

Applied Wave Optics: Waves at Interfaces

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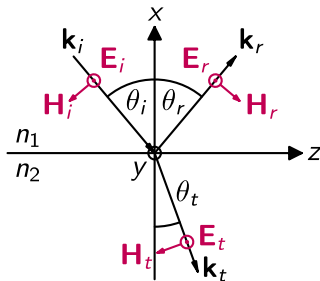


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All sources and vector graphics are available on the GitHub repository
https://github.com/reincas/AW0_course.

TE Waves at Material Interfaces

An **s-polarized** wave is polarized perpendicular to the plane of incidence:



The incident wave i is split into a reflected wave r and a transmitted wave t at the interface. With $k = 2\pi/\lambda$, the wave vectors are:

$$\mathbf{k}_i = n_1 k (-\cos \theta_i, 0, \sin \theta_i)$$

$$\mathbf{k}_r = n_1 k (\cos \theta_r, 0, \sin \theta_r)$$

$$\mathbf{k}_t = n_2 k (-\cos \theta_t, 0, \sin \theta_t)$$

TE Waves at Material Interfaces (cont.)

When we skip the common phase $e^{i\omega t}$ and the complex conjugate term, the electric field vectors are given by

$$\mathbf{E}_i = \hat{\mathbf{y}} E_i e^{ikn_1 x \cos \theta_i - ikn_1 z \sin \theta_i}$$

$$\mathbf{E}_r = \hat{\mathbf{y}} E_r e^{-ikn_1 x \cos \theta_r - ikn_1 z \sin \theta_r}$$

$$\mathbf{E}_t = \hat{\mathbf{y}} E_t e^{ikn_2 x \cos \theta_t - ikn_2 z \sin \theta_t}$$

and the magnetic field vectors are

$$\mathbf{H}_i = -(\hat{\mathbf{x}} \sin \theta_i + \hat{\mathbf{z}} \cos \theta_i) \frac{n_1}{Z_0} E_i e^{ikn_1 x \cos \theta_i - ikn_1 z \sin \theta_i}$$

$$\mathbf{H}_r = -(\hat{\mathbf{x}} \sin \theta_r - \hat{\mathbf{z}} \cos \theta_r) \frac{n_1}{Z_0} E_r e^{-ikn_1 x \cos \theta_r - ikn_1 z \sin \theta_r}$$

$$\mathbf{H}_t = -(\hat{\mathbf{x}} \sin \theta_t + \hat{\mathbf{z}} \cos \theta_t) \frac{n_2}{Z_0} E_t e^{ikn_2 x \cos \theta_t - ikn_2 z \sin \theta_t}$$

TE Fresnel Equations

At the material interface $x = 0$ the boundary conditions $E_{1\parallel} = E_{2\parallel}$ and $H_{1\parallel} = H_{2\parallel}$ apply, resulting in

$$E_i e^{-ikn_1 z \sin \theta_i} + E_r e^{-ikn_1 z \sin \theta_r} = E_t e^{-ikn_2 z \sin \theta_t}$$
$$n_1 \cos \theta_i E_i e^{-ikn_1 z \sin \theta_i} - n_1 \cos \theta_r E_r e^{-ikn_1 z \sin \theta_r} = n_2 \cos \theta_t E_t e^{-ikn_2 z \sin \theta_t}$$

These equations are directly derived from Maxwell's equations and must therefore be valid everywhere for any incident field. This is only possible if all **phases** are equal:

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

resulting in

$$\begin{array}{ll} \theta_r = \theta_i & \text{law of reflection} \\ n_1 \sin \theta_i = n_2 \sin \theta_t & \text{Snell's law} \end{array}$$

TE Fresnel Equations (cont.)

For the **amplitudes** the boundary conditions result in

$$\begin{aligned}E_i + E_r &= E_t \\ n_1 \cos \theta_i E_i - n_1 \cos \theta_i E_r &= n_2 \cos \theta_t E_t\end{aligned}$$

These equations are used to derive the **Fresnel equations** for TE waves:

$$\begin{aligned}r_E &= \frac{E_r}{E_i} = \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} = -\frac{H_r}{H_i} = -r_H \\ t_E &= \frac{E_t}{E_i} = \frac{2n_1 \cos \theta_i}{n_1 \cos \theta_i + n_2 \cos \theta_t} = \frac{n_1 H_t}{n_2 H_i} = \frac{n_1}{n_2} t_H\end{aligned}$$

where the impedance relations $E_r/H_r = -n_1/Z_0$ and $E_t/H_t = n_2/Z_0$ lead to the respective Fresnel equations for magnetic fields.

Total Internal Reflection

We use Snell's law $n_1 \sin \theta_i = n_2 \sin \theta_t$ and the trigonometric identity relation $\sin^2 \theta_t + \cos^2 \theta_t = 1$ to express θ_t by the given θ_i in the Fresnel equations:

$$\cos \theta_t = \pm \sqrt{1 - \frac{n_1^2}{n_2^2} \sin^2 \theta_i}$$

For $n_2 < n_1$ there is a **critical angle** of incidence $\sin \theta_c = n_2/n_1$ separating the range of real and imaginary values of $\cos \theta_t$:

$$\cos \theta_t = \begin{cases} +\sqrt{1 - \frac{n_1^2}{n_2^2} \sin^2 \theta_i} & \text{for } \theta_i < \theta_c \text{ (normal reflection)} \\ -i\sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1} & \text{for } \theta_i > \theta_c \text{ (total internal reflection)} \end{cases}$$

Note: The sign of the square root cannot be decided mathematically. Physical arguments based on the normal phase $\exp(ikn_2x \cos \theta_t)$ are used instead.

Total Internal Reflection (cont.)

In case of total internal reflection, numerator and denominator of r_E are complex conjugates of each other resulting in a pure phase factor with $|r_E| = 1$:

$$\begin{aligned} r_E = \frac{E_r}{E_i} &= \frac{n_1 \cos \theta_i + in_2 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1}}{n_1 \cos \theta_i - in_2 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1}} \\ &= \frac{\left(n_1 \cos \theta_i + in_2 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1} \right)^2}{n_1^2 + n_2^2} \stackrel{!}{=} e^{2i\Phi_{TE}} \end{aligned}$$

Total internal reflection thus comes with a **phase shift** $2\Phi_{TE}$ for the reflected wave with

$$\tan \Phi_{TE} = \frac{\sqrt{n_1^2 \sin^2 \theta_i - n_2^2}}{n_1 \cos \theta_i}$$

Poynting Vector

Identity relation from vector analysis applied to electro-magnetic fields:

$$\nabla(\mathbf{E} \times \mathbf{H}) = \mathbf{H}(\nabla \times \mathbf{E}) - \mathbf{E}(\nabla \times \mathbf{H})$$

We define the **Poynting vector** $\mathbf{S} = \mathbf{E} \times \mathbf{H}$ with the SI unit W/m^2 of an energy flux or intensity and we insert Faradays's and Ampère's law:

$$\nabla \mathbf{S} = -\mathbf{H} \frac{\partial \mathbf{B}}{\partial t} - \mathbf{j} \mathbf{E} - \mathbf{E} \frac{\partial \mathbf{D}}{\partial t}$$

Replacing \mathbf{B} and \mathbf{D} by \mathbf{H} and \mathbf{E} we get

$$\nabla \mathbf{S} = -\mathbf{j} \mathbf{E} - \left(\mu \mu_0 \mathbf{H} \frac{\partial \mathbf{H}}{\partial t} + \varepsilon \varepsilon_0 \mathbf{E} \frac{\partial \mathbf{E}}{\partial t} \right)$$

and finally

$$\nabla \mathbf{S} = -\mathbf{j} \mathbf{E} - \frac{\partial}{\partial t} \left[\frac{1}{2} (\mu \mu_0 \mathbf{H}^2 + \varepsilon \varepsilon_0 \mathbf{E}^2) \right]$$

Poynting Vector (cont.)

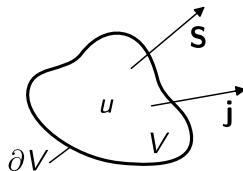
With the energy density

$$u = \frac{1}{2} (\mu\mu_0 \mathbf{H}^2 + \varepsilon\varepsilon_0 \mathbf{E}^2)$$

of the electro-magnetic field with the SI unit J/m³ we get the fundamental equation

$$-\frac{\partial u}{\partial t} = \nabla \cdot \mathbf{S} + \mathbf{j} \cdot \mathbf{E}$$

It shows that two effects alter the energy density inside a given volume: Radiation $\nabla \cdot \mathbf{S}$ and charge transport by an electric current $\mathbf{j} \cdot \mathbf{E}$ through the surface ∂V of the volume:



Radiation Intensity

Poynting vector of a plane wave:

$$\begin{aligned}\mathbf{S} = \mathbf{E} \times \mathbf{H} &= \frac{1}{2} \left(\hat{\mathbf{E}} e^{i(\omega t - \mathbf{k} \cdot \mathbf{r})} + \hat{\mathbf{E}}^* e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})} \right) \times \frac{1}{2} \left(\hat{\mathbf{H}} e^{i(\omega t - \mathbf{k} \cdot \mathbf{r})} + \hat{\mathbf{H}}^* e^{-i(\omega t - \mathbf{k} \cdot \mathbf{r})} \right) \\ &= \frac{1}{4} \left[(\mathbf{E} \times \mathbf{H}) e^{2i(\omega t - \mathbf{k} \cdot \mathbf{r})} + (\mathbf{E}^* \times \mathbf{H} + \mathbf{E} \times \mathbf{H}^*) + (\mathbf{E}^* \times \mathbf{H}^*) e^{-2i(\omega t - \mathbf{k} \cdot \mathbf{r})} \right]\end{aligned}$$

The radiation **intensity** is defined as absolute value of the temporal average of \mathbf{S} :

$$I = |\langle \mathbf{S} \rangle| = \frac{1}{4} |\mathbf{E}^* \times \mathbf{H} + \mathbf{E} \times \mathbf{H}^*| = \frac{1}{2} |\Re(\mathbf{E}^* \times \mathbf{H})|$$

and is thus directly connected to the measured radiation power.

Intensity at the Interface

Intensity of the incident, reflected, and transmitted waves normal to the interface:

$$I_i = \frac{1}{2} |\Re(\mathbf{E}_{i\parallel}^* \times \mathbf{H}_{i\parallel})| = \frac{1}{2} |\Re(E_i^* H_i \cos \theta_i)| = \frac{1}{2} |E_i|^2 \frac{n_1}{Z_0} \cos \theta_i$$

$$I_r = \frac{1}{2} |\Re(\mathbf{E}_{r\parallel}^* \times \mathbf{H}_{r\parallel})| = \frac{1}{2} |\Re(E_r^* H_r \cos \theta_r)| = \frac{1}{2} |E_r|^2 \frac{n_1}{Z_0} \cos \theta_i$$

$$I_t = \frac{1}{2} |\Re(\mathbf{E}_{t\parallel}^* \times \mathbf{H}_{t\parallel})| = \frac{1}{2} |\Re(E_t^* H_t \cos \theta_t)| = \frac{1}{2} |E_t|^2 \frac{n_2}{Z_0} |\Re(\cos \theta_t)|$$

For **total internal reflection** with $\theta_i > \theta_c$ we have an imaginary $\cos \theta_t$ and thus $I_t = 0$:

$$R = \frac{I_r}{I_i} = \frac{|E_r|^2}{|E_i|^2} = |r_E|^2 = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2 = 1$$

$$T = \frac{I_t}{I_i} = 0$$

Intensity at the Interface (cont.)

For **normal reflection** with $\theta_i < \theta_c$ we obtain

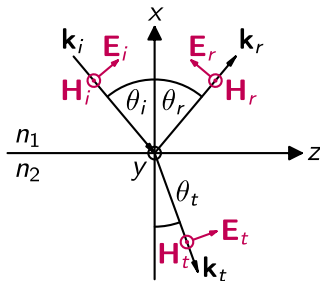
$$R = \frac{I_r}{I_i} = \frac{|E_r|^2}{|E_i|^2} = \left| \frac{n_1 \cos \theta_i - n_2 \cos \theta_t}{n_1 \cos \theta_i + n_2 \cos \theta_t} \right|^2$$
$$T = \frac{I_t}{I_i} = \frac{n_2 \cos \theta_t}{n_1 \cos \theta_i} \frac{|E_t|^2}{|E_i|^2} = \frac{n_1 n_2 \cos \theta_i \cos \theta_t}{(n_1 \cos \theta_i + n_2 \cos \theta_t)^2}$$

with $R + T = 1$, and in case of normal incidence with $\theta_i = 0$ the reflection factor reduces to

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2$$

TM Waves at Material Interfaces

An **p-polarized** wave is polarized parallel to the plane of incidence:



The incident wave i is split into a reflected wave r and a transmitted wave t at the interface in exactly the same way as for the TE wave:

$$\mathbf{k}_i = n_1 k (-\cos \theta_i, 0, \sin \theta_i)$$

$$\mathbf{k}_r = n_1 k (\cos \theta_r, 0, \sin \theta_r)$$

$$\mathbf{k}_t = n_2 k (-\cos \theta_t, 0, \sin \theta_t)$$

TM Waves at Material Interfaces (cont.)

When we skip the common phase $e^{i\omega t}$ and the complex conjugate term, the electric field vectors are given by

$$\mathbf{E}_i = (\hat{\mathbf{x}} \sin \theta_i + \hat{\mathbf{z}} \cos \theta_i) E_i e^{ikn_1 x \cos \theta_i - ikn_1 z \sin \theta_i}$$

$$\mathbf{E}_r = (\hat{\mathbf{x}} \sin \theta_r - \hat{\mathbf{z}} \cos \theta_r) E_r e^{-ikn_1 x \cos \theta_r - ikn_1 z \sin \theta_r}$$

$$\mathbf{E}_t = (\hat{\mathbf{x}} \sin \theta_t + \hat{\mathbf{z}} \cos \theta_t) E_t e^{ikn_2 x \cos \theta_t - ikn_2 z \sin \theta_t}$$

and the magnetic field vectors are

$$\mathbf{H}_i = \hat{\mathbf{y}} \frac{n_1}{Z_0} E_i e^{ikn_1 x \cos \theta_i - ikn_1 z \sin \theta_i}$$

$$\mathbf{H}_r = \hat{\mathbf{y}} \frac{n_1}{Z_0} E_r e^{-ikn_1 x \cos \theta_r - ikn_1 z \sin \theta_r}$$

$$\mathbf{H}_t = \hat{\mathbf{y}} \frac{n_2}{Z_0} E_t e^{ikn_2 x \cos \theta_t - ikn_2 z \sin \theta_t}$$

TM Fresnel Equations

With the boundary conditions $E_{1\parallel} = E_{2\parallel}$ and $H_{1\parallel} = H_{2\parallel}$ at $x = 0$, we get

$$\begin{aligned}\cos \theta_i E_i e^{-ikn_1 z \sin \theta_i} - \cos \theta_r E_r e^{-ikn_1 z \sin \theta_r} &= \cos \theta_t E_t e^{-ikn_2 z \sin \theta_t} \\ n_1 E_i e^{-ikn_1 z \sin \theta_i} + n_1 E_r e^{-ikn_1 z \sin \theta_r} &= n_2 E_t e^{-ikn_2 z \sin \theta_t}\end{aligned}$$

The phases must be equal again, resulting in the law of reflection and Snell's law again.

$$\begin{aligned}\cos \theta_i E_i - \cos \theta_r E_r &= \cos \theta_t E_t \\ n_1 E_i + n_1 E_r &= n_2 E_t\end{aligned}$$

These equations are used to derive the **Fresnel equations** for TM waves:

$$\begin{aligned}r_E = \frac{E_r}{E_i} &= \frac{n_2 \cos \theta_i - n_1 \cos \theta_t}{n_2 \cos \theta_i + n_1 \cos \theta_t} = -\frac{H_r}{H_i} = -r_H \\ t_E = \frac{E_t}{E_i} &= \frac{2n_1 \cos \theta_i}{n_2 \cos \theta_i + n_1 \cos \theta_t} = \frac{n_1 H_t}{n_2 H_i} = \frac{n_1}{n_2} t_H\end{aligned}$$

Total Internal Reflection

The critical angle for total internal reflection is the same for TM waves. Numerator and denominator of r_E are again complex conjugates of each other:

$$\begin{aligned} r_E = \frac{E_r}{E_i} &= \frac{n_2 \cos \theta_i + in_1 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1}}{n_2 \cos \theta_i - in_1 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1}} \\ &= \frac{\left(n_2 \cos \theta_i + in_1 \sqrt{\frac{n_1^2}{n_2^2} \sin^2 \theta_i - 1} \right)^2}{n_2^2 \cos^2 \theta_i + \frac{n_1^2}{n_2^2} (n_1^2 \sin^2 \theta_i - n_2^2)} \stackrel{!}{=} e^{2i\Phi_{TM}} \end{aligned}$$

The **phase shift** $2\Phi_{TM}$ for the reflected wave in case of total internal reflection thus is

$$\tan \Phi_{TM} = \frac{n_1^2}{n_2^2} \frac{\sqrt{n_1^2 \sin^2 \theta_i - n_2^2}}{n_1 \cos \theta_i} = \frac{n_1^2}{n_2^2} \tan \Phi_{TE}$$

Brewster Angle

Fresnel's equations for TM waves allow for a certain angle of incidence $\theta_i = \theta_B$ with vanishing reflection $r_E(\theta_B) = 0$:

$$n_2 \cos \theta_B = n_1 \sqrt{1 - \frac{n_1^2}{n_2^2} \sin^2 \theta_B}$$
$$\frac{n_2^2}{n_1^2} \cos^2 \theta_B = 1 - \frac{n_1^2}{n_2^2} \sin^2 \theta_B$$

We use the trigonometric identity $\sin^2 \theta_B + \cos^2 \theta_B = 1$ and collect the $\sin^2 \theta_B$ terms on the left side of the equation:

$$\left(\frac{n_1^2}{n_2^2} - \frac{n_2^2}{n_1^2} \right) \sin^2 \theta_B = 1 - \frac{n_2^2}{n_1^2}$$
$$\frac{n_1^4 - n_2^4}{n_1^2 n_2^2} \sin^2 \theta_B = \frac{n_1^2 - n_2^2}{n_1^2}$$

Brewster Angle (cont.)

Using the identity $n_1^4 - n_2^4 = (n_1^2 + n_2^2)(n_1^2 - n_2^2)$ and expressing $\sin^2 \theta_B$ by $\tan^2 \theta_B$ results in

$$\begin{aligned}\sin^2 \theta_B &= \frac{n_2^2}{n_1^2 + n_2^2} \\ \frac{\tan^2 \theta_B}{1 + \tan^2 \theta_B} &= \frac{n_2^2/n_1^2}{1 + n_2^2/n_1^2}\end{aligned}$$

A comparison of both sides reveals the final expression for the **Brewster angle**:

$$\tan \theta_B = \frac{n_2}{n_1}$$

Note that a Brewster angle exists only for p-polarisation.

Power Reflection Diagram

Summary: Power reflection factor and phase shift for the reflection of an electro-magnetic wave at a material with lower or higher refractive index.

