Class overview:

1. Brief review of physical optics, wave propagation, interference, diffraction, and polarization
2. Introduction to Integrated optics and integrated electrical circuits
3. Guide-wave optics: 2D and 3D optical waveguide, optical fiber, mode dispersion, group velocity and group velocity dispersion.
4. Mode-coupling theory, Mach-zehnder interferometer, Directional coupler, taps and WDM coupler.
5. Electro-optics, index tensor, electro-optic effect in crystal, electro-optic coefficient
6. Electro-optical modulators
7. Passive and active optical waveguide devices, Fiber Optical amplifiers and semiconductor optical amplifiers, Photonic switches and all optical switches
8. Opto-electronic integrated circuits (OEIC)

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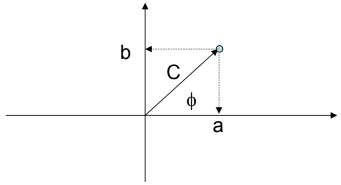
Complex numbers

$c = a + ib$ or $Ce^{i\phi}$ C: amplitude ϕ: angle



$c_1 \pm c_2 = (a_1 \pm a_2) + i(b_1 \pm b_2)$

Real numbers do not have phases

Complex numbers have phases

$Ce^{i\phi}$ ϕ is the phase of the complex number

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Physical meaning of multiplication of two complex numbers

$$c_1 \cdot c_2 = C_1 e^{i\phi_1} \cdot C_2 e^{i\phi_2} = C_1 \cdot C_2 e^{i(\phi_1+\phi_2)}$$

$C_1 e^{i\phi_1}$ → $C_2 e^{i\phi_2}$ →

Number: $C_1 \cdot C_2$

Phase: $\phi_1 + \phi_2$

C_2 times

Phase delay ϕ_2

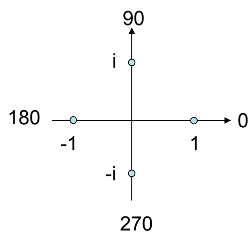
Why $i \cdot i = -1$?

$$i = 1 \cdot e^{i\frac{\pi}{2}}$$

$$i \cdot i = 1 \cdot 1 \cdot e^{i(\frac{\pi}{2}+\frac{\pi}{2})} = e^{i(\pi)}$$

$$i^3 = -i \qquad i^4 = 1$$

$$\sqrt{-1} = \pm i \qquad \sqrt[4]{1} = \pm i; \pm 1$$



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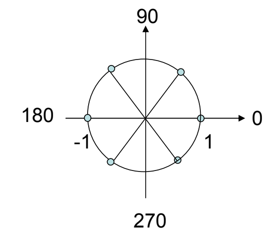
$$\sqrt[6]{1} = ?$$

$$\sqrt[6]{1} = e^{i(\frac{2\pi}{6}n)}, n = 0,1 \ldots 5$$

$$\sqrt[12]{2} = \sqrt[12]{2} e^{i(\frac{2\pi}{12}n)}, n = 0,1 \ldots 11$$

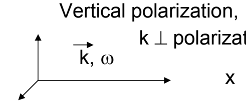


Optical wave

$Ae^{i(kx-\omega t+\phi)}$

- Initial phase
- Phase delay by time
- Phase delay by position
- Amplitude, $I=|A|^2$, Optical intensity

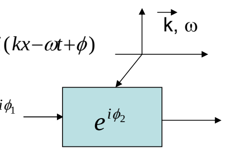
Vertical polarization,



k vector, to x-direction

Horizontal polarization

Optical wave propagation in air (free-space)



$$Ae^{i(kx-\omega t+\phi)} \qquad Ae^{i(kx-\omega t+\phi+\phi_{delay})}$$

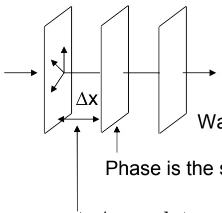
$$C_1 e^{i\phi_1} \rightarrow e^{i\phi_2}$$

Usually, ignore t term. Because look at system at the same time. Snap shoot.

$$Ae^{i(kx+\phi)}$$

Phase delay $\phi_{delay} = k \cdot x = \frac{2\pi}{\lambda} x$

Optical wave propagation in air (free-space)

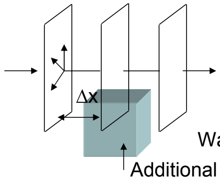


$$Ae^{i(kx+\phi)}$$

Phase is the same on the plane --- plane wave

$$\Delta\phi = k\Delta x \quad \frac{2\pi}{\lambda}\Delta x$$

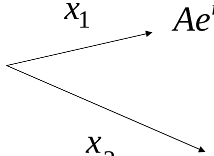
Phase distortion in atmosphere



$$Ae^{i(kx+\phi)}$$

Additional phase delay, → non ideal plane wave

Optical wave to different directions



x_1 $Ae^{i(kx_1+\phi)}$

Phase delay

$$\phi_{delay} = k\Delta x = \frac{2\pi}{\lambda}(x_1 - x_2)$$

x_2 $Ae^{i(kx_2+\phi)}$

Refractive index n

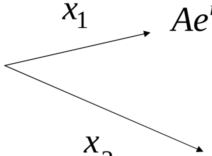
In vacuum,

$$k = \frac{2\pi}{\lambda} \quad V = c = \frac{\lambda}{T} = \lambda f$$ c: speed of light

In media, like glass,

$$k = \frac{2\pi}{\lambda/n} = \frac{2\pi}{\lambda}n \quad V = c/n = \frac{\lambda/n}{T} = \lambda f/n$$

Optical wave to different directions



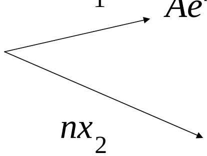
x_1 $Ae^{i(kx_1+\phi)}$

Phase delay

$$\phi_{delay} = k\Delta x = \frac{2\pi}{\lambda}(x_1 - x_2)$$

x_2 $Ae^{i(kx_2+\phi)}$

In media with refractive index n



nx_1 $Ae^{i(knx_1+\phi)}$

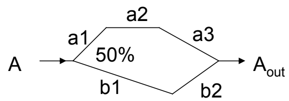
Phase delay

$$\phi_{delay} = kn\Delta x = \frac{2\pi}{\lambda}n(x_1 - x_2)$$

nx_2 $Ae^{i(knx_2+\phi)}$

nx1, nx2, optical path

Interference of two optical waves



Upper arm : $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)}$

Lower arm : $\frac{1}{2}Ae^{ikn(b_1+b_2)}$

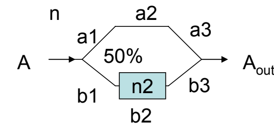
$$A_{out} = \frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} + \frac{1}{2}Ae^{ikn(b_1+b_2)}$$

Phase delay between the two arms:

$$kn(b_1 + b_2 - a_1 - a_2 - a_3)$$

If phase delay is 2mπ, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = \frac{1}{2}Ae^{ikn(b_1+b_2)}$

If phase delay is 2mπ +π, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = -\frac{1}{2}Ae^{ikn(b_1+b_2)}$



Upper arm : $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)}$

Lower arm : $\frac{1}{2}Ae^{ikn(b_1+b_2)}$

$$b_1 + b_2 + b_3 = a_1 + a_2 + a_3$$

Phase delay between the two arms:

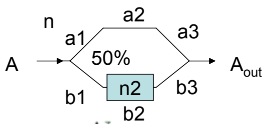
$$k(n_2 b_2 - n a_2)$$

If phase delay is 2mπ, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = \frac{1}{2}Ae^{ikn(b_1+b_2)}$

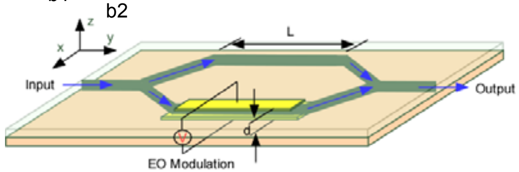
If phase delay is 2mπ +π, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = -\frac{1}{2}Ae^{ikn(b_1+b_2)}$

Electro-optic effect, n2 changes with E -field

Electro-optic modulator based on March-Zehnder interferometer



Electro-optic effect, n2 changes with E -field



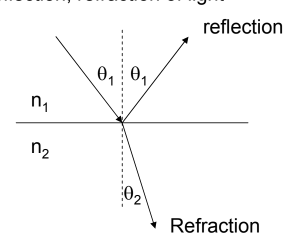
Phase delay between the two arms:

$$k(n_2 b_2 - n a_2)$$

If phase delay is 2mπ, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = \frac{1}{2}Ae^{ikn(b_1+b_2)}$

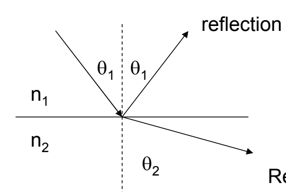
If phase delay is 2mπ +π, then: $\frac{1}{2}Ae^{ikn(a_1+a_2+a_3)} = -\frac{1}{2}Ae^{ikn(b_1+b_2)}$

Reflection, refraction of light



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

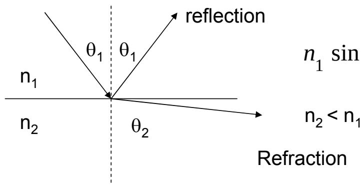
$n_2 > n_1 \Rightarrow \theta_2 < \theta_1$



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$n_2 < n_1 \Rightarrow \theta_2 > \theta_1$

Total internal reflection (TIR)



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

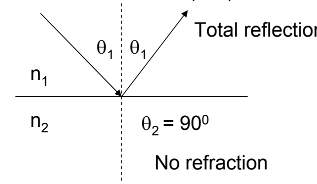
$n_2 < n_1 \Rightarrow \theta_2 > \theta_1$

When $\theta_2 = 90^0$, θ_1 is critical angle

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \,|_{\theta_2 = 90^0} = n_2,$$

$$\sin\theta_1 = n_2 / n_1$$

Total internal reflection (TIR)

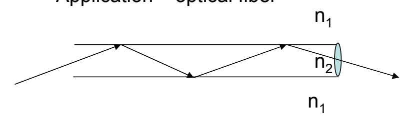


When $\theta_2 = 90^0$, θ_1 is critical angle

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \,|_{\theta_2 = 90^0} = n_2,$$

$$\sin\theta_1 = n_2 / n_1$$

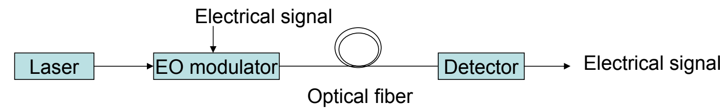
Application – optical fiber



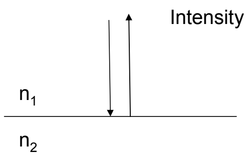
Low loss, TIR

Flexible

Communication system



Reflection percentage



Intensity reflection = $[(n1-n2)/(n1+n2)]^2$

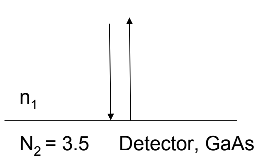
Example 1:

Refractive index of glass n = 1.5;

Refractive index of air n = 1;

The reflection from glass surface is 4%;

Example 2: detector is usually made from Gallium Arsenide (GaAs), n = 3.5;

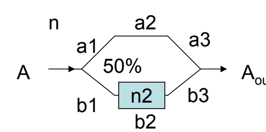


Intensity reflection = $[(n1-n2)/(n1+n2)]^2$

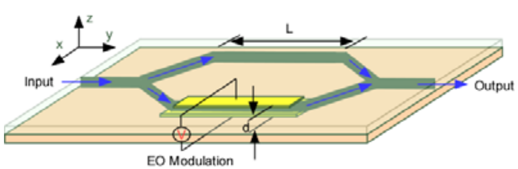
The reflection from GaAs surface is 31%;

Interference of two optical beams, applications

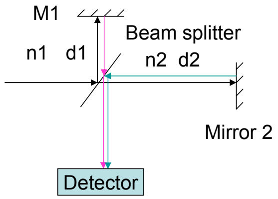
1, Mach-Zehnder interferometer



Electro-optic effect, n2 changes with E -field



2, Michelson interferometer



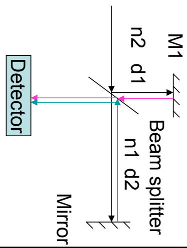
Phase difference:

$$k(n_2 2d_2 - n_1 2d_1)$$

Measuring small moving or displacement

If the detected light changes from bright to dark,
Then the distance moved is half wavelength/2

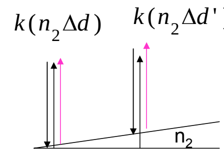
Michelson interferometer measuring speed of light in ether,
speed of light not depends on direction



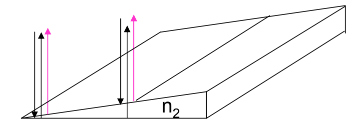
Phase difference:

$$k(n_1 2b_2 - n_2 2d_1)$$

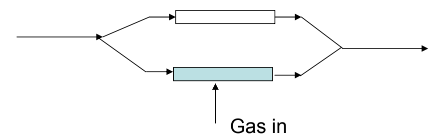
3, Measuring surface flatness



Accuracy: 0.1 wavelength = 0.1*500nm = 50nm



4, Measuring refractive index of liquid or gas



Equal difference series

$$a_1, a_2 \ldots a_n \ldots$$

$$a_2 - a_1 = b$$

$$a_3 - a_2 = b$$

$$+ \quad a_n - a_{n-1} = b$$

$$= \quad a_n - a_1 = (n-1)b$$

$$S_n = a_1 + a_2 + \ldots a_n$$

$$+ \quad S_n = a_n + a_{n-1} + \ldots a_1$$

$$= \quad 2S_n = n(a_n + a_1)$$

$$a_2 + a_{n-1} = a_1 + b + a_{n-1} = a_1 + a_n$$

$$a_3 + a_{n-2} = a_1 + 2b + a_{n-2} = a_1 + a_n$$

$$S_n = \frac{n}{2}(a_n + a_1) = \frac{n}{2}(a_n - a_1) + na_1 = \frac{n}{2}(n-1)b + na_1$$

Power series

$$a_1, a_2 \ldots a_n \ldots$$

$$a_2 = ba_1$$

$$a_3 = ba_2$$

$$\ldots$$

$$\times \quad a_n = ba_{n-1}$$

$$a_n = b^{n-1}a_1$$

$$S_n = a_1 + a_2 + \ldots a_n$$

$$- \quad bS_n = ba_1 + ba_2 + \ldots ba_n = a_2 + a_3 + \ldots a_{n+1}$$

$$= \quad (1-b)S_n = a_1 - a_{n+1}$$

$$S_n = \frac{a_1 - a_{n+1}}{1-b} = \frac{a_1 - b^n a_1}{1-b}$$

Power series

$$a_1, a_2 \ldots a_n \ldots$$

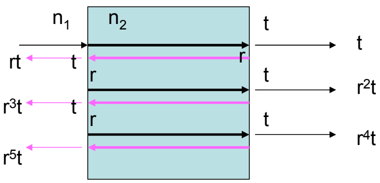
$$S = a_1 + a_2 + \ldots a_n + \ldots$$

$$= \lim_{n\to\infty} \frac{a_1(1-b^n)}{1-b} = \frac{a_1}{1-b}$$ When |b|<1

b can be anything, number, variable, complex number or function

Optical cavity, multiple reflections

$$S_r = t_1 r + t_2 + \ldots t_n + \ldots = \frac{t_1 r}{1-r^2}$$



$$S_t = t_1 + t_2 + \ldots t_n + \ldots = \frac{t_1}{1-r^2}$$

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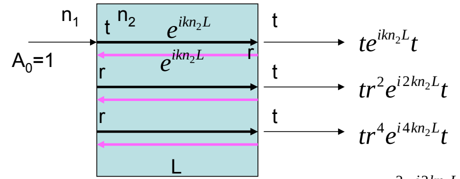
Optical cavity, wavelength dependence, resonant



$$b = r^2 e^{i2kn_2L}$$

$$A_t = A_1 + A_2 + \ldots = \frac{t^2 e^{ikn_2L}}{1-r^2 e^{i2kn_2L}}$$

$$I_t = |S_t|^2 = \left|\frac{t^2 e^{ikn_2L}}{1-r^2 e^{i2kn_2L}}\right|^2 = \left|\frac{t^2}{1-\mathrm{R}e^{i2kn_2L}}\right|^2$$ R, intensity reflection

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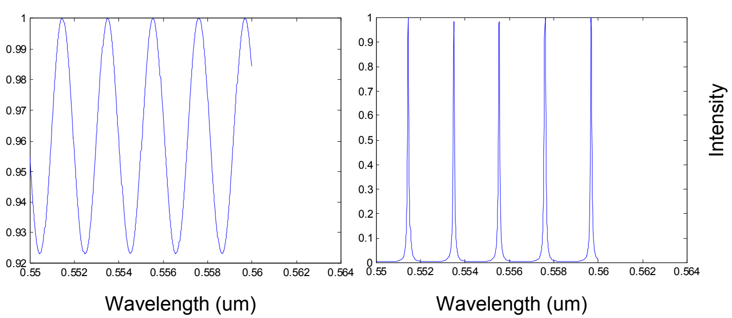
Optical cavity, wavelength dependence, resonant

$$I_t = |S_t|^2 = \left|\frac{t^2 e^{ikn_2L}}{1-r^2 e^{i2kn_2L}}\right|^2 = \left|\frac{t^2}{1-\mathrm{R}e^{i2kn_2L}}\right|^2$$

Example: n_2 = 1.5, R=0.04, L = 0.05mm, λ=0.55μm R, intensity reflection



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Optical cavity, wavelength dependence, resonant

$$I_t = |S_t|^2 = \left|\frac{t^2 e^{ikn_2L}}{1-r^2 e^{i2kn_2L}}\right|^2 = \left|\frac{t^2}{1-\mathrm{R}e^{i2kn_2L}}\right|^2$$

Resonant condition

$2kn_2L = (2m+1)\pi$ Destructively Interference

$2kn_2L = 2m\pi$ Constructively Interference

$\frac{2\pi}{\lambda} n_2 L = m\pi$ $\quad 2n_2L = m\lambda$ Resonant condition, m = 1, 2, 3, …

m=1, half-λ cavity

m=2, λ cavity

Optical cavity, Free-spectral range (FSR)

$2n_2L = m\lambda$ Resonant condition, m = 1, 2, 3, …

$$\frac{2n_2L}{\lambda_m} = m$$

$$-\ \frac{2n_2L}{\lambda_{m+1}} = m+1$$

$$\frac{2n_2L}{\lambda_{m+1}} - \frac{2n_2L}{\lambda_m} = 1 \qquad \frac{2n_2L(\lambda_m - \lambda_{m+1})}{\lambda_{m+1}\lambda_m} = 1$$

$$\frac{2n_2L\Delta\lambda}{\lambda^2} = 1 \qquad \Delta\lambda = \frac{\lambda^2}{2n_2L} \qquad FSR = \frac{\lambda^2}{2n_2L}$$

Example: n_2 = 1.5, R=0.04, L = 1mm, λ=0.55μm

Optical cavity, Free-spectral range (FSR)

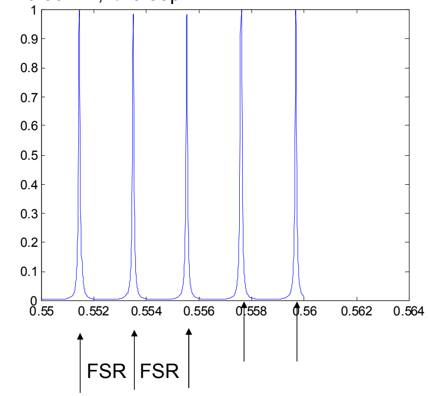
$$FSR = \frac{\lambda^2}{2n_2L}$$ L increase, FSR decrease, FSR not dependent on R

Example: n_2 = 1.5, R=0.04, L = 0.05mm, λ=0.55μm

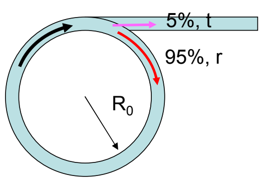
$$FSR = \frac{\lambda^2}{2n_2L} = 0.02\mu m$$

L = 0.5mm

$$FSR = \frac{\lambda^2}{2n_2L} = 0.002\mu m$$



Ring cavity, Ring resonator



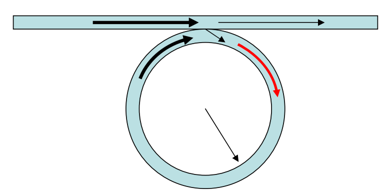
L = 2πR$_0$

$$I_t = |S_t|^2 = \left|\frac{t^2 e^{ikn_2L}}{1 - r^2 e^{i2kn_2L}}\right|^2 = \left|\frac{t^2}{1 - \mathrm{R}e^{i2kn_2L}}\right|^2$$

$$\frac{2\pi}{\lambda} n_2 L = m\pi \qquad 2n_2L = m\lambda$$

$$FSR = \frac{\lambda^2}{2n_2L}$$

Ring cavity, Ring resonator filter

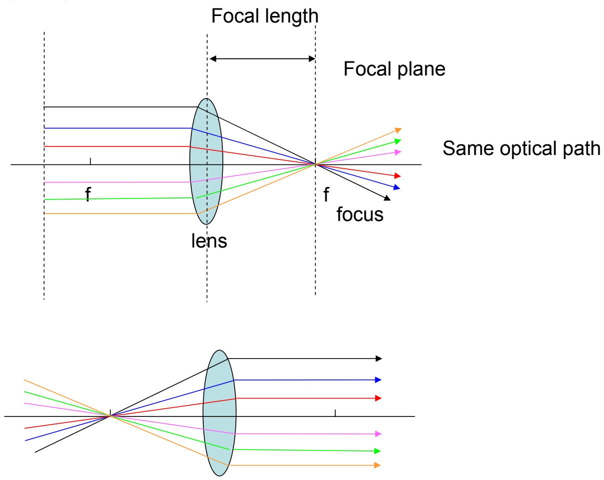


L = 2πR$_0$

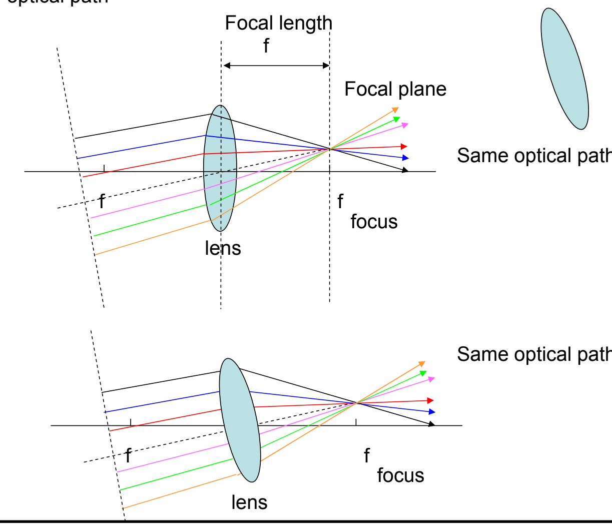
$$\frac{2\pi}{\lambda} n_2 L = m\pi$$

$$FSR = \frac{\lambda^2}{2n_2L} \qquad 2n_2L = m\lambda$$

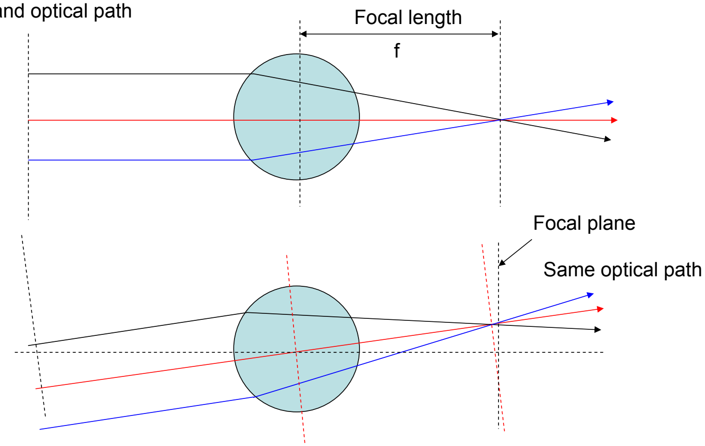
Lens and optical path



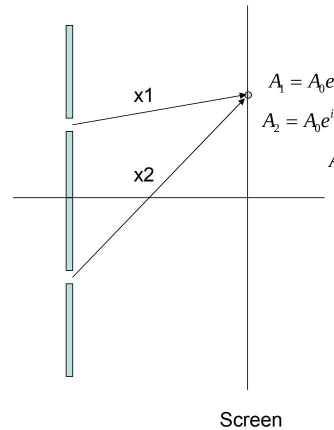
Lens and optical path



Lens and optical path



Interference of multiple Waves, gratings



Near field pattern

$$A_1 = A_0 e^{iknx_1}$$

$$A_2 = A_0 e^{iknx_2}$$

$$A_{totoal} = A_1 + A_2 = A_0 e^{iknx_1} + A_0 e^{iknx_2}$$

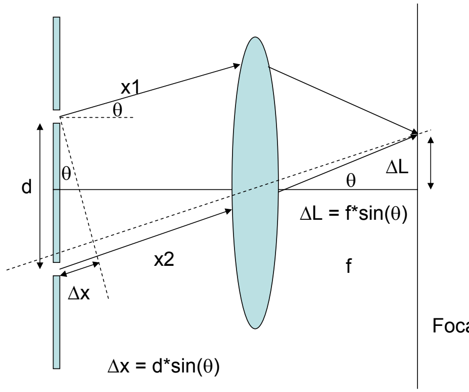
$$I_{totoal} = |A_{total}|^2 = \left|A_0 e^{iknx_1} + A_0 e^{iknx_2}\right|^2$$

$$= \left|A_0 e^{iknx_1}(1 + e^{ikn(x_2 - x_1)})\right|^2 = |A_0|^2 \left|(1 + e^{ikn(x_2 - x_1)})\right|^2$$

$$= |A_0|^2 \left|1 + \cos(kn\Delta x) + i\sin(kn\Delta x)\right|^2$$

$$= |A_0|^2 \{[1 + \cos(kn\Delta x)]^2 + \sin^2(kn\Delta x)\}$$

Diffraction of Waves



$\Delta x = d*\sin(\theta)$

$\Delta\phi = k*\Delta x = (2\pi/\lambda)\, d*\sin(\theta)$

When $\Delta\phi = 2m\pi$, bright

When $\Delta\phi = 2m\pi + \pi$, dark

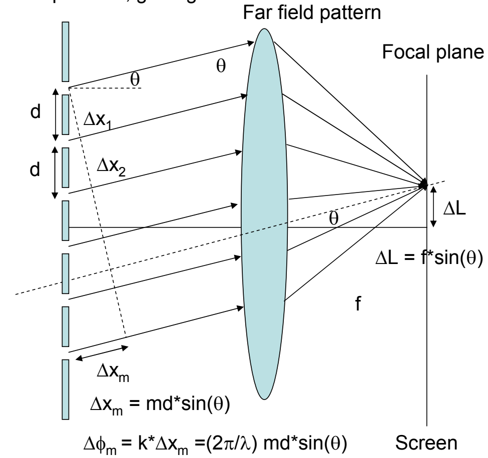
$2m\pi = (2\pi/\lambda)\, d*\sin(\theta)$

$m\,\lambda = d*\sin(\theta)$

$m\,\lambda = d*\,\Delta L\,/f$

$\Delta L = m\,\lambda*f/d$, bright spots

Multiple slots, grating



$\Delta x_m = md*\sin(\theta)$

$\Delta\phi_m = k*\Delta x_m = (2\pi/\lambda)\, md*\sin(\theta)$

When $\Delta\phi = 2m\pi$, bright

When $\Delta\phi = 2m\pi + \pi$, dark

$2m\pi = (2\pi/\lambda)\, d*\sin(\theta)$

$m\,\lambda = d*\sin(\theta)$

$\tan(\theta) = \Delta L\,/f$

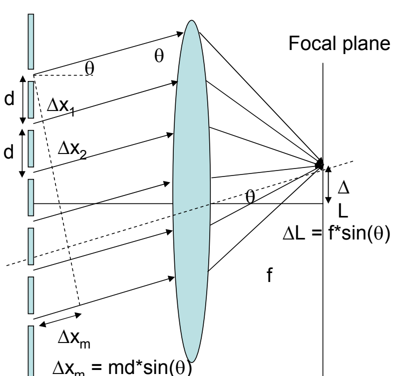
$\theta \sim \tan(\theta) \sim \sin(\theta)$, when θ is small

$m\,\lambda = d*\,\Delta L\,/f$

$\Delta L = m\,\lambda*f/d$, bright spots

Bright spot still at small position

Multiple slots, grating



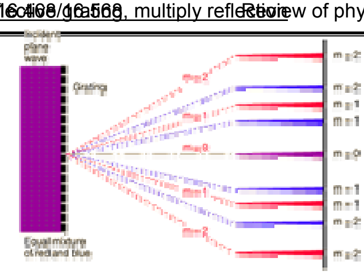
$\Delta x_m = md*\sin(\theta)$

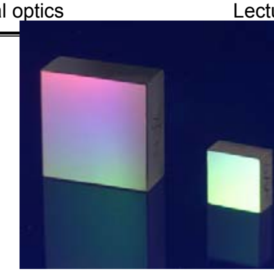
$\Delta\phi_m = k*\Delta x_m = (2\pi/\lambda)\, md*\sin(\theta)$

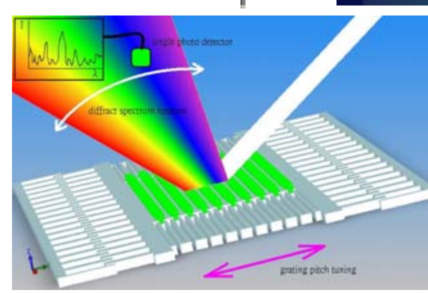
$$A_{totoal} = A_0 + + A_1 + A_2 + \ldots + A_m$$
$$= A_0 e^{ikx_0} + A_0 e^{ikx_1} + A_0 e^{ikx_2} + \ldots + A_0 e^{ikx_m}$$
$$= A_0 e^{ikx_0}(1 + e^{ik\Delta x_1} + e^{ik\Delta x_2} + \ldots + e^{ik\Delta x_m})$$
$$= A_0 e^{ikx_0}(1 + e^{ikd\sin\theta} + e^{ik2d\sin\theta} + \ldots + e^{ikmd\sin\theta})$$
$$= A_0 e^{ikx_0}\frac{1 - e^{ik(m+1)d\sin\theta}}{1 - e^{ikd\sin\theta}}$$

$$I_{totoal} = |A_{total}|^2 = \left|A_0 e^{ikx_0}\frac{1 - e^{ik(m+1)d\sin\theta}}{1 - e^{ikd\sin\theta}}\right|^2$$
$$= |A_0|^2 \frac{[1-\cos(kmd\sin\theta)]^2 + \sin^2(kmd\sin\theta)}{[1-\cos(kd\sin\theta)]^2 + \sin^2(kd\sin\theta)}$$

Reflective grating, multiply reflection







Optical wave, photon

Photon energy: $E = h\nu$, ν is the frequency of the photon, $c = f\lambda = \nu\lambda$,

$$E = hc/\lambda = \frac{2\pi}{\lambda}\hbar c = \hbar kc = pc,$$

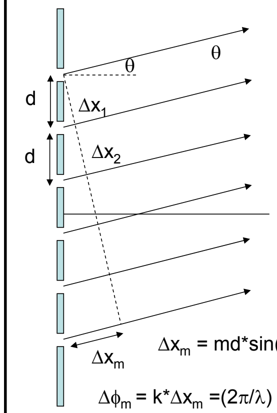
$p = \hbar k$, momentum of the photon,

$$E = mc^2 = mcc = pc,$$

For photon:

$$E = pc = h\nu,$$
$$p = \hbar k,$$
$$k = \frac{2\pi}{\lambda},$$

More on grating, Grating period, Phase matching condition



$\Delta x_m = md\cdot\sin(\theta)$

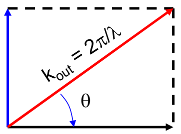
$\Delta\phi_m = k\cdot\Delta x_m = (2\pi/\lambda)\, md\cdot\sin(\theta)$

k vector, $k = (2\pi/\lambda)$, along the beam propagation direction

d is called grating period, often use symbol: Λ,

Grating vector = $2\pi/\Lambda$,

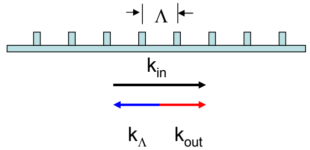
Phase-matching condition



$k_{out}\cdot\sin(\theta) = k_{grating} = 2\pi/\Lambda$

$d\cdot\sin(\theta) = \lambda$

Distributed feedback grating (DFB grating)

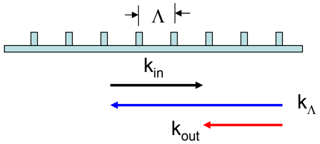


$k_{out} = k_{in} - k_{\Lambda}$

Phase-matching condition

$2\pi n_{out}/\lambda_{out} = 2\pi n_{in}/\lambda_{in} - 2\pi/\Lambda$

Effective reflection



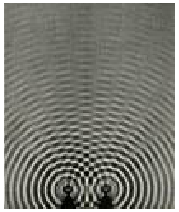
$k_{out} = k_{in} - k_{\Lambda} = -k_{in}$

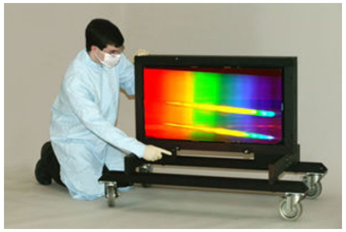
Phase-matching condition

$2\pi/\Lambda = 2\cdot 2\pi/\lambda$

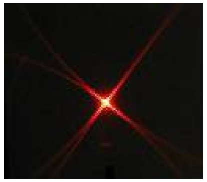
$\Lambda = \lambda/2$

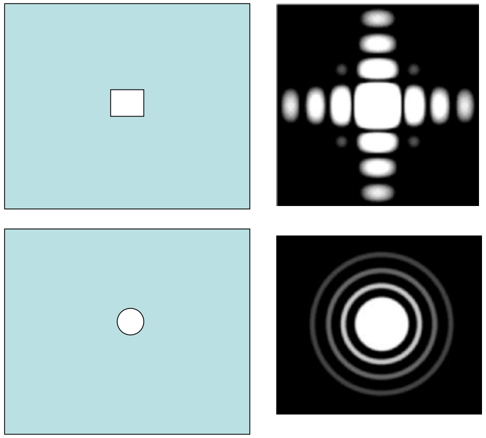
Diffraction: Multiple beam interference



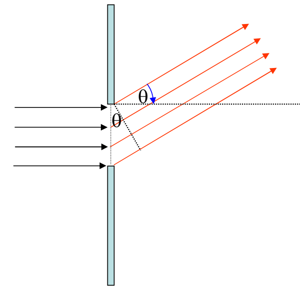


Diffraction:





Single slot diffraction:



$$A_{totoal} = A_0 + + A_1 + A_2 + \ldots + A_m$$

$$= A_0 e^{ikx_0} + A_0 e^{ikx_1} + A_0 e^{ikx_2} + \ldots + A_0 e^{ikx_m}$$

$$= \int_0^d A_0 e^{ikz\sin(\theta)} \frac{dz}{d} = \frac{A_0(1 - e^{ikd\sin(\theta)})}{ikd\sin(\theta)}$$

$$I_{totoal} = |A_{totoal}|^2 = \left| \frac{A_0(1 - e^{ikd\sin(\theta)})}{kd\sin(\theta)} \right|^2$$

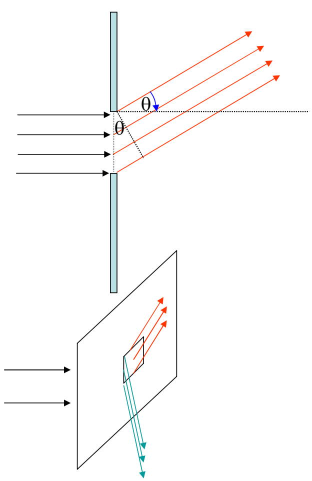
$$= I_0 \left| \frac{e^{ikd\sin\theta/2}(e^{-ikd\sin\theta/2} - e^{ikd\sin\theta/2})}{kd\sin(\theta)} \right|^2$$

$$= I_0 \left| \frac{2i\sin(kd\sin\theta/2)}{kd\sin(\theta)} \right|^2 = I_0 \left| \frac{\sin(kd\sin\theta/2)}{kd\sin\theta/2} \right|^2$$

$$= I_0 \frac{\sin^2(\alpha)}{\alpha^2},$$

$$\alpha = kd\sin\theta/2 = \frac{\pi}{\lambda} d\sin\theta$$

Single slot diffraction:

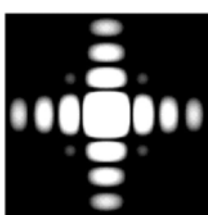


$$I_{totoal} = I_0 \frac{\sin^2(\alpha)}{\alpha^2},$$

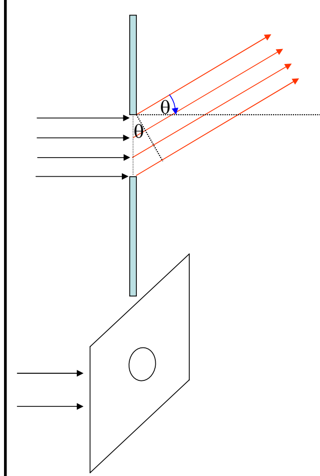
$$\alpha = kd\sin\theta/2 = \frac{\pi}{\lambda} d\sin\theta$$

When $\alpha = \frac{\pi}{\lambda} d\sin\theta = m\pi + \frac{\pi}{2}$ bright

When $\alpha = \frac{\pi}{\lambda} d\sin\theta = m\pi$ dark



Single slot diffraction:



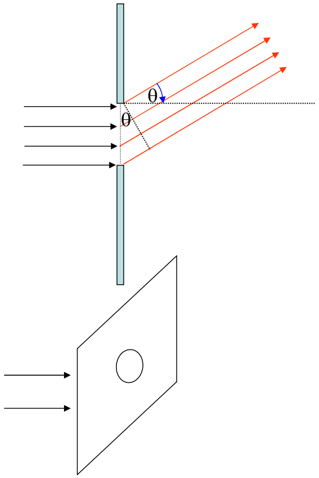
$$I_{totoal} = I_0 \frac{\sin^2(\alpha)}{\alpha^2},$$

$$\alpha = kd\sin\theta/2 = \frac{\pi}{\lambda} d\sin\theta$$

When $\alpha = \frac{\pi}{\lambda} d\sin\theta = m\pi + \frac{\pi}{2}$ bright

When $\alpha = \frac{\pi}{\lambda} d\sin\theta = m\pi$ dark

Angular width :



$$I_{totoal} = I_0 \frac{\sin^2(\alpha)}{\alpha^2},$$

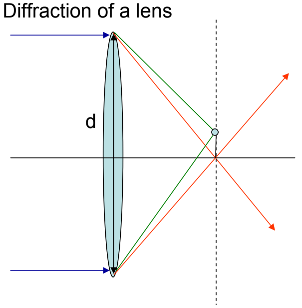
$$\alpha = kd\sin\theta/2 = \frac{\pi}{\lambda} d\sin\theta$$

first dark: $\alpha = \frac{\pi}{\lambda} d\sin\theta = m\pi$

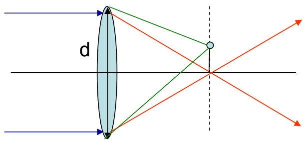
$$\sin\theta = \frac{\lambda}{d} \qquad \theta \cong \frac{\lambda}{d}$$

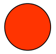
Half angular width

Diffraction of a lens



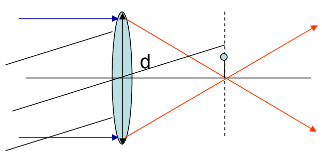
Focus size





Focus size

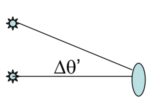
Resolution of optical instrument



$$\theta \cong \frac{\lambda}{d}$$

Focus size $f * \theta \cong f\frac{\lambda}{d}$

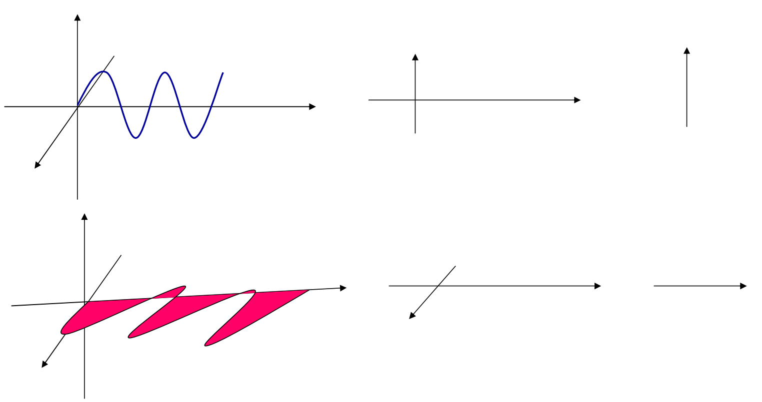
$$\Delta\theta' > 1.22\frac{\lambda}{d}$$



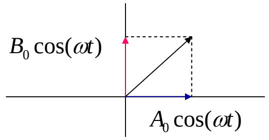
$$\Delta\theta' > 1.22\frac{\lambda}{d}$$

d = 16mm.

Polarization of light: Linear polarization



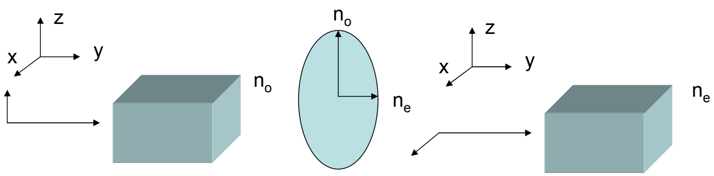
Polarization of light: linear polarization



Any linear polarization can be decomposed into two primary polarization with the same phase

Why decompose into two primary polarization directions?

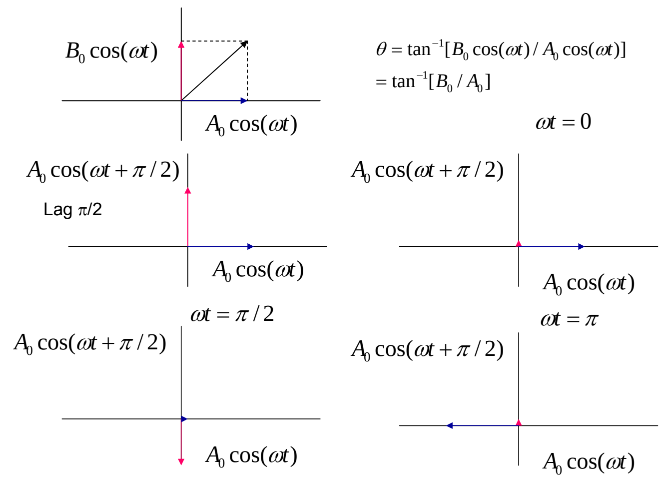
In crystal, the refractive index is different along different polarizations



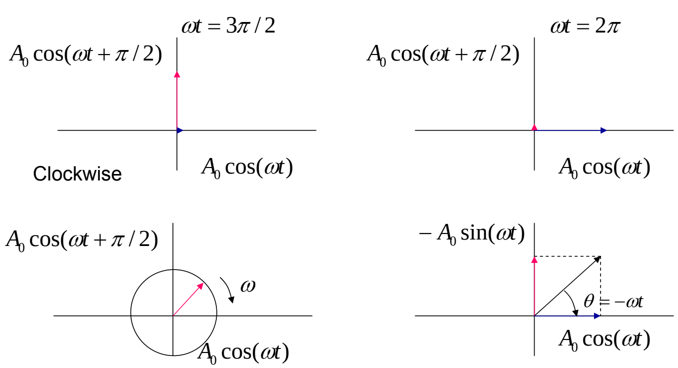
Refractive index ellipsoid

Polarization of light: circular polarization

$$\theta = \tan^{-1}[B_0 \cos(\omega t) / A_0 \cos(\omega t)] = \tan^{-1}[B_0 / A_0]$$



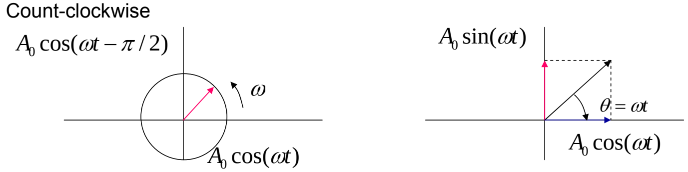
Polarization of light: circular polarization



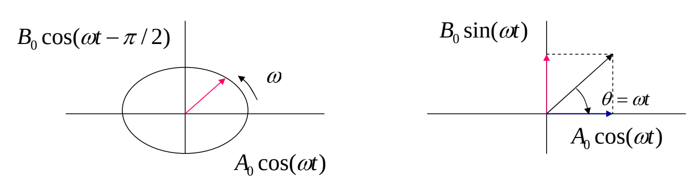
$A_0 \cos(\omega t)$

Polarization of light: circular polarization

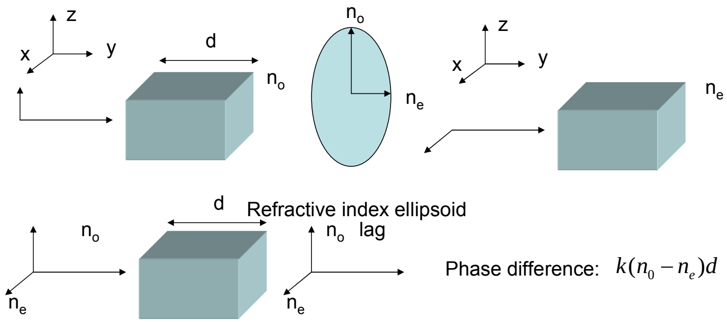
Count-clockwise



elliptical polarization



Delays along different directions:

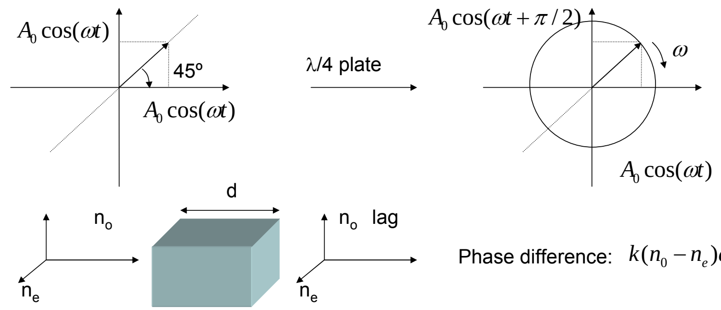


Phase difference: $k(n_0 - n_e)d$

when $k(n_0 - n_e)d = \pi / 2$ Right (clockwise) circular polarization

$(n_0 - n_e)d = \lambda / 4$ Quarter-wavelength λ/4 plate

Right (clockwise) circular polarization

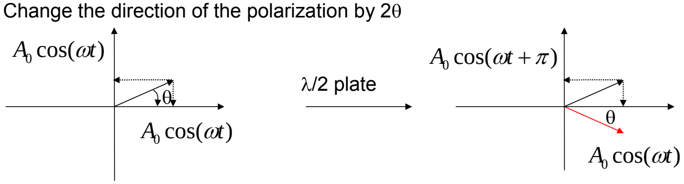


Phase difference: $k(n_0 - n_e)d$

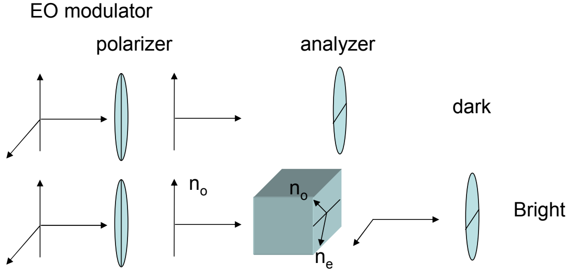
when $k(n_0 - n_e)d = \pi$ Change the direction of the polarization

$(n_0 - n_e)d = \lambda / 2$ half-wavelength λ/2 plate

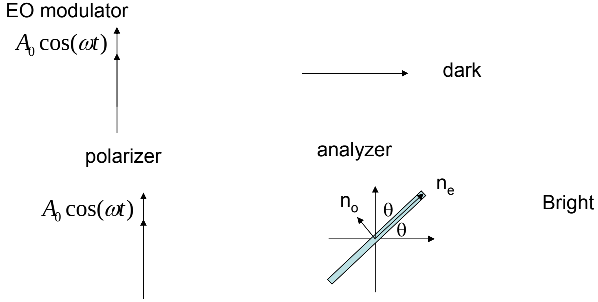
Change the direction of the polarization by 2θ



EO modulator



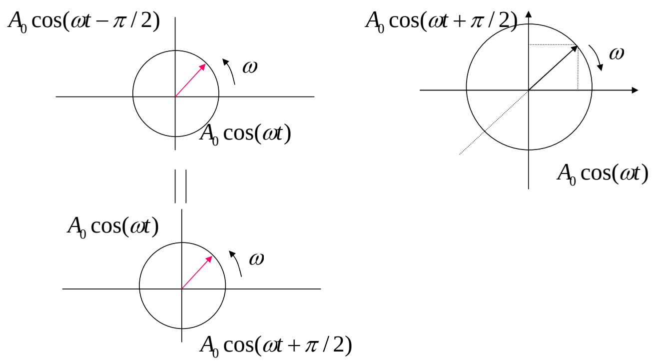
EO modulator



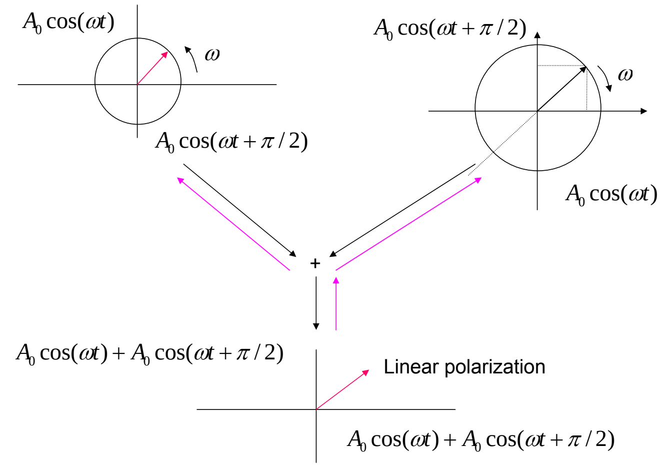
$k(n_0 - n_e)d = \pi$

$n_0 \propto E = \frac{V}{t}$ V_π

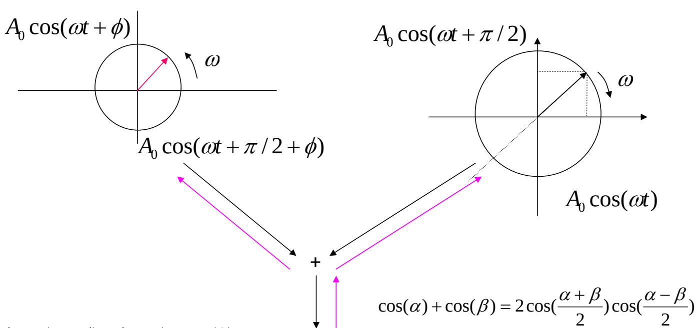
Circular polarizations and linear polarizations



Circular polarizations and linear polarizations

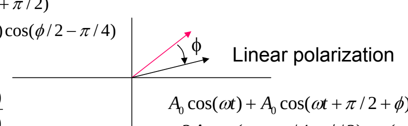


Circular polarizations and linear polarizations



$$\cos(\alpha) + \cos(\beta) = 2\cos(\frac{\alpha+\beta}{2})\cos(\frac{\alpha-\beta}{2})$$

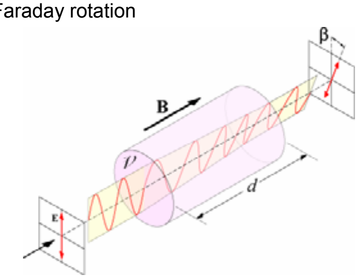
$$A_0\cos(\omega t + \phi) + A_0\cos(\omega t + \pi/2) = 2A_0\cos(\omega t + \phi/2 + \pi/4)\cos(\phi/2 - \pi/4)$$



$$\tan(\theta') = \frac{\cos(\pi/4 - \phi/2)}{\cos(\pi/4 + \phi/2)}$$

$$A_0\cos(\omega t) + A_0\cos(\omega t + \pi/2 + \phi) = 2A_0\cos(\omega t + \pi/4 + \phi/2)\cos(\pi/4 + \phi/2)$$

Faraday rotation



Apply B field generate delay for left or right polarization