Si Photonics

Lecture 4: Reflection and Transmission at Dielectric Interface

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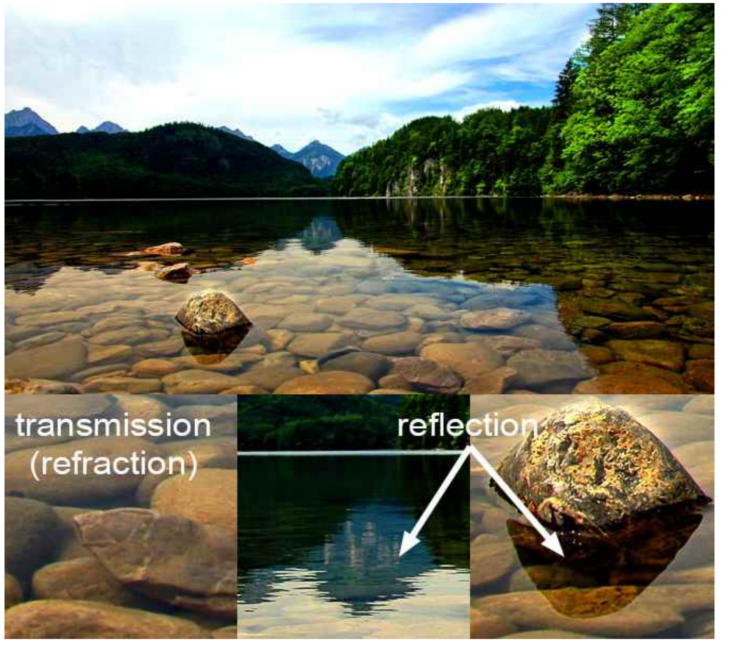
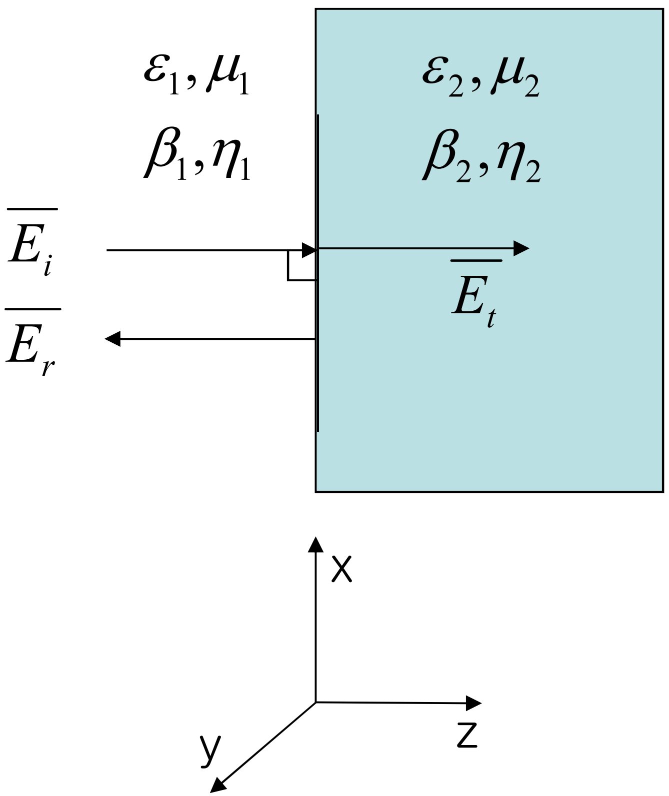
Lecture 4: Reflection and Transmission at Dielectric Interface



Lecture 4: Reflection and Transmission at Dielectric Interface

$\sigma = 0$



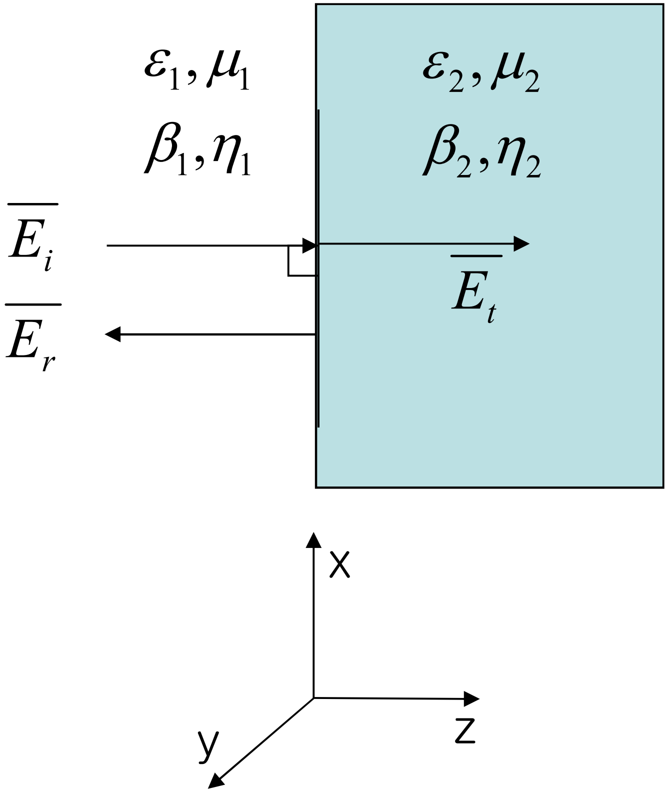
$$\overline{E}_i = \overline{y} E_0 \exp(-j\beta_1 z), \quad \overline{H}_i = -\overline{x} \frac{E_0}{\eta_1} \exp(-j\beta_1 z)$$

$$\overline{E}_r = \overline{y} E_r \exp(j\beta_1 z), \quad \overline{H}_r = \overline{x} \frac{E_r}{\eta_1} \exp(j\beta_1 z)$$

$$\overline{E}_t = \overline{y} E_t \exp(-j\beta_2 z), \quad \overline{H}_t = -\overline{x} \frac{E_t}{\eta_2} \exp(-j\beta_2 z)$$

Unknowns: E_r, E_t

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\overline{E}_i = \overline{y} E_0 \exp(-j\beta_1 z), \quad \overline{H}_i = -\overline{x} \frac{E_0}{\eta_1} \exp(-j\beta_1 z)$$

$$\overline{E}_r = \overline{y} E_r \exp(j\beta_1 z), \quad \overline{H}_r = \overline{x} \frac{E_r}{\eta_1} \exp(j\beta_1 z)$$

$$\overline{E}_t = \overline{y} E_t \exp(-j\beta_2 z), \quad \overline{H}_t = -\overline{x} \frac{E_t}{\eta_2} \exp(-j\beta_2 z)$$

B.C.'s

1) E_{tan} should be continuous at z=0

$$E_0 + E_r = E_t$$

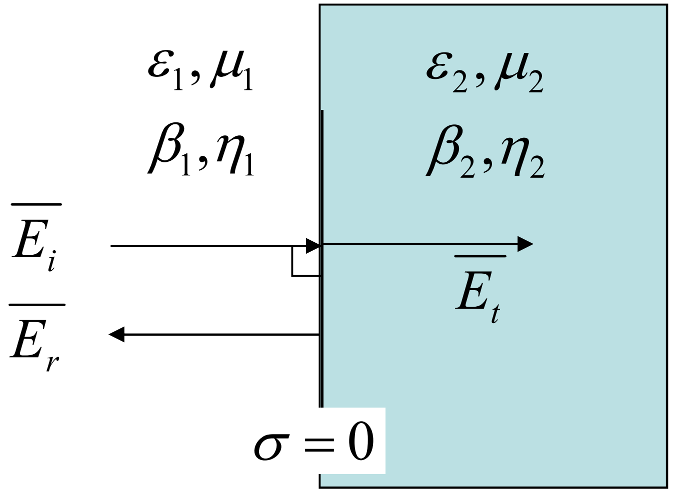
Define $E_r = \Gamma E_0$, and $E_t = \tau E_0$

Γ: reflection coef.

τ : transmission coef.

$\Rightarrow \quad 1 + \Gamma = \tau$

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\overline{H}_i = -\overline{x}\frac{E_0}{\eta_1}\exp(-j\beta_1 z)$$

$$\overline{H}_r = \overline{x}\frac{E_r}{\eta_1}\exp(j\beta_1 z)$$

$$\overline{H}_t = -\overline{x}\frac{E_t}{\eta_2}\exp(-j\beta_2 z)$$

2) H_{tan} should be continuous at z=0

$$\overline{a}_n \times (\overline{H}_2 - \overline{H}_1) = \overline{J}_s \quad = 0$$

$$H_i + H_r = H_t$$

$$-\frac{E_0}{\eta_1} + \frac{E_r}{\eta_1} = -\frac{E_t}{\eta_2}$$

$$\therefore -\frac{1}{\eta_1} + \frac{\Gamma}{\eta_1} = -\frac{\tau}{\eta_2}, \qquad (1 + \Gamma = \tau)$$

$$\boxed{\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}, \quad \tau = \frac{2\eta_2}{\eta_2 + \eta_1}}$$

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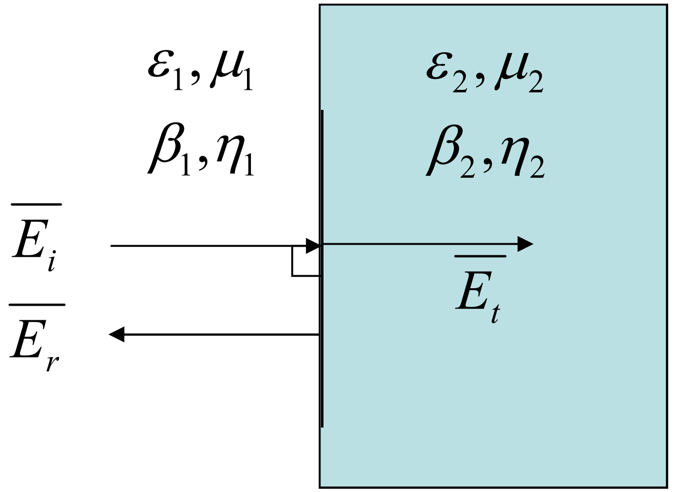


$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}, \quad \tau = \frac{2\eta_2}{\eta_2 + \eta_1}$$

$$\eta = \sqrt{\frac{\mu}{\varepsilon}}$$

In dielectric materials,

$$\mu = \mu_0 \qquad \varepsilon = \varepsilon_r \varepsilon_0 = n^2 \varepsilon_0$$

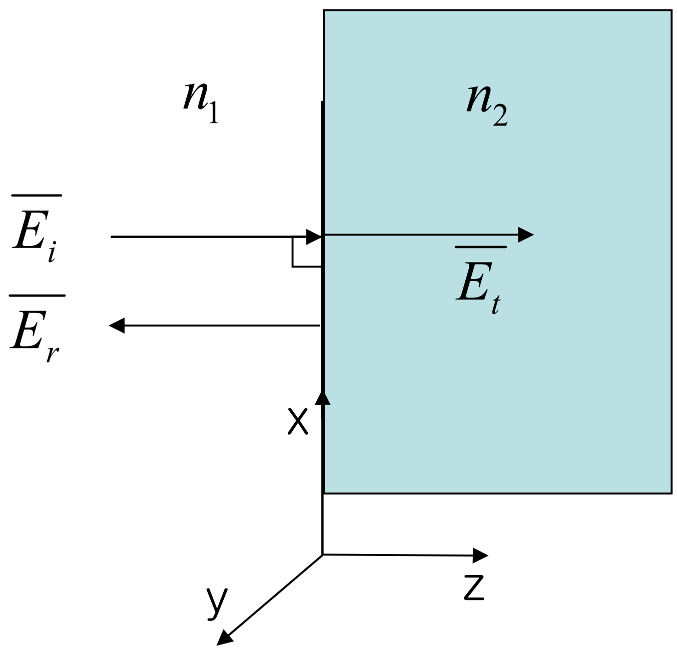
n: refractive index

$$\frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{n\sqrt{\mu_0 \varepsilon_0}}$$

$$\Gamma = \frac{\sqrt{\frac{\mu_2}{\varepsilon_2}} - \sqrt{\frac{\mu_1}{\varepsilon_1}}}{\sqrt{\frac{\mu_2}{\varepsilon_2}} - \sqrt{\frac{\mu_1}{\varepsilon_1}}} = \frac{\frac{1}{n_2}\sqrt{\frac{1}{\varepsilon_0}} - \frac{1}{n_1}\sqrt{\frac{1}{\varepsilon_0}}}{\frac{1}{n_2}\sqrt{\frac{1}{\varepsilon_0}} + \frac{1}{n_1}\sqrt{\frac{1}{\varepsilon_0}}} = \frac{n_1 - n_2}{n_1 + n_2}, \qquad \tau = \frac{2n_1}{n_1 + n_2}$$

$$\beta = \omega\sqrt{\mu\varepsilon} = n\beta_0$$

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\Gamma = \frac{n_1 - n_2}{n_1 + n_2}, \quad \tau = \frac{2n_1}{n_1 + n_2}$$

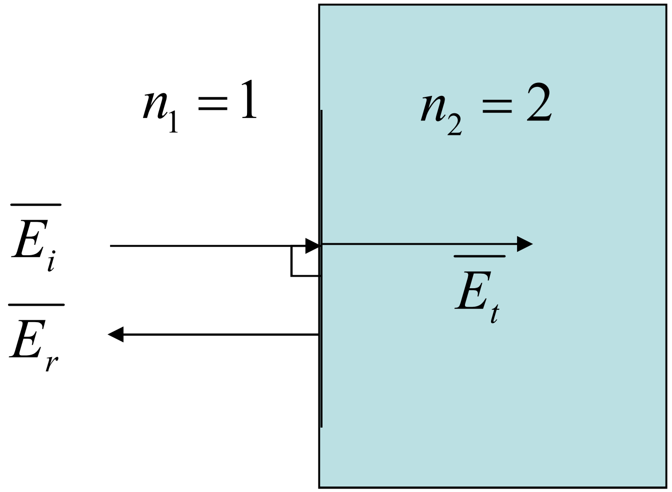
$$\text{Max. } \Gamma: \ 1, \ n_1 >> n_2$$

$$\tau: \ 2$$

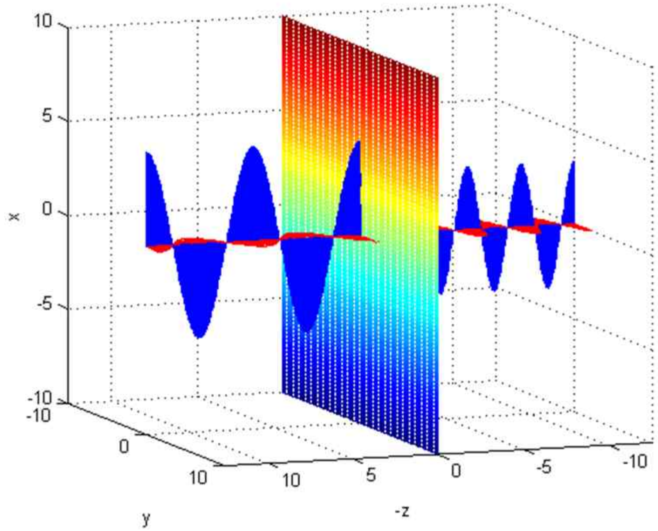
$$\text{Min. } \Gamma: \ \text{-}1, \ n_1 << n_2$$

$$\tau: \ 0$$

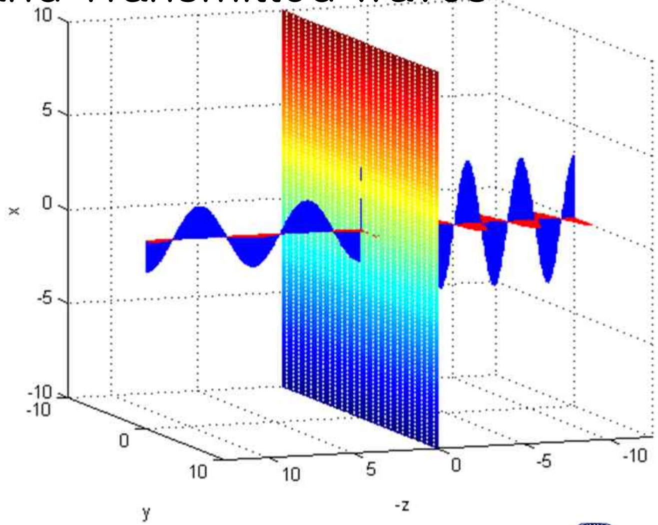
Lecture 4: Reflection and Transmission at Dielectric Interface



Incident and Transmitted waves



Reflected and Transmitted waves



$$\Gamma = \frac{n_1 - n_2}{n_1 + n_2} = -\frac{1}{3}$$

$$\tau = \frac{2n_1}{n_1 + n_2} = \frac{2}{3}$$

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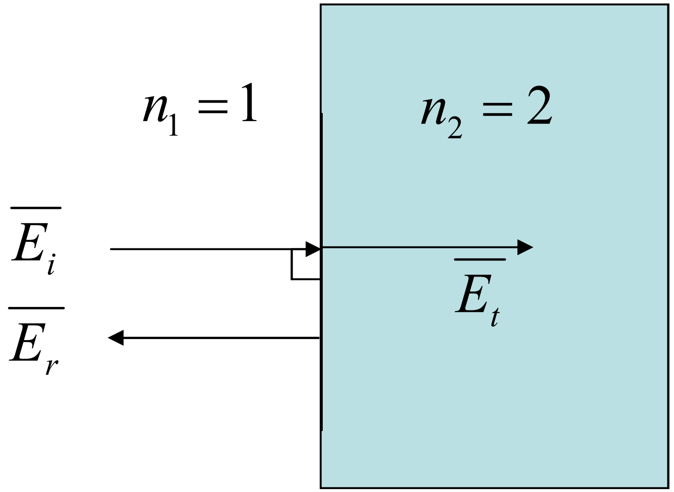
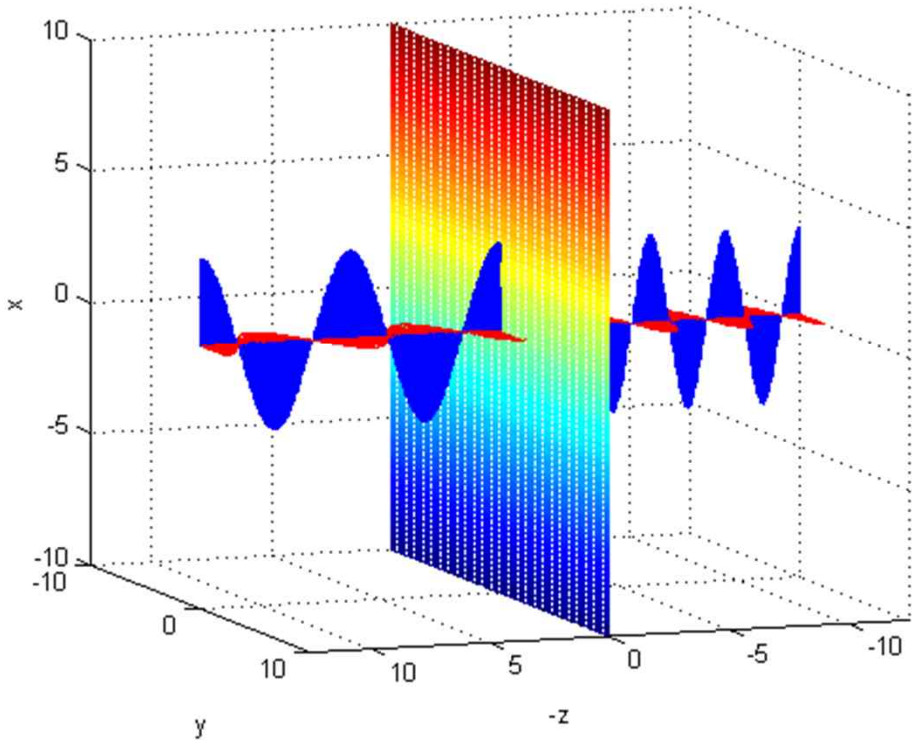


$$\Gamma = \frac{n_1 - n_2}{n_1 + n_2} = -\frac{1}{3}$$

$$\tau = \frac{2n_1}{n_1 + n_2} = \frac{2}{3}$$

Total waves



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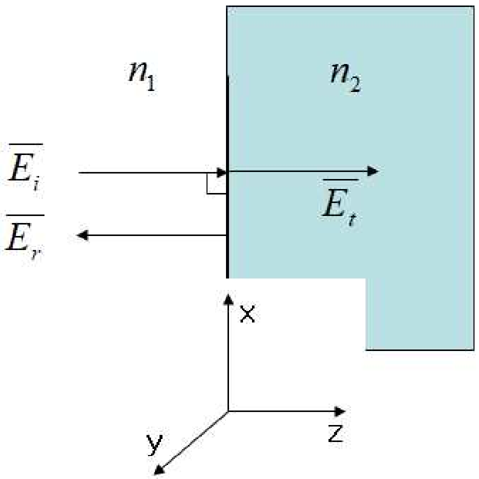
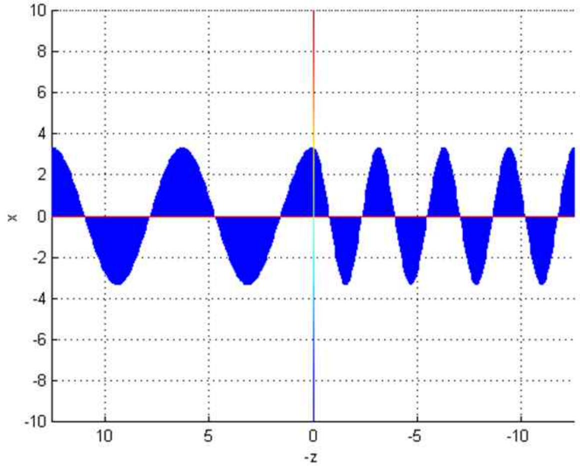


Total E-field for z<0

$$\overline{E}_{total}(z<0) = \overline{E}_i + \overline{E}_r = \overline{y}E_0(e^{-jn_1\beta_0 z} + \Gamma e^{jn_1\beta_0 z})$$

$$= \overline{y}E_0\left\{(1+\Gamma)e^{-jn_1\beta_0 z} + \Gamma(e^{jn_1\beta_0 z} - e^{-jn_1\beta_0 z})\right\}$$

$$= \overline{y}E_0\left\{\underbrace{(1+\Gamma)e^{-jn_1\beta_0 z}}_{\text{transmitting wave}} + \underbrace{2j\Gamma\sin(n_1\beta_0 z)}_{\text{standing wave}}\right\}$$



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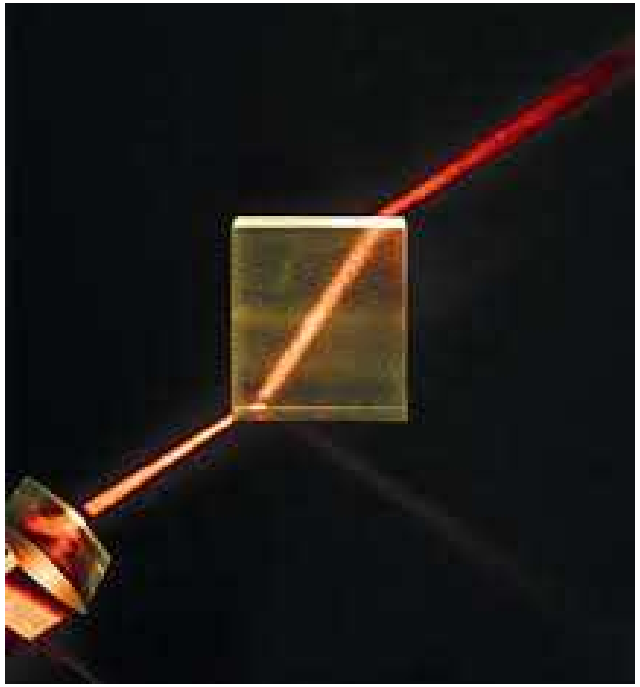
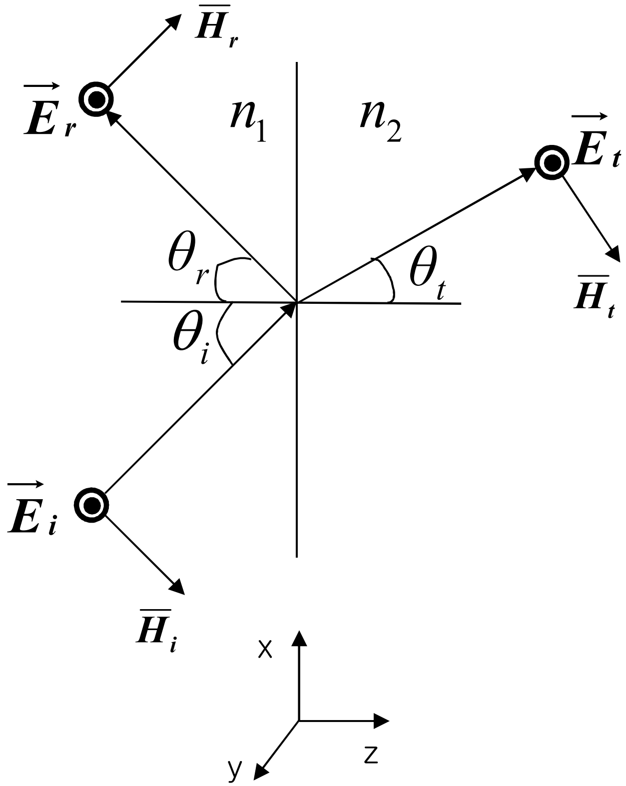
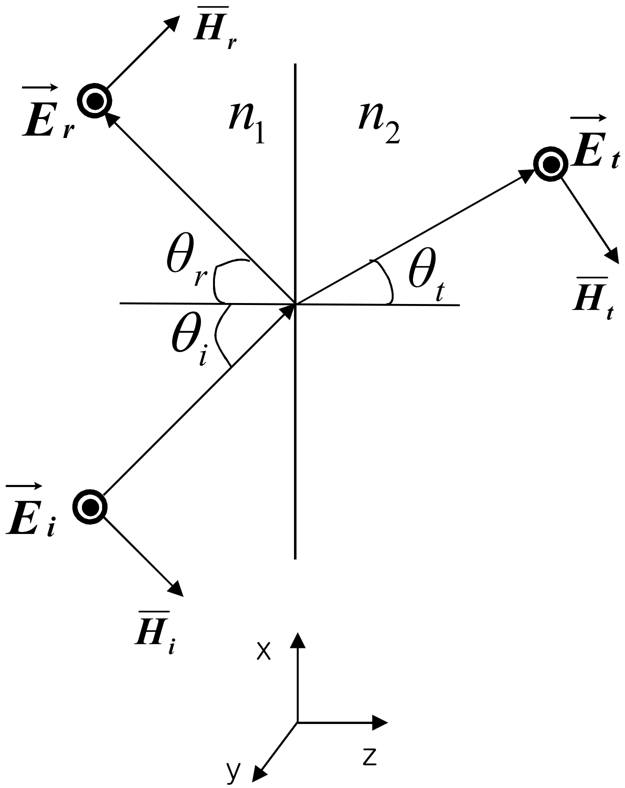




➔ Reflection, Transmission (Refraction)

(Perpendicular Polarization)

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\overline{E_i} = \overline{y} E_i \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\beta_{1x} = \quad n_1 k_0 \sin\theta_i$$

$$\beta_{1z} = \quad n_1 k_0 \cos\theta_i$$

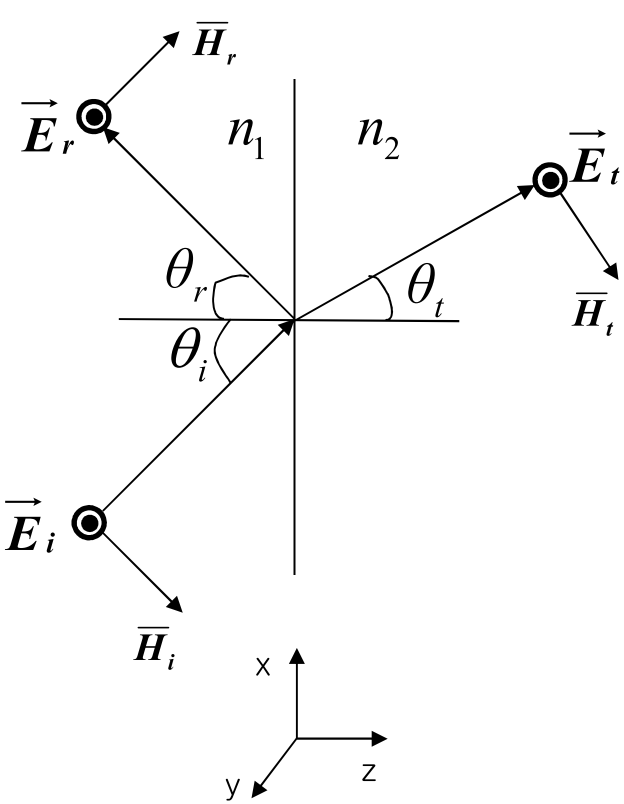
$$\overline{E_r} = \overline{y}\ \Gamma E_i \exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

Γ: reflection coefficient

$$\overline{E_t} = \overline{y}\ \tau E_i \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

τ : transmission coefficient

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\overline{E_i} = \bar{y} E_i \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{H_i} = (-\bar{x}\cos\theta_i + \bar{z}\sin\theta_i)\frac{E_i}{\eta_1}\exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{E_r} = \bar{y}\,\Gamma E_i \exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

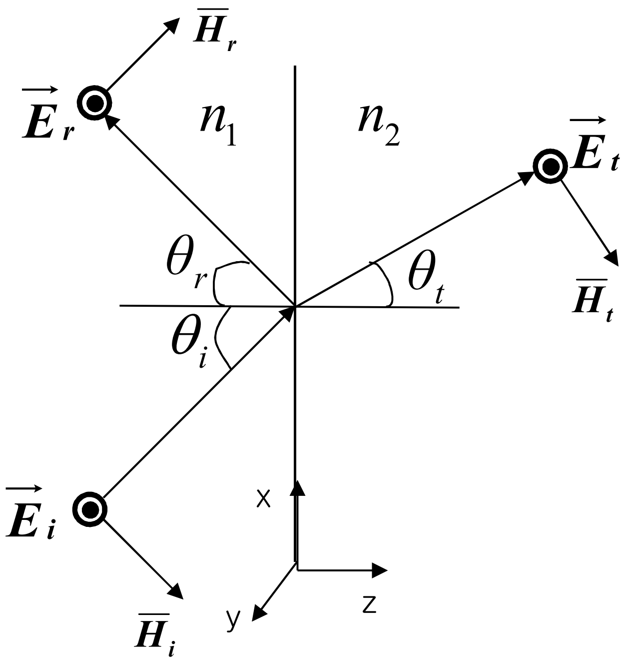
$$\overline{H_r} = (\bar{x}\cos\theta_r + \bar{z}\sin\theta_r)\frac{\Gamma E_i}{\eta_1}\exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{E_t} = \bar{y}\,\tau E_i \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

$$\overline{H_t} = (-\bar{x}\cos\theta_t + \bar{z}\sin\theta_t)\frac{\tau E_i}{\eta_2}\exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

Unknowns: $\Gamma, \tau, \theta_r, \theta_t$

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\overline{E_i} = \overline{y} E_i \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{E_r} = \overline{y}\, \Gamma E_i \exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{E_t} = \overline{y}\, \tau E_i \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

B.C.'s at $z=0$

1) $\overline{E}_{tan}$ continuous $(\overline{E_i}+\overline{E_r}=\overline{E_t})$

$$\exp(-j\beta_{1x}x) + \Gamma\exp(-j\beta_{rx}x) = \tau\exp(-j\beta_{2x}x)$$

$\therefore$ (a) $\beta_{1x} = \beta_{rx} = \beta_{2x}$ and (b) $1+\Gamma=\tau$

From $\beta_{1x} = \beta_{rx} = \beta_{2x}$

$$n_1 k_0 \sin\theta_i = n_1 k_0 \sin\theta_r = n_2 k_0 \sin\theta_t$$

$$\theta_i = \theta_r$$

$$n_1 \sin\theta_i = n_2 \sin\theta_t \qquad \text{Snell's Law}$$

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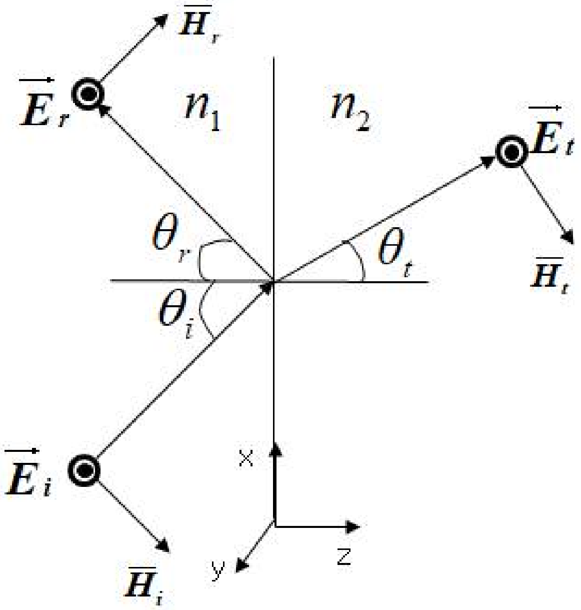


$\theta_i = \theta_r \qquad n_1 \sin\theta_i = n_2 \sin\theta_t \qquad \Gamma, \tau$?

B.C. on $\bar{H}$ at z=0

$\bar{H}_{\tan}$ and $\bar{H}_{n}$ continuous at z=0

From BC on $\bar{H}_{\tan}$ $\quad -\dfrac{\cos\theta_i}{\eta_1} + \dfrac{\cos\theta_i}{\eta_1}\Gamma = -\dfrac{\cos\theta_t}{\eta_2}\tau$

With $1+\Gamma=\tau$, $\quad \Gamma_{\perp} = \dfrac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}$

$$\tau_{\perp} = \frac{2n_1\cos\theta_i}{n_1\cos\theta_i + n_2\cos\theta_t}$$

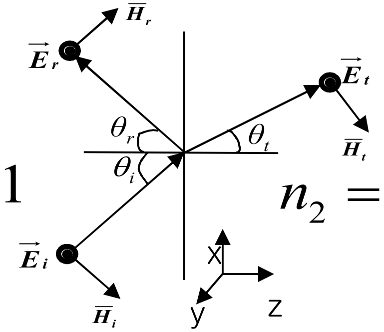
$$\overline{H_i} = (-\bar{x}\cos\theta_i + \bar{z}\sin\theta_i)\frac{E_i}{\eta_1}\exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{H_r} = (\bar{x}\cos\theta_i + \bar{z}\sin\theta_i)\frac{\Gamma E_i}{\eta_1}\exp(-j\beta_{1x}x)\exp(j\beta_{1z}z)$$

$$\overline{H_t} = (-\bar{x}\cos\theta_t + \bar{z}\sin\theta_t)\frac{\tau E_i}{\eta_2}\exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

Remember for normal incident

$$\Gamma = \frac{n_1 - n_2}{n_1 + n_2}, \quad \tau = \frac{2n_1}{n_1 + n_2}$$

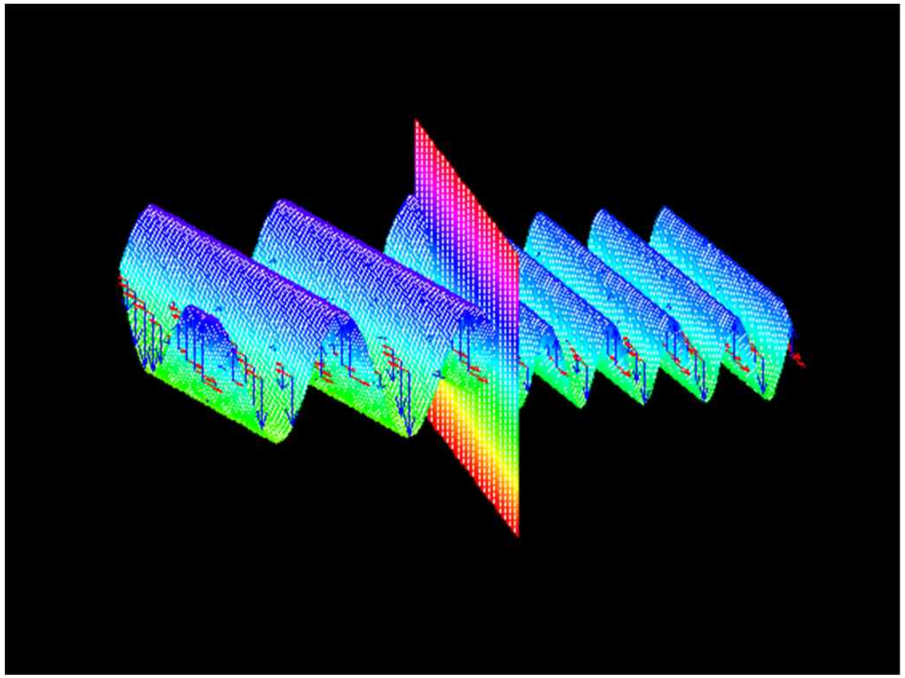


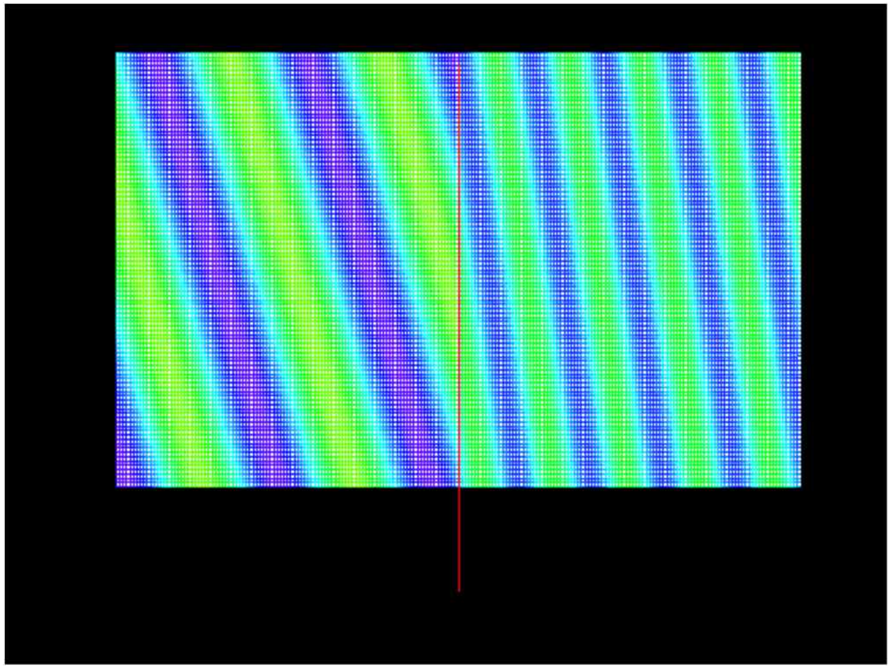
$n_1 = 1$ $\quad n_2 = 2$

$\theta_i = 20^\circ \qquad n_1 \sin\theta_i = n_2 \sin\theta_t \qquad \theta_t = \sin^{-1}\left[\frac{1}{2}\sin(20^\circ)\right] \simeq 9.85^\circ$

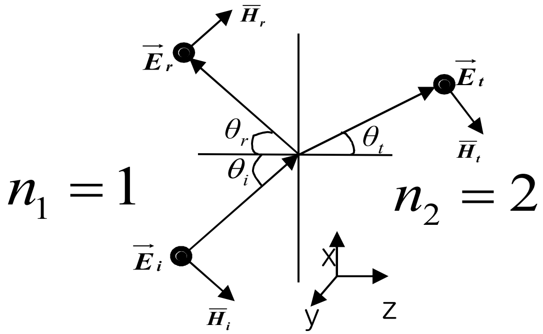
$\Gamma_\perp = \dfrac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t} = \text{-}0.3542 \qquad \tau_\perp = \dfrac{2n_1\cos\theta_i}{n_1\cos\theta_i + n_2\cos\theta_t} = 0.6458$

Incident and Transmitted Waves (Refraction)





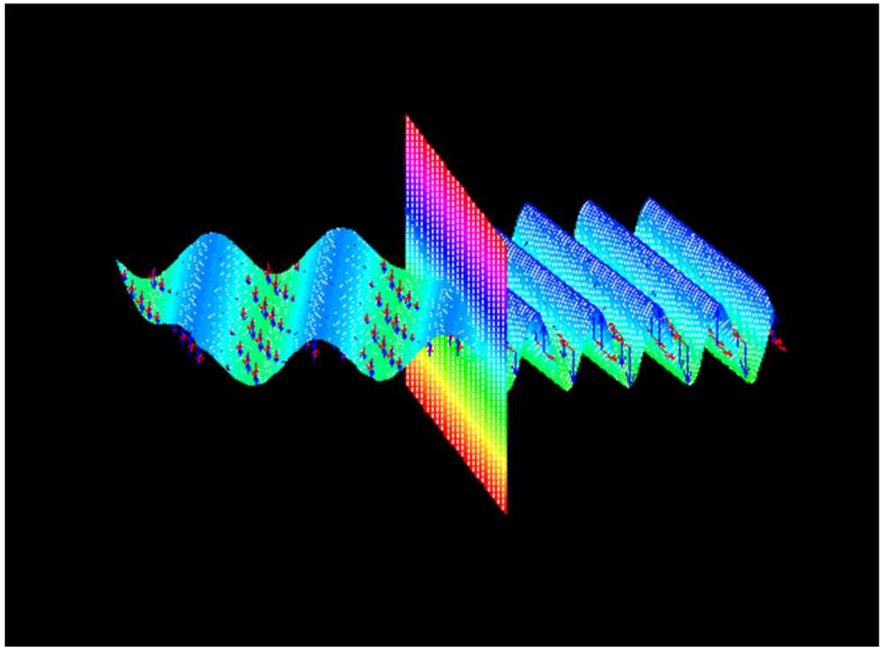
Lecture 4: Reflection and Transmission at Dielectric Interface

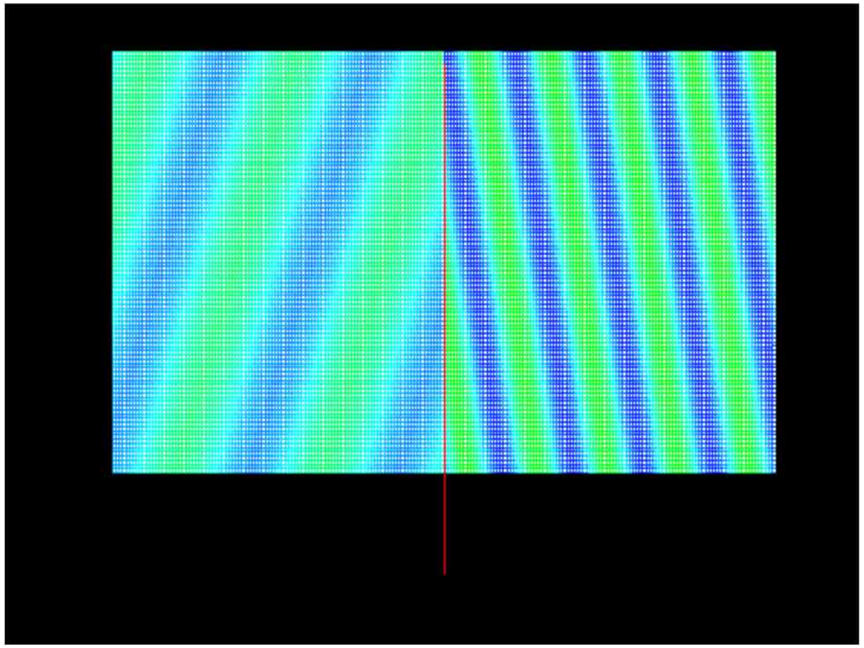


For $\theta_i = 20^\circ$ $\theta_t \simeq 9.85^\circ$

Γ = -0.3542, τ = 0.6458

Reflected and Transmitted Waves





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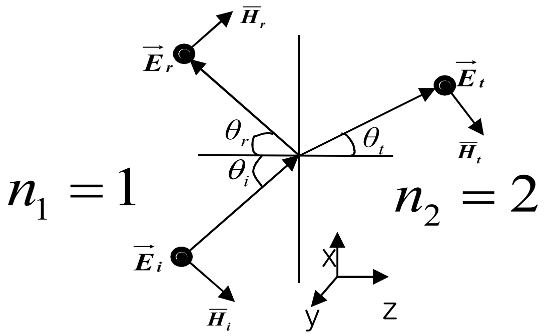
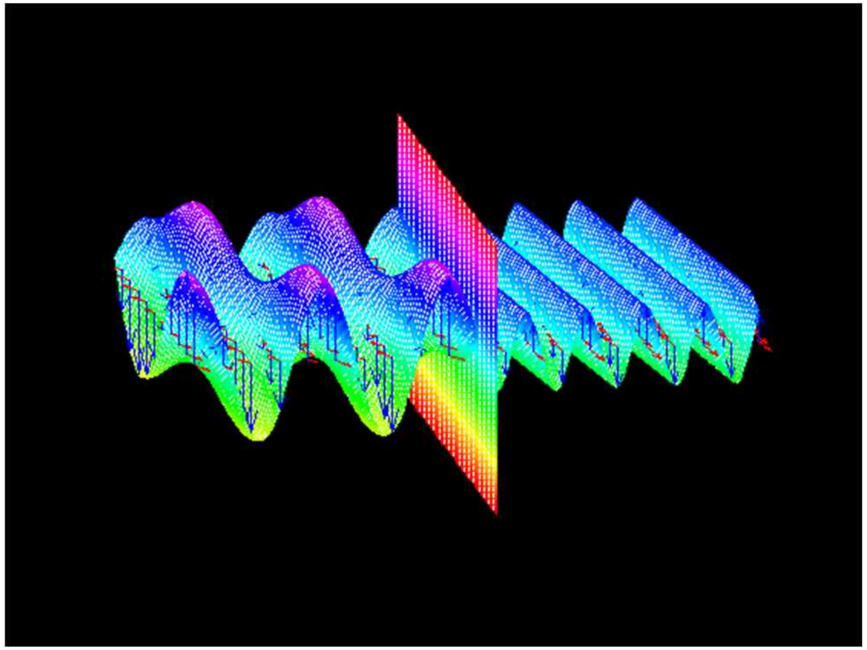
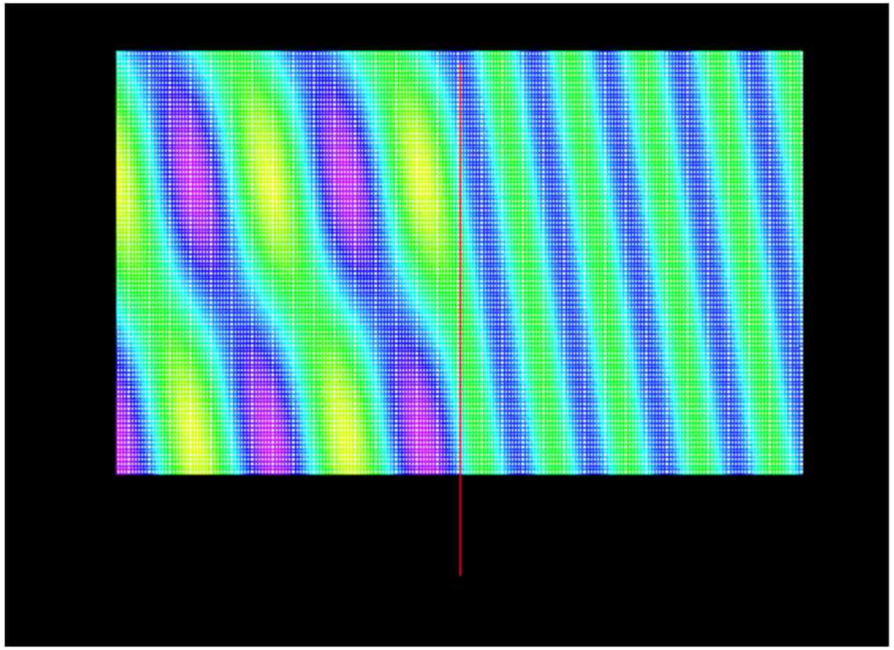


For $\theta_i = 20^\circ$ $\theta_t \simeq 9.85^\circ$

$\Gamma =$ -0.3542, $\tau =$ 0.6458

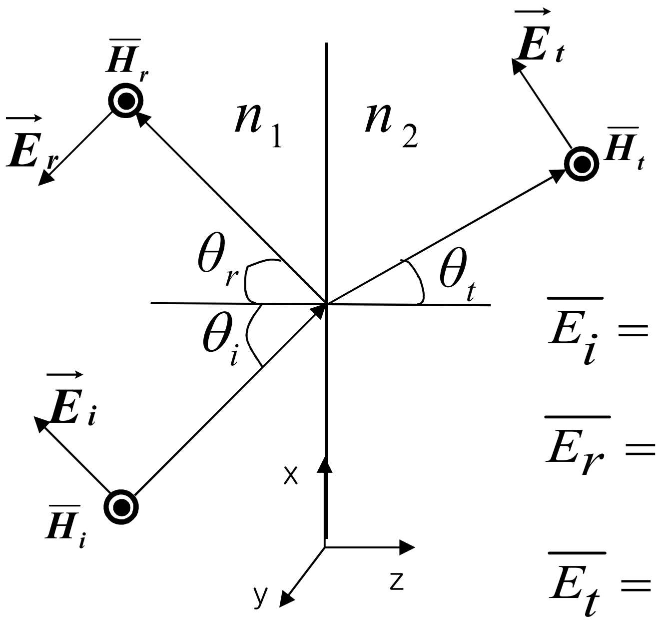
Total and Transmitted Waves





Lecture 4: Reflection and Transmission at Dielectric Interface

✓ Parallel Polarization



$$\overline{H_i} = \bar{y} H_i \exp(-j\beta_{1x} x)\exp(-j\beta_{1z} z)$$

$$\overline{H_r} = \bar{y} H_r \exp(-j\beta_{rx} x)\exp(j\beta_{rz} z)$$

$$\overline{H_t} = \bar{y} H_t \exp(-j\beta_{2x} x)\exp(-j\beta_{2z} z)$$

$$\overline{E_i} = (\bar{x}\cos\theta_i - \bar{z}\sin\theta_i) H_i \eta_1 \exp(-j\beta_{1x} x)\exp(-j\beta_{1z} z)$$

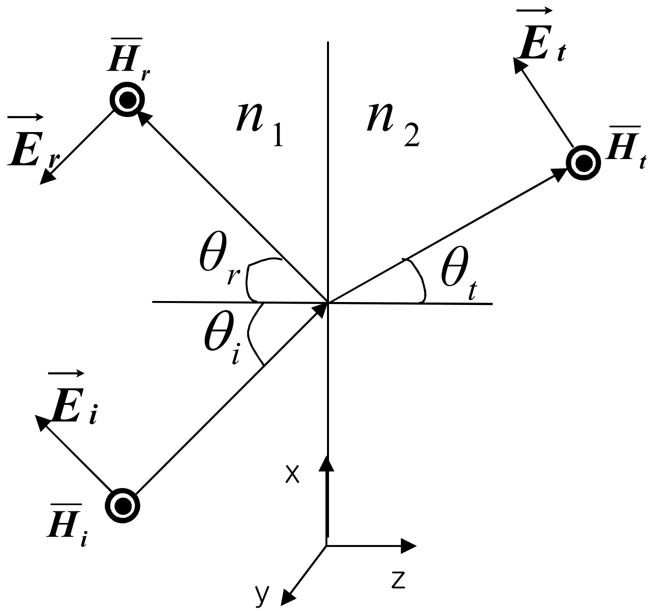
$$\overline{E_r} = (-\bar{x}\cos\theta_r - \bar{z}\sin\theta_r) H_r \eta_1 \exp(-j\beta_{rx} x)\exp(j\beta_{rz} z)$$

$$\overline{E_t} = (\bar{x}\cos\theta_t - \bar{z}\sin\theta_t) H_t \eta_2 \exp(-j\beta_{2x} x)\exp(-j\beta_{2z} z)$$

$$\frac{E_r}{E_i} = \Gamma \qquad \frac{H_r}{H_i} = -\Gamma \qquad \frac{E_t}{E_i} = \tau \qquad \frac{H_t}{H_i} = \frac{E_t / \eta_2}{E_i / \eta_1} = \tau \frac{\eta_1}{\eta_2}$$

Lecture 4: Reflection and Transmission at Dielectric Interface

✓ Parallel Polarization



$$\frac{H_r}{H_i} = -\Gamma \qquad \frac{H_t}{H_i} = \tau\frac{\eta_1}{\eta_2}$$

$$\overline{H_i} = \overline{y}H_i \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{H_r} = \overline{y}(-\Gamma)H_i \exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{H_t} = \overline{y}\frac{\eta_1}{\eta_2}\tau H_i \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

$$\overline{E_i} = (\overline{x}\cos\theta_i - \overline{z}\sin\theta_i)H_i\eta_1 \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{E_r} = (-\overline{x}\cos\theta_r - \overline{z}\sin\theta_r)H_i\eta_1(-\Gamma)\exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{E_t} = (\overline{x}\cos\theta_t - \overline{z}\sin\theta_t)H_i\eta_1\tau \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

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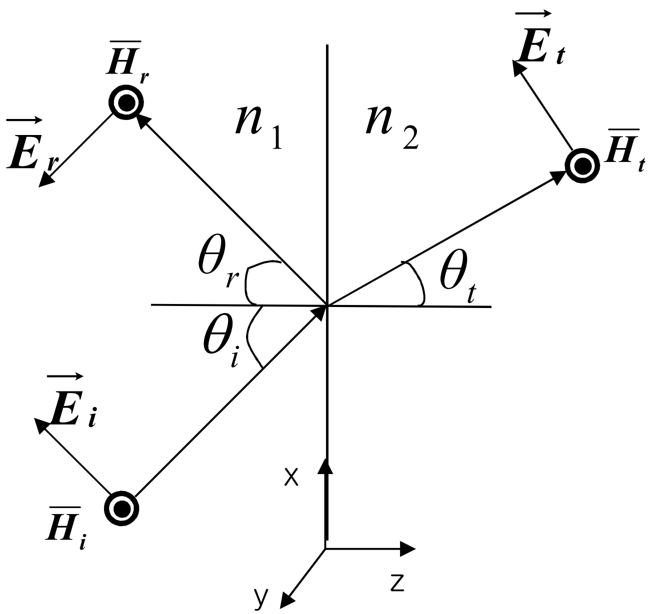


$$\overline{H_i} = \overline{y} H_i \exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{H_r} = \overline{y}(-\Gamma) H_i \exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{H_t} = \overline{y}\frac{\eta_1}{\eta_2}\tau H_i \exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

B.C.'s at $z=0$

1) $\bar{H}_{\tan}$ coutinuous $(\bar{H}_i + \bar{H}_r = \bar{H}_t)$

$$\exp(-j\beta_{1x}x) - \Gamma\exp(-j\beta_{rx}x) = \frac{\eta_1}{\eta_2}\tau\exp(-j\beta_{2x}x)$$

(a) $\beta_{1x} = \beta_{rx} = \beta_{2x}$

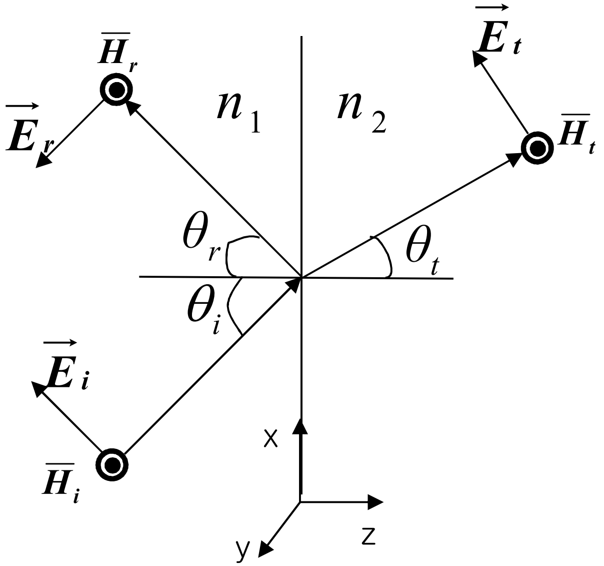
$\theta_i = \theta_r$

$n_1 \sin\theta_i = n_2 \sin\theta_t$: Snell's Law

(b) $1 - \Gamma = \frac{\eta_1}{\eta_2}\tau$

$1 - \Gamma = \frac{n_2}{n_1}\tau$

Lecture 4: Reflection and Transmission at Dielectric Interface



B.C.'s at z=0   2) $\overline{E}_{\tan}$ continuous

$$\cos\theta_i + \Gamma\cos\theta_i = \tau\cos\theta_t \qquad \text{With} \quad 1-\Gamma = \frac{n_2}{n_1}\tau,$$

$$\boxed{\Gamma_{ll} = \frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}, \quad \tau_{ll} = \frac{2n_1\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}}$$

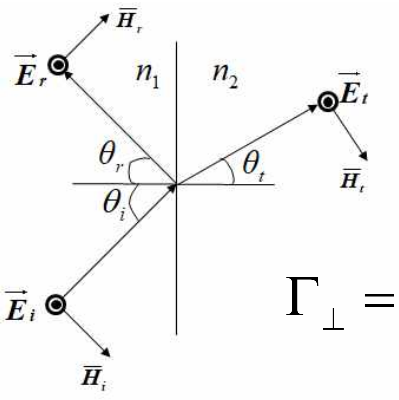
For normal incidence $\Gamma = \dfrac{n_1 - n_2}{n_1 + n_2}, \quad \tau = \dfrac{2n_1}{n_1 + n_2}$

$$\overline{E_i} = (\overline{x}\cos\theta_i - \overline{z}\sin\theta_i)H_i\eta_1\exp(-j\beta_{1x}x)\exp(-j\beta_{1z}z)$$

$$\overline{E_r} = (-\overline{x}\cos\theta_r - \overline{z}\sin\theta_r)H_i\eta_1(-\Gamma)\exp(-j\beta_{rx}x)\exp(j\beta_{rz}z)$$

$$\overline{E_t} = (\overline{x}\cos\theta_t - \overline{z}\sin\theta_t)H_i\eta_1\tau\exp(-j\beta_{2x}x)\exp(-j\beta_{2z}z)$$

Lecture 4: Reflection and Transmission at Dielectric Interface

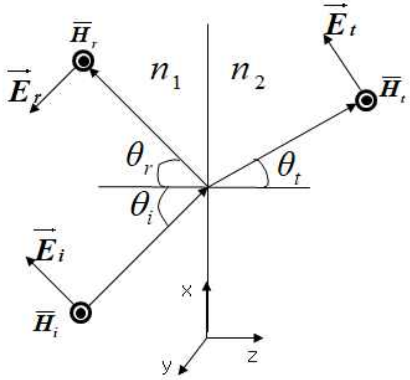


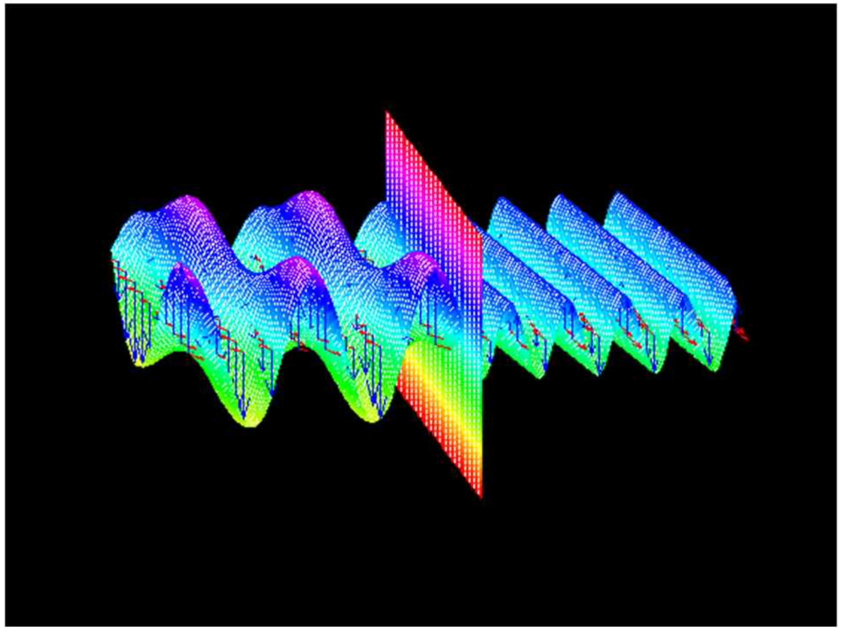
Perpendicular vs Parallel

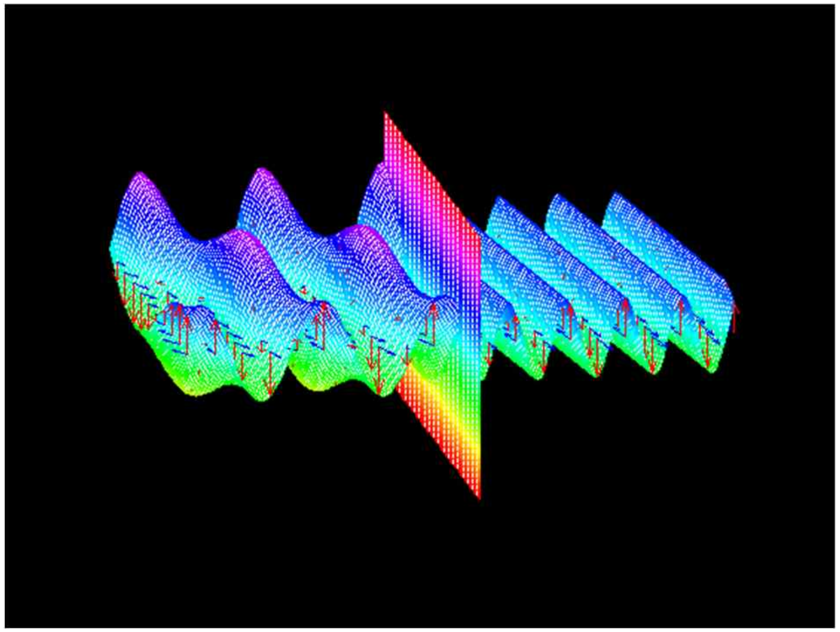
$n_1 = 1,\ n_2 = 2 \quad \theta_i = 20^\circ$

$n_1 \sin\theta_i = n_2 \sin\theta_t \quad \theta_t = 9.85^\circ$

$\Gamma_\perp = -0.354, \tau_\perp = 0.646 \qquad \Gamma_\parallel = -0.312, \tau_\parallel = 0.656$





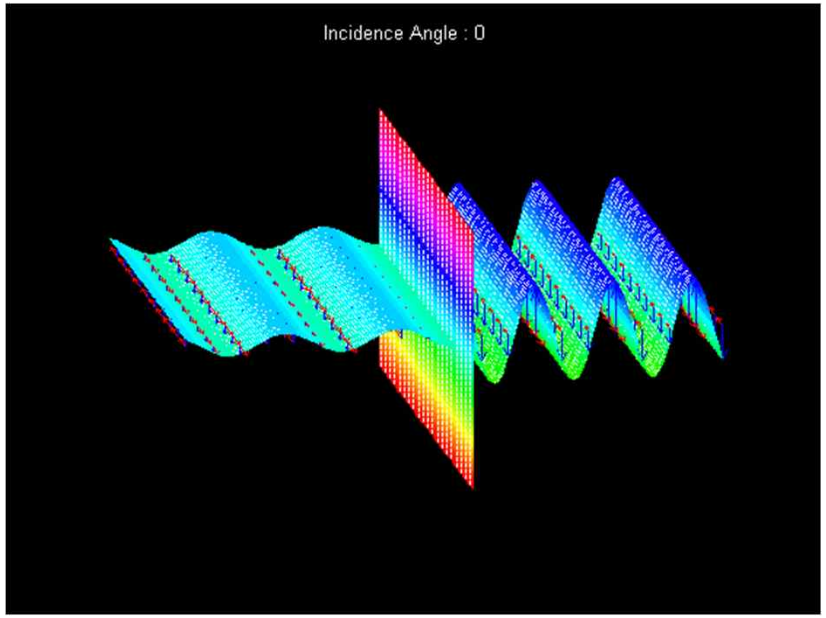


Lecture 4: Reflection and Transmission at Dielectric Interface

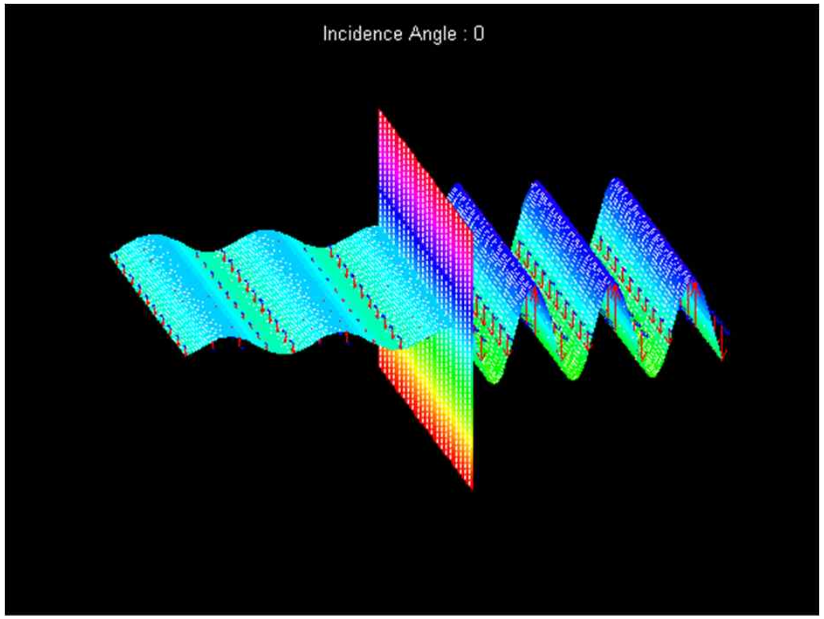
θ_i: from 0° to 90°

(Reflected and Transmitted Waves Only)

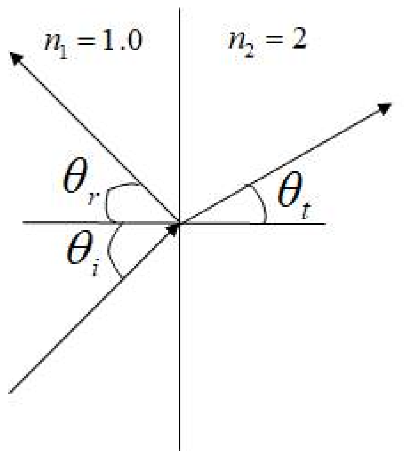
Perpendicular



Parallel

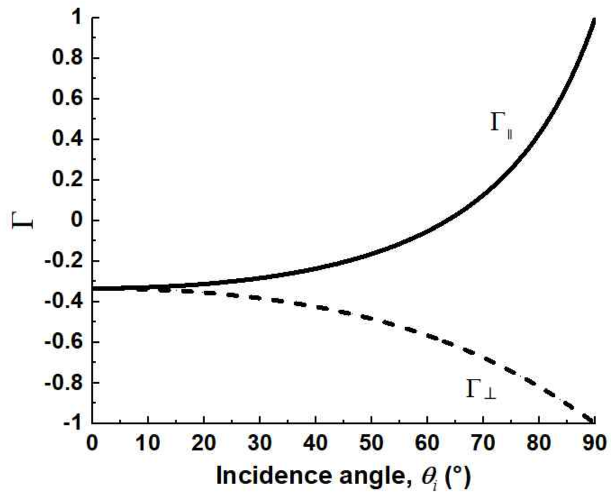


Lecture 4: Reflection and Transmission at Dielectric Interface



$$\Gamma_{\perp} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}$$

$$\Gamma_{\parallel} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}$$



For $\Gamma_{\parallel} = \dfrac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} = 0$ $\qquad n_2 \cos\theta_i = n_1 \cos\theta_t \qquad$ and $\; n_1 \sin\theta_i = n_2 \sin\theta_t$

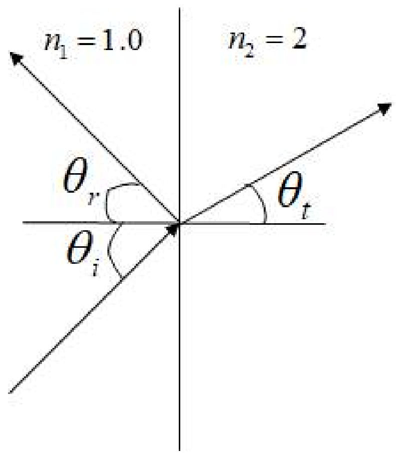
$$\sin^2\theta_i = \frac{n_2^{\,2}}{n_1^{\,2} + n_2^{\,2}}, \quad \cos^2\theta_i = \frac{n_1^{\,2}}{n_1^{\,2} + n_2^{\,2}} \qquad \therefore \theta_i = \tan^{-1}\left(\frac{n_2}{n_1}\right) = \tan^{-1}(2) = 63.4^\circ$$

No reflection for parallel polarization on dielectric interface at certain incident angle

➔ Brewster angle

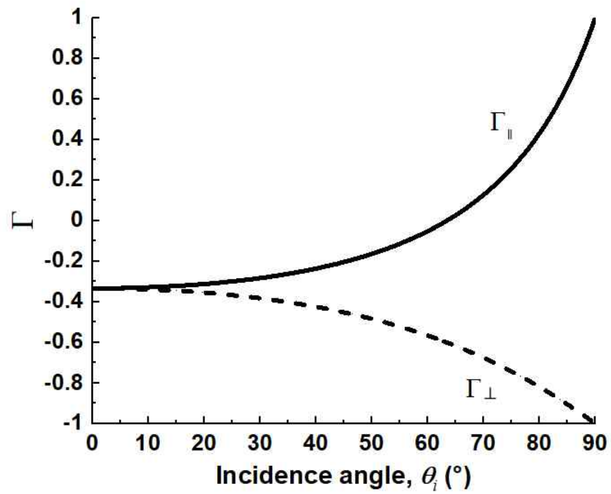
Small reflection around Brewster angle

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\Gamma_{\perp} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}$$

$$\Gamma_{\parallel} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}$$



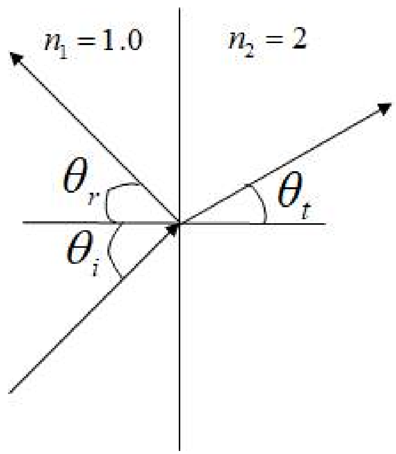
For $\Gamma_{\parallel} = \dfrac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i} = 0$ $\quad n_2 \cos\theta_i = n_1 \cos\theta_t \quad$ and $\; n_1 \sin\theta_i = n_2 \sin\theta_t$

$$\sin^2\theta_i = \frac{n_2^{\,2}}{n_1^{\,2} + n_2^{\,2}}, \quad \cos^2\theta_i = \frac{n_1^{\,2}}{n_1^{\,2} + n_2^{\,2}} \qquad \therefore \theta_i = \tan^{-1}\left(\frac{n_2}{n_1}\right) = \tan^{-1}(2) = 63.4^\circ$$

No reflection for parallel polarization on dielectric interface at certain incident angle

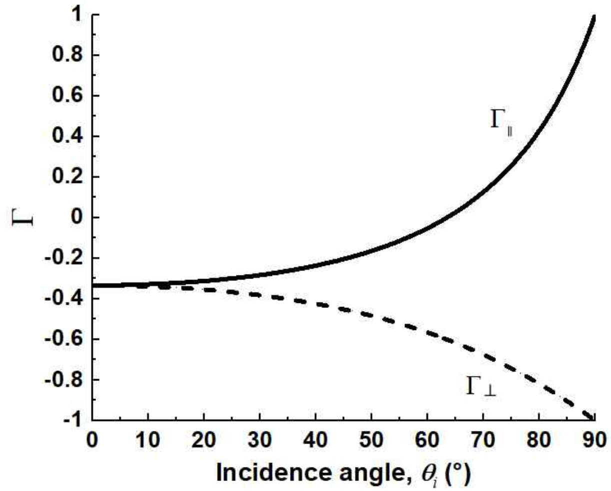
➔ Brewster angle

Lecture 4: Reflection and Transmission at Dielectric Interface



$$\Gamma_{\perp} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}$$

$$\Gamma_{\parallel} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}$$



Brewster angle for perpendicular polarization?

$$n_1 \cos\theta_i = n_2 \cos\theta_t$$

$$\text{But} \quad n_1 \sin\theta_i = n_2 \sin\theta_t \quad \text{(Snell's Law)}$$

$$\theta_i = \theta_t$$

(This is true only when $\mu_1 = \mu_2$)

Lecture 4: Reflection and Transmission at Dielectric Interface

- Incident sunlight is unpolarized: random E-field direction
  (Both perpendicular and parallel polarization)
- At the Brewster angle, only perpendicular polarization reflected
- Polarizer can block reflected light with perpendicular polarization
- Light from inside the container can have both polarizations
- We can see inside the container

Lecture 4: Reflection and Transmission at Dielectric Interface

Filter located at the Brewster angle can almost block the reflected light from the window

➔ We can see through the window

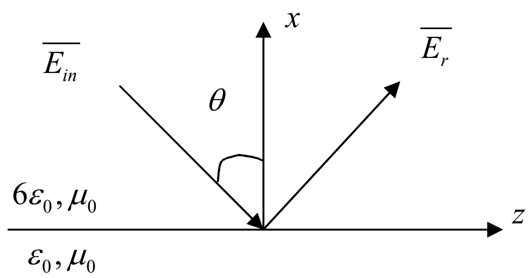
Lecture 4: Reflection and Transmission at Dielectric Interface

Polarizaed Sunglasses

Lecture 4: Reflection and Transmission at Dielectric Interface

Homework (Due 9/20 Tuesday 11am)

An EM wave whose E-field given as
$\underline{E} = (\underline{x} \sin\Theta + \underline{y} + \underline{z}\, E_z) \exp(jk_x x) \exp(-jk_z z)$
is obliquely incident on the dielectric interface as shown below.



(a) Determine E_z.
(b) If the reflected E-field has only y component, what is the incident angle?
(c) Determine the expression for the transmitted E-field for the incident angle determined in (b).

Lecture 4: Reflection and Transmission at Dielectric Interface

- No class next week

- Make up classes during the self-study period (12/8 and 12/13)