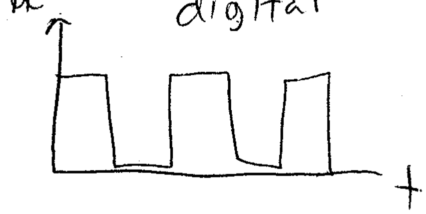
waveguide modulators

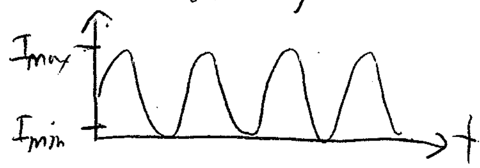
direct laser modulation - simple AM, cheap
but chirp @ high speeds (both AM + FM)

external modulation - pure FM or AM. or PM
more expensive

digital



analog



figures of merit

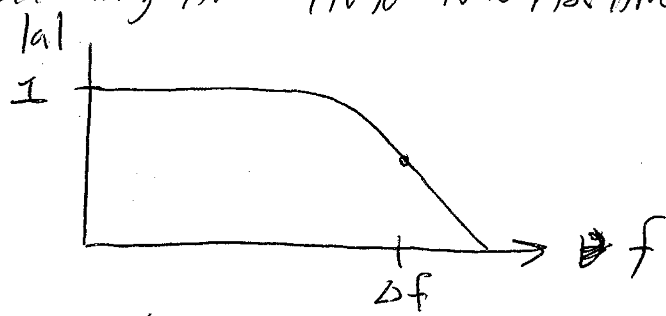
modulation efficiency, amplitude $\eta = \frac{I_{max} - I_{min}}{I_{max}} \times 100\%$

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

contrast ratio $= 10 \log \frac{I_{max}}{I_{min}}$

bandwidth - 3dB point of modulation transfer function, Δf

switching time (10% - 90% rise time) $\tau = .35/\Delta f$



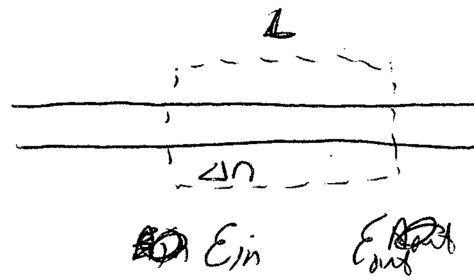
insertion loss $L = 10 \log \frac{P_{out}}{P_{in}}$ P_{out} = power w/o mod
P_{in} = power w/ mod @ max transmission

power consumption - power/unit bandwidth or power/unit radian

isolation $= 10 \log \frac{I_2}{I_1}$

ratio of switched to not switched

Phase modulators



~~A_{out}~~ ~~A_{in}~~

$$E_{out} = E_{in}\, e^{-j(\beta + \Delta\beta)z}$$

$\Delta\beta = \frac{2\pi}{\lambda}\Delta n$ total phase change $= \Delta\phi = \Delta\beta L$

Δn can result from:
- temperature (thermo-optic)
- electric field (electro-optic, electrostriction)
- strain (strain-optic) (acousto-optic)

with thermo-optic, n and L can change

$$\frac{d(nL)}{dT} = L\frac{dn}{dT} + n\frac{dL}{dT}$$ $\frac{dn}{dT}$ usually dominates

for Si: $\frac{dn}{dT} \sim 1.86 \times 10^{-4}/K$

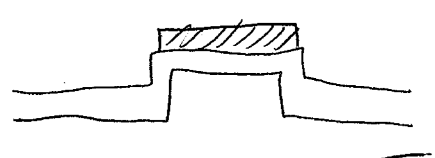
for π phase shift, assume $L = 1\text{mm}$, $\lambda = 1\mu m$

$$\frac{2\pi}{\lambda}\Delta n \cdot L = \frac{2\pi}{\lambda}\frac{dn}{dT}\Delta T \cdot L = \pi$$

$$\Delta T = \lambda / L \cdot dn/dT = 1\mu m / 1mm \cdot 1.86 \times 10^{-4}\ 1/K$$

$$= 1/.186\ K \sim 5\text{-}6\ K$$

heater element typically NiCr, used as resistive heater



response time typically in ms range, but depends on thermal conductivity

SiO_2	1.4	W/m·K
SiON	1.4	
Si	140	
NiCr	100	

can be sub-10μs in Si channel w.g.
(100x slower in glasses)
in SiON/Si, 2W/π