# 6장. Reflection and refraction

액정 편광 http://www.youtube.com/watch?v=C98CTBl1xro

반사 편광 http://www.youtube.com/watch?v=dKSMZGpMNtE&NR=1&feature=endscreen

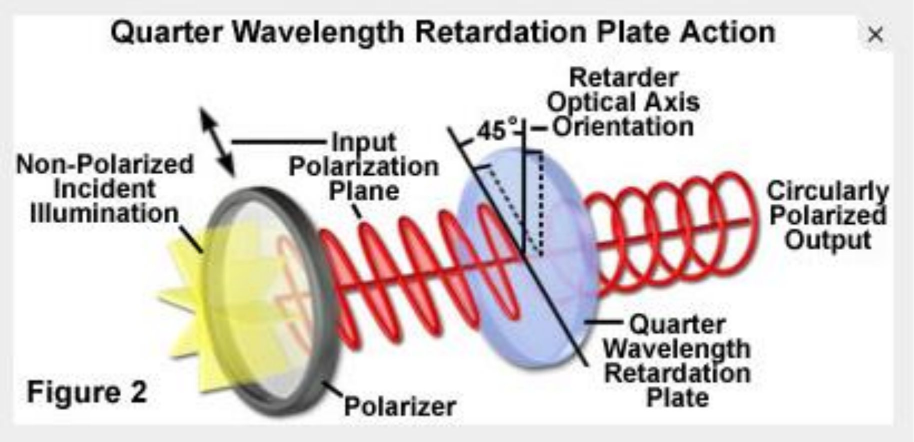
카메라 필터 http://www.youtube.com/watch?v=2PlfAqIlTVs

편광필터 효과

# 3D Display

http://kin.naver.com/qna/detail.nhn?d1id=11&dirId=110304&docId=148414175&qb=M2QgdHYg7JuQ66as&enc=utf8&section=kin&rank=3&search_sort=0&spq=0

http://interaction.tistory.com/314



$$\tilde{\mathbf{E}}(z) = \left(\hat{\mathbf{x}}a_x + \hat{\mathbf{y}}a_y e^{-j\delta}\right)e^{-jkz}$$

$$\delta = 0, \pi$$

$$\mathbf{E}(0,t) = (\hat{\mathbf{x}}a_x + \hat{\mathbf{y}}a_y)\cos(\varpi t - kz) \quad (in - phase)$$

$$\mathbf{E}(0,t) = (\hat{\mathbf{x}}a_x - \hat{\mathbf{y}}a_y)\cos(\varpi t - kz) \quad (out - of - phase)$$

Inclination angle

$$\psi(z,t) = \tan^{-1}\left(\frac{E_y(z,t)}{E_x(z,t)}\right)$$

$$\psi = \tan^{-1}\left(\frac{a_y}{a_x}\right)$$

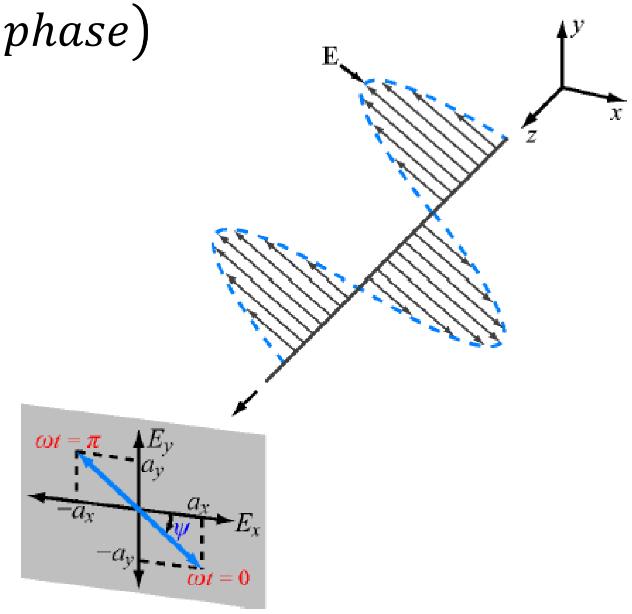



Figure 7-7: Linearly polarized wave traveling in the $+z$-direction (out of the page).

$$\psi(z,t) = \tan^{-1}\left(\frac{E_y(z,t)}{E_x(z,t)}\right)$$

$$\psi = \tan^{-1}\left[\frac{a\sin(\varpi t - kz)}{a\cos(\varpi t - kz)}\right]$$
$$= (\varpi t - kz)$$

$$\delta = \pi/2 \qquad \textit{left–hand circular}$$
$$\delta = -\pi/2 \qquad \textit{right–hand circular}$$

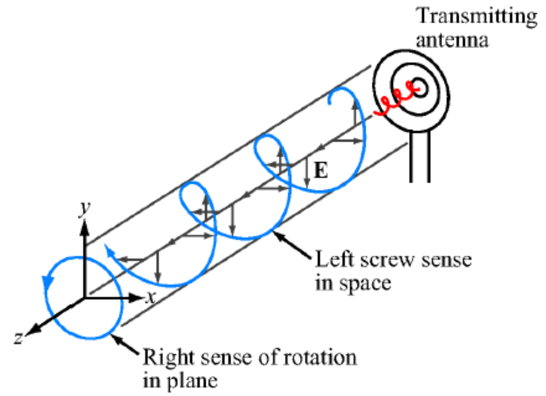



Figure 7-9: Right-hand circularly polarized wave radiated by a helical antenna.

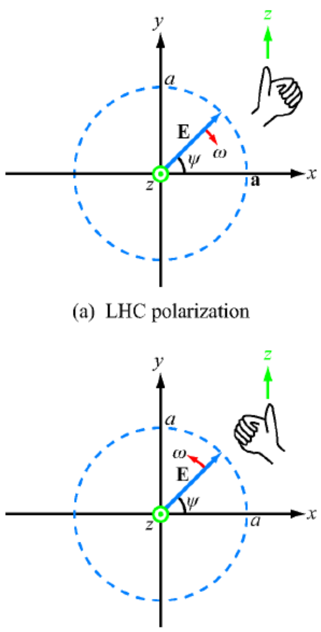



Figure 7-8: Circularly polarized plane waves propagating in the $+z$-direction (out of the page).

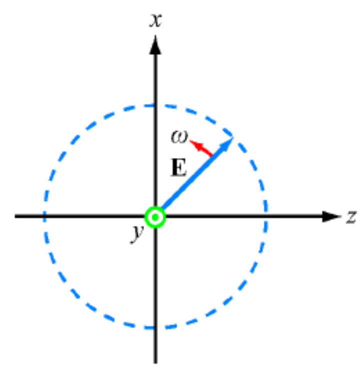
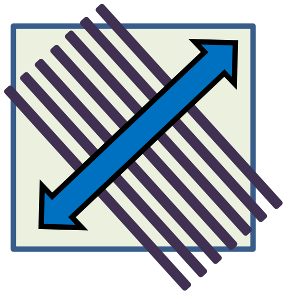



Figure 7-10: Right-hand circularly polarized wave of Example 7-2.

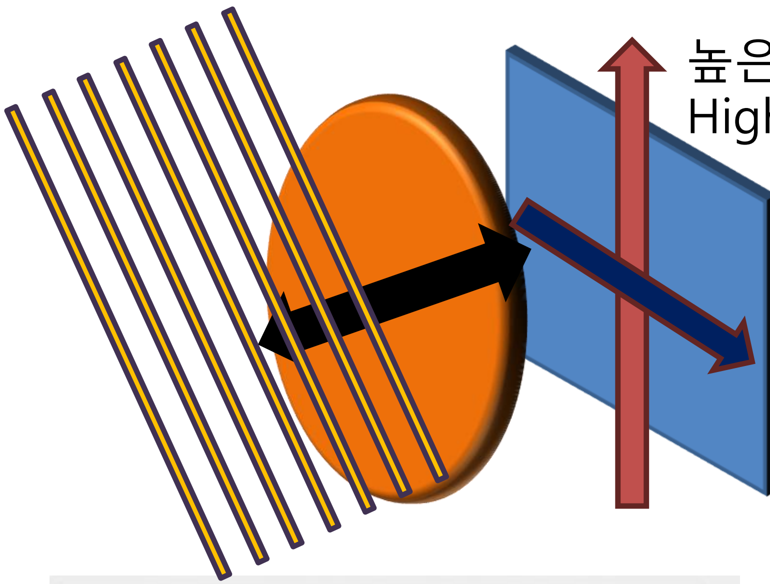
# Quarterwave(1/4 파장) plate
# (phase retarder)



Left handed circular

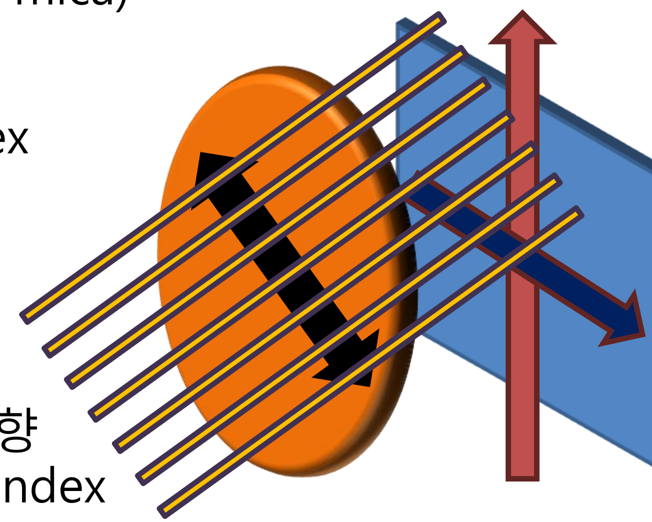
Right handed circular

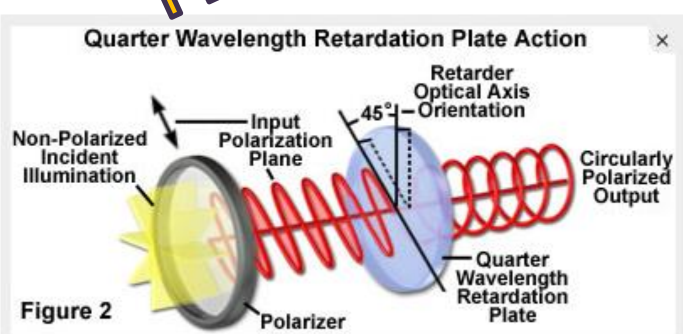
**Birefringent** materials( quartz, mica)



높은 굴절률 방향
High refractive index

낮은 굴절률 방향
Low refractive index

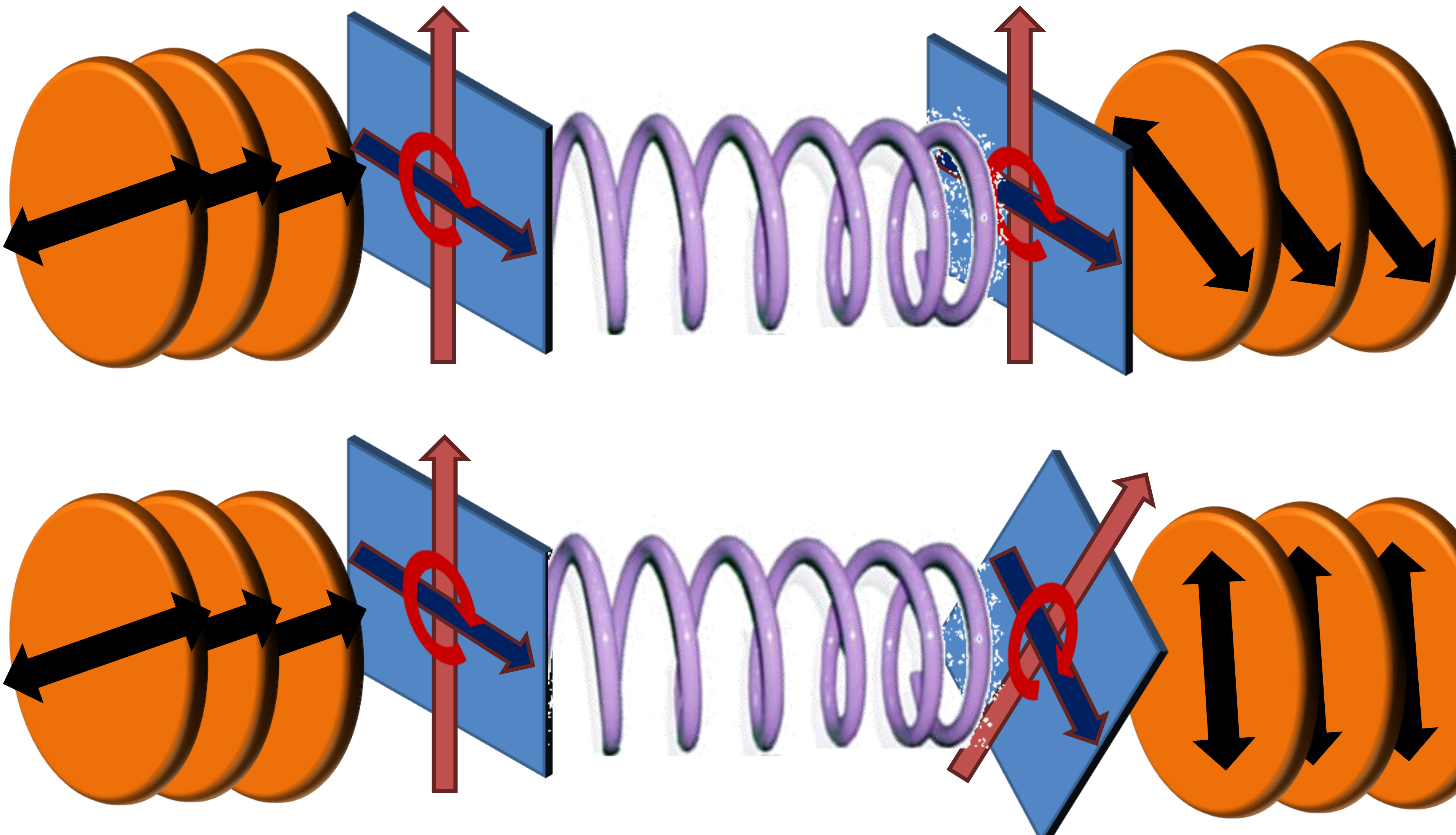


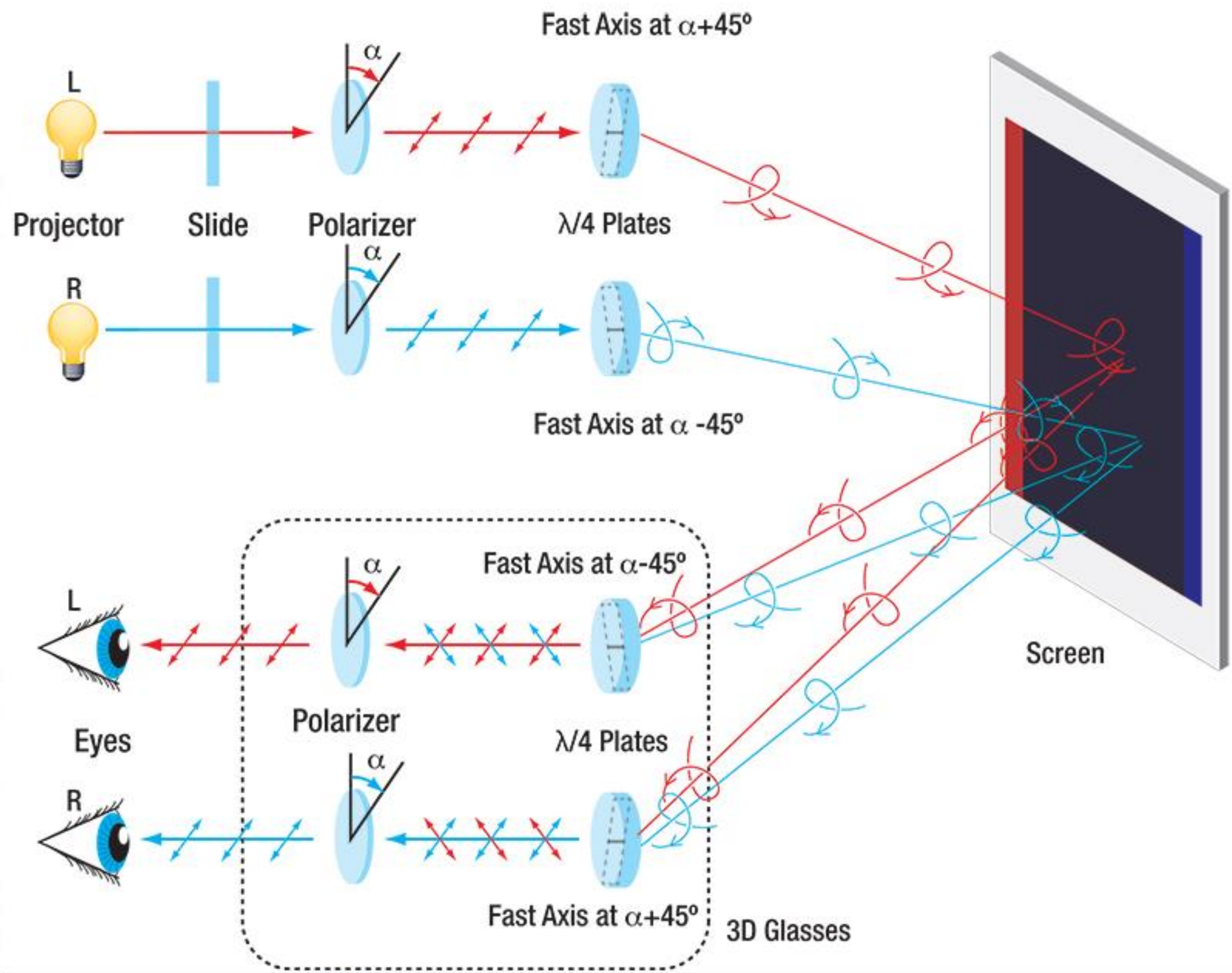


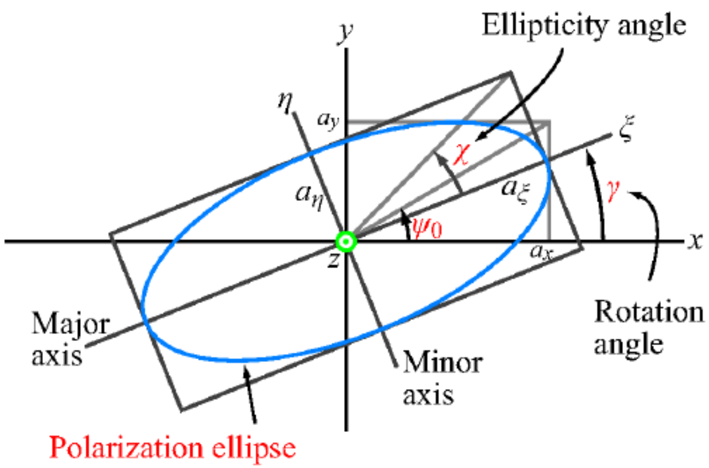

We can set the phase retardation as $\pm\frac{\pi}{2}$ by controlling **the thickness** of birefringent materials (복굴절률)

$n_{high} = 3$, $n_{low} = 1.5$   파장 500nm, retarder 두께는?   기출문제

# 3D display-LG




Fast Axis at α+45°
L
Projector
Slide
Polarizer
λ/4 Plates
α
R
Fast Axis at α -45°
Fast Axis at α-45°
L
Eyes
Polarizer
λ/4 Plates
R
Fast Axis at α+45°
3D Glasses
Screen



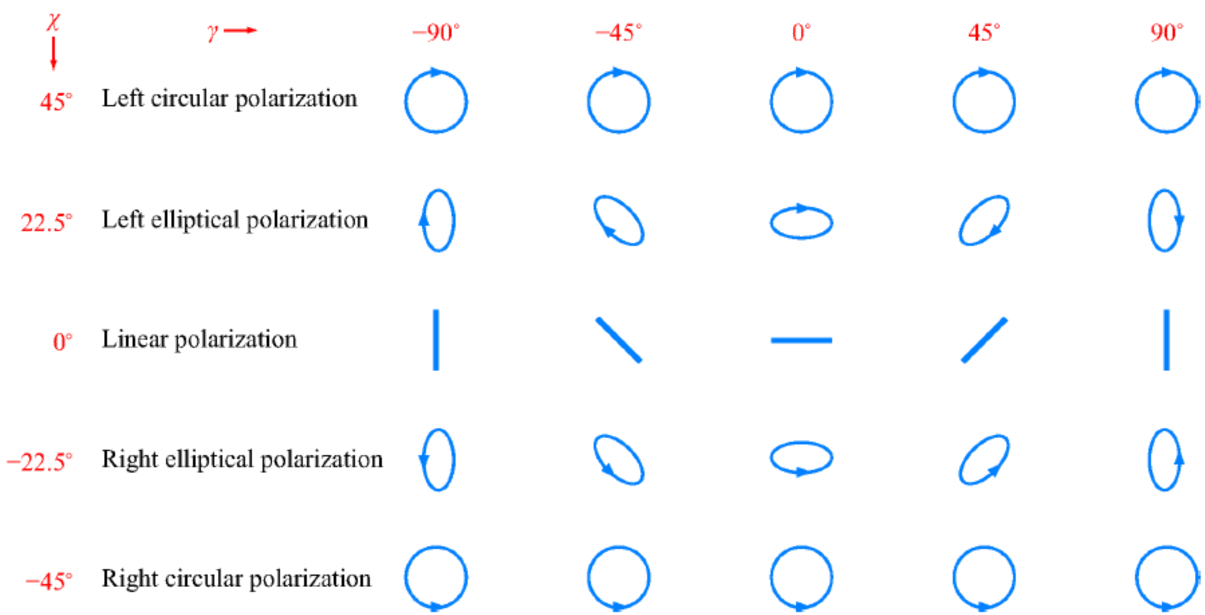

$$\tan\chi = \pm\frac{a_\eta}{a_\xi} = \pm\frac{1}{R}$$ Ellipticity angle

$$\sin 2\chi = (\sin 2\psi_0)\sin\delta \qquad (-\frac{\pi}{4} \le \chi \le -\frac{\pi}{4})$$

Rotation angle

$$\tan 2\gamma = (\tan 2\psi_0)\cos\delta \qquad (-\frac{\pi}{2} \le \gamma \le -\frac{\pi}{2})$$

$$a_x, a_y \Rightarrow positive \Rightarrow 0 < \psi_0 < 90^0$$




$$\gamma > 0 \quad if \quad \cos\delta > 0$$
$$\gamma < 0 \quad if \quad \cos\delta < 0$$

$$\chi > 0 \quad if \quad \sin\delta > 0$$
$$\chi < 0 \quad if \quad \sin\delta < 0$$

**Figure 7-12:** Polarization states for various combinations of the polarization angles $(\gamma, \chi)$ for a wave traveling out of the page.

# Jones matrix

1.Polarization

$$\mathcal{E}(z,t) = \mathrm{Re}\left\{\mathbf{A}\exp\left[j\omega\left(t-\frac{z}{c}\right)\right]\right\},$$

$$\mathbf{A} = A_x\hat{\mathbf{x}} + A_y\hat{\mathbf{y}},$$

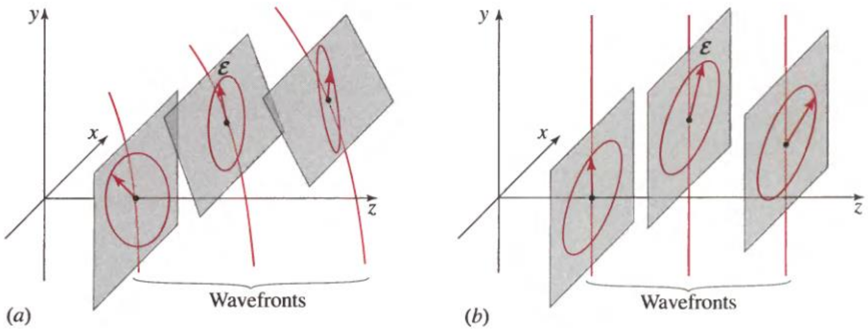
$$A_x = \mathrm{a}_x\exp(j\varphi_x) \quad A_y = \mathrm{a}_y\exp(j\varphi_y)$$

$$\mathcal{E}(z,t) = \mathcal{E}_x\hat{\mathbf{x}} + \mathcal{E}_y\hat{\mathbf{y}},$$

$$\mathcal{E}_x = \mathrm{a}_x\cos\left[\omega\left(t-\frac{z}{c}\right)+\varphi_x\right]$$

$$\mathcal{E}_y = \mathrm{a}_y\cos\left[\omega\left(t-\frac{z}{c}\right)+\varphi_y\right]$$

**circularly polarized.**
**linearly polarized**
**elliptically polarized.**



$$\widetilde{\mathrm{E}}(z) = (\hat{\mathbf{x}} a_x + \hat{\mathbf{y}} a_y e^{-j\delta}) e^{-jkz}$$

$$\delta = 0, \pi$$

$$\mathrm{E}(0,t) = (\hat{\mathbf{x}} a_x + \hat{\mathbf{y}} a_y)\cos(\varpi t - kz) \qquad (in - phase)$$

$$\mathrm{E}(0,t) = (\hat{\mathbf{x}} a_x - \hat{\mathbf{y}} a_y)\cos(\varpi t - kz) \qquad (out - of - phase)$$

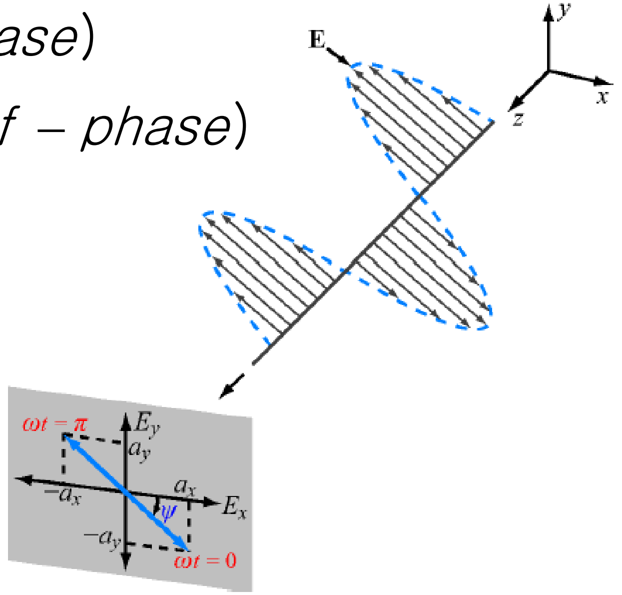



Figure 7-7: Linearly polarized wave traveling in the $+z$-direction (out of the page).

Inclination angle

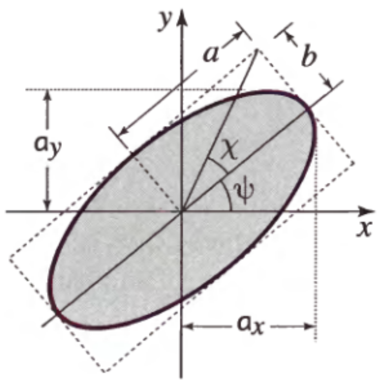
$$\psi(z,t) = \tan^{-1}\left(\frac{E_y(z,t)}{E_x(z,t)}\right)$$

$$\psi = \tan^{-1}\left(\frac{a_y}{a_x}\right)$$

http://em.eecs.umich.edu/

# Jones matrix

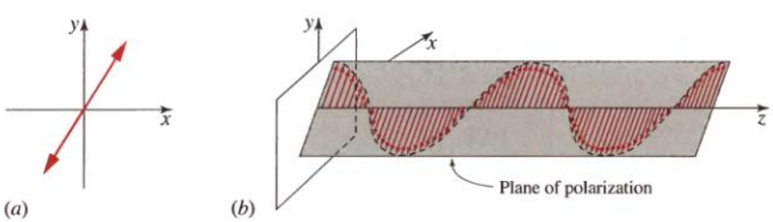
## 2.Polarization Ellipse



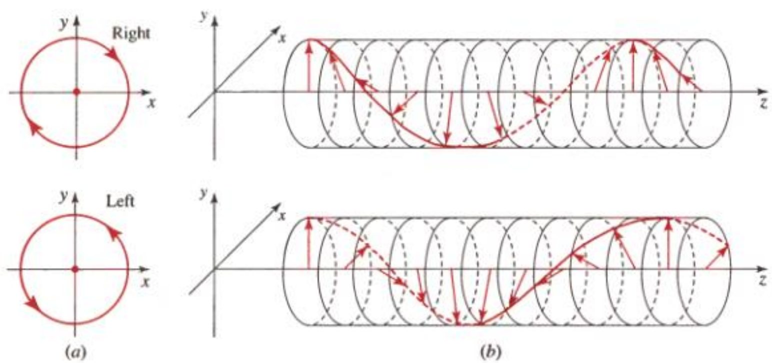

$$\tan 2\psi = \frac{2r}{1-r^2}\cos\varphi\,, \qquad r = \frac{a_y}{a_x}\,,$$

$$\sin 2\chi = \frac{2r}{1+r^2}\sin\varphi\,, \qquad \varphi = \varphi_y - \varphi_x\,.$$

## 3.Linear Polarization




## 4.Circularly Polarization



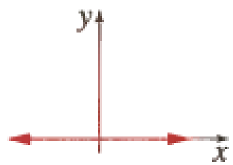
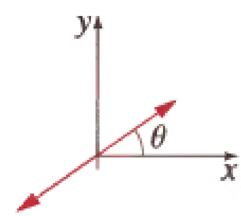
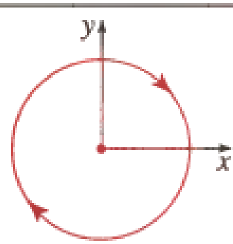
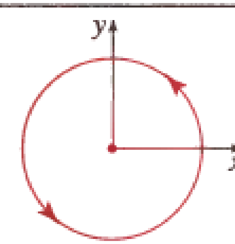
# Jones matrix

5.The Jones vector

$$A_y = a_y \exp(j\varphi_y) \qquad A_x = a_x \exp(j\varphi_x)$$

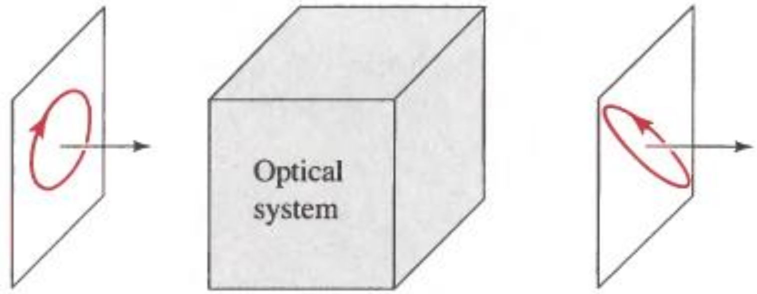
$$\mathbf{J} = \begin{bmatrix} A_x \\ A_y \end{bmatrix}.$$

**Table 6.1-1** Jones vectors of linearly polarized (LP) and right- and left-circularly polarized (RCP, LCP) light.

| | | | | | |
|---|---|---|---|---|---|
| LP in $x$ direction | $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ |  | LP at angle $\theta$ | $\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$ |  |
| RCP | $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ j \end{bmatrix}$ |  | LCP | $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -j \end{bmatrix}$ |  |

# Jones matrix

5.The Jones Matrix



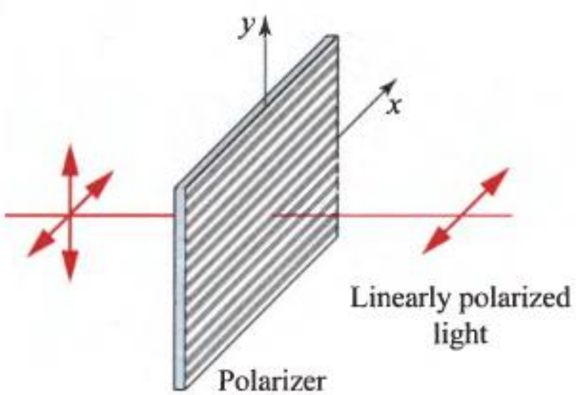

$$\begin{bmatrix} A_{2x} \\ A_{2y} \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} A_{1x} \\ A_{1y} \end{bmatrix}. \qquad \mathbf{J}_2 = \mathbf{T}\mathbf{J}_1.$$

The matrix $\mathbf{T}$, called the **Jones matrix,**

**Linear polarizers.**

$$\boxed{\mathbf{T} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}}$$

Linear Polarizer
Along $x$ Direction



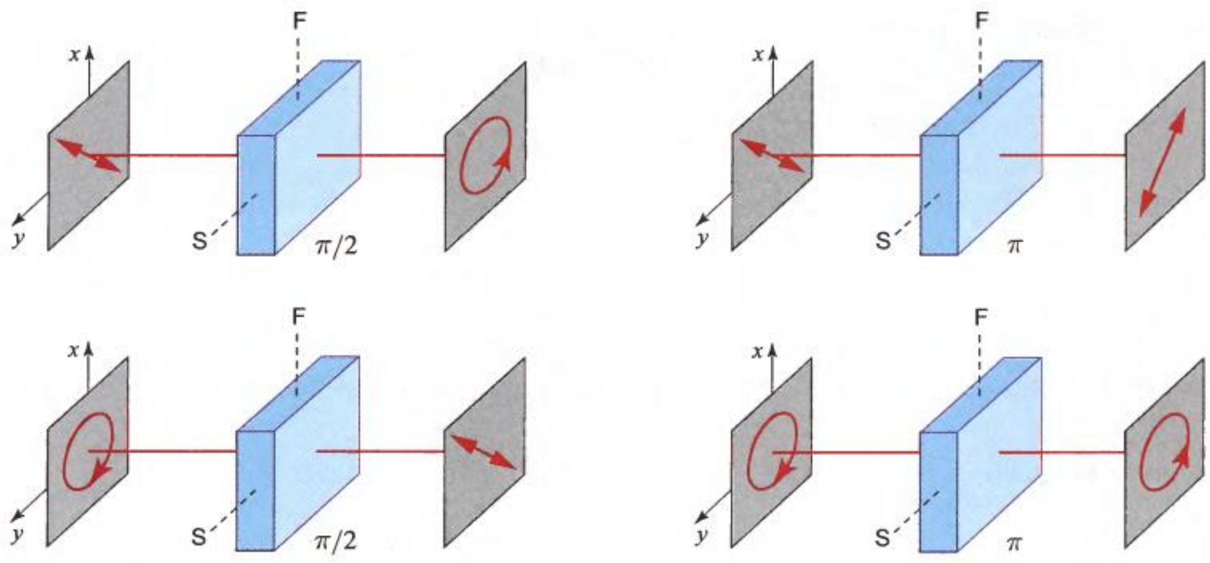
# Jones matrix

**Wave retarders.** The system represented by the matrix

$$\boxed{\mathbf{T} = \begin{bmatrix} 1 & 0 \\ 0 & e^{-j\Gamma} \end{bmatrix}}$$

Wave-Retarder
(Fast Axis Along $x$ Direction)

$$(A_{1x}, A_{1y}) \longrightarrow (A_{1x},\, e^{-j\Gamma}A_{1y})$$




(*a*) Quarter-wave retarder (*b*) Half-wave retarder

Operations of quarter-wave ($\pi/2$) and half-wave ($\pi$) retarders on several particular states of polarization are shown in (*a*) and (*b*), respectively. F and S represent the fast and slow axes of the retarder, respectively.

# 2.Optical activity

- Right-and left-circular polarization have different phase velocities, $c_0 / n_+$ and $c_0 / n_-$

Intrinsically helical structure

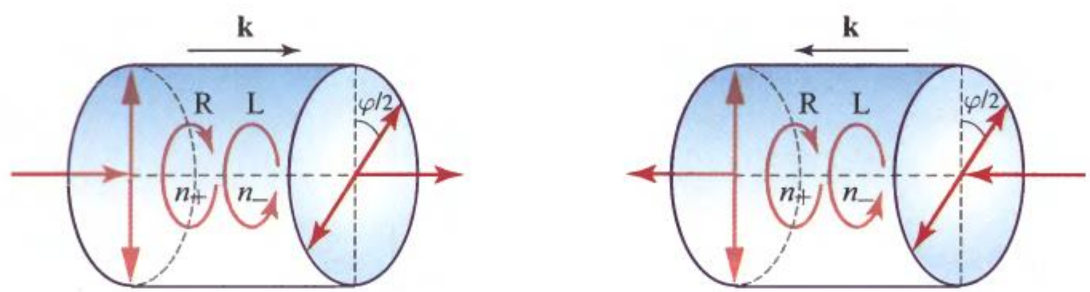
Their normal modes are circularly wave

Levorotatory, dextrorotatory

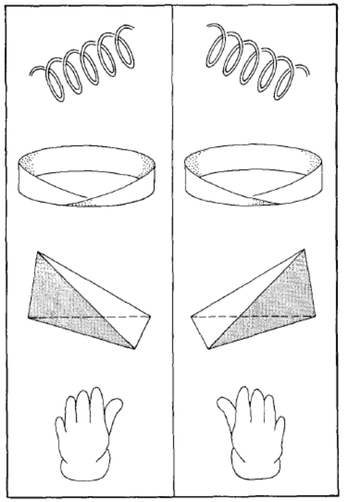
Selenium, tellurium oxide(TeO2), quartz……chiral morecules

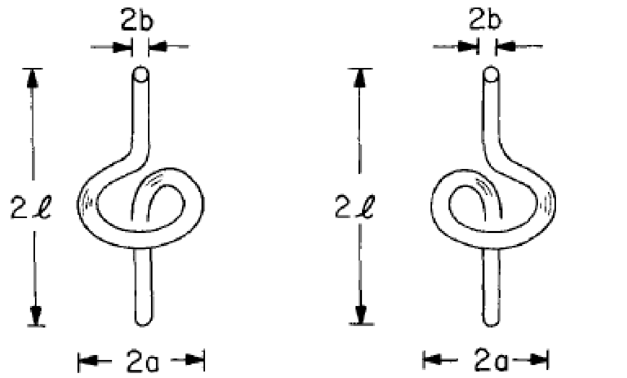
Almost all amino acids are levorotator
…sugars can be both forms.

right circularly polarized wave (R) is faster than the left circularly polarized wave (L), i.e., $n_+ < n_-$




(*a*) Forward wave (*b*) Backward wave






Time varying magnetic flux density B

$$\frac{dB}{dt} = -\nabla \times E = j\varpi B$$

Induces a cirulation current

Electric dipole moment

$$D = \varepsilon E + j\varepsilon_o \varpi \xi B$$

Isotropic dielectric response

Chiral term –optical activity

$$D = \varepsilon E - \varepsilon_o \xi \nabla \times E$$

for plane wave $E(r) = E\exp(-jk \bullet r), \nabla \times E = -jk \times E$

$$D = \varepsilon E + j\varepsilon_o \xi k \times E,$$

$G = \xi k$

$D = \varepsilon E + j\varepsilon_o G \times E,$

we assume that wave propagete in z direction $\mathrm{k} = (0,0,\mathrm{k}), \mathrm{G} = (0,0,\mathrm{G})$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \epsilon_o \begin{bmatrix} n^2 & -jG & 0 \\ jG & n^2 & 0 \\ 0 & 0 & n^2 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Not normal mode

where $n^2 = \epsilon/\epsilon_o$.

$\mathbf{E} = (E_0, \pm jE_0, 0)$

New normal mode

The + and − signs correspond to right and left circularly polarized waves,

$\mathbf{D} = (D_0, \pm jD_0, 0) \qquad D_0 = \epsilon_o(n^2 \pm G)E_0$

$\mathbf{D} = \epsilon_o n_\pm^2 \mathbf{E}$

$$\boxed{n_\pm = \sqrt{n^2 \pm G}.}$$

$TE = \lambda E$

$(T - \lambda I)E = 0$

$\det(T - \lambda I) = 0$

$\lambda$...*eigenvalue*,

*eigenvector*

## APPENDIX B: EFFECTIVE PARAMETER RETRIEVAL

For normal incidence, the rosette structure can be modeled as a reciprocal bi-isotropic medium and the constitutive equation is given by

$$\begin{pmatrix} \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \begin{pmatrix} \varepsilon_0\varepsilon & i\kappa/c_0 \\ -i\kappa/c_0 & \mu_0\mu \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix}, \qquad \text{(B1)}$$

where $\varepsilon_0$, $\mu_0$, and $c_0$ are the permittivity, permeability, and the speed of light in vacuum, respectively. The eigensolutions in bi-isotropic media are right-handed and left-handed circularly polarized plane electromagnetic waves. The refractive index for RCP and LCP is given by $n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa$, where (+) and (−) denote RCP and LCP. From the complex transmission and reflection coefficients, $T$ and $R$, which we both calculate and experimentally measure (see Fig. 7), the refractive index, $n$, and the impedance, $z$, can be obtained,[19]

Chiral materials exhibit a different refractive index for each polarization. The dispersion of wave vector, $k$, with $\omega$ is shown (Fig. 2A). Formally speaking we introduce a tensor, $\chi$,

$$\chi_A = \begin{bmatrix} \chi_{EE} & \chi_{EH} \\ \chi_{HE} & \chi_{HH} \end{bmatrix} \qquad (2)$$

which defines the response of the medium to an electromagnetic field:

$$\mathbf{D} = \chi_{EE}\mathbf{E} + \chi_{EH}\mathbf{H}$$
$$\mathbf{B} = \chi_{HE}\mathbf{E} + \chi_{HH}\mathbf{H} \qquad (3)$$

$$\begin{pmatrix} c\eta_0\mathbf{D} \\ c\mathbf{B} \end{pmatrix} = \begin{pmatrix} \epsilon & -j\kappa \\ j\kappa & \mu \end{pmatrix} \begin{pmatrix} \mathbf{E} \\ \eta_0\mathbf{H} \end{pmatrix} = \mathsf{M} \begin{pmatrix} \mathbf{E} \\ \eta_0\mathbf{H} \end{pmatrix} \qquad (6)$$

in other words,

$$\mathsf{d} = \mathsf{M}\mathsf{e} \qquad (7)$$

The limitation for material parameters in lossless chiral media are [4]

$$\kappa^2 \leq \epsilon\mu$$

This restriction comes from the requirement that the wave numbers $k_{\pm} = k_0(\sqrt{\mu\epsilon} \pm \kappa)$ (for lossless media) should be positive. However, why is it necessary to have both wave numbers positive? The answer to this is not obvious. Another way to justify restriction (8) is to consider the eigenvalues of the material matrix. These are—being the solutions for the equation

$$\mathsf{M}\mathsf{e} = \lambda\mathsf{e}$$

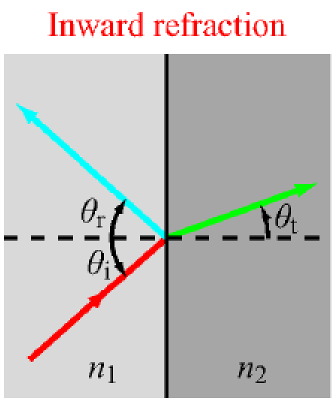
for the eigenproblem—the following two values

$$\lambda_{1,2} = \frac{\epsilon+\mu}{2} \pm \sqrt{\left(\frac{\epsilon-\mu}{2}\right)^2 + \kappa^2}$$

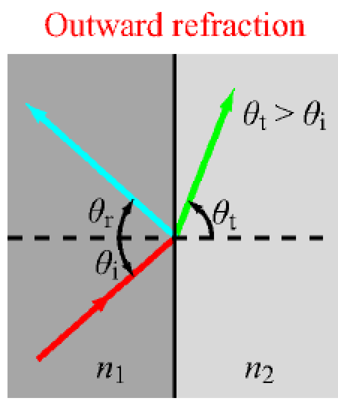
Now, the usually accepted limitations (8) are seen to correspond to the requirement that

$$\lambda_1 \geq 0, \quad \lambda_2 \geq 0$$

# 8.4 Oblique incident

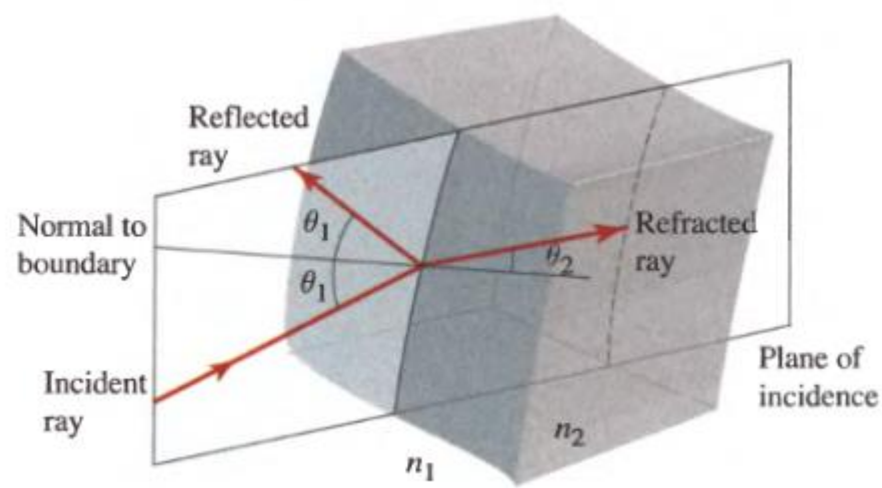


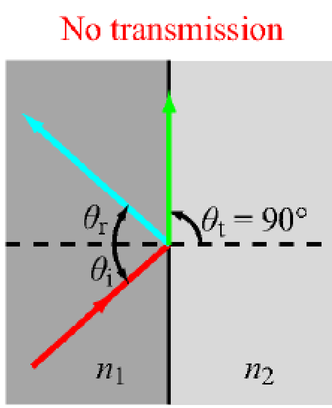

(a) $n_1 < n_2$




(b) $n_1 > n_2$

Plane of incident




(c) $n_1 > n_2$ and $\theta_i = \theta_c$

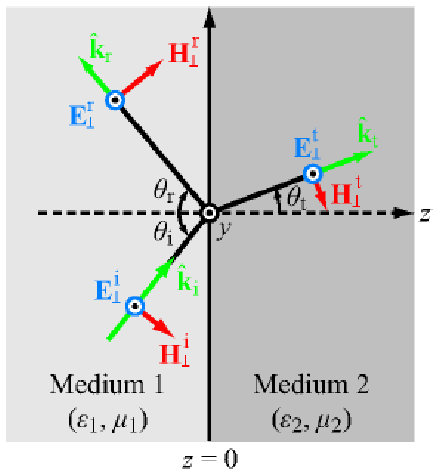
**Total reflection**

http://www.youtube.com/watch?v=8VZHym6HqVU&feature=related

http://www.youtube.com/watch?v=RqOLOZMnXzE&feature=endscreen

# 8.4 Oblique incident

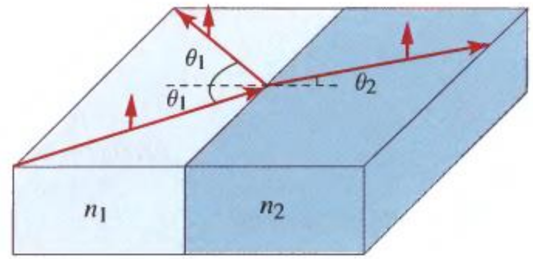
TE/TM modes (기준: 입사면 plane of incident)

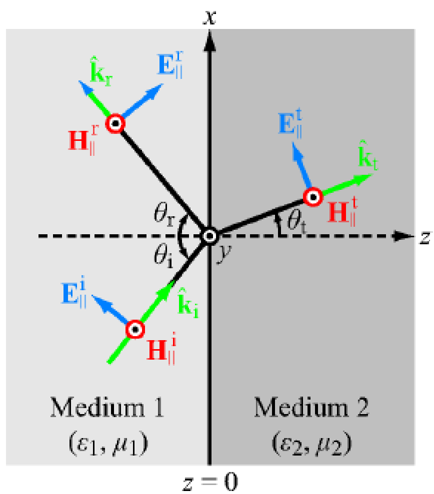



(a) Perpendicular polarization

**Transverse electric(TE)**

**=Perpendicular polarization**

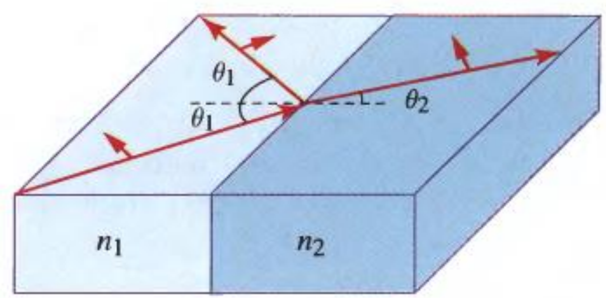



(b) Parallel polarization

**Transverse magnetic(TM)**

**=Parallel polarization**



# Boundary condition

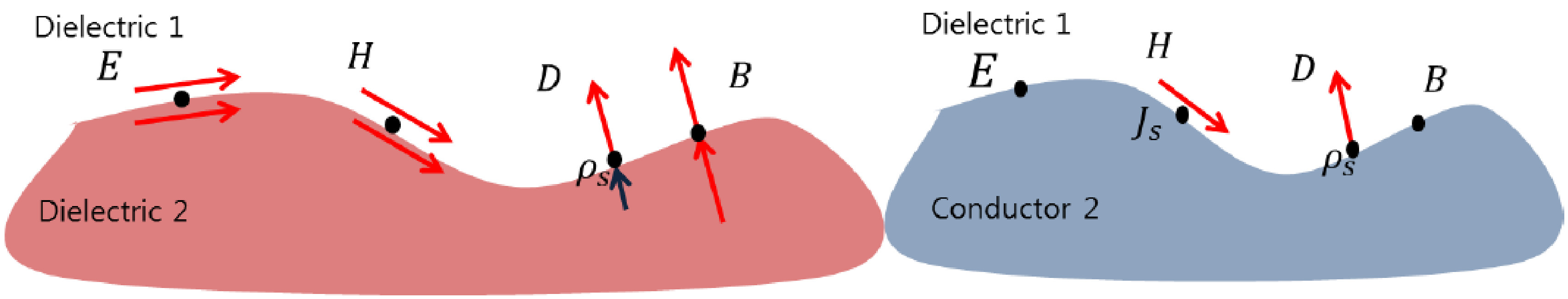



**Table 6-2:** Boundary conditions for the electric and magnetic fields.

| Field Components | General Form | Medium 1 Dielectric | Medium 2 Dielectric | Medium 1 Dielectric | Medium 2 Conductor |
|---|---|---|---|---|---|
| Tangential E | $\hat{\mathbf{n}}_2 \times (\mathbf{E}_1 - \mathbf{E}_2) = 0$ | $E_{1t} = E_{2t}$ | | $E_{1t} = E_{2t} = 0$ | |
| Normal D | $\hat{\mathbf{n}}_2 \cdot (\mathbf{D}_1 - \mathbf{D}_2) = \rho_s$ | $D_{1n} - D_{2n} = \rho_s$ | | $D_{1n} = \rho_s$ | $D_{2n} = 0$ |
| Tangential H | $\hat{\mathbf{n}}_2 \times (\mathbf{H}_1 - \mathbf{H}_2) = \mathbf{J}_s$ | $H_{1t} = H_{2t}$ | | $H_{1t} = J_s$ | $H_{2t} = 0$ |
| Normal B | $\hat{\mathbf{n}}_2 \cdot (\mathbf{B}_1 - \mathbf{B}_2) = 0$ | $B_{1n} = B_{2n}$ | | $B_{1n} = B_{2n} = 0$ | |

Notes: (1) $\rho_s$ is the surface charge density at the boundary; (2) $\mathbf{J}_s$ is the surface current density at the boundary; (3) normal components of all fields are along $\hat{\mathbf{n}}_2$, the outward unit vector of medium 2; (4) $E_{1t} = E_{2t}$ implies that the tangential components are equal in magnitude and parallel in direction; (5) direction of $\mathbf{J}_s$ is orthogonal to $(\mathbf{H}_1 - \mathbf{H}_2)$.

# Transverse electric(TE) =Perpendicular polarization

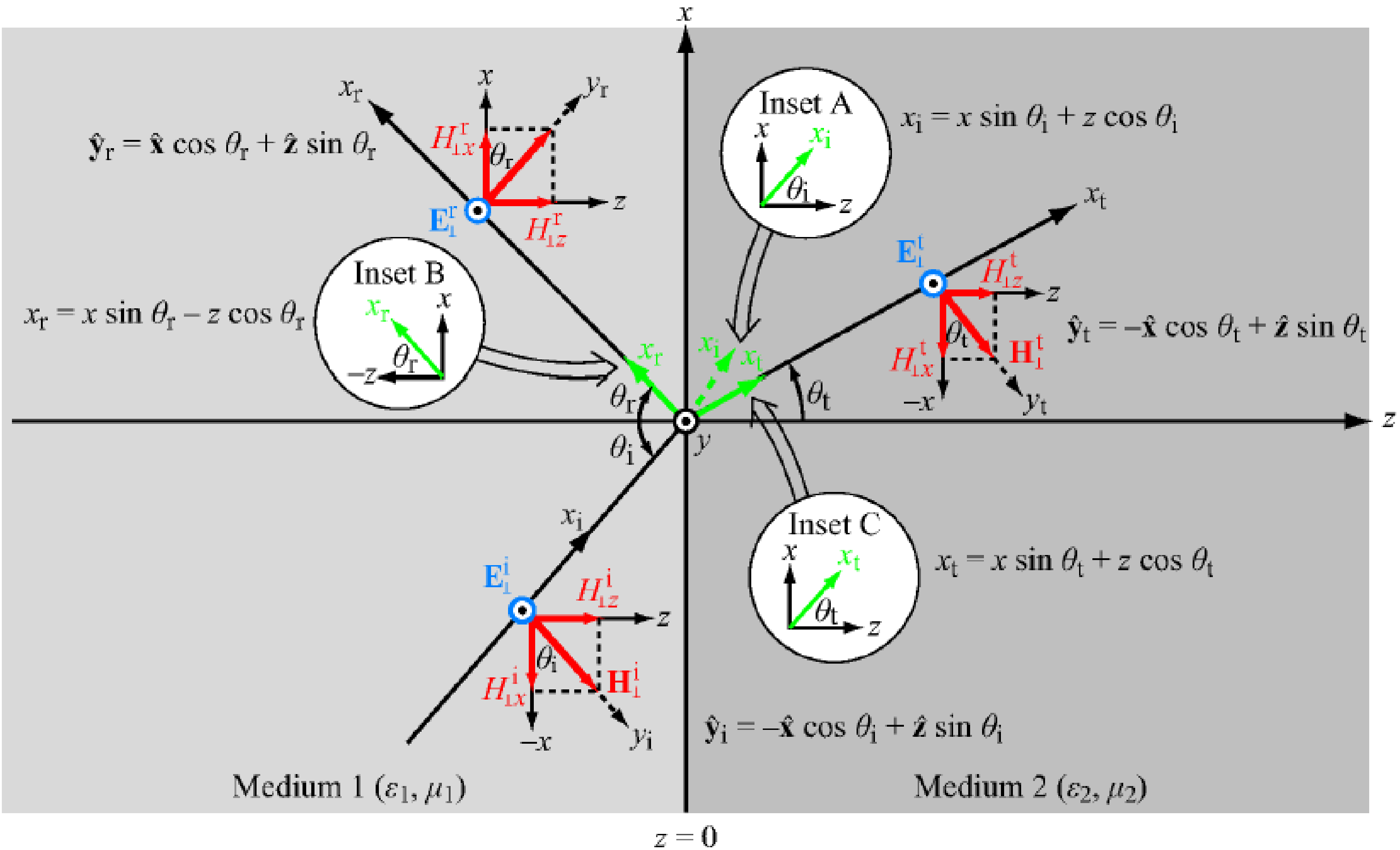



**Figure 8-15:** Perpendicularly polarized plane wave incident at an angle $\theta_i$ upon a planar boundary.

$$\begin{cases} E^i_{\perp 0} + E^r_{\perp 0} = E^t_{\perp 0} \\ \dfrac{\cos\theta_i}{\eta_1}\left(E^i_{\perp 0} - E^r_{\perp 0}\right) = \dfrac{\cos\theta_t}{\eta_2} E^t_{\perp 0} \end{cases}$$

**H field** 수평성분 같다는 조건
(수직성분은 연속일 필요는?)

$$\boxed{\begin{aligned} \Gamma_\perp &= \frac{\eta_2 \cos\theta_i - \eta_1 \cos\theta_t}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t} \\ \tau_\perp &= \frac{E^t_{\perp 0}}{E^i_{\perp 0}} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t} \\ \tau_\perp &= \Gamma_\perp + 1 \end{aligned}}$$

$$\Gamma_\perp = \frac{\cos\theta_i - \sqrt{\left({}^{\varepsilon_2}/_{\varepsilon_1}\right) - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\left({}^{\varepsilon_2}/_{\varepsilon_1}\right) - \sin^2\theta_i}}$$

(for $\mu_1 = \mu_2$).

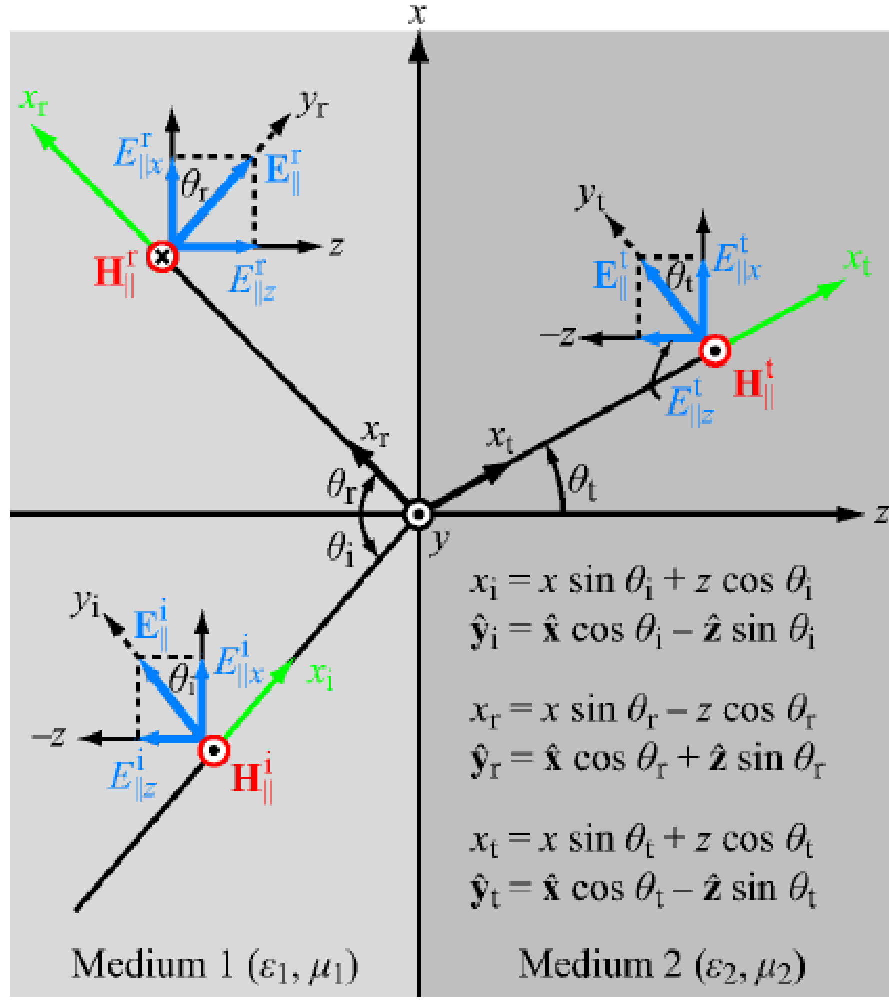



**Figure 8-16:** Parallel polarized plane wave incident at an angle $\theta_i$ upon a planar boundary.

$$\begin{cases} \cos\theta_i \left(E^i_{\parallel 0} + E^r_{\parallel 0}\right) = \cos\theta_t \, E^t_{\parallel 0} \\[2ex] \dfrac{1}{\eta_1}\left(E^i_{\parallel 0} - E^r_{\parallel 0}\right) = \dfrac{1}{\eta_2} E^t_{\parallel 0} \end{cases}$$

$$\begin{cases} \cos\theta_i \ (A + B) = \cos\theta_t \ C \\[2ex] \dfrac{1}{\eta_1}(A - B) = -\dfrac{1}{\eta_2} C \end{cases}$$

$$\cos\theta_i \ A = A'$$
$$\cos\theta_i \ B = B'$$
$$\cos\theta_t \ C = C'$$

$$\frac{B}{A} = \frac{B'}{A'} \qquad \frac{C}{A} = \frac{C'}{A'}\frac{\cos\theta_i}{\cos\theta_t}$$

$$\Gamma_{\parallel} = \frac{\eta_2 \cos\theta_t - \eta_1 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$$

$$\tau_{\parallel} = \frac{E_{\parallel 0}^t}{E_{\parallel 0}^i} = \frac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$$

$$\tau_{\parallel} = (1 + \Gamma_{\parallel}) \frac{\cos\theta_i}{\cos\theta_t}$$

$$\Gamma_{\parallel} = \frac{-(\varepsilon_2/\varepsilon_1)\cos\theta_i + \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_i}}{(\varepsilon_2/\varepsilon_1)\cos\theta_i + \sqrt{(\varepsilon_2/\varepsilon_1) - \sin^2\theta_i}}$$

(for $\mu_1 = \mu_2$).

Snell 의 법칙을 이용해서 $\cos\theta_i$ 만의 함수 표현 가능

# Brewster angle (브루스터 각)

$\Gamma$=0 인 조건

($\mu_1 = \mu_2$ 일 때)

▣ Perpendicular polarization: $\eta_2 \cos\theta_i = \eta_1 \cos\theta_t$ : 비자성 물질에서 해없음

▣ Parallel polarization wave : $\eta_2 \cos\theta_t = \eta_1 \cos\theta_i$ :

+snell 이용

$$\theta_i = \sin^{-1}\sqrt{\frac{1}{1 + \frac{\varepsilon_1}{\varepsilon_2}}}$$

$$\theta_i = \tan^{-1}\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} = \tan^{-1}\left(\frac{n_2}{n_1}\right)$$

Parallel polarization wave(평행편파) 전부 투과(반사없다)

$$\begin{cases} \eta_2 \cos\theta_i = \eta_1 \cos\theta_t \\ \dfrac{\eta_2}{\eta_1} = \dfrac{\cos\theta_t}{\cos\theta_i} = \dfrac{\sin\theta_t}{\sin\theta_i} \end{cases}$$

$$\tan\theta_t = \tan\theta_i$$

+snell 법칙

---

$$\begin{cases} \eta_2 \cos\theta_t = \eta_1 \cos\theta_1 \\ \dfrac{\eta_2}{\eta_1} = \dfrac{\cos\theta_i}{\cos\theta_t} = \dfrac{\sin\theta_t}{\sin\theta_i} = \beta \end{cases}$$

+snell 법칙

$$\begin{cases} \cos\theta_i = \beta\cos\theta_t \\ \sin\theta_t = \beta\sin\theta_i \end{cases}$$

$$\begin{cases} \cos^2\theta_i = \beta^2\cos^2\theta_t \\ \sin^2\theta_t = \beta^2\sin^2\theta_i \end{cases}$$

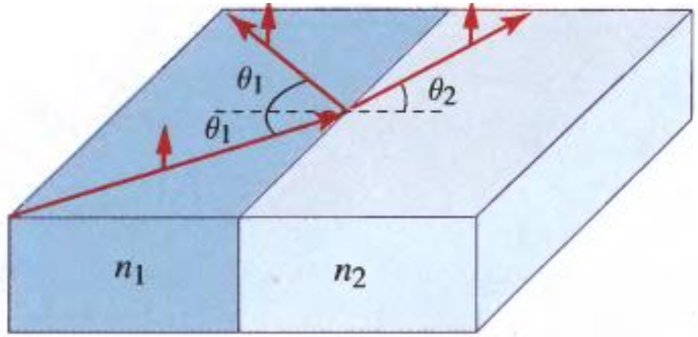
$$\cos^2\theta_i = \beta^2 - \beta^4\sin^2\theta_i$$

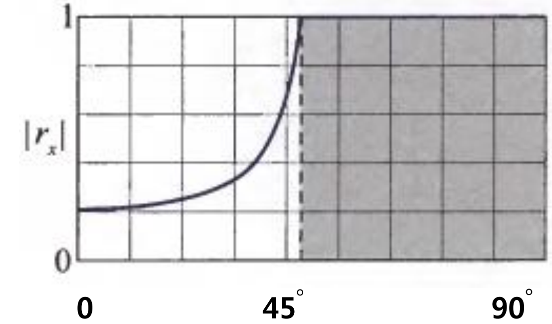
$$1 - \beta^2 = (1 - \beta^4)\sin^2\theta_i$$

$n_1 > n_2$

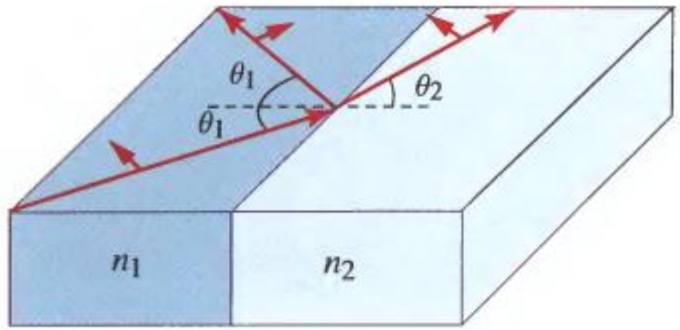
$\frac{n_1}{n_2} = 1.5$

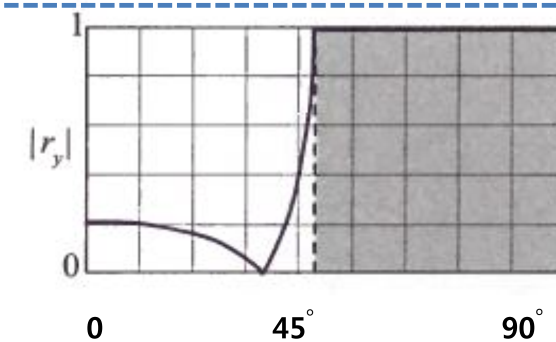
**TE**




**TM**

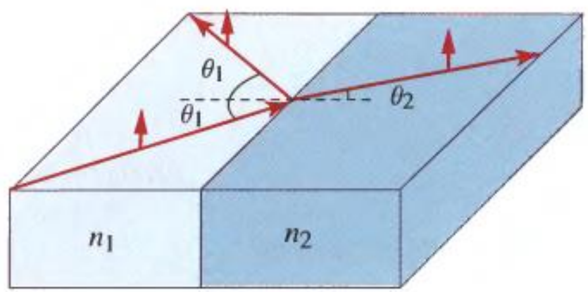


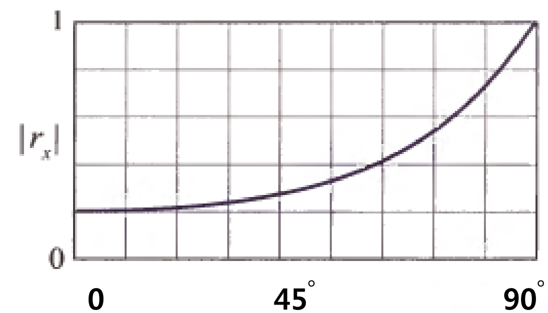




$n_2 > n_1$

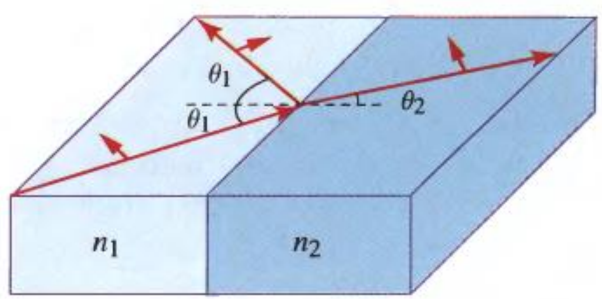
$\frac{n_1}{n_2} = \frac{1}{1.5}$

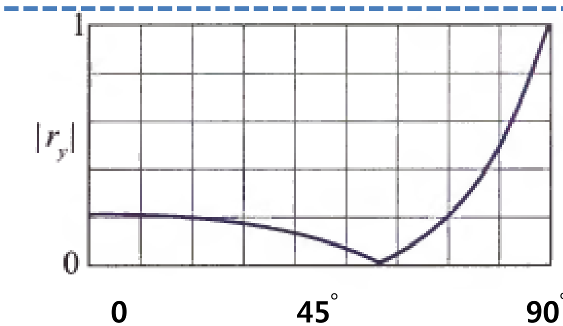
**TE**



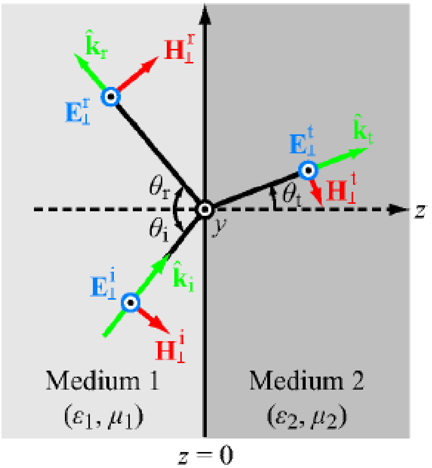




**TM**



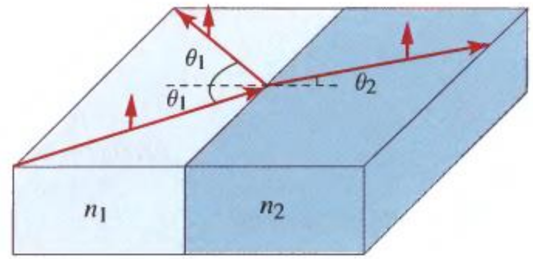



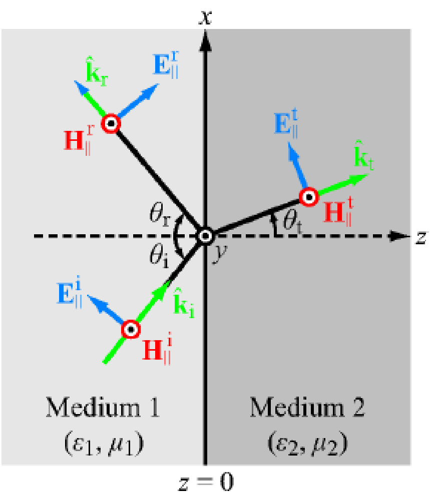
# TE/TM modes (plane of incident)




(a) Perpendicular polarization

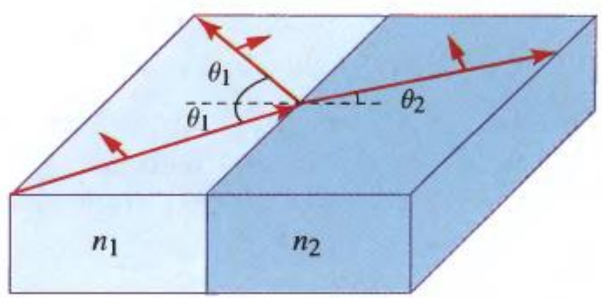
**Transverse electric(TE)**
**=Perpendicular polarization**



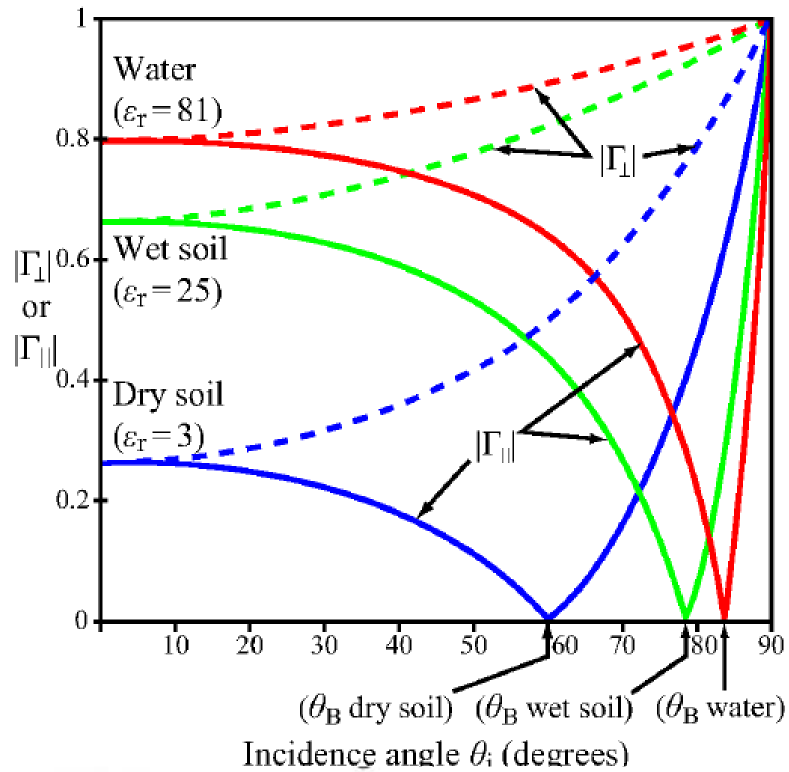

(b) Parallel polarization

**Transverse magnetic(TM)**
**=Parallel polarization**



| Property | Normal Incidence $\theta_i = \theta_t = 0$ | Perpendicular Polarization | Parallel Polarization |
|---|---|---|---|
| **Reflection coefficient** | $\Gamma = \dfrac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$ | $\Gamma_\perp = \dfrac{\eta_2 \cos\theta_i - \eta_1 \cos\theta_t}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$ | $\Gamma_\parallel = \dfrac{\eta_2 \cos\theta_t - \eta_1 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$ |
| **Transmission coefficient** | $\tau = \dfrac{2\eta_2}{\eta_2 + \eta_1}$ | $\tau_\perp = \dfrac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_i + \eta_1 \cos\theta_t}$ | $\tau_\parallel = \dfrac{2\eta_2 \cos\theta_i}{\eta_2 \cos\theta_t + \eta_1 \cos\theta_i}$ |
| **Relation of $\Gamma$ to $\tau$** | $\tau = 1 + \Gamma$ | $\tau_\perp = 1 + \Gamma_\perp$ | $\tau_\parallel = (1 + \Gamma_\parallel) \dfrac{\cos\theta_i}{\cos\theta_t}$ |
| **Reflectivity** | $R = \lvert\Gamma\rvert^2$ | $R_\perp = \lvert\Gamma_\perp\rvert^2$ | $R_\parallel = \lvert\Gamma_\parallel\rvert^2$ |
| **Transmissivity** | $T = \lvert\tau\rvert^2 \left(\dfrac{\eta_1}{\eta_2}\right)$ | $T_\perp = \lvert\tau_\perp\rvert^2 \dfrac{\eta_1 \cos\theta_t}{\eta_2 \cos\theta_i}$ | $T_\parallel = \lvert\tau_\parallel\rvert^2 \dfrac{\eta_1 \cos\theta_t}{\eta_2 \cos\theta_i}$ |
| **Relation of $R$ to $T$** | $T = 1 - R$ | $T_\perp = 1 - R_\perp$ | $T_\parallel = 1 - R_\parallel$ |

Notes: (1) $\sin\theta_t = \sqrt{\mu_1\varepsilon_1/\mu_2\varepsilon_2}\,\sin\theta_i$; (2) $\eta_1 = \sqrt{\mu_1/\varepsilon_1}$; (3) $\eta_2 = \sqrt{\mu_2/\varepsilon_2}$; (4) for nonmagnetic media, $\eta_2/\eta_1 = n_1/n_2$.



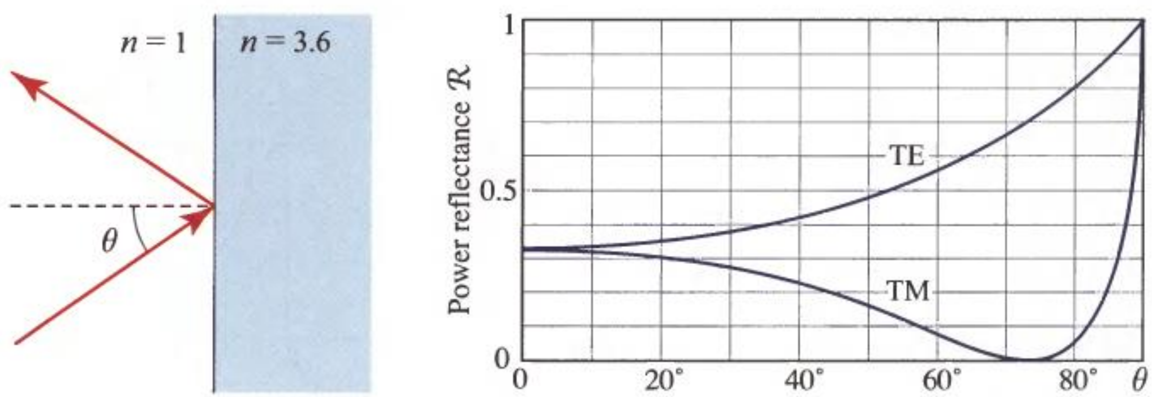




**Figure 6.2-7** Power reflectance of TE- and TM-polarization plane waves at the boundary between

- **Check point**

1. In case normal incident

   $\Gamma_{\perp} = \Gamma_{\parallel}$ , $\tau_{\perp} = \tau_{\parallel}$

2. $\tau_{\perp} = 1 + \Gamma_{\perp}$, $\tau_{\parallel} = (1 + \Gamma_{\parallel}) \frac{\cos \theta_i}{\cos \theta_t}$

   Energy conservation?

어떻게 투과파의 계수가 1보다 클 수 있나.

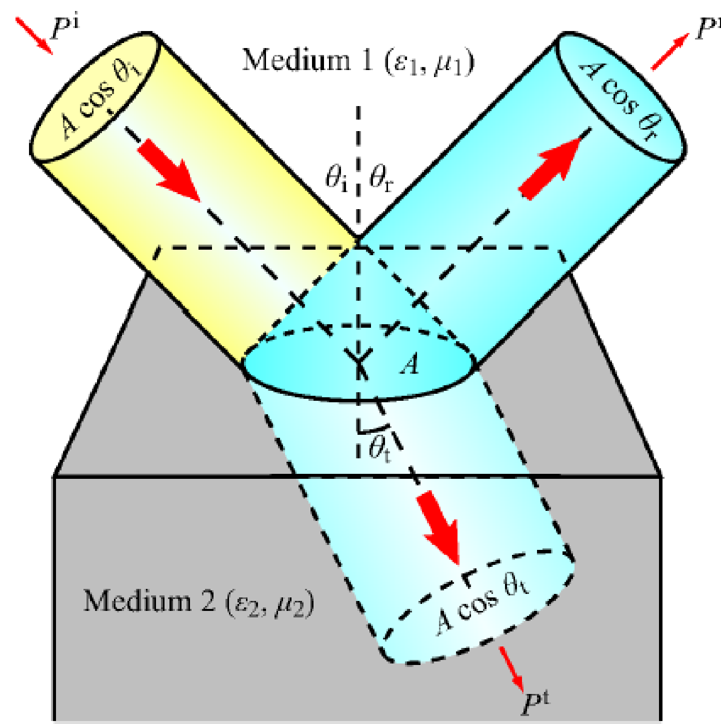
- $T_{\perp} = |\tau_{\perp}|^2 \frac{\eta_1 \cos\theta_i}{\eta_2 \cos\theta_t}$, $T_{\parallel} = |\tau_{\parallel}|^2 \frac{\eta_1 \cos\theta_i}{\eta_2 \cos\theta_t}$
- $\frac{\eta_1}{\eta_2} = \frac{n_2}{n_1}$ *non magnetic*

**Solid angle**
**과 굴절률 보정 고려**

*Power density

$$S_{av} = \frac{1}{2} \mathrm{Re}\{\tilde{E} \times \tilde{H}^*\}$$

$$S_{av} = \hat{z} \frac{|\tilde{E}|^2}{2\eta} \qquad (\mathrm{W/m^2})$$



- Electric flux density
- $\mathrm{D} = \epsilon E$ $\epsilon$: $3 \times 3$ tensor
  - Electric permittivity tensor

$$\mathrm{D_j} = \sum_j \epsilon_{ij} E_j$$

Principal axes

$\mathrm{D}_1 = \epsilon_1 E_1$ $\mathrm{D}_1 = \epsilon_2 E_1$ $\mathrm{D}_1 = \epsilon_2 E_1$