9. Electro-Optic Modulators

$\left\{ \begin{array}{l} \text{Optical-signal modulation} \\ \quad \text{"} \qquad \text{"} \quad \text{switching} \end{array} \right\}$ depending on the strength of the interaction

9.1 Basic Operation Characteristics of Switches and Modulators

9.1.1 Modulation Depth (Modulation Index)

(1) $\eta = \dfrac{I_o - I}{I_o} > 0 \qquad (I_o > I)$ modulator

I : transmitted intensity (decreased)

I_o : I with no electrical signal applied
(NOT input intensity)

(2) $\eta = \dfrac{I - I_o}{I_m} \qquad$ (switch)

I : transmitted (increased) $\leq I_m$

Maximum modulation depth (or extinction ratio)

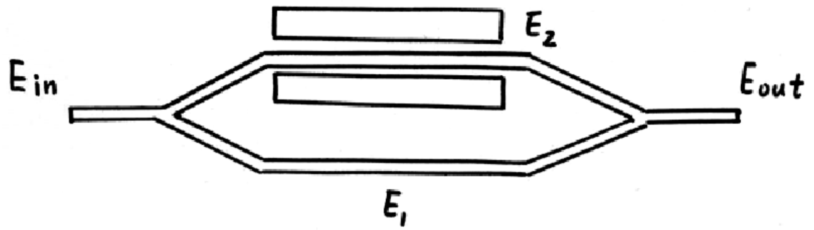
$$\eta_{max} = \frac{I_o - I_m}{I_o}, \quad I_m \leq I_o \quad \text{(modulator)}$$

$$\eta_{max} = \frac{I_m - I_o}{I_m}, \quad I_m \geq I_o \quad \text{(switch)}$$

(3) Modulation depth for phase modulators
Phase change is functionally related to an equivalent intensity change.
For the case of interference modulators

$$\eta = \sin^2(\Delta\phi/2)$$

$\Delta\phi$ = phase change



$$E_1 = E_0 e^{i\phi}$$

$$E_2 = E_0 e^{i(\phi + \Delta\phi)}$$

$$E_{out} = E_1 + E_2 = E_0 \left(e^{i\phi} + e^{i(\phi+\Delta\phi)} \right)$$

$$= E_0 \left(e^{i(\phi + \frac{\Delta\phi}{2} - \frac{\Delta\phi}{2})} + e^{i(\phi + \frac{\Delta\phi}{2} + \frac{\Delta\phi}{2})} \right)$$

$$= E_0 \, 2\cos\left(\frac{\Delta\phi}{2}\right) e^{i(\phi + \frac{\Delta\phi}{2})}$$

Intensity $\propto$ (Field Amplitude)^2

$$\therefore \quad I_0 = 4E_0^2 \qquad (\Delta\phi = 0)$$

$$I = 4E_0^2 \cos^2\left(\frac{\Delta\phi}{2}\right) \qquad (\Delta\phi \neq 0)$$

$$\eta = \frac{I_0 - I}{I_0} = \sin^2\left(\frac{\Delta\phi}{2}\right)$$

(4) Modulation depth of frequency modulator

$$D_{max} = \frac{|f_m - f_0|}{f_0} = \text{figure of merit}$$

f_0 : optical carrier frequency

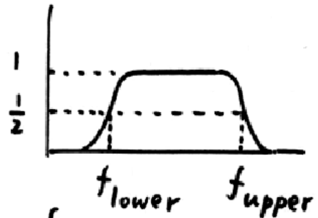
f_m : shifted optical frequency

$I \propto hf$ (Quantum Mechanism)

9.1.2 Bandwidth

Modulator

$$\eta = \frac{1}{2}\eta_{max}$$



$$\Delta f = f_{upper} - f_{lower} \approx f_{upper}$$

Switch

Switching time T

bandwidth $\Delta f = \frac{2\pi}{T}$

Usually, $\Delta f \uparrow \quad T \downarrow$

9.1.3 Insertion Loss

$$\mathcal{L}_i = 10 \log \left(\frac{I_t}{I_0} \right) \quad \text{modulator} \quad (I_t \le I_0)$$

$$\mathcal{L}_i = 10 \log \left(\frac{I_t}{I_m} \right) \quad \text{switch} \quad (I_t \le I_m)$$

$V=0,\ I=I_0$

$I_t \le I_m$

9.1.4 Power Consumption

Modulator

Driving power $\propto$ modulation frequency

$\because E = hf$

A useful figure of merit $\frac{P}{\Delta f}$ $\quad \frac{mW}{MHz}$

The smaller, the better

$\begin{cases} \text{Channel-waveguide modulator} & \text{small } \frac{P}{\Delta f} \\ \text{Bulk modulator} & \text{large } \frac{P}{\Delta f} \end{cases}$

Switch

Same figure of merit $\frac{P}{\Delta f}$

P_{hold} : the amount of power required to hold the switch in a given state.

- Ideal switch $\quad P_{hold} = 0$

  Consume power during the change of state.
- EO switch

  Require the presence of $\vec{\mathcal{E}}$ to maintain at least one state

  $\because$ leakage current $\approx 0 \Rightarrow P_{hold} \approx 0$

9.1.5 Isolation

I_1 : Driving port optical intensity

I_2 : Driven port optical intensity at off state with respect to port #1.

e.g. $\frac{I_2}{I_1} = 1\%$

isolation $= 10 \log \left(\frac{I_2}{I_1} \right) = -20\,dB$

9.2 The Electro-Optic Effect

$\Delta n \propto E$ linear EO effect (Pockels effect)

$\Delta n \propto E^2$ nonlinear " " (Kerr effect)

Linear EO effect

The equation of the index ellipsoid in the presence of an electric field is

$$\left(\frac{1}{n^2}\right)_1 x^2 + \left(\frac{1}{n^2}\right)_2 y^2 + \left(\frac{1}{n^2}\right)_3 z^2 + 2\left(\frac{1}{n^2}\right)_4 yz$$

$$+ 2\left(\frac{1}{n^2}\right)_5 xz + 2\left(\frac{1}{n^2}\right)_6 xy = 1$$

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{3} r_{ij} E_j \qquad i = 1, 2, \cdots, 6$$

r_{ij} electro-optic tensor

(1) $r_{ij} = 0$ in crystals with inversion symmetry (centrosymmetric)

(2) Noncentrosymmetric crystals
For most symmetry classes, only a few nonzero elements.

e.g. r_{41} GaP, GaAs

r_{33} $LiNbO_3$. $LiTaO_3$

$$\Delta n = -\frac{1}{2} n^3 r \mathcal{E}$$

$$\Delta\lambda \propto \frac{d}{\lambda} \propto \frac{\mathcal{E}}{\lambda}$$

$\ominus$ $d\uparrow$ $\oplus$ dipole moment $\vec{P}$

$|\vec{P}| \propto d \propto |\vec{\mathcal{E}}|$

$\lambda \Delta\lambda \propto \mathcal{E}$, $\quad \Delta(\lambda^2) \propto \mathcal{E}$

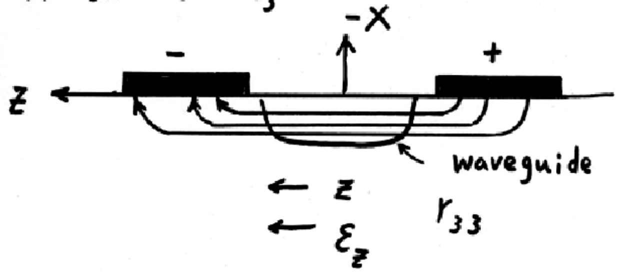
$$\lambda = \frac{2\pi}{k n}$$

$$\therefore \quad \Delta\left(\frac{1}{n^2}\right) \propto \mathcal{E}$$

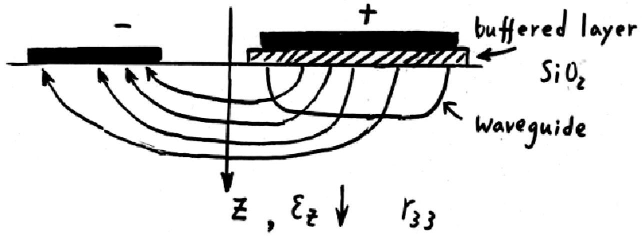
$$\Delta\left(\frac{1}{n^2}\right) = r\mathcal{E} \qquad (f \text{ is not changed})$$

The nonlinear (quadratic) Kerr electro-optic coefficient is relatively weak in commonly used waveguide materials.
A nonlinear dependence on electric field introduces unwanted modulation crossproducts (distortion) into the modulated signal.

X- Cut $LiNbO_3$



Z- cut $LiNbO_3$



buffered layer insulator, $n_{buff} < n_{LiNbO_3}$

$$\vec{\nabla}\times\vec{H} = \vec{J} + \dot{\vec{D}} = \sigma\vec{E} + j\omega\epsilon\vec{E} = j\omega\epsilon_0\left(\frac{\sigma}{j\omega\epsilon_0} + \kappa\right)\vec{E}$$

$$\therefore\ \kappa_{eff} = \kappa - j\underbrace{\frac{\sigma}{\omega\epsilon_0}}_{\text{lossy}}$$

9.3 Single-Waveguide Electro-Optic Modulators

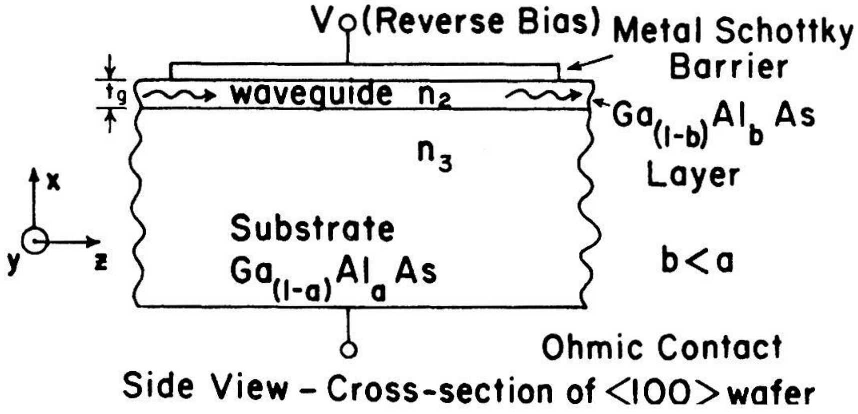


Fig. 9.1.

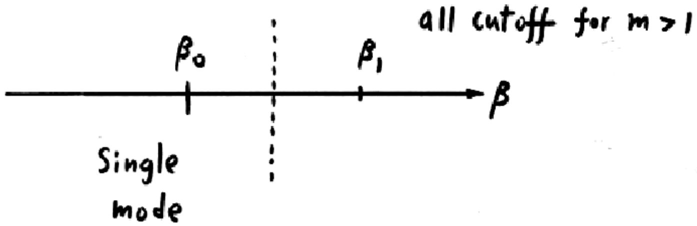
9.3.1 Phase Modulation

$$\Delta n_{23} = n_2 - n_3$$

$$= \Delta n_{chemical} + \Delta n_{CCR} + \Delta n_{EO}$$

(a-b ≠ 0)   (carrier conc. ↓)   (EO effect)

Condition



Asymmetric Waveguide

$$\frac{1}{32 n_2}\left(\frac{\lambda_0}{t_g}\right)^2 < \Delta n_{chemical} + \Delta n_{CCR} < \frac{9}{32 n_2}\left(\frac{\lambda_0}{t_g}\right)^2$$

For a TE wave

$$\Delta n_{EO} = n^3 r_{41}\left(\frac{V}{2 t_g}\right) = \frac{\Delta\beta_{EO}}{k} = \frac{\lambda_0 \Delta\beta_0}{2\pi}$$

$$\Delta\varphi_{EO} = (\Delta\beta_0)L = \frac{2\pi}{\lambda_0} n_2^3 r_{41} \frac{VL}{t_g}$$

E_x

x index

Examples

- $LiNbO_3$ planar waveguide by outdiffusion

  modulation power 0.4 mW/MHz/rad

  $\Delta\varphi = 1$ rad

  $\lambda_0 = 6328$ Å

- $LiNbO_3$ ion-beam etched ridge waveguide

  $w = 19\ \mu m$

  modulation power 20μW/MHz/rad

- Ti-indiffused $LiNbO_3$ channel waveguide

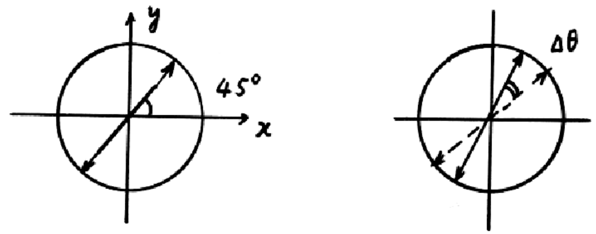
  $w = 5\ \mu m$

  modulation power 1.7μW/MHz/rad

9.3.2 Polarization Modulation

In a phase modulator, phase coherent detection system must be used ⇒ complicated

Simple modification ⇒ Polarization Modulation



$\zeta = 0$ $\qquad$ $\zeta = \zeta'$

$$\begin{cases} E_y : \text{changed} \\ E_x : \text{Not changed} \end{cases}$$

$\Delta\theta$ can be detected by

- polarization-sensitive detector
- polarization-selective filter (analyzer) ahead of the detector

Analyzer

- Discrete waveguide (used for an air beam)
  - conventional wire-grid polarizer
  - absorptive polarizing filter
- Optical integrated circuit
  - grating } couplers (polarization sensitive)
  - prism

The difficulty of fabricating an effective analyzer monolithically has limited the use of polarization modulators in OIC's, and has led to a preference for intensity modulation.

9.3.3 Intensity Modulation

The zero field threshold condition for an intensity modulator is given by

$$\Delta n_{23} = \Delta n_{\text{chemical}} + \Delta n_{CCR} = \frac{1}{32\, n_2}\left(\frac{\lambda_0}{t_g}\right)^2$$

(Cutoff condition of an asymmetric guide)

Examples :

(i) Modulators

(1) GaAs carrier-concentration-reduction planar waveguide (Hall et al.)

$\lambda = 1.15\ \mu m$

$V = 130\ V$

Bring the TE_0 mode from cutoff to propagating.

(2) GaAs c.c.r. channel waveguide (Campbell et al.)

$\eta = 95\%$

$\Delta f = 150\ MHz$

$\frac{P}{\Delta f} = 300\ \mu W/MHz$

(3) Ti-indiffused $LiNbO_3$ channel waveguide

$W = 2.4\ \mu m$

$\lambda = 6328\ \text{Å}$

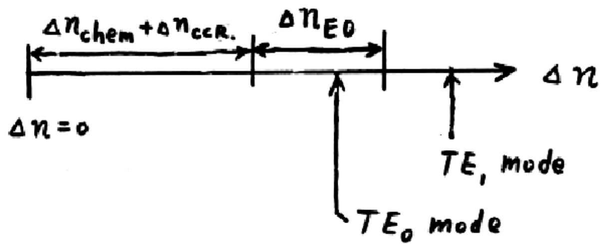
$V = -10V \quad (\mathcal{E} = 15\ kV/cm) \quad$ guided

$\quad\ +10V \quad$ cutoff

This type of intensity modulator can also function as effective optical switches.

$\eta = -19 dB$

(ii) Switches



$\Delta n_{23} = \Delta n_{chem} + \Delta n_{c.c.R.} \qquad V = 0 \qquad TE_0$ cutoff

$\Delta n = \Delta n_{23} + \Delta n_{EO} \qquad V \neq 0 \qquad TE_0$ propagates

9.3.4 Electro-Absorption Modulation

$\begin{cases} \text{Electro-Optic effect — Pockels effect} \\ \text{Electro-Absorption effect — Franz-Keldysh effect} \end{cases}$

In the presence of strong electric field the absorption edge of a semiconductor is shifted to a longer wavelength.

Example : GaAs

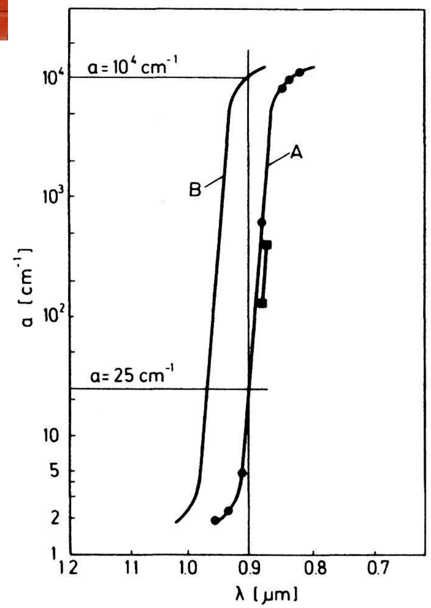


Fig. 9.2.

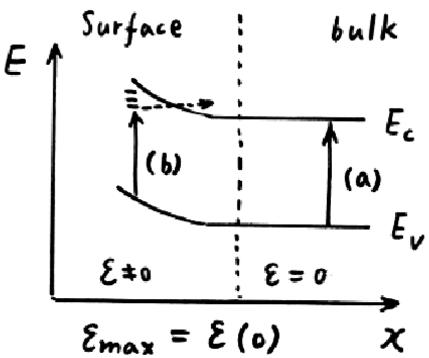
$\mathcal{E} = 1.3 \times 10^5$ V/cm

$\lambda = 9000$ Å

$\alpha = 25\ \text{cm}^{-1} \Rightarrow 10^4\ \text{cm}^{-1}$

$(\mathcal{E} = 0) \qquad (\mathcal{E} \neq 0)$

Mechanism



$\mathcal{E}_{max} = \mathcal{E}(0)$

(Schottky contact)
reverse-biased

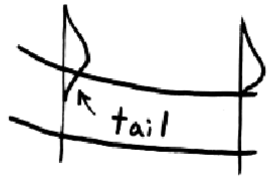
At low $\mathcal{E}$

No allowed electron state within the bandgap.

At high $\mathcal{E}$

density function broadening $\Rightarrow$

"finite probability of finding the electron in the gap"



$E_g' < E_g$

bandgap narrowing at high field

$\lambda_g' > \lambda_g$ Shifted to a longer wavelength

$$\Delta E_g = \frac{3}{2} (m^*)^{-\frac{1}{3}} (q \hbar \mathcal{E})^{2/3}$$

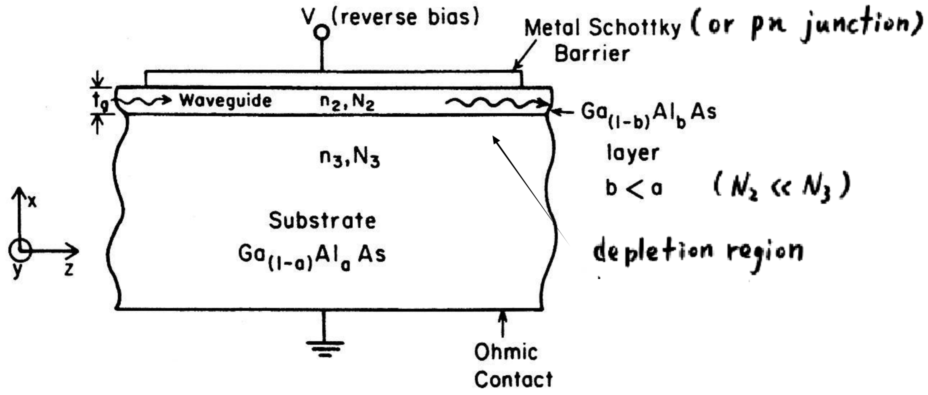
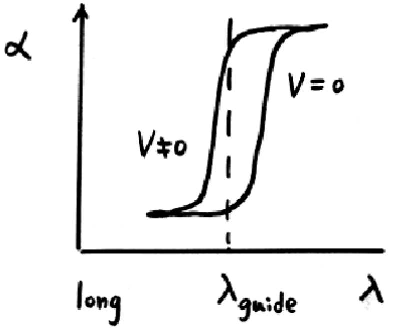


Fig. 9.4.

$V = 0$ transparent

$\neq 0$ modulated or cutoff



Examples

(1) Reinhart $Al_x Ga_{1-x} As$

$\lambda = 9000 \, \mathring{A}$

$V = -8$ volts change a factor of 100

$\eta = 90\%$

$\frac{P}{\Delta f} = 0.1 \, mW/MH_z$

(2) Campbell

$\lambda = 0.9 \sim 1.2 \, \mu m$ typical $1.06 \, \mu m$

$\mathcal{L}_{insertion} = -3 \, dB$

extinction ratio $= -16 \, dB$

$\Delta f > 500 \, MH_z$

9.4 Dual-Channel Waveguide Electro-Optic Modulators

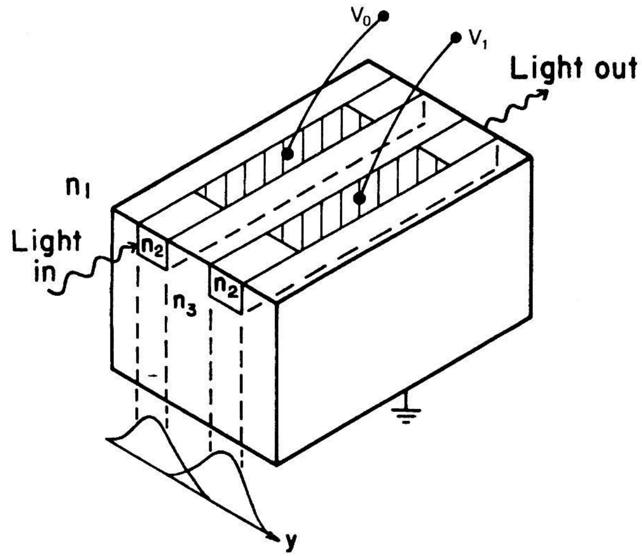


Fig. 9.5.

9.4.1 Theory of Operation

The Coupling Equations

$$\frac{\mathrm{d}A_0(z)}{\mathrm{d}z} = -\mathrm{i}\beta_0 A_0(z) - \mathrm{i}\kappa A_1(z)$$

$$\frac{\mathrm{d}A_1(z)}{\mathrm{d}z} = -\mathrm{i}\beta_1 A_1(z) - \mathrm{i}\kappa A_0(z)$$

Boundary Condition

$$A_0(0) = 1 \quad \text{and} \quad A_1(0) = 0$$

Solutions

$$A_0(z) = \left(\cos gz - \mathrm{i}\frac{\Delta\beta}{2g}\sin gz\right)\exp\left[-\mathrm{i}\left(\beta_0 - \frac{\Delta\beta}{2}\right)z\right]$$

$$A_1(z) = -\left(\frac{-\mathrm{i}k}{g}\sin gz\right)\exp\left[-\mathrm{i}\left(\beta_1 + \frac{\Delta\beta}{2}\right)z\right]$$

where $\Delta\beta = \beta_0 - \beta_1 \qquad g^2 \equiv \kappa^2 + \left(\frac{\Delta\beta}{2}\right)^2$

Optical Power

$$P_0(z) = A_0(z)A_0^*(z) = \cos^2(gz)\mathrm{e}^{-\alpha z} + \left(\frac{\Delta\beta}{2}\right)^2 \frac{\sin^2(gz)}{g^2}\mathrm{e}^{-\alpha z}$$

$$P_1(z) = A_1(z)A_1^*(z) = \frac{\kappa^2}{g^2}\sin^2(gz)\mathrm{e}^{-\alpha z}$$

*The condition for total transfer of power for zero applied voltage is given by

$$\kappa L = \frac{\pi}{2} + m\pi \qquad m = 0, 1, 2, \cdots$$

*The condition for completely cancelled

$$gL = \pi + m\pi \qquad m = 0, 1, 2, \cdots$$

Consider $m = 0$

$$\begin{cases} \kappa L = \frac{\pi}{2} \\ gL = \pi \end{cases} \quad \text{and} \quad g^2 = \kappa^2 + \left(\frac{\Delta\beta}{2}\right)^2$$

Solving gives

$$\Delta\beta = \frac{\sqrt{3}\,\pi}{L}$$

effective index $n_g = \frac{\beta}{k}$

$$\Delta n_g = \frac{\Delta\beta}{k} = \frac{\sqrt{3}\,\pi}{kL}$$

Example : AlGaAs dual-channel waveguide modulators (100 %)

$3\ \mu m \times 3\ \mu m$

$L = 1$ cm

$\lambda = 9000$ Å

Need $\Delta n_g = 1 \times 10^{-4}$ Surprising small!

Required $\mathcal{E} = 3 \times 10^{4}$ V/cm

or $V = \mathcal{E} t_g = 10$ V

9.4.2 Operating Characteristics of Dual-Channel Modulators

- 1969 Marcatili
  The concept of using dual-channel directional coupler as a modulator.
- 1975 Campbell
  The first operational device.

— Theory (Taylor)

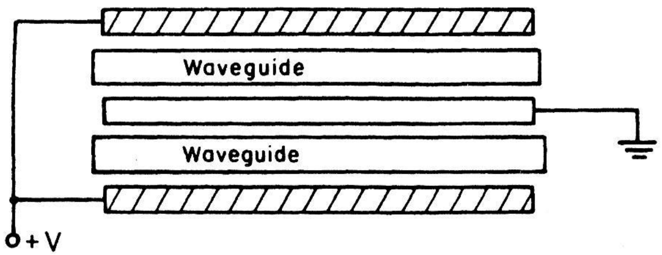


Fig. 9.6.

— Experiment (Campbell)

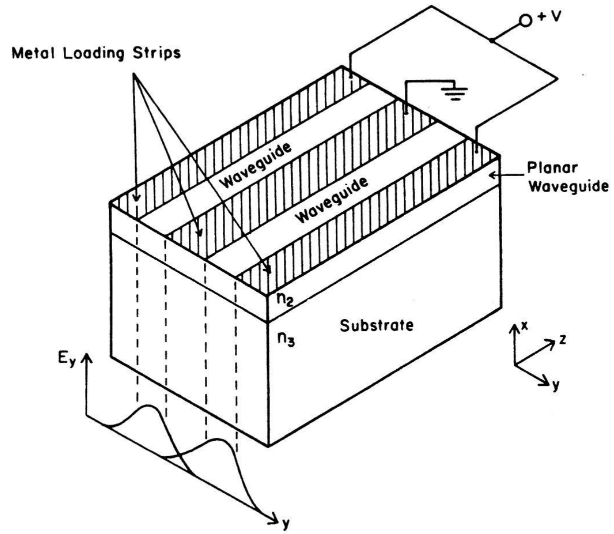


Fig. 9.7.

Substrate	GaAs	GaAs	TE_0 modes
η		95%	
Extinction ratio		13dB	
Nd:YAG laser λ		1.06 μm	
Width		6 μm	
Separation		7 μm	
V_{max}		35 V	
Rise-time		7 ns	
Δf (3dB)		100 MHz	
$P/\Delta f$		180 μW/MHz	

Dual-channel modulator with three electrodes are limited by the capacitance of the electrodes

$\Rightarrow$ Reducing the width of the Schottky barrier contacts.

- 1975 Papuchon

  Two electrode type of dual-channel modulators (Commutateur Optique Binaire RApide, COBRA)

  Offers the potential advantage of low capacitance by eliminating the center electrode.

Ti-diffused $LiNbO_3$ waveguide

Ti strip width	2 μm	
Coupling length	500 μm	1 mm
λ	5145 Å	
Separation	2 μm	3 μm

Switch off voltage 6 V

- 1976 Kogelnik and Schmidt

  — Splited electrodes (Alternate $\Delta\beta$)

  The basic electrodes are split in half.

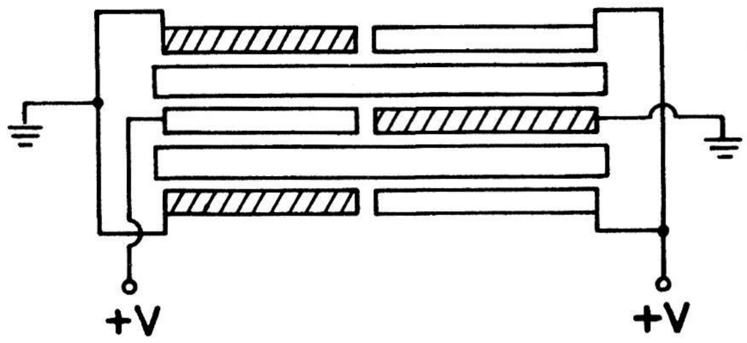


Fig. 9.8.

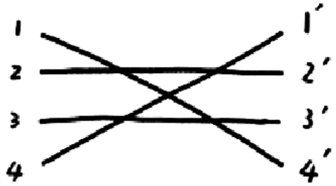
- The effect of stepped $\Delta\beta$ reversal is to yield a device in which both the off and on states can be electrically adjusted for a relative wide range of lengths.
- This also allows one to maximize the extinction ratio and minimize crosstalk.

  Complete transfer by electrical adjustment is possible if

$$\frac{L}{\ell} < 1 \qquad \ell = \frac{\pi}{2\kappa}$$

L : total length of the modulator

e.g. Schmidt and Buhl 4×4 optical switching network



five stepped $\Delta\beta$ switches

$\lambda = 6328\ \mathring{A}$

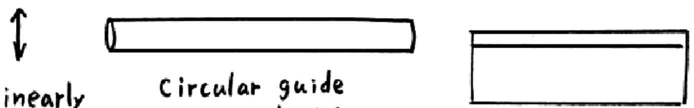
Crosstalk $-18\,dB$

$I_{input} \approx 1\ kW/cm^2$

• 1977 Steinberg et al.
Polarization insensitive modulators

– Electro-optic modulators are generally sensitive to the polarization of the light waves
Proper choice of polarization for a maximum desired interaction is needed.

– Problem



linearly polarized light

Circular guide
Single-mode fiber
(elliptically polarized)

rectangular guide of an OIC excite's both TE and TM modes

Needs polarization-insensitive modulator

– Solution

Combination of different types of electrode

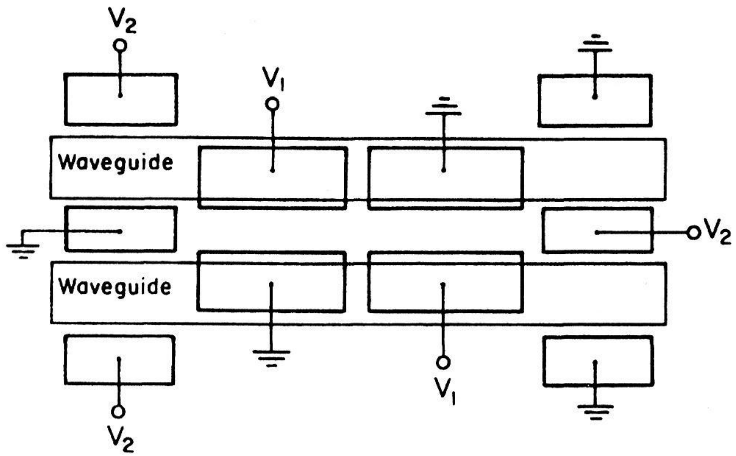


Fig. 9.9.

• Between-guide electrodes produce $\vec{\mathcal{E}}$ parallel to the substrate plane.

• Over-guide electrodes with a stepped $\Delta\beta$ reversal pattern, produce $\vec{\mathcal{E}}$ perpendicular to the substrate plane.

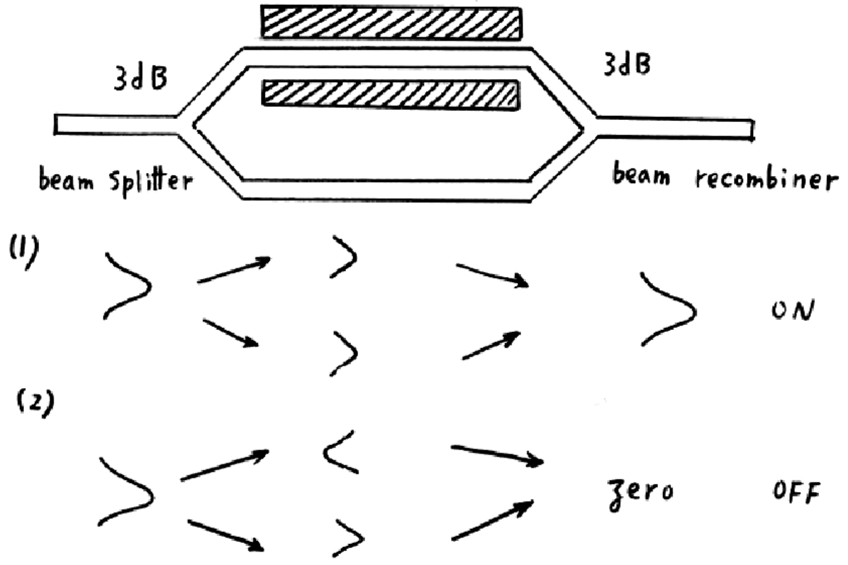
Designer has an additional degree of freedom that can be used to cancel polarization sensitivity.

9.5 Mach-Zehnder Type Electro-Optic Modulators

Two-channel modulators

- Employ the synchronous coupling of energy between overlaping mode tails
  e.g. directional coupler

- Employ the difference in optical path lengths traveled by two coherent light waves
  e.g. Mach-Zehnder interferometer



Single bend, 3-electrode, Asymmetric synchronous

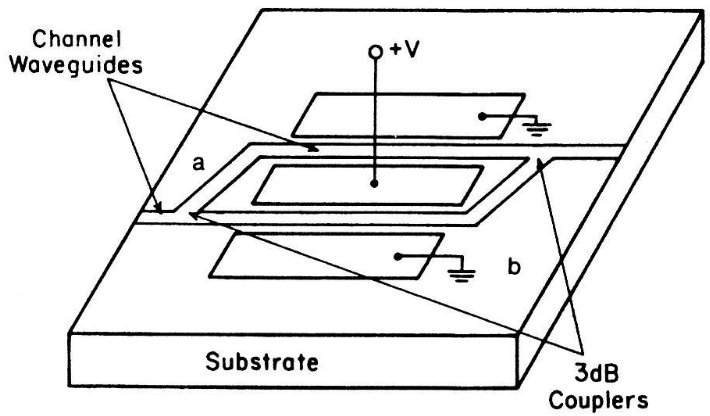
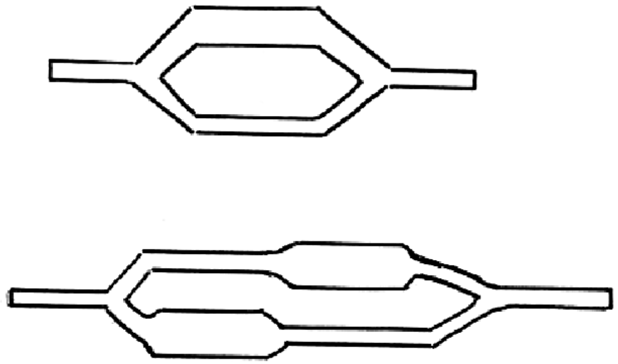


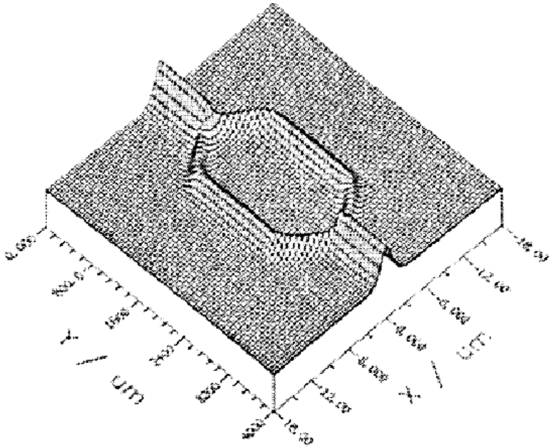
Fig. 9.10.

Asymmetric, nonsynchronous

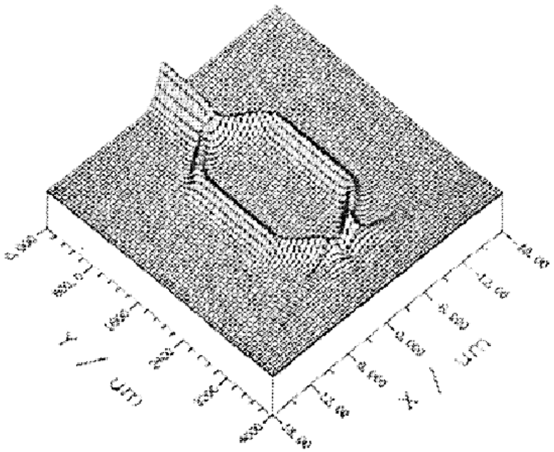


Mach Zehnder Interferometer

A. ON STATE - THROUGHPUT = 99.8%



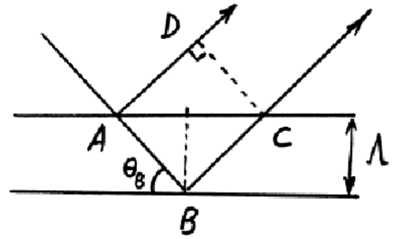
B. OFF STATE - THROUGHPUT = 1.8%



9.6 Electro-Optic Modulators Employing Reflection or Diffraction

9.6.1 Bragg-Effect Electro-Optic Modulators

Bragg Effect

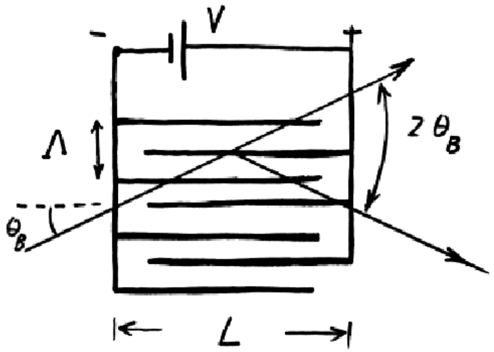


$$\delta = n_g (AB + BC) - AD$$

$$= 2 n_g \Lambda \sin\theta_B = \lambda_0 m$$

constructive

$$\therefore\ 2\Lambda \sin\theta_B = \frac{m\lambda_0}{n_g}$$



grating is produced by the applied voltage.

$$2\Lambda \sin\theta_B = \frac{\lambda_0}{n_g} \qquad (m = 1)$$

Based on the thick grating assumption

$$2\pi\lambda_0 L \gg \Lambda^2$$

If $\theta \neq \theta_B$ efficiency reduced!

$\Delta\theta_B$: angular range for a 50% reduction

$$\Delta\theta_B = \frac{2\Lambda}{L} = \frac{4S}{L} \qquad S = \frac{\Lambda}{2}$$

Diffracted light intensity

$$\frac{I}{I_0} = \sin^2(VB)$$

cf. page 121

$$\eta = \sin^2\left(\frac{\Delta\varphi}{2}\right)$$

B : constant

$V \propto \Delta\phi$

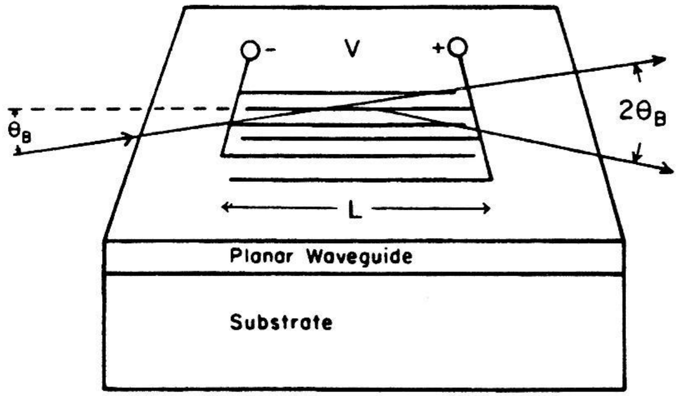


Fig. 9.11.

Examples

(1) Hammer et al. 1971

Waveguide film	ZnO	$LiNb_xTa_{1-x}O_3$
Substrate	Sapphire	$LiTaO_3$

(2) Tangonan et al. 1978

Waveguide film	$Ti:LiNbO_3$
Substrate	$LiNbO_3$

$\lambda = 1.06\ \mu m$ extinction ratio 24.7dB (300:1)

6328 Å 24 dB (250:1)

9.6.2 Electro-Optic Reflection Modulators

It is possible to use the linear E-O effect to reduce the index of refraction in a layer, thereby bringing about the TIR of an optical beam.

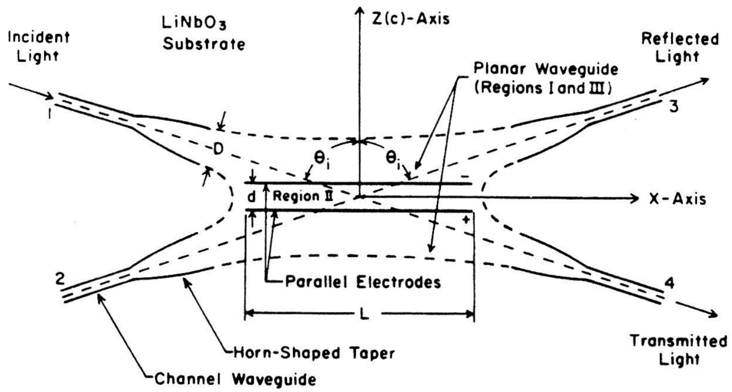


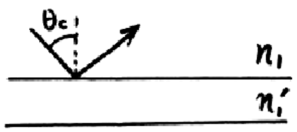
Fig. 9.12.

Horn-shaped waveguide is to minimize scattering and mode conversion, very little crosstalk will occur at port 3

$$\begin{cases} V=0 & \text{port \# 1} \longrightarrow \text{port \# 4} \\ & \text{port \# 3} \quad = 0 \\ V \neq 0 & \text{reflection to port \# 3, port \# 4} \quad = 0 \end{cases}$$

At $\theta = \theta_c$ = critical angle, TIR may occur at the first interface.

$$\theta_c = \sin^{-1}\left[1 - \frac{1}{2} n_1^2 r_{33} \left(\frac{V}{d}\right)\right]$$



Snell's law

$$n_1 \sin\theta_c = n_1' \sin 90^\circ$$
$$= (n_1 - \Delta n_1)$$

$$\Delta n_1 = \frac{1}{2} n_1^3 r_{33} \frac{V}{d}$$

$$\therefore \quad \theta_c = \sin^{-1}\left(1 - \frac{1}{2} n_1^2 r_{33} \frac{V}{d}\right)$$

$$\theta_i \approx \frac{\pi}{2}$$

$$\left(\frac{V}{d}\right)_{TIR} = \mathcal{E}_{TIR} = \frac{2(1-\sin\theta_i)}{n_1^2 r_{33}}$$

$$= \frac{2\left[1-\cos\left(\frac{\pi}{2}-\theta_i\right)\right]}{n_1^2 r_{33}} \doteqdot \frac{2\left[1-1+\frac{\left(\frac{\pi}{2}-\theta_i\right)^2}{2}\right]}{n_1^2 r_{33}}$$

$$= \frac{1}{n_1^2 r_{33}} \left(\frac{\pi}{2} - \theta_i\right)^2$$

Example

Tsai 1978

Y-cut $LiNbO_3$

Ti indiffusion

waveguide horn 4.7 mm

tapering from 4 μm to 40 μm in width

$\lambda = 6328 \text{Å}$

$\Rightarrow$ $V \approx 50V$ Complete switching

Cross talk to port 3 with $V=0$ −15 dB

Switching speed 6 GHz

9.7 Comparison of Waveguide Modulators To Bulk Electro-Optic Modulators

P_e : average external power

$$P_e = (\Delta f)\,\mathcal{W}$$

the energy supplied from an external source

Bandwidth

For an ideal EO modulator with no ohmic losses, all this goes into the stored electric field between the electrodes. Hence, we can take

$$\mathcal{W} = \frac{1}{2}\int \epsilon E_a^2\, dV$$

peak amplitude of the applied field

permittivity

$$\approx \frac{\epsilon}{2} E_a^2 (WL)\, t$$

thickness

Length

Width

$$\therefore\ P_e = \frac{\Delta f\, \epsilon\, W t L\, E_a^2}{2}$$

Modulating Power $\propto$ Active Volume

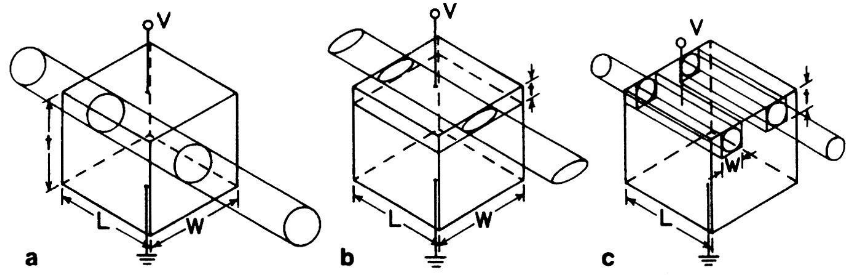


Fig. 9.13a–c.

Examples : GaAs, r_{41}, single channel

$$\Delta n = \frac{1}{2} n_2^3 r_{41} \mathcal{E} \qquad (\mathcal{E} = E_a)$$

$$\therefore\ P_e = \frac{2\,\Delta f\, \epsilon\, W t L}{n_2^6\, r_{41}^2} (\Delta n)^2$$

For the special case of the dual-channel 100% modulator

$$\Delta n = \frac{\sqrt{3}\,\pi}{kL} = \frac{\sqrt{3}\,\lambda_0}{2L}$$

$$\therefore\ P_e = \frac{3\,\epsilon\, W t\, \lambda_0^2}{2 n_2^6\, r_{41}^2 L}$$

Typical numerical values

$w = 6\ \mu m \quad t = 3\ \mu m \quad \lambda_0 = 0.9\ \mu m$

$n_2 = 3.6 \quad r_{41} = 1.2 \times 10^{-12}\ m/V$

$\frac{\epsilon}{\epsilon_0} = 12, \quad L = 0.5\ cm$

$$\frac{P_e}{\Delta f} = 0.148\ mW/MHz$$

$$\begin{cases} \text{Planar} & \frac{P_e}{\Delta f} \approx 10 \text{ times large} & \because\ W \uparrow \\ \text{bulk} & 100 \sim 1000 & W, t \uparrow \end{cases}$$

Correction

The calculated $\frac{P_e}{\Delta f}$ is based on the assumption that the optical fields and the electric field are both uniformly confined to a volume V

$V = WtL$

* Actual case P_e'

$$P_e' = \frac{2(\Delta f)\epsilon\left(\frac{W}{c_1}\right)\left(\frac{t}{c_2}\right)L}{n_2^6\, r_{41}^2}\,\Delta n^2 < P_e$$

$c_1 > 1, \quad c_2 > 1 \qquad$ Needs less power

9.8 Traveling Wave Electrode Configurations

For high frequency operation, the dimension of the electrode should not be regarded as "lumped"

z: characteristic impedance of a traveling wave electrode

$$\frac{1}{z} = \frac{c}{\sqrt{e_{eff}}}\left(\frac{C}{L}\right)$$

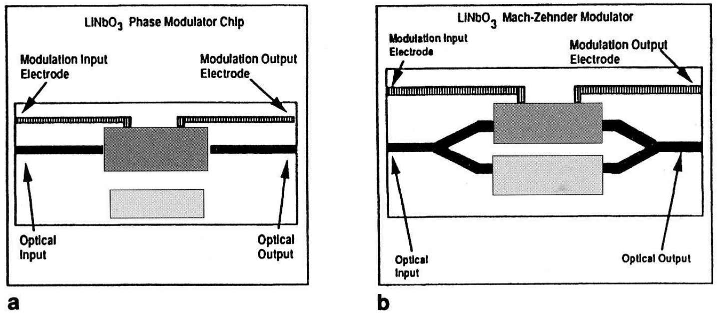


Fig. 9.14a,b.

Electrodes with Coplanar Waveguide (CPW) structure

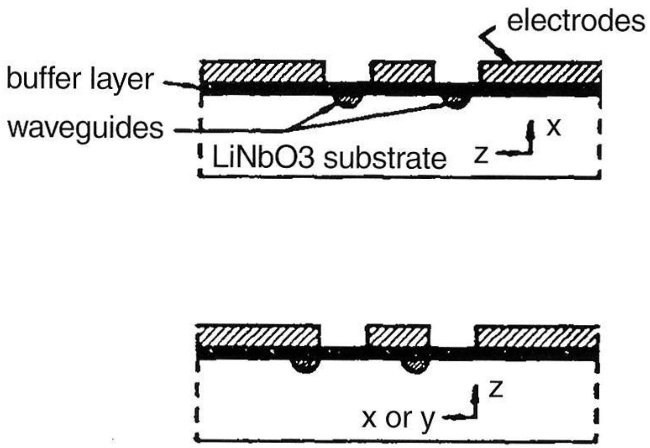


Fig. 9.15.