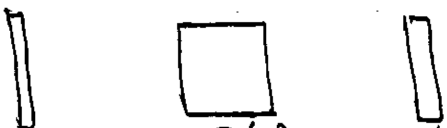


phase of light controllable.

$n \to n + \Delta n$.

④ Controllable wave retarders from anisotropic crystals.

⑤ Polarization rotation switch.



$\Gamma(E) = e^{j\frac{\Delta n d}{\lambda}2\pi}$

Pockels Effect

$$n(E) = n + a_1 E + \frac{1}{2} a_2 E^2 + \cdots$$

$$n = n(E=0), \quad a_1 = (dn/dE)\Big|_{E=0}, \quad a_2 = \left(\frac{d^2 n}{dE^2}\right)\Big|_{E=0}.$$

We write $\quad r = \frac{-2a_1}{n^3} \qquad s = \frac{-a_2}{n^3}.$

$$\Rightarrow \quad n(E) = n \underbrace{- \frac{1}{2} r n^3 E - \frac{1}{2} s n^3 E^2}_{\text{typically very small terms}} + \cdots$$

Recall $\eta = \frac{\epsilon_0}{\epsilon} = \frac{1}{n^2}$ $\qquad \Delta\eta = \left(\frac{d\eta}{dn}\right)\Delta n = (-2/n^3)\left(-\frac{1}{2} r n^3 E - \frac{1}{2} s n^3 E^2\right)$

$$= rE + sE^2.$$

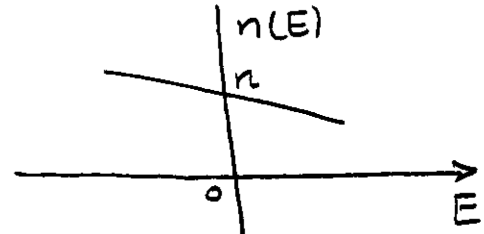
$\eta(E) = \eta + \underbrace{rE}_{} + \underbrace{sE^2}_{}$: impermeability.

$\eta = \eta(0)$ explains definitions of r & s. (η has simple form).

<u>Pockels Effect</u>.

$$sE^2 << rE.$$

$$\Rightarrow \quad n(E) = n - \tfrac{1}{2} r n^3 E$$



Pockels medium.
(Pockels cell)

r - Pockels coefficient or linear electro-optic coefficient.

$$10^{-12} < r < 10^{-10} \text{ m/V} \quad (1 \rightarrow 100 \text{ pm/V}).$$

Example $E = 10^6$ V/m   10kV across 1cm

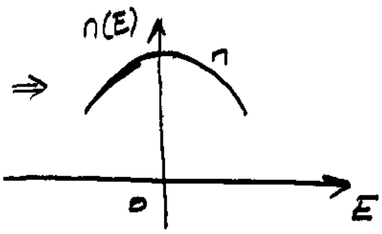
$$\tfrac{1}{2} r n^3 E \sim 10^{-6} \text{ to } 10^{-4}.$$

Pockels cells: $NH_4H_2PO_4$ (ADP), KH_2PO_4 (KDP), $LiNbO_3$, $LiTaO_3$, CdTe.

<u>Kerr Effect</u>   centrosymmetric materials: liquids, gases, certain crystals

$n(E)$ must be an even symmetric function

$\Rightarrow$



$$\Rightarrow \left(\frac{dn}{dE}\right)\Bigg|_{E=0} = 0 \quad \Rightarrow \quad r = 0$$

$$n(E) = n - \tfrac{1}{2} s n^3 E^2$$

Kerr medium (or a Kerr cell). s- Kerr coefficient or quadratic electro-optic coefficient.

$10^{-18} < s < 10^{-14}$ m²/V² in crystals.

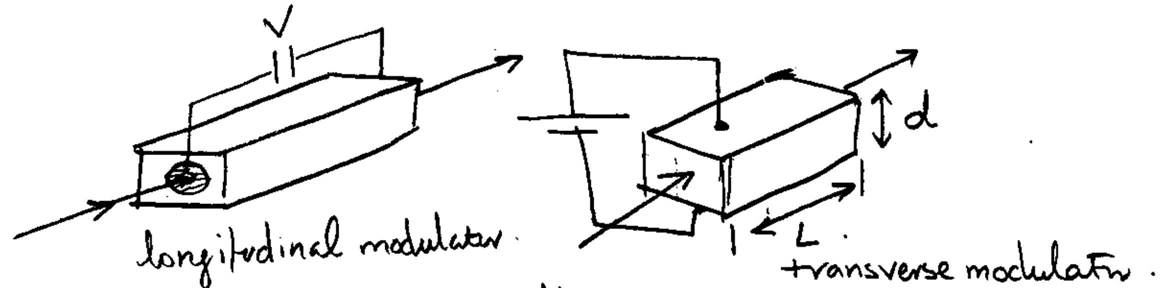
$10^{-22} < s < 10^{-19}$ m²/V² in liquids.

$E = 10^6$ V/m $\tfrac{1}{2} s n^3 E^2 \sim 10^{-6}$ to 10^{-2} in crystals

10^{-10} to 10^{-7} in liquids

Electro-optic Modulators and Switches

Phase modulators.

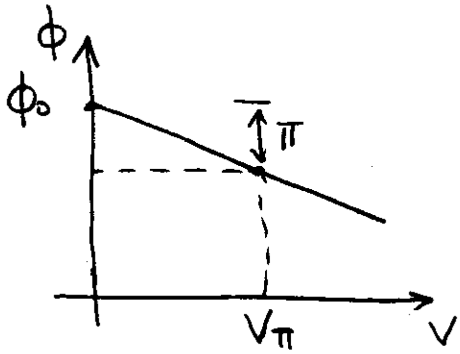


$$\phi = n(E)k_o L = \frac{2\pi n(E)L}{\lambda_o}$$

(plane wave $e^{j\underbrace{kz}_{phase}}$)

λ_o - free space wavelength.

$$\phi = \phi_o - \frac{\pi r n^3 E L}{\lambda_o} \qquad \phi_o = \frac{2\pi n L}{\lambda_o} \qquad E = \frac{V}{d}.$$



$$\boxed{\phi = \phi_o - \pi \frac{V}{V_\pi}} \qquad \boxed{V_\pi = \frac{d}{L}\frac{\lambda_o}{r n^3}}$$

Half-wave Voltage.

V_π - half-wave voltage - phase changes by π

$\Rightarrow$ We can modulate the phase with application of the voltage.

V_π - important characteristic of the modulator.
- depends on material properties (r & n).
- depends on λ_o
- depends on aspect ratio $\frac{d}{L}$.

If V applied along length $\Rightarrow$ $d = L$.

r - depends on directions of propagation.
- because crystal is anisotropic.

$V_\pi \sim 1 \rightarrow 10^3$ V for longitudinal modulators.
100's V for transverse mods.

Modulation speeds ~ MHz → GHz. easily.

Dynamic Wave retarders.

- anisotropic medium - Two normal modes $\sim \frac{c_0}{n_1}, \frac{c_0}{n_2}$ see n_1 and n_2

Application of electric field E modifies two refractive indices.

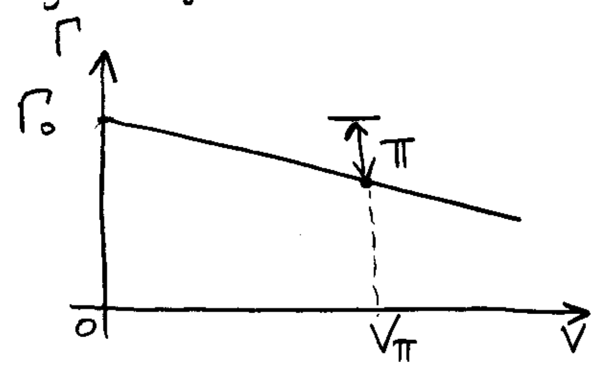
$$n_1(E) \simeq n_1 - \frac{1}{2} r_1 n_1^3 E$$

$$n_2(E) \simeq n_2 - \frac{1}{2} r_2 n_2^3 E$$

r_1, r_2 ~ Pockels coefficients. After distance L phase retardation:

$$\Gamma = k_0 \left(n_1(E) - n_2(E) \right) L$$
$$= k_0 (n_1 - n_2) L - \frac{1}{2} k_0 (r_1 n_1^3 - r_2 n_2^3) E L.$$

E - applying voltage V between two surfaces of the medium.

- 

$$\boxed{\Gamma = \Gamma_0 - \pi \frac{V}{V_\pi}}$$ Phase retardation.

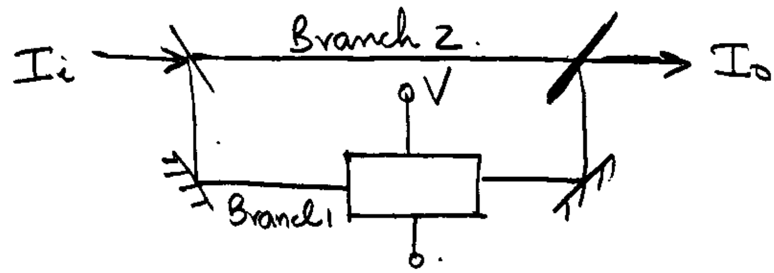
$\Gamma_0 = k_0 (n_1 - n_2) L$ - phase retardation with $E = 0$.

$$V_\pi = \frac{d}{L} \cdot \frac{\lambda_0}{r_1 n_1^3 - r_2 n_2^3}.$$

⇒ electical controllable dynamic wave retarder.

- Intensity Modulators: Use of a phase modulator in an Interferometer

Mach-Zehnder interferometer.



By adding fields at the output. Beamsplitters divide optical power equally $\Rightarrow$

$$I_o = \frac{1}{2} I_i + \frac{1}{2} I_i \cos\phi = I_i \cos^2 \frac{\phi}{2}.$$

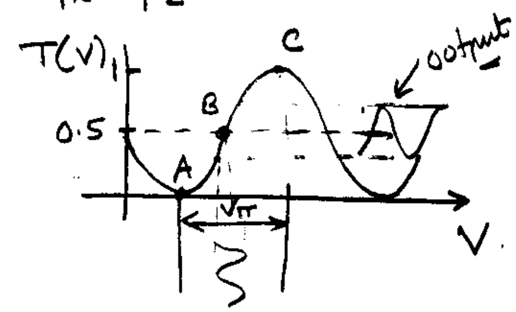
$\phi = \phi_1 - \phi_2$ - difference between phase shifts encountered by light.

$$T = \frac{I_o}{I_i} = \cos^2\left(\frac{\phi}{2}\right).$$

Add modulator in branch 1 $\Rightarrow$ $\phi_1 = \phi_{10} - \frac{\pi V}{V_\pi}$

$$\Rightarrow \phi = \phi_1 - \phi_2 = \phi_0 - \frac{\pi V}{V_\pi} \qquad \phi_0 = \phi_{10} - \phi_2.$$

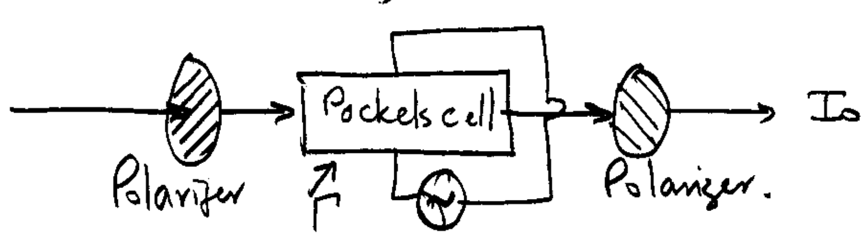
$$\Rightarrow T(V) = \cos^2\left(\frac{\phi_0}{2} - \frac{\pi V}{V_\pi}\right).$$



$\phi_0 = \frac{\pi}{2}$, $T = 0.5$ or $\phi_0 = n2\pi$ $T(0) = 1$
$T(V_\pi) = 0$.

modulator switches the light on/off as V $0/V_\pi$.

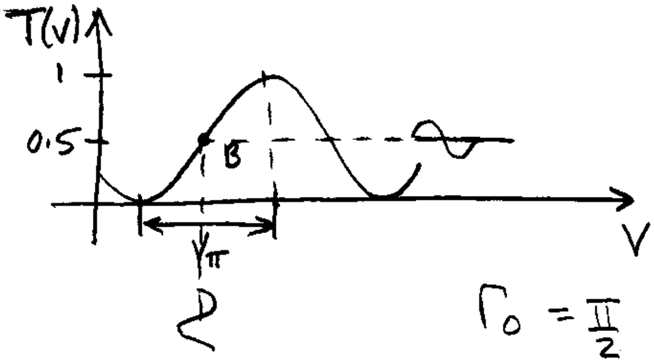
Intensity Modulators: Use of a retarder between crossed polarizer.



$$T = \sin^2\left(\frac{\Gamma}{2}\right)$$

if retarder is a Pockels cell, Γ linearly dependent on applied voltage V.

$$\Rightarrow \Gamma = \Gamma_0 - \frac{\pi V}{V_\pi} \quad \Rightarrow \quad T = \sin^2\left(\frac{\Gamma_0}{2} - \frac{\pi}{2}\frac{V}{V_\pi}\right).$$



Linear operation: cell is biased to point B.

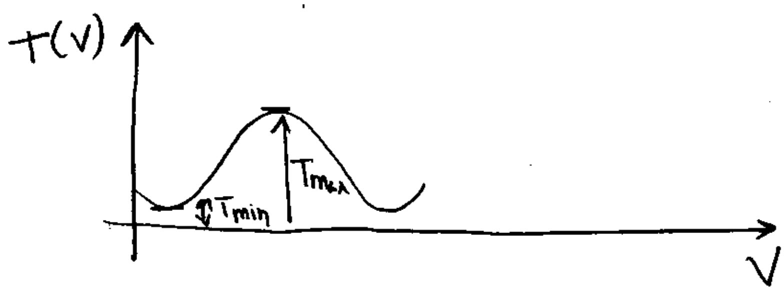
$$\Gamma_0 = \frac{\pi}{2} \qquad V \ll V_\pi.$$

$$T(V) = \sin^2\left(\frac{\pi}{4} - \frac{\pi}{2}\frac{V}{V_\pi}\right) = \underbrace{T(0) + \left.\frac{dT}{dV}\right|_{V=0} V}_{\text{Taylor series expansion.}} = \frac{1}{2} - \frac{\pi}{2}\frac{V}{V_\pi}$$

$\frac{\pi}{2V_\pi}$ – sensitivity of modulator.

Γ_0 – adjusted optically (adding phase retarder, a compensator) or electrically by adding a constant bias voltage to V.
i.e., $V = V_0 + V_{mod}$.

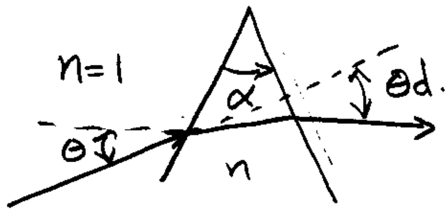
Ratio between maximum and minimum transmittances is called the extinction ratio.



real devices.

Ratios $\frac{T_{max}}{T_{min}} > 1000:1$ are possible.

Prism as Scanner.



$$\theta_d = \theta - \alpha + \sin^{-1}\left((n^2 - \sin^2\theta)^{1/2} \sin\alpha - \sin\theta\cos\alpha \right).$$

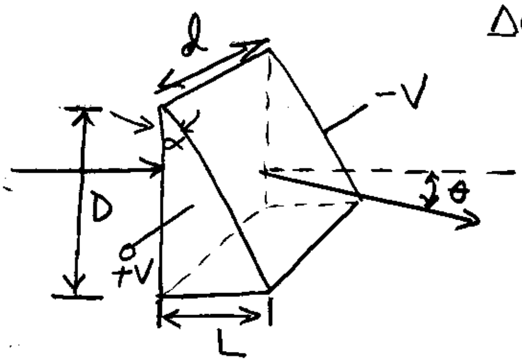
determined by applying Snells law twice.

if α, θ small $\Rightarrow \theta_d \simeq (n-1)\alpha$.

$\Rightarrow$ if we use Pockel effect.

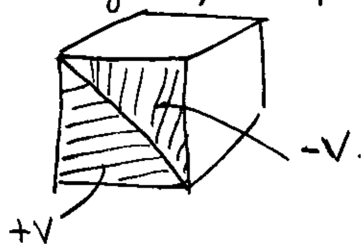
$$\theta_d = (n-1)\alpha$$

$$\Delta\theta_d = \alpha\Delta n = -\frac{1}{2}\alpha r n^3 E = -\frac{1}{2}\alpha r n^3 \frac{V}{d}.$$



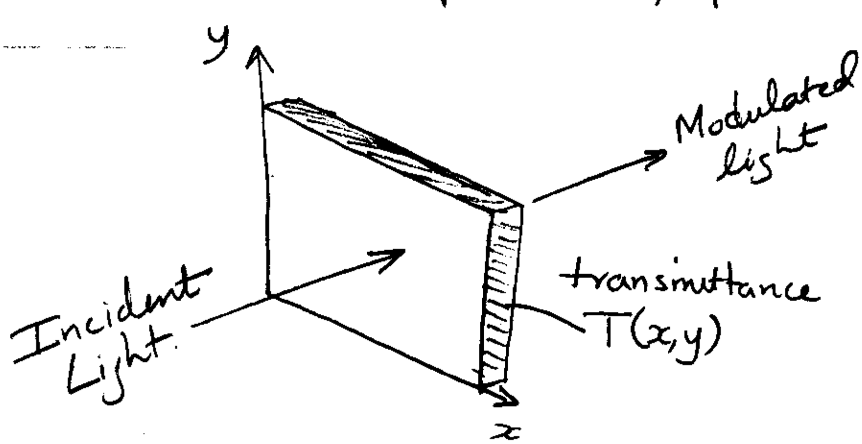
Incident light is scanned.

More convenient to use triangularly shaped electrodes on a cubic crystal.



Spatial Light Modulators.

– modulates intensity of light a different positions by prescribed factors.

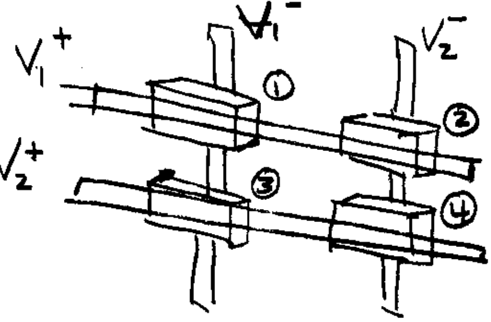


$I_{out}(x,y) = I_i(x,y)T(x,y)$.

If $I_i(x,y)$ is uniform in intensity $\Rightarrow$ $I_{out} \propto T(x,y)$.

$\therefore$ we read the image $T(x,y)$

$T(x,y)$ is controllable.



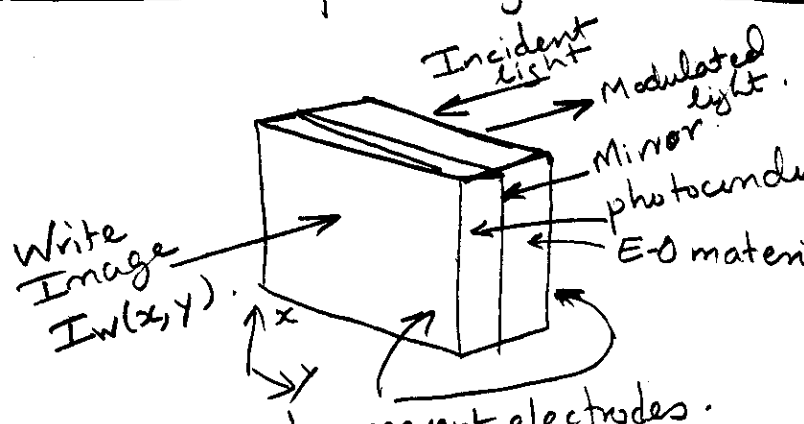
$$V_① = V_1^+ - V_1^-$$
$$V_② = V_1^+ - V_2^-$$
$$V_③ = V_2^+ - V_1^-$$
$$V_④ = V_2^+ - V_2^-$$

can modify voltage across each device.
$\Rightarrow$ controllable transmission.

$\Rightarrow$ each e-o-modulator acts as a pixel
as each gets smaller. $T(x_i, y_i) \rightarrow T(x,y)$.
$i = 1, 2, 3 \cdots$

(Used in Liquid-crystal 'spatial light modulators used for display).

Optically addressed E-O spatial light modulator



Photoconductive material: photo conductivity depends on light intensity $G(x,y)$.

$I_W(x,y)$ - image written in spatial intensity.

$$G(x,y) \propto I_W(x,y). \qquad E(x,y) \propto \frac{1}{G(x,y)} \propto \frac{1}{I_W(x,y)}.$$

$$T(x,y) \propto E(x,y) \propto \frac{1}{I_W(x,y)}.$$

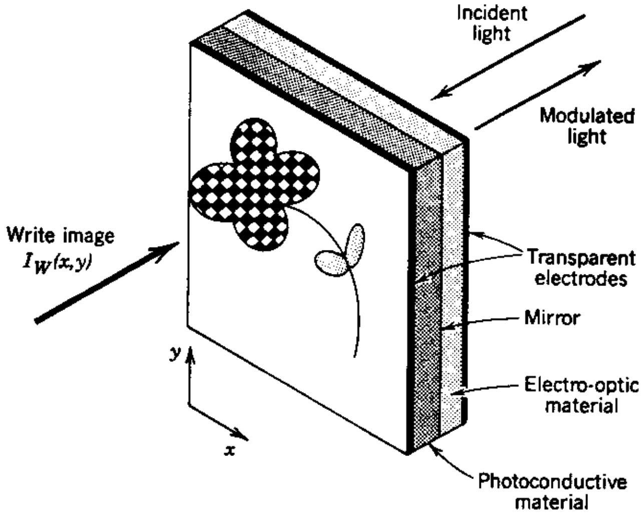


Figure 18.1-14 The electro-optic spatial light modulator uses a photoconductive material to create a spatial distribution of electric field which is used to control an electro-optic material.

The Pockels Readout Optical Modulator

An ingenious implementation of this principle is the Pockels readout optical modulator (PROM). The device uses a crystal of bismuth silicon oxide, $Bi_{12}SiO_{20}$ (BSO), which has an unusual combination of optical and electrical properties: (1) it exhibits the electro-optic (Pockels) effect; (2) it is photoconductive for blue light, but not for red light; and (3) it is a good insulator in the dark. The PROM (Fig. 18.1-15) is made of a thin wafer of BSO sandwiched between two transparent electrodes. The light that is to be modulated (read light) is transmitted through a polarizer, enters the BSO layer, and is reflected by a dichroic reflector, whereupon it crosses a second polarizer. The reflector reflects red light but is transparent to blue light. The PROM is operated as

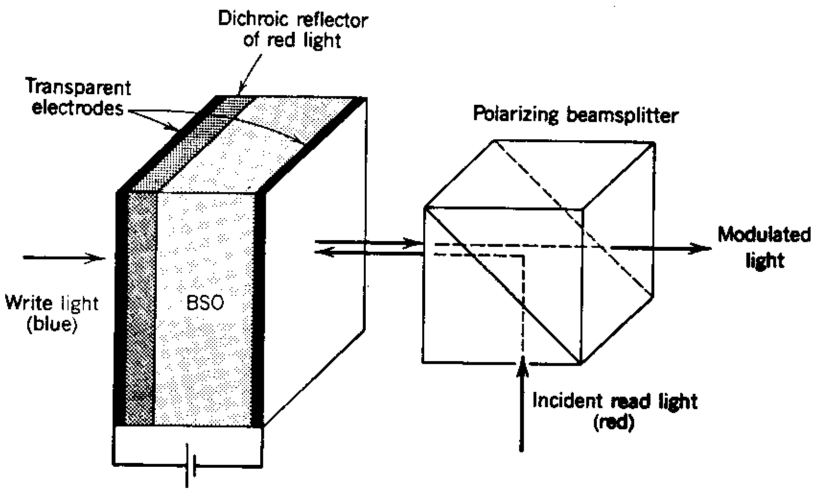


Figure 18.1-15 The Pockels readout optical modulator (PROM).