Integrated Modulator II --- Acousto-Optics

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

Fundamental Principles of AO effect

$\boxed{\text{Mechanical strain in a solid causes a change in the index of refraction}}$

$$\Delta n = \sqrt{n^6 p^2 10^7 P_a / (2\rho \upsilon_a{}^3 A)}$$

Cross-Section Area

Refractive Index (unstrained)

Photoelastic Tensor

Acoustic Power

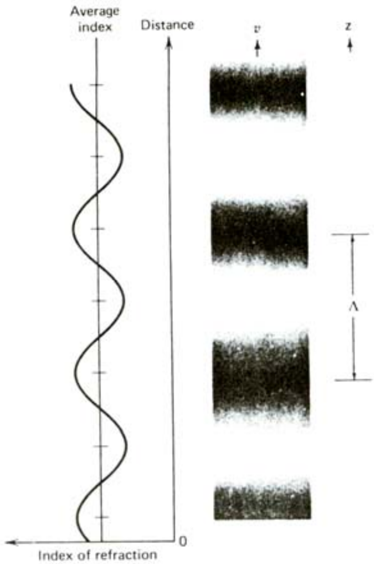
Mass Density

Acoustic Velocity

$$\Delta n = \sqrt{M_2 10^7 P_a / (2A)} \quad \text{where} \quad M_2 \equiv \frac{n^6 p^2}{\rho \upsilon_a{}^3} \quad \text{(AO figure of merit)}$$

- In crystalline solids, the AO effect (photoelastic effect) depends strongly on the orientation (p).
- Overall, the AO effect is small (10^{-4}) even for an acoustic power density 100W/cm^2
- Both bulk acoustic waves and surface acoustic waves (planar waveguide) are used

Fundamental Principles of AO effect



The acousto-optic effects are traditionally defined in terms of the changes in the elements of the relative impermeability tensor

$$\Delta\eta_i = p_{ij}S_j$$

i = 1,…6

j = 1,…6

Strain-optic Tensor

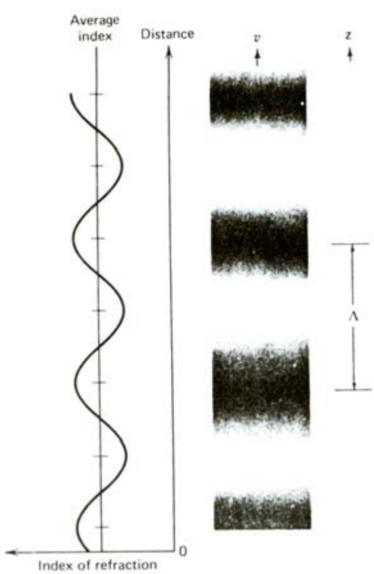
Strain (strain tensor is symmetric)

Acoustic Wave (strain)

$$\vec{u}(z,t) = \vec{S}\sin(\Omega t - \vec{K}\cdot\vec{r})$$

$$\left|\vec{K}\right| = \frac{2\pi}{\Lambda}$$

Fundamental Principles of AO effect



The equation of index ellipsoid in the presence of strain field can be written by

$$\begin{aligned}
&x^2\left(\frac{1}{n_x^2} + p_{11}S_1 + p_{12}S_2 + p_{13}S_3 + p_{14}S_4 + p_{15}S_5 + p_{16}S_6\right)\\
&+y^2\left(\frac{1}{n_y^2} + p_{21}S_1 + p_{22}S_2 + p_{23}S_3 + p_{24}S_4 + p_{25}S_5 + p_{26}S_6\right)\\
&+z^2\left(\frac{1}{n_z^2} + p_{31}S_1 + p_{32}S_2 + p_{33}S_3 + p_{34}S_4 + p_{35}S_5 + p_{36}S_6\right)\\
&+2yz(p_{41}S_1 + p_{42}S_2 + p_{43}S_3 + p_{44}S_4 + p_{45}S_5 + p_{46}S_6)\\
&+2zx(p_{51}S_1 + p_{52}S_2 + p_{53}S_3 + p_{54}S_4 + p_{55}S_5 + p_{56}S_6)\\
&+2xy(p_{61}S_1 + p_{62}S_2 + p_{63}S_3 + p_{64}S_4 + p_{65}S_5 + p_{66}S_6) = 1
\end{aligned}$$

where n_x, n_y, n_z are the principle indices of refraction

Examples of Strain-Optic Tensor

Triclinic (36)†

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{26} \\ p_{31} & p_{32} & p_{33} & p_{34} & p_{35} & p_{36} \\ p_{41} & p_{42} & p_{43} & p_{44} & p_{45} & p_{46} \\ p_{51} & p_{52} & p_{53} & p_{54} & p_{55} & p_{56} \\ p_{61} & p_{62} & p_{63} & p_{64} & p_{65} & p_{66} \end{pmatrix}$$

Monoclinic (20)

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & p_{15} & 0 \\ p_{21} & p_{22} & p_{23} & 0 & p_{25} & 0 \\ p_{31} & p_{32} & p_{33} & 0 & p_{35} & 0 \\ 0 & 0 & 0 & p_{44} & 0 & p_{46} \\ p_{51} & p_{52} & p_{53} & 0 & p_{55} & 0 \\ 0 & 0 & 0 & p_{64} & 0 & p_{66} \end{pmatrix}$$

Orthorhombic (12)

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & 0 \\ p_{21} & p_{22} & p_{23} & 0 & 0 & 0 \\ p_{31} & p_{32} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{66} \end{pmatrix}$$

Tetragonal (10)
classes $4, \bar{4}, 4/m$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & p_{16} \\ p_{12} & p_{11} & p_{13} & 0 & 0 & -p_{16} \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & p_{45} & 0 \\ 0 & 0 & 0 & -p_{45} & p_{44} & 0 \\ p_{61} & -p_{61} & 0 & 0 & 0 & p_{66} \end{pmatrix}$$

Tetragonal (7)
classes $4mm, 422, 4/mmm$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{13} & 0 & 0 & 0 \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{66} \end{pmatrix}$$

Trigonal (12)
classes $3, \bar{3}$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{16} \\ p_{12} & p_{11} & p_{13} & -p_{14} & -p_{15} & -p_{16} \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ p_{41} & -p_{41} & 0 & p_{44} & p_{45} & -p_{51} \\ p_{51} & -p_{51} & 0 & -p_{45} & p_{44} & p_{41} \\ -p_{16} & p_{16} & 0 & -p_{15} & p_{14} & \frac{1}{2}(p_{11}-p_{12}) \end{pmatrix}$$

Trigonal (8)
classes $3m, 32, \bar{3}m$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & p_{14} & 0 & 0 \\ p_{12} & p_{11} & p_{13} & -p_{14} & 0 & 0 \\ p_{13} & p_{13} & p_{33} & 0 & 0 & 0 \\ p_{41} & -p_{41} & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & p_{41} \\ 0 & 0 & 0 & 0 & p_{14} & \frac{1}{2}(p_{11}-p_{12}) \end{pmatrix}$$

Hexagonal (8)
classes $6, \bar{6}, 6/m$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & p_{16} \\ p_{12} & p_{11} & p_{13} & 0 & 0 & -p_{16} \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & p_{45} & 0 \\ 0 & 0 & 0 & -p_{45} & p_{44} & 0 \\ -p_{16} & p_{16} & 0 & 0 & 0 & \frac{1}{2}(p_{11}-p_{12}) \end{pmatrix}$$

Hexagonal (6)
classes $\bar{6}m2, 6mm, 622, 6/mmm$

$$\begin{pmatrix} p_{11} & p_{12} & p_{13} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{13} & 0 & 0 & 0 \\ p_{31} & p_{31} & p_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}(p_{11}-p_{12}) \end{pmatrix}$$

Cubic (4)
classes $23, m3$

$$\begin{pmatrix} p_{11} & p_{12} & p_{21} & 0 & 0 & 0 \\ p_{21} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{21} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{pmatrix}$$

Cubic (3)
classes $\bar{4}3m, 432, m3m$

$$\begin{pmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{pmatrix}$$

A. Yariv, "Optical Waves in Crystals"

Examples of Strain-Optic Tensor

Table 9.1. (*Continued*).

Isotropic (2)

$$\begin{pmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2}(p_{11}-p_{12}) & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2}(p_{11}-p_{12}) & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2}(p_{11}-p_{12}) \end{pmatrix}$$

†The number inside the parentheses indicates the number of independent coefficients.

A. Yariv, "Optical Waves in Crystals"

Examples of Strain-Optic Tensor

Table 9.2. Strain–Optic Coefficients[a] [1]

(a) Isotropic System

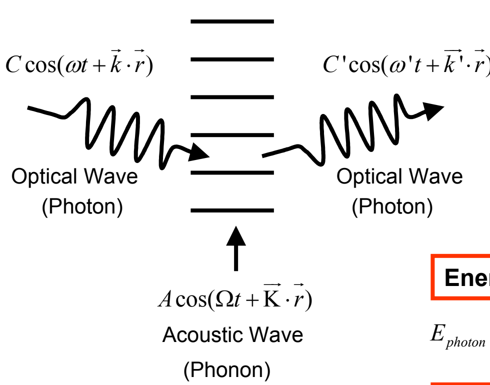
Substance	Wavelength λ (μm)	p_{11}	p_{12}
Fused silica (SiO_2)	0.63	0.121	0.270
As_2S_3 glass	1.15	0.308	0.299
Water	0.63	±0.31	±0.31
$Ge_{33}Se_{55}As_{12}$ (glass)	1.06	±0.21	±0.21
Lucite	0.63	±0.30	±0.28
Polystyrene	0.63	±0.30	±0.31

(b) Cubic System: Classes $\bar{4}3m$, 432, and m3m

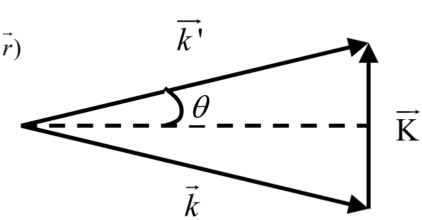
Substance	Wavelength λ (μm)	p_{11}	p_{12}	p_{44}	$p_{11}-p_{12}$
CdTe	10.60	-0.152	-0.017	-0.057	-0.135
GaAs	1.15	-0.165	-0.140	-0.072	-0.025
GaP	0.633	-0.151	-0.082	-0.074	-0.069
Ge	2.0–2.2	-0.063	-0.0535	-0.074	-0.0095
	10.60	0.27	0.235	0.125	
NaCl	0.55–0.65	0.115	0.159	-0.011	-0.042

A. Yariv, "Optical Waves in Crystals"

Particle Picture of Acousto-optic Interaction



Momentum (wave vector)



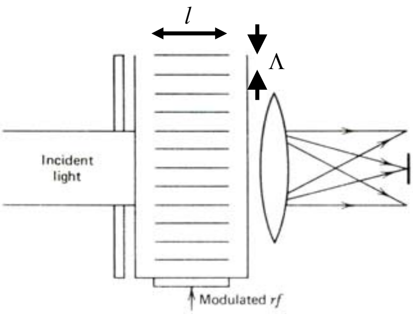
Energy Conservation:

$$E_{photon}' = E_{photon} + E_{phonon} \rightarrow \omega' = \omega + \Omega$$

Momentum Conservation:

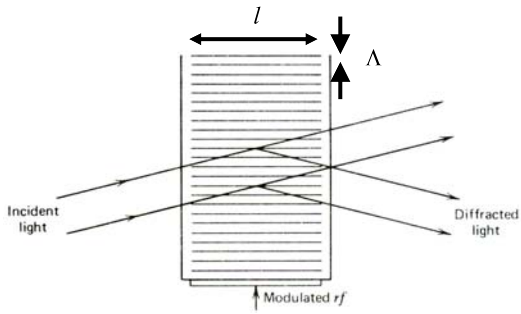
$$\vec{p}_{photon}' = \vec{p}_{photon} + \vec{p}_{phonon} \rightarrow \vec{k}' = \vec{k} + \vec{K}$$

Raman-Nath-Type vs. Bragg-Type Modulators



Raman-Nath-Type Modulator

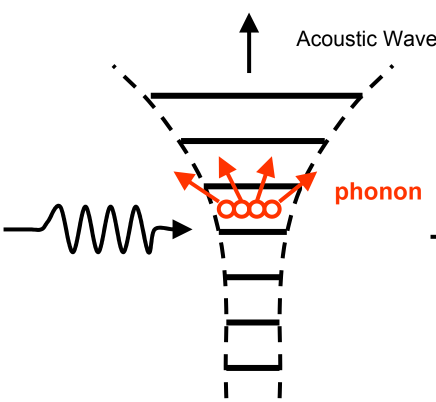
$l \ll \dfrac{\Lambda^2}{\lambda}$



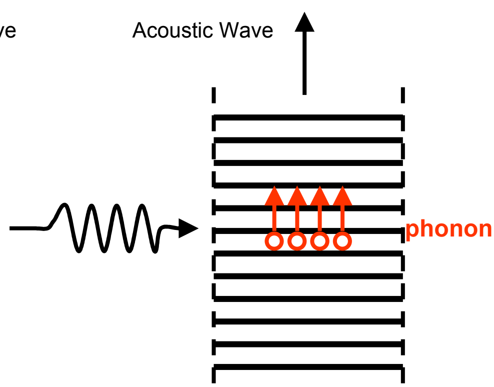
Bragg-Type Modulator

$l \gg \dfrac{\Lambda^2}{\lambda}$

Momentum Figures of Raman-Nath Scattering and Bragg Scattering



Raman-Nath Scattering



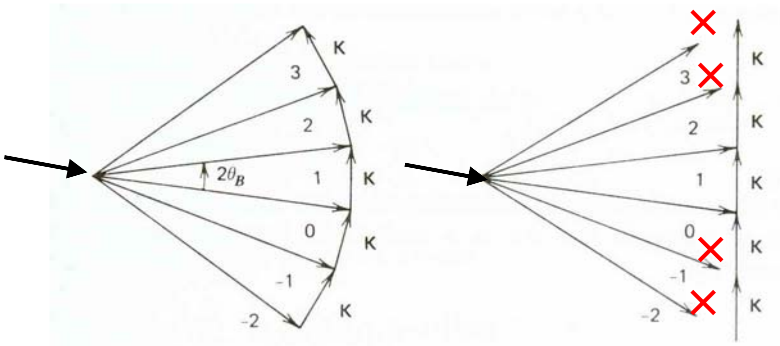
Bragg Scattering

- **In Raman-Nath cases, the direction of phonon momentum or the wavevector of acoustic wave is diverged**

Momentum Figures of Raman-Nath Scattering and Bragg Scattering

Multiple Beam Diffraction

Bragg Diffraction



Multiple Raman-Nath Scattering

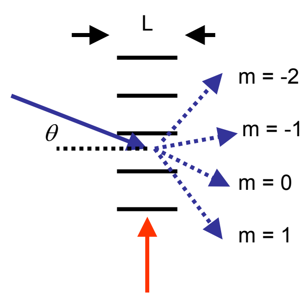
Multiple Bragg Scattering

- **In Bragg scattering cases, since the phonon momentum is constant, multiple scattering is difficult due to momentum non-conservative (phase mismatched)**

Intensity Modulation of Raman-Nath AO Modulator

To evaluate the diffraction efficiencies associated with each diffraction order, we consider the periodically perturbed sheet acting as a phase grating

$$\Delta n(x,y,z,t)=\begin{cases}\Delta n_0 \sin(\Omega t-\vec{K}\cdot\vec{r}) & 0<z<L \\ 0 & \text{Otherwise}\end{cases}$$

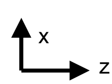


An incident optical wave

$$E=E_0\exp\left[j(\omega t-\vec{k}\cdot\vec{r})\right]$$

Thus, the transmitted wave can be written

$$E_t=E_0\exp\left[-j\phi+j(\omega t-\vec{k}\cdot\vec{r})\right]$$



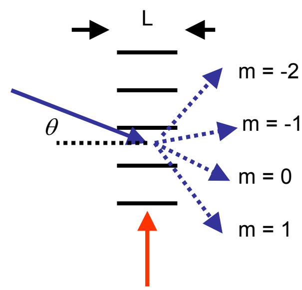
where $\phi=\int\frac{\omega}{c}\Delta n ds$ s: interaction path

Intensity Modulation of Raman-Nath AO Modulator

If L is small enough, the integration can simply be given by

$$\phi = \frac{\omega}{c}\Delta n_0 \frac{L}{\cos\theta}\sin(\Omega t - \vec{K}\cdot\vec{r}) \equiv \delta \sin(\Omega t - \vec{K}\cdot\vec{r})$$

modulated index



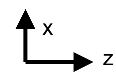
Then the transmitted wave

$$E_t = E_0 \exp\left[-j\delta\sin(\Omega t - \vec{K}\cdot\vec{r}) + j(\omega t - \vec{k}\cdot\vec{r})\right]$$

By using the identity for Bessel functions

$$e^{-j\delta\sin x} = \sum_{m=-\infty}^{\infty} J_m(\delta) e^{-jmx}$$

$$E_t = E_0 \sum_{m=-\infty}^{\infty} J_m(\delta)\exp\left[j(\omega - m\Omega)t - j(\vec{k} - m\vec{K})\cdot\vec{r}\right]$$



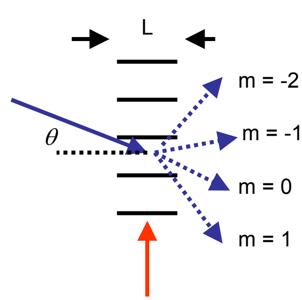
Intensity Modulation of Raman-Nath AO Modulator

The diffraction efficiency for the mth-order Raman-Nath diffraction is

$$\eta_m = J_m^{\,2}(\delta) = J_m^{\,2}\left(\frac{2\pi L \Delta n_0}{\lambda\cos\theta}\right)$$

The diffraction efficiency for the order of m = 1 or -1 is maximum when the modulation index

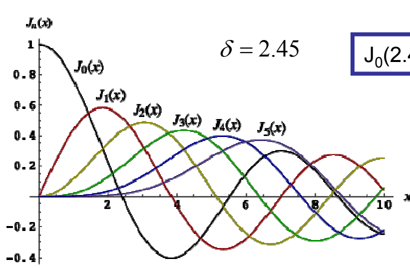
$$\delta = 1.85$$

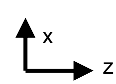


The zeroth order is completely quenched as

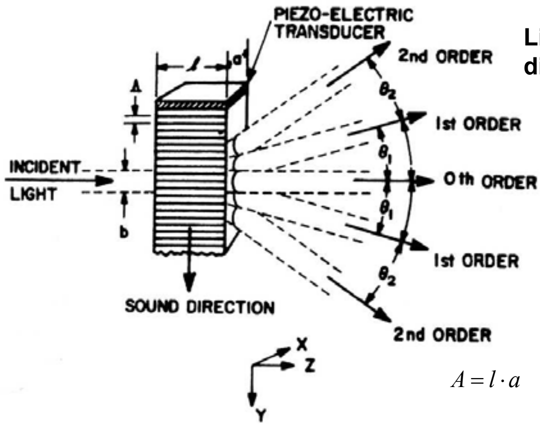
$$\delta = 2.45$$

$\boxed{J_0(2.45)=0}$





Raman-Nath-Type Modulators



Light passing through in the z-direction undergoes a phase shift

$$\Delta\varphi = \frac{\Delta n 2\pi l}{\lambda_0}\sin\left(\frac{2\pi y}{\Lambda}\right)$$

Δn : index change (AO)

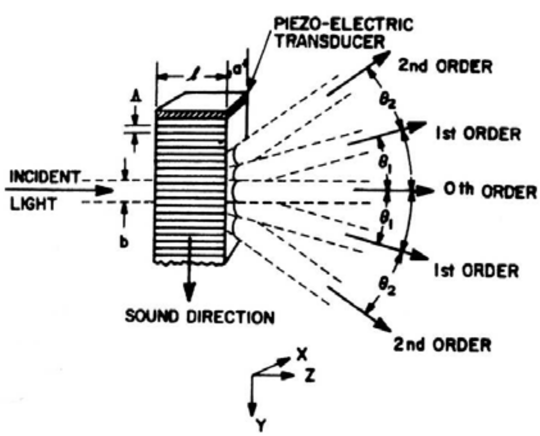
l : interaction length

Λ : acoustic wavelength

$$A = l \cdot a \qquad \Delta\varphi = \frac{2\pi}{\lambda_0}\sqrt{\frac{M_2 10^7 P_a l}{2a}}\sin\left(\frac{2\pi y}{\Lambda}\right)$$

- The optical beam is incident transversely to the acoustic beam.
- The optical waves undergo a simple phase grating diffraction (short acoustic beam width)

Raman-Nath-Type Modulators



For Raman-Nath type diffraction, the interaction length should be small

$$l \ll \frac{\Lambda^2}{\lambda}$$

The diffraction angle (mode)

$$\sin\theta = \frac{m\lambda_o}{\Lambda},\ m = 0, \pm 1, \pm 2, \ldots$$

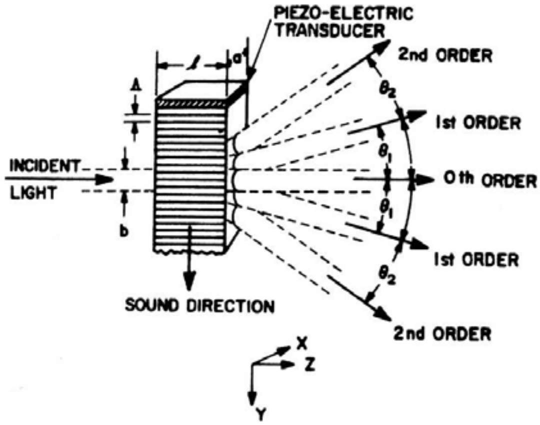
The intensity of these order modes

$$\frac{I}{I_0} = \begin{cases} [J_m(\Delta\varphi')]^2/2, & |m| > 0 \\ [J_0(\Delta\varphi')]^2, & |m| = 0 \end{cases}$$

where $\Delta\varphi' = \max\{\Delta\varphi\} = \dfrac{\Delta n 2\pi l}{\lambda_0} = \dfrac{2\pi}{\lambda_0}\sqrt{\dfrac{M_2 10^7 P_a l}{2a}}$

I_0 : the intensity of the transmitted optical beam in the absent of acoustic waves

Raman-Nath-Type Modulators



The output channel is usually taken to be the zeroth-order mode. The modulation index is defined by

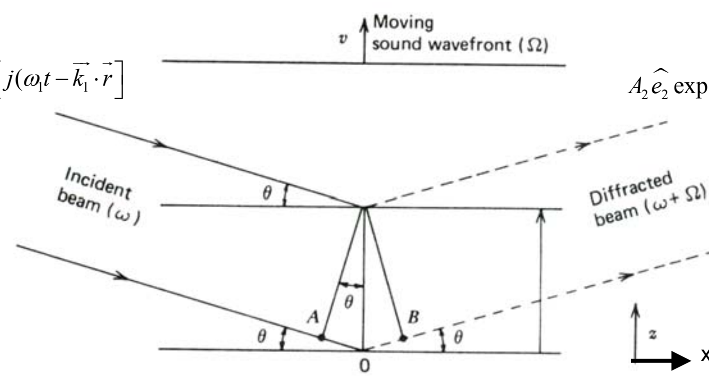
$$\eta_{RN} = \frac{[I_0 - I(m=0)]}{I_0} = 1 - \left[J_0\left(\Delta\varphi'\right)\right]^2$$

- Raman-Nath modulators generally have a smaller modulation index
- They can not be used as switches because the light is distributed over many orders

Intensity Modulation of Bragg-type AO Modulator

$A_1 \widehat{e_1} \exp\left[j(\omega_1 t - \vec{k_1} \cdot \vec{r}\right]$

$A_2 \widehat{e_2} \exp\left[j(\omega_2 t - \vec{k_2} \cdot \vec{r}\right]$



$$\begin{aligned} \vec{E} &= A_1 \widehat{e_1} \exp\left[j(\omega_1 t - \vec{k_1} \cdot \vec{r}\right] + A_2 \widehat{e_2} \exp\left[j(\omega_2 t - \vec{k_2} \cdot \vec{r}\right] \\ &= A_1 \widehat{e_1} \exp\left[j(\omega_1 t - \alpha_1 x - \beta_1 z\right] + A_2 \widehat{e_2} \exp\left[j(\omega_2 t - \alpha_2 x - \beta_2 z\right] \end{aligned}$$

x-component z-component

all the wavevectors are on x-z plane

Intensity Modulation of Bragg-type AO Modulator

The electric field E must satisfy the following wave equation:

$$\left(\nabla^2+\omega^2\mu\varepsilon+\omega^2\mu\Delta\varepsilon\right)E=0$$

Photoelastic perturbation

According to the expression of electric field in the previous slide

$$\sum_{m=1,2}\left[\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial z^2}-2j\beta_m\frac{\partial}{\partial z}-2j\alpha_m\frac{\partial}{\partial x}\right]A_m\widehat{e_m}\exp\left[j(\omega_m t-\alpha_m x-\beta_m z)\right]$$

$$=-\omega^2\mu\sum_{i=1,2}\Delta\varepsilon A_i\widehat{e_i}\exp\left[j(\omega_i t-\alpha_i x-\beta_i z)\right]$$

$$\varepsilon_1\left\{\exp\left[j(\Omega t-\mathrm{K}z)\right]+\exp\left[-j(\Omega t-\mathrm{K}z)\right]\right\}$$

Suppose the second derivatives are neglected and only the first derivative remains

$$\frac{\partial^2}{\partial x^2}=0\qquad\frac{\partial^2}{\partial z^2}=0$$

Intensity Modulation of Bragg-type AO Modulator

Suppose A_1 and A_2 only vary in x direction

$$-2j\alpha_1\frac{dA_1}{dx}\widehat{e_1}\exp\left[j(\omega_1 t-\alpha_1 x-\beta_1 z)\right]-2j\alpha_2\frac{dA_2}{dx}\widehat{e_2}\exp\left[j(\omega_2 t-\alpha_2 x-\beta_2 z)\right]$$

$$=-\omega^2\mu\left\{\varepsilon_1\exp\left[j(\Omega t-\mathrm{K}z)\right]+\varepsilon_1\exp\left[-j(\Omega t-\mathrm{K}z)\right]\right\}$$

$$\times\left\{A_1\widehat{e_1}\exp\left[j(\omega_1 t-\alpha_1 x-\beta_1 z)\right]+A_2\widehat{e_2}\exp\left[j(\omega_2 t-\alpha_2 x-\beta_2 z)\right]\right\}$$

By scalar multiplication $\widehat{e_i}^*\exp\left[-j(\omega_i t-\alpha_i x-\beta_i z)\right]$ i=1,2

$$\frac{dA_1}{dx}=-j\kappa_{12}A_2\exp(j\Delta\alpha x)$$

$$\frac{dA_2}{dx}=-j\kappa_{12}^*A_1\exp(-j\Delta\alpha x)$$

supposing

$$\boxed{\theta_B=\sin^{-1}\left(\frac{\mathrm{K}}{2k}\right)=\sin^{-1}\left(\frac{\lambda}{2\Lambda n}\right)}$$

$$\beta_2=\beta_1\pm\mathrm{K}$$
$$\omega_2=\omega_1\pm\Omega$$

(+: phonon absorbed
-: phonon generated)

where $\kappa_{12}=\dfrac{\sqrt{\omega_1\omega_2}}{4\mu}\left[\widehat{e_1}^*\cdot\varepsilon_1\cdot\widehat{e_2}\right]$

Intensity Modulation of Bragg-type AO Modulator

Suppose the x-direction momentum matched

$$\Delta\alpha = 0$$

The coupled equations become

$$\frac{dA_1}{dx} = -j\kappa_{12}A_2$$
$$\frac{dA_2}{dx} = -j\kappa_{12}^{*}A_1$$

The solution is

$$A_1(x) = A_1(0)\cos\kappa x - j\frac{\kappa_{12}}{\kappa}A_2(0)\sin\kappa x$$
$$A_2(x) = A_2(0)\cos\kappa x - j\frac{\kappa_{12}^{*}}{\kappa}A_1(0)\sin\kappa x$$

where $\kappa = |\kappa_{12}|$

Intensity Modulation of Bragg-type AO Modulator

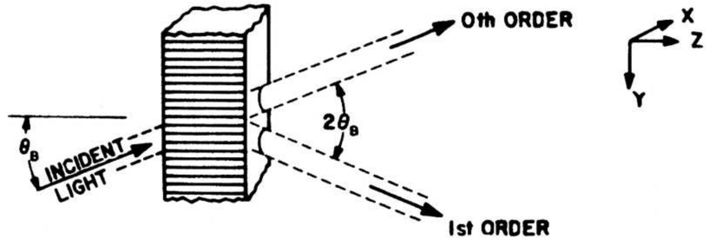
In the special case of a single wave incident at x = 0, the solution is

$$A_1(x) = A_1(0)\cos\kappa x$$
$$A_2(x) = -j\frac{\kappa_{12}^{*}}{\kappa}A_1(0)\sin\kappa x$$

The fraction of the power of the incident beam transferred in a distance L into the diffracted beam

$$\frac{I_{diffrected}}{I_{incident}} = \frac{|A_2(L)|^2}{|A_1(0)|^2} = \sin^2\kappa L$$

Bragg-Type Modulators



For Bragg-type diffraction, the interaction length between the optical and acoustic beams must be relatively long. Therefore, the multiple diffraction can occur

$$l \gg \frac{\Lambda^2}{\lambda}$$

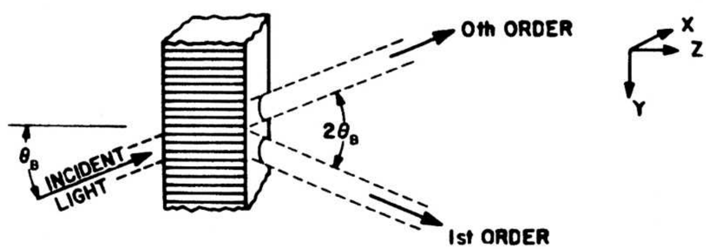
effective wavelength

In the case of Bragg-type modulators, the input angle of incident beam should be the Bragg angle

$$\sin\theta_B = \frac{\lambda}{2\Lambda n}$$

n: refractive index

Bragg-Type Modulators

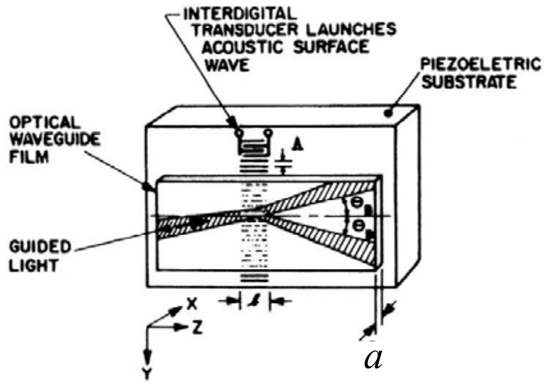


Generally, the output of modulator is taken to be the zeroth-order beam. Therefore, the modulation index is given

$$\eta_B = \frac{I_0 - I}{I_0} = \sin^2\left(\frac{\Delta\varphi'}{2}\right)$$ **Recall** $$\Delta\varphi' = \max\{\Delta\varphi\} = \frac{\Delta n 2\pi l}{\lambda_0} = \frac{2\pi}{\lambda_0}\sqrt{\frac{M_2 10^7 P_a l}{2a}}$$

$$\longrightarrow \quad \eta_B = \frac{I_0 - I}{I_0} = \sin^2\left[\frac{\pi}{\lambda_0}\sqrt{\frac{10^7 M_2 P_a l}{2a}}\right]$$

Waveguide AO Bragg Modulators



- **The drive power can be reduced in waveguide-based AO modulators**

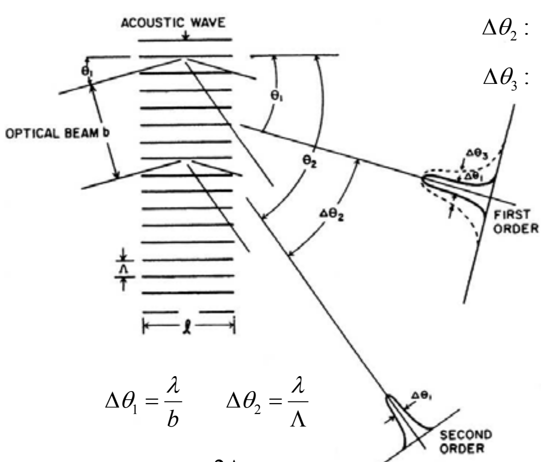
$$\eta_B = \sin^2\left[\frac{\pi}{\lambda_0}\sqrt{\frac{10^7 M_2 P_a l}{2a}}\right] \qquad a \downarrow \text{ then } P_a \downarrow$$

Bragg-Type Beam Deflectors and Switches

$\Delta\theta_1$: **half intensity width**

$\Delta\theta_2$: **angular separation of the peaks**

$\Delta\theta_3$: **half intensity width of scanned angle**



In fact, the AO frequency is equivalent to a frequency shift of optical frequency (Doppler Effect)

The variation of acoustic frequency will reduce the intensity (spoil Bragg condition)

$$\Delta\theta_1 = \frac{\lambda}{b} \qquad \Delta\theta_2 = \frac{\lambda}{\Lambda}$$

$$\Delta\theta_3 = \frac{2\Lambda}{l}$$

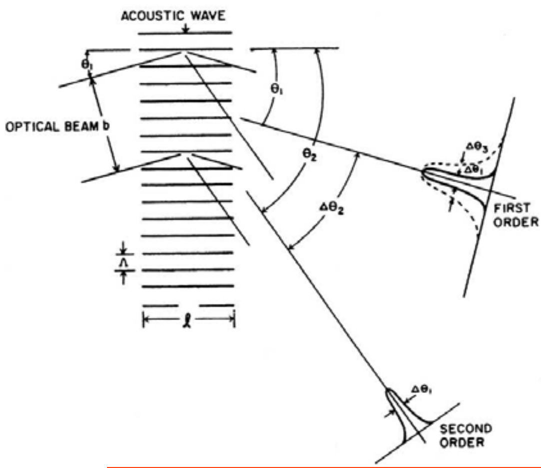
quasi-Raman-Nath

Acoustic wave velocity

$$\Delta f_0 \cong \frac{2\upsilon_a \Lambda}{\lambda l}$$

(bandwidth of half intensity due to variation)

Bragg-Type Beam Deflectors and Switches



The overall response time τ (bandwidth) is limited by the three factors

$$\tau = \frac{1}{\Delta f_0} + \frac{1}{\Delta f_a} + t \qquad t = \frac{b}{\upsilon_a}$$

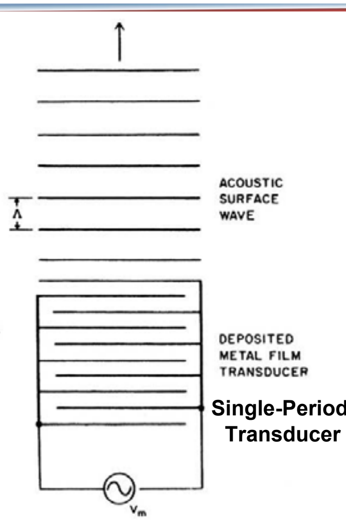
frequency variation range

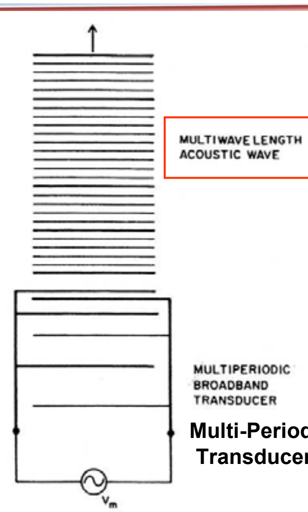
transducer bandwidth

acoustic transit time

How to increase the bandwidth Δf_0

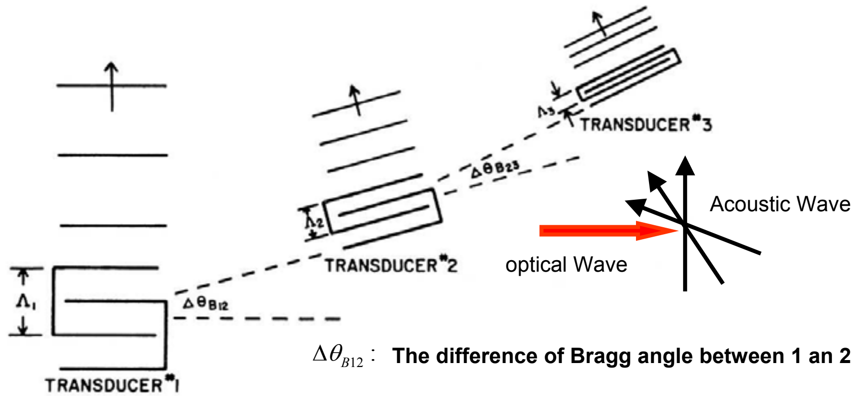
Single Chirp-Transducer





- **Both wide bandwidth and high diffraction efficiency are obtained**

Multi-Period Transducers in a Tilted Array

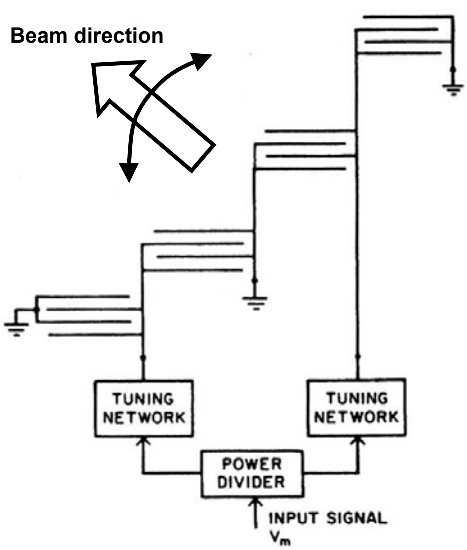


$\Delta\theta_{B12}$: **The difference of Bragg angle between 1 an 2**

$\Delta\theta_{B23}$: **The difference of Bragg angle between 2 an 3**

- **The composite of surface acoustic waves can satisfy the Bragg condition in multiple frequency ranges.**

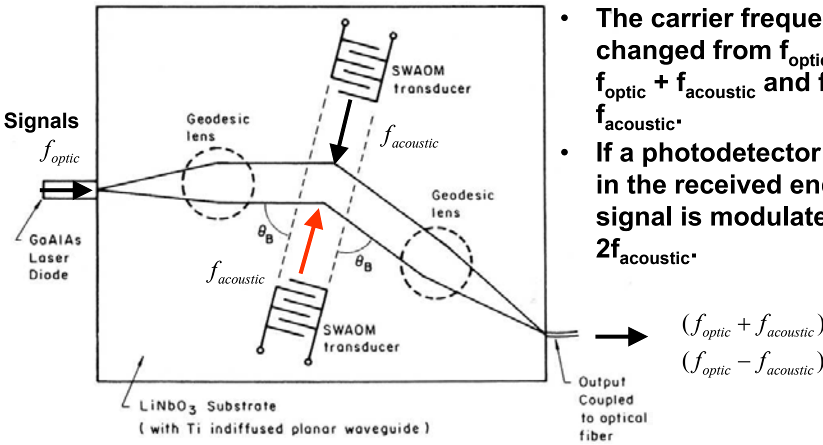
Phase Array Transducer



- **The transducers are arranged in a stepped configuration, resulting in a spatial phase shift.**
- **The acoustic wave beam is scanned as the frequency changes (like a scanning radar)**
- **The scanning acoustic beam automatically tracks the Bragg-condition**

Ming-Chang Lee, Integrated Photonic Devices

Acousto-Optic Frequency Shifter



- The carrier frequency is changed from f_{optic} to $f_{optic} + f_{acoustic}$ and $f_{optic} - f_{acoustic}$.
- If a photodetector is put in the received end, the signal is modulated at $2f_{acoustic}$.

- It can be applied in RF photonics and frequency division multiplexing.