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Wave propagation

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Reflection, diffraction and damping of plane waves

2.5 Reflection, diffraction and damping of plane waves
2.5.1 Reflection by a flat surface
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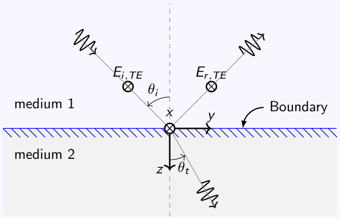
2.5.4 Diffraction & Physical optics

Reflection of plane waves

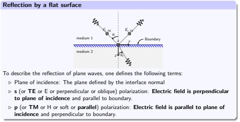
Reflection by a flat surface



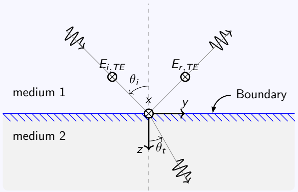
To describe the reflection of plane waves, one defines the following terms:

- Plane of incidence: The plane defined by the interface normal
- **s** (or **TE** or E or perpendicular or oblique) polarization: **Electric field is perpendicular to plane of incidence** and parallel to boundary.
- **p** (or **TM** or H or soft or **parallel**) polarization: **Electric field is parallel to plane of incidence** and perpendicular to boundary.

Reflection of plane waves



Snell's law



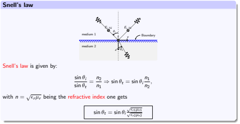
Snell's law is given by:

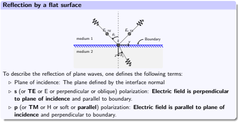
$$\frac{\sin\theta_i}{\sin\theta_t} = \frac{n_2}{n_1} \Rightarrow \sin\theta_t = \sin\theta_i \frac{n_1}{n_2},$$

with $n = \sqrt{\epsilon_r \mu_r}$ being the refractive index one gets

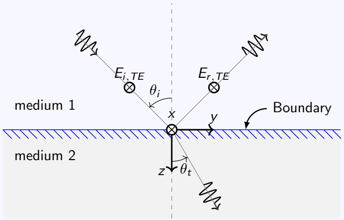
$$\boxed{\sin\theta_t = \sin\theta_i \frac{\sqrt{\epsilon_{r1}\mu_{r1}}}{\sqrt{\epsilon_{r2}\mu_{r2}}}}$$

Reflection of plane waves

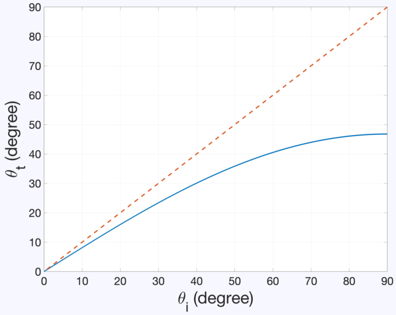




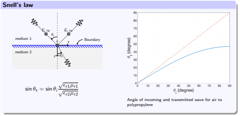
Snell's law

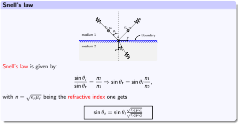


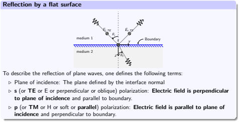
$$\sin\theta_t = \sin\theta_i \frac{\sqrt{\epsilon_{r1}\mu_{r1}}}{\sqrt{\epsilon_{r2}\mu_{r2}}}$$



Angle of incoming and transmitted wave for air to polypropylene







Reflection by a flat surface – TM

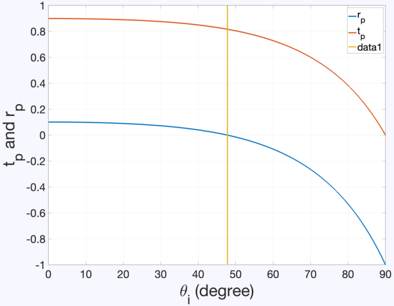
For p polarization (E-Field parallel to plane of incidence – **TM**):

$$r_\mathrm{p} = r_\mathrm{TM} = \frac{n_2\cos\theta_\mathrm{i} - n_1\cos\theta_\mathrm{t}}{n_2\cos\theta_\mathrm{i} + n_1\cos\theta_\mathrm{t}},$$

$$t_\mathrm{p} = t_\mathrm{TM} = \frac{2n_1\cos\theta_\mathrm{i}}{n_2\cos\theta_\mathrm{i} + n_1\cos\theta_\mathrm{t}},$$

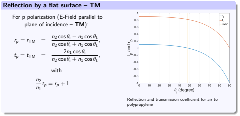
with

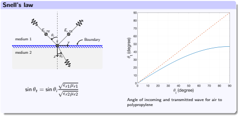
$$\frac{n_2}{n_1} t_p = r_p + 1$$

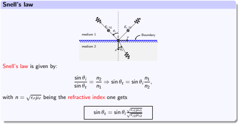


Reflection and transmission coefficient for air to polypropylene

Brewster Angle







Brewster Angle

An electromagnetic wave with p polarization is completely transmitted in case of

$$\theta_B = \operatorname{atan}\left(\frac{n_2}{n_1}\right).$$

Reflection of plane waves

Brewster Angle

An electromagnetic wave with p polarization is completely transmitted in case of

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Reflection by a flat surface – TM

For p polarization (E-Field parallel to plane of incidence – **TM**):

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$$t_p = t_{TM} = \frac{2 n_1 \cos\theta_i}{n_2 \cos\theta_i + n_1 \cos\theta_t},$$

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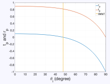
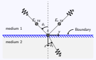
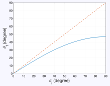


Reflection and transmission coefficient for air to polypropylene

Snell's law



$$\sin\theta_t = \sin\theta_i \frac{\sqrt{\epsilon_{r1}\mu_{r1}}}{\sqrt{\epsilon_{r2}\mu_{r2}}}$$



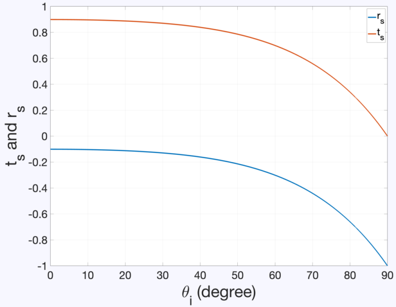
Angle of incoming and transmitted wave for air to polypropylene

Reflection by a flat surface – TE

For s polarization (E-Field perpendicular to plane of incidence – **TE**):

$$r_s = r_{TE} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t},$$

$$t_s = t_{TE} = \frac{2 n_1 \cos\theta_i}{n_1 \cos\theta_i + n_2 \cos\theta_t},$$



Reflection and transmission coefficient for air to polypropylene

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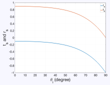

Reflection and transmission coefficient for air to polypropylene

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$$\theta_B = \operatorname{atan}\left(\frac{n_2}{n_1}\right).$$

Reflection by a flat surface – TM

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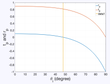
$$t_p = t_{TM} = \frac{2 n_1 \cos\theta_i}{n_2 \cos\theta_i + n_1 \cos\theta_t},$$

with

$$\frac{n_2}{n_1} t_p = r_p + 1$$



Reflection and transmission coefficient for air to polypropylene

Reflection by a flat perfectly conducting surface

Using a complex permittivity

$$\varepsilon_{r,2} = \varepsilon'_{r,2} + j\varepsilon''_{r,2},$$

with $\varepsilon''_{r,2} \to \infty$ one gets

$$\begin{aligned} r_\mathrm{p} = r_\mathrm{TM} &= 1, \\ t_\mathrm{p} = t_\mathrm{TM} &= 0, \\ r_\mathrm{s} = r_\mathrm{TE} &= -1, \\ t_\mathrm{s} = t_\mathrm{TE} &= 0 \end{aligned}$$

Hint: Negative sign of r_TE can be explained by boundary condition (no tangential electrical field).

Reflection, diffraction and damping of plane waves

2.5 Reflection, diffraction and damping of plane waves
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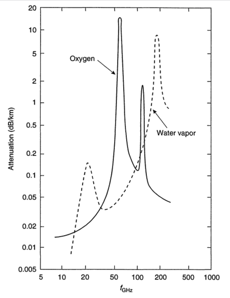
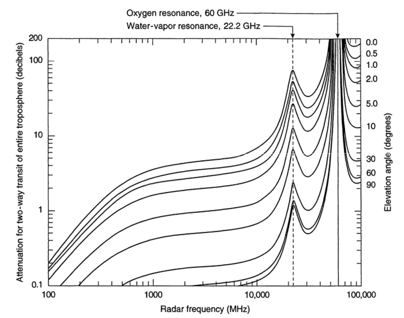
2.5.4 Diffraction & Physical optics

Damping of plane waves

Road Surface





Theoretical attenuation for oxygen and water vapor and wave attenuation in standard atmosphere for target outside the troposphere (source: Peebles, radar principles)

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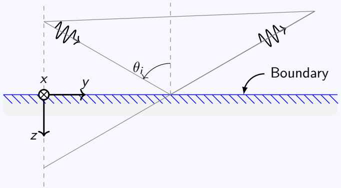
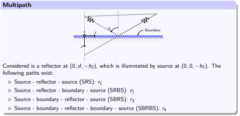
Multipath



Considered is a reflector at $(0, d, -h_2)$, which is illuminated by source at $(0, 0, -h_1)$. The following paths exist:

- Source - reflector - source (SRS): r_1
- Source - reflector - boundary - source (SRBS): r_2
- Source - boundary - reflector - source (SBRS): r_3
- Source - boundary - reflector - boundary - source (SBRBS): r_4



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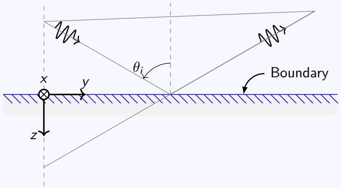
Multipath

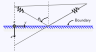


Thus, the overall signal (assuming that the reflector is isotropic):

$$R_x \sim \frac{e^{-jkr_1}}{r_1} + r_{p,s}\frac{e^{-jkr_2}}{r_2} + r_{p,s}\frac{e^{-jkr_3}}{r_3} + r_{p,s}^2\frac{e^{-jkr_4}}{r_4},$$

with $r_1 = 2\sqrt{(h_2 - h_1)^2 + d^2}$, $r_2 = r_3 = \sqrt{(h_2 + h_1)^2 + d^2}$ and $r_4 = 2\sqrt{(h_2 + h_1)^2 + d^2}$, for $h_2 > h_1$.

Multipath



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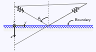
Multipath



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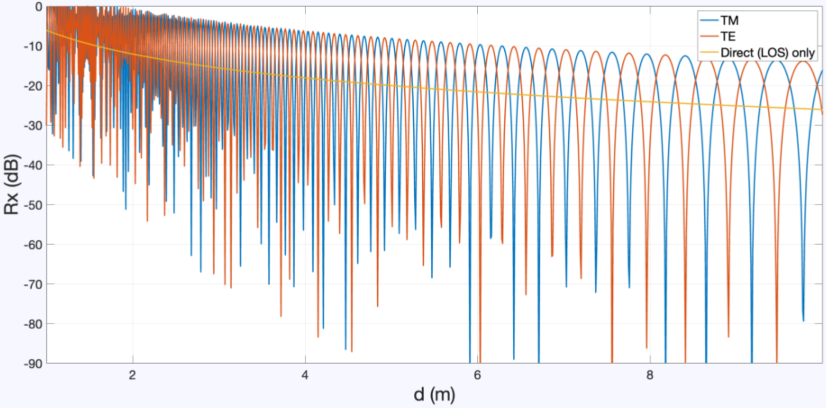
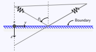
Perfectly conducting surface



$h_2 = 0.6\,\mathrm{m},\ h_1 = 0.5\,\mathrm{m},\ f = 76\,\mathrm{GHz}$

Multipath

Multipath



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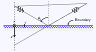
with $r_1 = 2\sqrt{(h_2-h_1)^2+d^2}$, $r_2 = r_3 = \sqrt{(h_2+h_1)^2+d^2}$ and $r_4 = 2\sqrt{(h_2+h_1)^2+d^2}$, for $h_2 > h_1$.

Multipath



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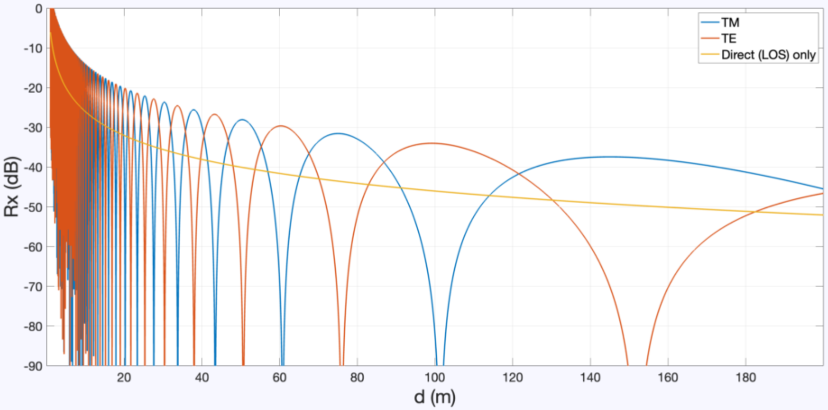
Perfectly conducting surface



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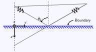
Multipath

Multipath



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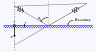
Multipath



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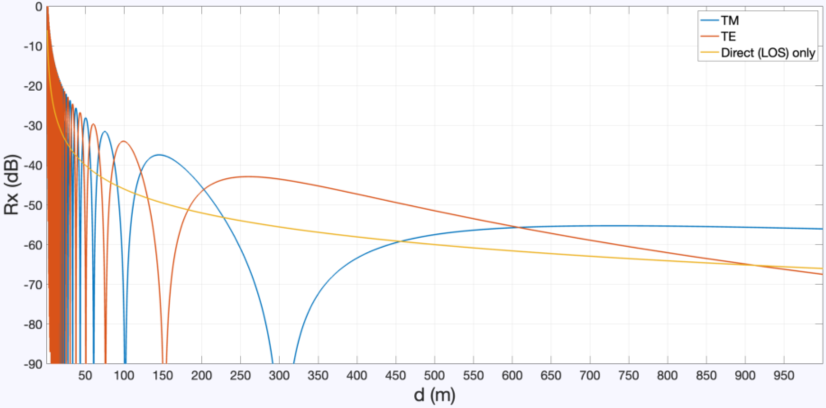
Perfectly conducting surface



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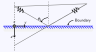
Multipath



Thus, the overall signal (assuming that the reflector is isotropic):

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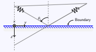
Multipath



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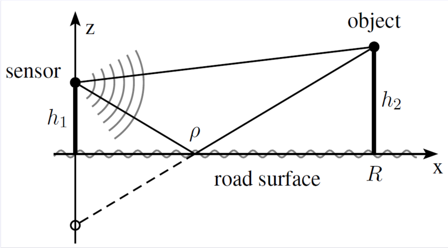
Road Surface



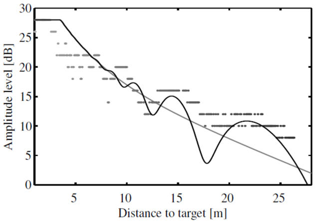


Fig. 4. Measured (dots) and simulated (line) radar amplitude of measurement with Opel Vectra as target

Source: Büren, Yang, Characterization of Automotive Radar Targets from 22 to 29 GHz

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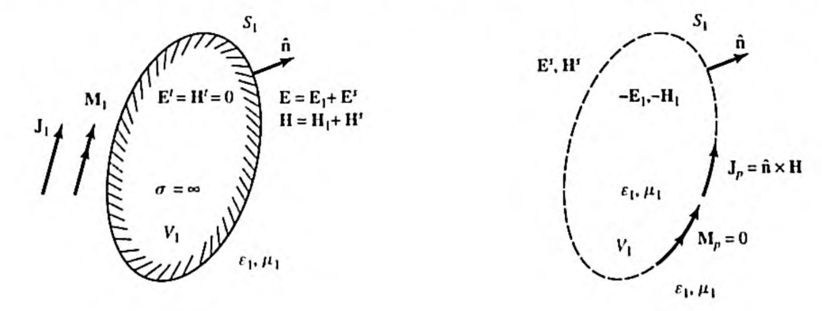
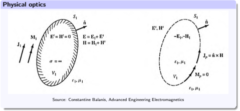
Physical optics

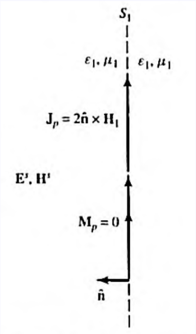


Source: Constantine Balanis, Advanced Engineering Electromagnetics

Physical optics



Physical optics



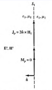
Source: Constantine Balanis, Advanced Engineering Electromagnetics

Approximation

$$\boldsymbol{J} = 2\boldsymbol{n} \times \boldsymbol{H}.$$

Edge diffraction

Physical optics

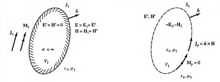


Source: Constantine Balanis, Advanced Engineering Electromagnetics

Approximation

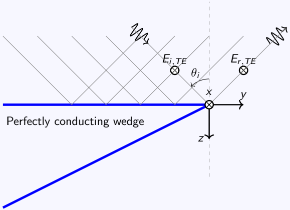
$J = 2n \times H.$

Physical optics

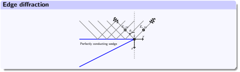


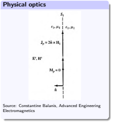
Source: Constantine Balanis, Advanced Engineering Electromagnetics

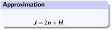
Edge diffraction

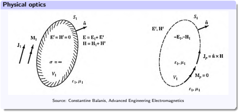


Edge diffraction

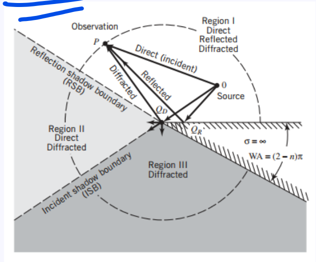








Edge diffraction



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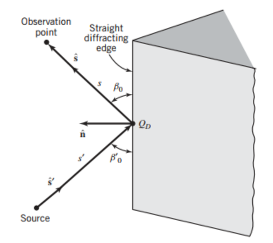

Source: Constantine Balanis, Advanced Engineering Electromagnetics

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2.3 Electromagnetic waves
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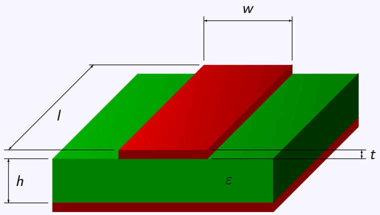
2.5 Reflection, diffraction and damping of plane waves
2.6 Micro Strip lines, (coplanar) waveguides

Micro Strip lines



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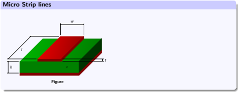
Coplanar waveguide



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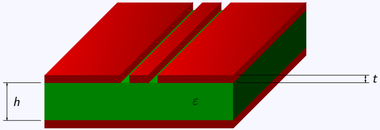


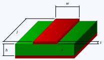
Figure

Notes

Coplanar waveguide

Figure

Micro Strip lines



Figure