電子情報通信特論
Advanced Course of Electronics, Information and Communications

Propagation Mechanisms

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Propagation Mechanism

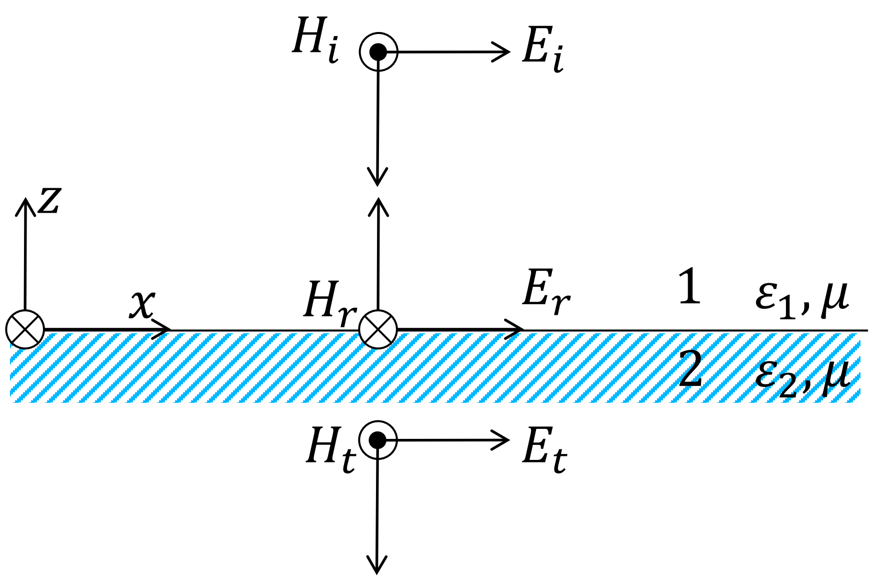
- Reflection
  - occurs when the electromagnetic wave impinges on an object which has very large dimensions as compared to the wavelength
- Diffraction
  - occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities (edges)
- Scattering
  - occurs when the medium has objects that are smaller or comparable to the wavelength (small objects, rough surfaces and other irregularities)

Reflection

- Radio wave that propagates in one medium impinges upon another medium having different electric properties
- If the radio wave is incident on a dielectric material
  - Part of the energy is reflected back
  - Part of the energy is transmitted
- If the radio wave is incident on a perfect conductor
  - ??

Normal Incidence

- Consider a planar interface, and a uniform plane wave with normal incidence on the interface
- The total fields at the interface must satisfy the boundary conditions for electromagnetic fields



E-field (x)	H-field (y)
$E_i = E_0 e^{+jk_1 z}$	$H_i = -\frac{1}{\eta_1} E_0 e^{+jk_1 z}$
$E_r = R E_0 e^{-jk_1 z}$	$H_r = \frac{R}{\eta_1} E_0 e^{-jk_1 z}$
$E_t = T E_0 e^{+jk_2 z}$	$H_t = -\frac{T}{\eta_2} E_0 e^{+jk_2 z}$

$$\boldsymbol{H} = \frac{1}{\eta} \hat{\boldsymbol{k}} \times \boldsymbol{E}$$

R: reflection coefficient
T: transmission coefficient

$\hat{\boldsymbol{k}}$: traveling direction unit vector

Normal Incidence

- Boundary conditions ($z = 0$)

$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{E}_1 - \boldsymbol{E}_2) = 0}$$

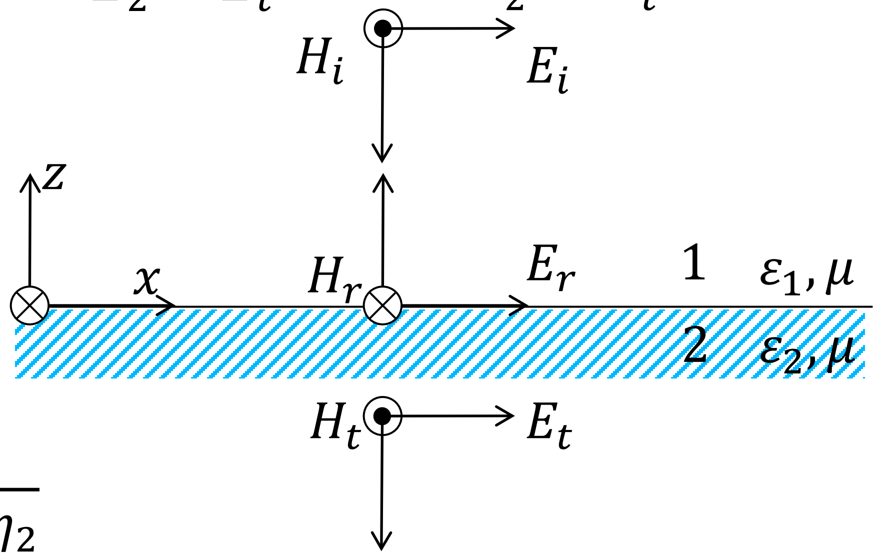
$$E_0 + RE_0 = TE_0$$

$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0}$$

$$\frac{1}{\eta_1}E_0 - \frac{R}{\eta_1}E_0 = \frac{T}{\eta_2}E_0$$

$$\boldsymbol{E}_1 = \boldsymbol{E}_i + \boldsymbol{E}_r \qquad \boldsymbol{H}_1 = \boldsymbol{H}_i + \boldsymbol{H}_r$$

$$\boldsymbol{E}_2 = \boldsymbol{E}_t \qquad \boldsymbol{H}_2 = \boldsymbol{H}_t$$



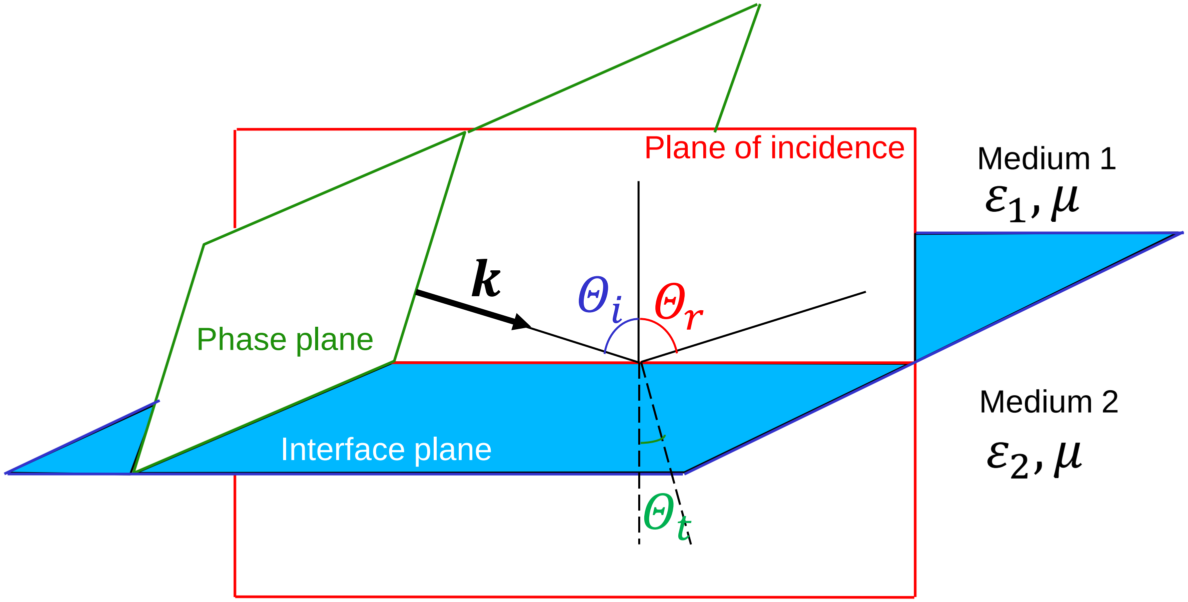
$$R = \frac{\eta_2 - \eta_1}{\eta_1 + \eta_2} \qquad T = \frac{2\eta_2}{\eta_1 + \eta_2}$$

Reflection coefficient   Transmission coefficient

- Special cases
  - Matched medium ($\eta_2 = \eta_1$) → R = ?, T = ?
  - Perfect conductor ($\eta_2 = 0$) → R = ?, T = ?

Oblique Incidence

- Consider a planar interface between two dielectric media. A plane wave is incident at an angle from medium 1
  - The interface plane defines the boundary between the media
  - The plane of incidence contains the propagation vector and is both perpendicular to the interface plane and to the phase planes of the wave

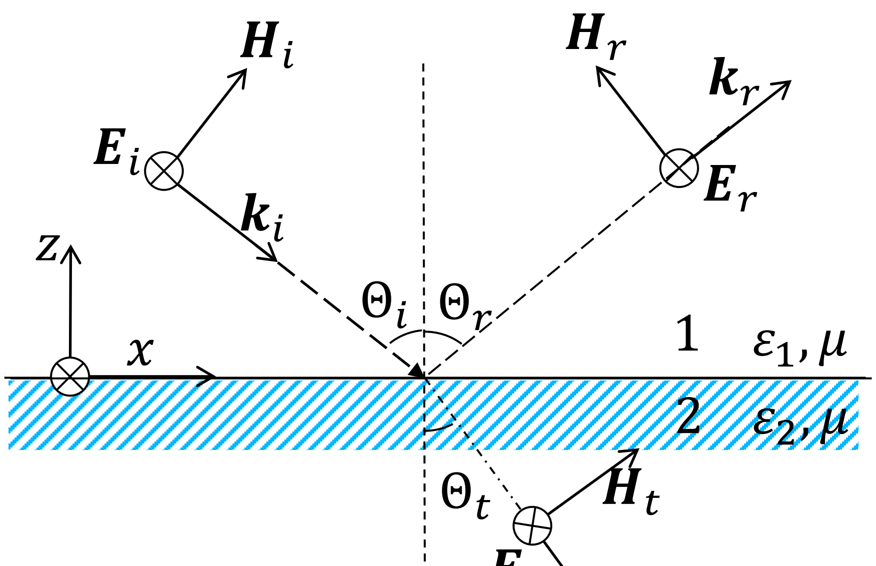


Oblique Incidence

- There are two elementary orientations (polarizations) for the electromagnetic fields:
- Perpendicular polarization (⊥)
  - The electric field is perpendicular to the plane of incidence and the magnetic field is parallel to the plane of incidence
  - The fields are configured as in the ***Transverse Electric (TE)*** modes
- Parallel polarization (‖)
  - The magnetic field is perpendicular to the plane of incidence and the electric field is parallel to the plane of incidence
  - The fields are configured as in the ***Transverse Magnetic (TM)*** modes
- Any plane wave with general field orientation can be obtained by superposition of two waves with perpendicular and parallel polarization

Perpendicular Polarization

- The electric field is perpendicular to the plane of incidence and the magnetic field is parallel to the plane of incidence
- The fields are configured as in the Transverse Electric (TE) modes



$$\hat{\boldsymbol{k}}_i = \hat{\boldsymbol{x}} \sin\Theta_i - \hat{\boldsymbol{z}} \cos\Theta_i$$
$$\hat{\boldsymbol{k}}_r = \hat{\boldsymbol{x}} \sin\Theta_r + \hat{\boldsymbol{z}} \cos\Theta_r$$
$$\hat{\boldsymbol{k}}_t = \hat{\boldsymbol{x}} \sin\Theta_t - \hat{\boldsymbol{z}} \cos\Theta_t$$

$$\boldsymbol{E}_i = \hat{\boldsymbol{y}} E_0 e^{-\mathrm{j}\boldsymbol{k}_i \cdot \boldsymbol{r}} = \hat{\boldsymbol{y}} E_0 e^{-\mathrm{j}k_1(x\sin\Theta_i - z\cos\Theta_i)}$$
$$\boldsymbol{E}_r = \hat{\boldsymbol{y}} R E_0 e^{-\mathrm{j}\boldsymbol{k}_r \cdot \boldsymbol{r}} = \hat{\boldsymbol{y}} R E_0 e^{-\mathrm{j}k_1(x\sin\Theta_r + z\cos\Theta_r)}$$
$$\boldsymbol{E}_t = \hat{\boldsymbol{y}} T E_0 e^{-\mathrm{j}\boldsymbol{k}_t \cdot \boldsymbol{r}} = \hat{\boldsymbol{y}} T E_0 e^{-\mathrm{j}k_2(x\sin\Theta_t - z\cos\Theta_t)}$$
$$\boldsymbol{H}_i = \frac{1}{\eta_1} \hat{\boldsymbol{k}}_i \times \boldsymbol{E}_i = (\hat{\boldsymbol{z}} \sin\Theta_i + \hat{\boldsymbol{x}} \cos\Theta_i) \frac{E_0}{\eta_1} e^{-\mathrm{j}k_1(x\sin\Theta_i - z\cos\Theta_i)}$$
$$\boldsymbol{H}_r = \frac{1}{\eta_1} \hat{\boldsymbol{k}}_r \times \boldsymbol{E}_r = (\hat{\boldsymbol{z}} \sin\Theta_r - \hat{\boldsymbol{x}} \cos\Theta_r) \frac{R E_0}{\eta_1} e^{-\mathrm{j}k_1(x\sin\Theta_r + z\cos\Theta_r)}$$
$$\boldsymbol{H}_t = \frac{1}{\eta_2} \hat{\boldsymbol{k}}_t \times \boldsymbol{E}_t = (\hat{\boldsymbol{z}} \sin\Theta_t + \hat{\boldsymbol{x}} \cos\Theta_t) \frac{T E_0}{\eta_2} e^{-\mathrm{j}k_2(x\sin\Theta_t - z\cos\Theta_t)}$$

Perpendicular Polarization

- Boundary conditions ($z = 0$)

$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{E}_1 - \boldsymbol{E}_2) = 0}$$

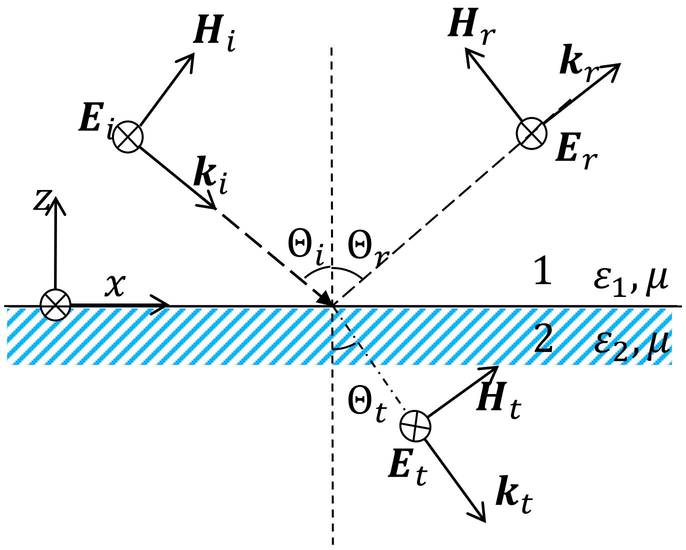
$$e^{-jk_1 x \sin\Theta_i} + Re^{-jk_1 x \sin\Theta_r} = Te^{-jk_2 x \sin\Theta_t} \;\ldots\ldots (1)$$

$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0}$$

$$\frac{\cos\Theta_i}{\eta_1} e^{-jk_1 x \sin\Theta_i} - \frac{R\cos\Theta_r}{\eta_1} e^{-jk_1 x \sin\Theta_r} = \frac{T\cos\Theta_t}{\eta_2} e^{-jk_2 x \sin\Theta_t} \;\ldots\ldots (2)$$

$\boldsymbol{E}_1 = \boldsymbol{E}_i + \boldsymbol{E}_r$ $\quad$ $\boldsymbol{H}_1 = \boldsymbol{H}_i + \boldsymbol{H}_r$

$\boldsymbol{E}_2 = \boldsymbol{E}_t$ $\quad$ $\boldsymbol{H}_2 = \boldsymbol{H}_t$



Reflection and Refraction Laws

- The relation (1) must be valid for any choice of x and we must have phase conservation law as

$$k_1 \sin\Theta_i = k_1 \sin\Theta_r = k_2 \sin\Theta_t$$

where $k = \frac{2\pi}{\lambda} = \omega\sqrt{\mu\varepsilon}$

Wavenumber

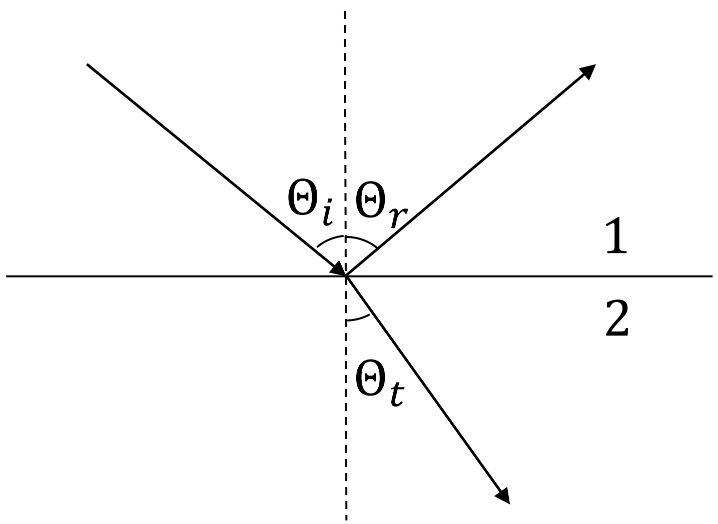
  - Reflection law: The angle of incidence is the same as the reflected angle

$$\boxed{\Theta_i = \Theta_r}$$

  - Snell's law (refraction)

$$\boxed{\sqrt{\varepsilon_1}\sin\Theta_i = \sqrt{\varepsilon_2}\sin\Theta_t}$$

$$\boxed{\frac{\sin\Theta_t}{\sin\Theta_i} = \frac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}} = \frac{n_1}{n_2} = \frac{v_2}{v_1}}$$



$$v = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{1}{\sqrt{\varepsilon_r\mu_r}}\boxed{\frac{1}{\sqrt{\varepsilon_0\mu_0}}} = \frac{c}{n} \qquad \boxed{n = \sqrt{\varepsilon_r}} \quad (\mu_r = 1)$$

c

Refractive index (屈折率)

Perpendicular Polarization

- The relations (1) and (2), we obtain

$$\begin{cases} 1 + R = T \\ \dfrac{\cos\Theta_i}{\eta_1} - \dfrac{R\cos\Theta_r}{\eta_1} = \dfrac{T\cos\Theta_t}{\eta_2} \end{cases}$$

<u>Reflection coefficient</u>

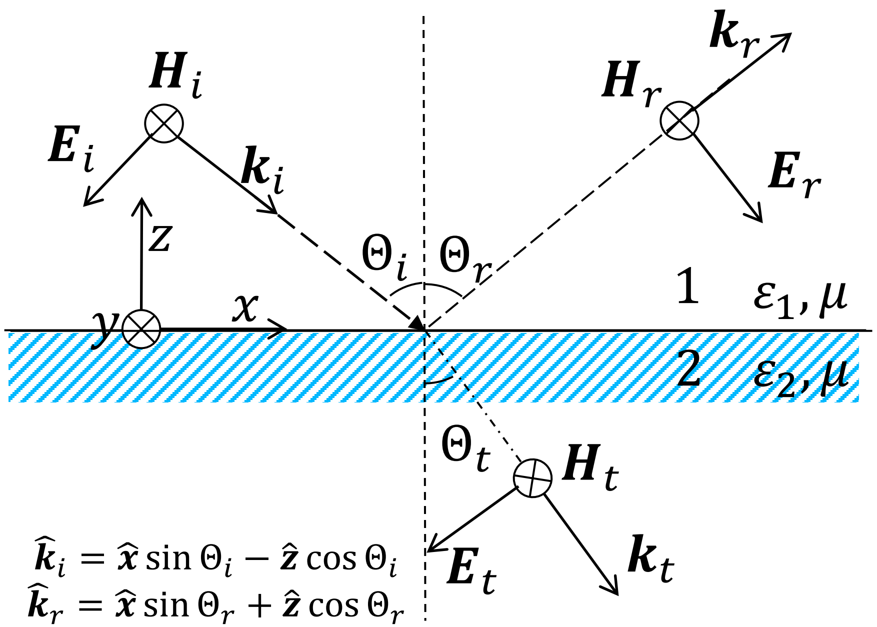
$$\boxed{R_\perp = \frac{\eta_2\cos\Theta_i - \eta_1\cos\Theta_t}{\eta_1\cos\Theta_t + \eta_2\cos\Theta_i} = -\frac{\sin(\Theta_i - \Theta_t)}{\sin(\Theta_i + \Theta_t)}}$$

<u>Transmission coefficient</u>

$$\boxed{T_\perp = \frac{2\eta_2\cos\Theta_i}{\eta_1\cos\Theta_t + \eta_2\cos\Theta_i} = \frac{2\sin\Theta_t\cos\Theta_i}{\sin(\Theta_i + \Theta_t)}}$$

Parallel Polarization

- The magnetic field is perpendicular to the plane of incidence and the electric field is parallel to the plane of incidence
- The fields are configured as in the Transverse Magnetic (TM) modes



$$\hat{\boldsymbol{k}}_i = \hat{\boldsymbol{x}} \sin\Theta_i - \hat{\boldsymbol{z}} \cos\Theta_i$$
$$\hat{\boldsymbol{k}}_r = \hat{\boldsymbol{x}} \sin\Theta_r + \hat{\boldsymbol{z}} \cos\Theta_r$$
$$\hat{\boldsymbol{k}}_t = \hat{\boldsymbol{x}} \sin\Theta_t - \hat{\boldsymbol{z}} \cos\Theta_t$$

$$\boldsymbol{H}_i = \hat{\boldsymbol{y}} \frac{E_0}{\eta_1} e^{-\mathrm{j}\boldsymbol{k}_i\cdot\boldsymbol{r}} = \hat{\boldsymbol{y}} \frac{E_0}{\eta_1} e^{-\mathrm{j}k_1(x\sin\Theta_i - z\cos\Theta_i)}$$
$$\boldsymbol{H}_r = \hat{\boldsymbol{y}} \frac{RE_0}{\eta_1} e^{-\mathrm{j}\boldsymbol{k}_r\cdot\boldsymbol{r}} = \hat{\boldsymbol{y}} \frac{RE_0}{\eta_1} e^{-\mathrm{j}k_1(x\sin\Theta_r + z\cos\Theta_r)}$$
$$\boldsymbol{H}_t = \hat{\boldsymbol{y}} \frac{TE_0}{\eta_1} e^{-\mathrm{j}\boldsymbol{k}_t\cdot\boldsymbol{r}} = \hat{\boldsymbol{y}} \frac{TE_0}{\eta_1} e^{-\mathrm{j}k_2(x\sin\Theta_t - z\cos\Theta_t)}$$
$$\boldsymbol{E}_i = \eta_1 \boldsymbol{H}_i \times \hat{\boldsymbol{k}}_i = (-\hat{\boldsymbol{z}}\sin\Theta_i - \hat{\boldsymbol{x}}\cos\Theta_i) E_0 e^{-\mathrm{j}k_1(x\sin\Theta_i - z\cos\Theta_i)}$$
$$\boldsymbol{E}_r = \eta_1 \boldsymbol{H}_r \times \hat{\boldsymbol{k}}_r = (-\hat{\boldsymbol{z}}\sin\Theta_r + \hat{\boldsymbol{x}}\cos\Theta_r) RE_0 e^{-\mathrm{j}k_1(x\sin\Theta_r + z\cos\Theta_r)}$$
$$\boldsymbol{E}_t = \eta_2 \boldsymbol{H}_t \times \hat{\boldsymbol{k}}_t = (-\hat{\boldsymbol{z}}\sin\Theta_t - \hat{\boldsymbol{x}}\cos\Theta_t) TE_0 e^{-\mathrm{j}k_2(x\sin\Theta_t - z\cos\Theta_t)}$$

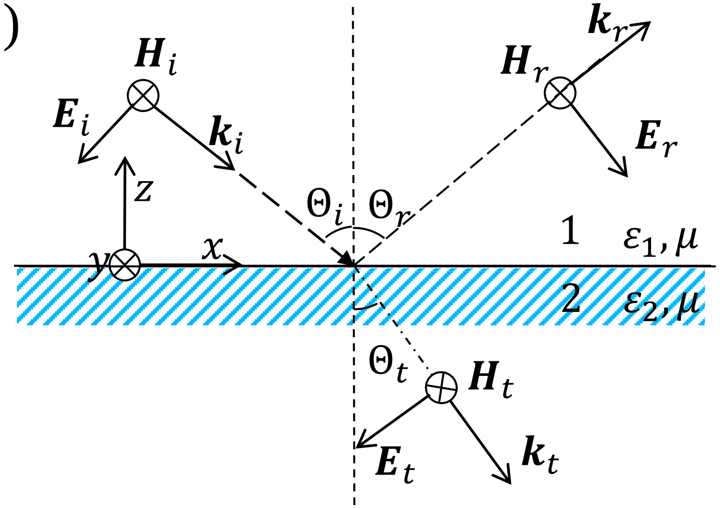
Parallel Polarization

- Boundary conditions ($z = 0$)

$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{E}_1 - \boldsymbol{E}_2) = 0}$$

$$\boldsymbol{E}_1 = \boldsymbol{E}_i + \boldsymbol{E}_r \qquad \boldsymbol{H}_1 = \boldsymbol{H}_i + \boldsymbol{H}_r$$
$$\boldsymbol{E}_2 = \boldsymbol{E}_t \qquad \boldsymbol{H}_2 = \boldsymbol{H}_t$$

$$-\cos\Theta_i\, e^{-jk_1 x \sin\Theta_i} + R\cos\Theta_r\, e^{-jk_1 x \sin\Theta_r} = -T\cos\Theta_t\, e^{-jk_2 x\sin\Theta_t} \;\cdots\cdots\; (1)$$



$$\boxed{\hat{\boldsymbol{n}} \times (\boldsymbol{H}_1 - \boldsymbol{H}_2) = 0}$$

$$\frac{1}{\eta_1} e^{-jk_1 x\sin\Theta_i} + \frac{R}{\eta_1} e^{-jk_1 x \sin\Theta_r} = \frac{T}{\eta_2} e^{-jk_2 x \sin\Theta_t} \;\cdots\cdots\; (2)$$

Parallel Polarization

- Similar to perpendicular polarization

$$\begin{cases} -\cos\Theta_i + R\cos\Theta_r = -T\cos\Theta_t \\ \dfrac{1}{\eta_1} + \dfrac{R}{\eta_1} = \dfrac{T}{\eta_2} \end{cases}$$

<u>Reflection coefficient</u>

$$\boxed{R_{\|} = \frac{\eta_1\cos\Theta_i - \eta_2\cos\Theta_t}{\eta_1\cos\Theta_i + \eta_2\cos\Theta_t} = -\frac{\tan(\Theta_i - \Theta_t)}{\tan(\Theta_i + \Theta_t)}}$$

<u>Transmission coefficient</u>

$$\boxed{T_{\|} = \frac{2\eta_2\cos\Theta_i}{\eta_1\cos\Theta_i + \eta_2\cos\Theta_t} = \frac{2\sin\Theta_t\cos\Theta_i}{\sin(\Theta_i + \Theta_t)\cos(\Theta_i - \Theta_t)}}$$

Total Transmission

- The reflection coefficients vanish at Brewster angle only in parallel polarization

$$R_\perp = -\frac{\sin(\Theta_i - \Theta_t)}{\sin(\Theta_i + \Theta_t)} < 0 \text{ : always negative}$$

$$R_\parallel = -\frac{\tan(\Theta_i - \Theta_t)}{\tan(\Theta_i + \Theta_t)} = 0 \quad \text{when } (\Theta_i + \Theta_t) = 90^\circ$$

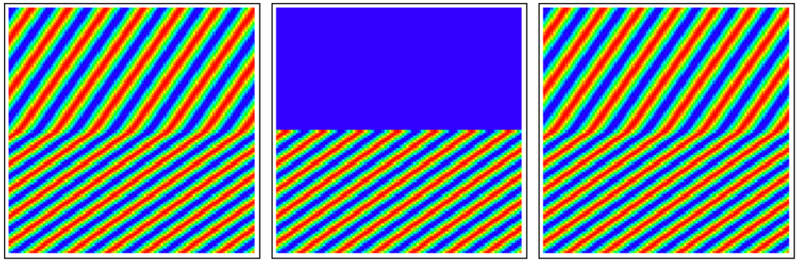
Brewster angle

$$\boxed{\Theta_{i,B}} + \Theta_t = 90^\circ$$

$$\frac{\sin\Theta_i}{\sin\Theta_t} = \frac{\sin\Theta_{i,B}}{\sin(90 - \Theta_{i,B})} = \frac{\sin\Theta_{i,B}}{\cos\Theta_{i,B}} = \tan\Theta_{i,B} = \frac{\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}}$$

$$\boxed{\Theta_{i,B} = \tan^{-1}\sqrt{\frac{\varepsilon_2}{\varepsilon_1}}}$$

$\varepsilon_2/\varepsilon_1 = 2,\ \Theta_i = 54.7^\circ$



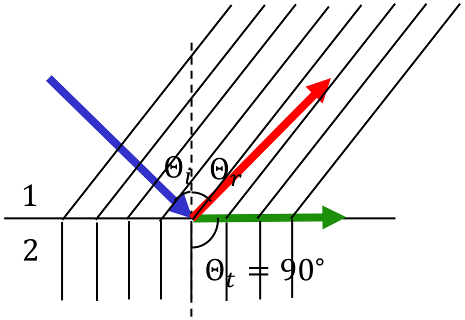
Incident & Transmitted | Reflected & Transmitted | Combined & Transmitted

http://www.takuichi.net/hobby/edu/em/fresnel/para/e1e2/brewster/index-j.html

Total Reflection

- We have a limit condition for total reflection, valid for both polarizations.
- When $\Theta_t = 90°$, from Snell's law, we have

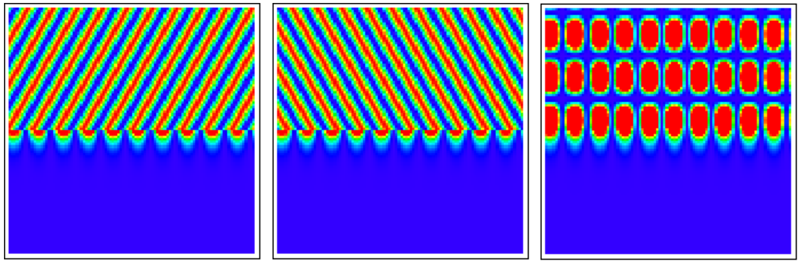
$$\frac{\sin\Theta_i}{\sin\Theta_t} = \frac{\sin\Theta_i}{1} = \frac{\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}}$$



- This particular angle of incidence is called Critical angle

$$\boxed{\Theta_{i,C} = \sin^{-1}\sqrt{\frac{\varepsilon_2}{\varepsilon_1}}}$$

$\varepsilon_2/\varepsilon_1 = 1/2,\ \Theta_i = 60°(\Theta_{i,C} = 45°)$



Incident & Transmitted | Reflected & Transmitted | Combined & Transmitted

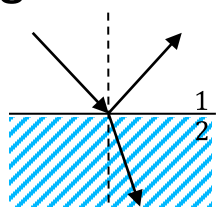
http://www.takuichi.net/hobby/edu/em/fresnel/ver/e2e1/inc60deg/index-j.html

Total Reflection

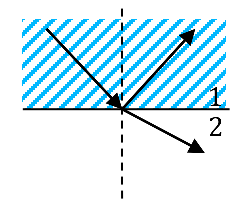
Reflection Coefficient

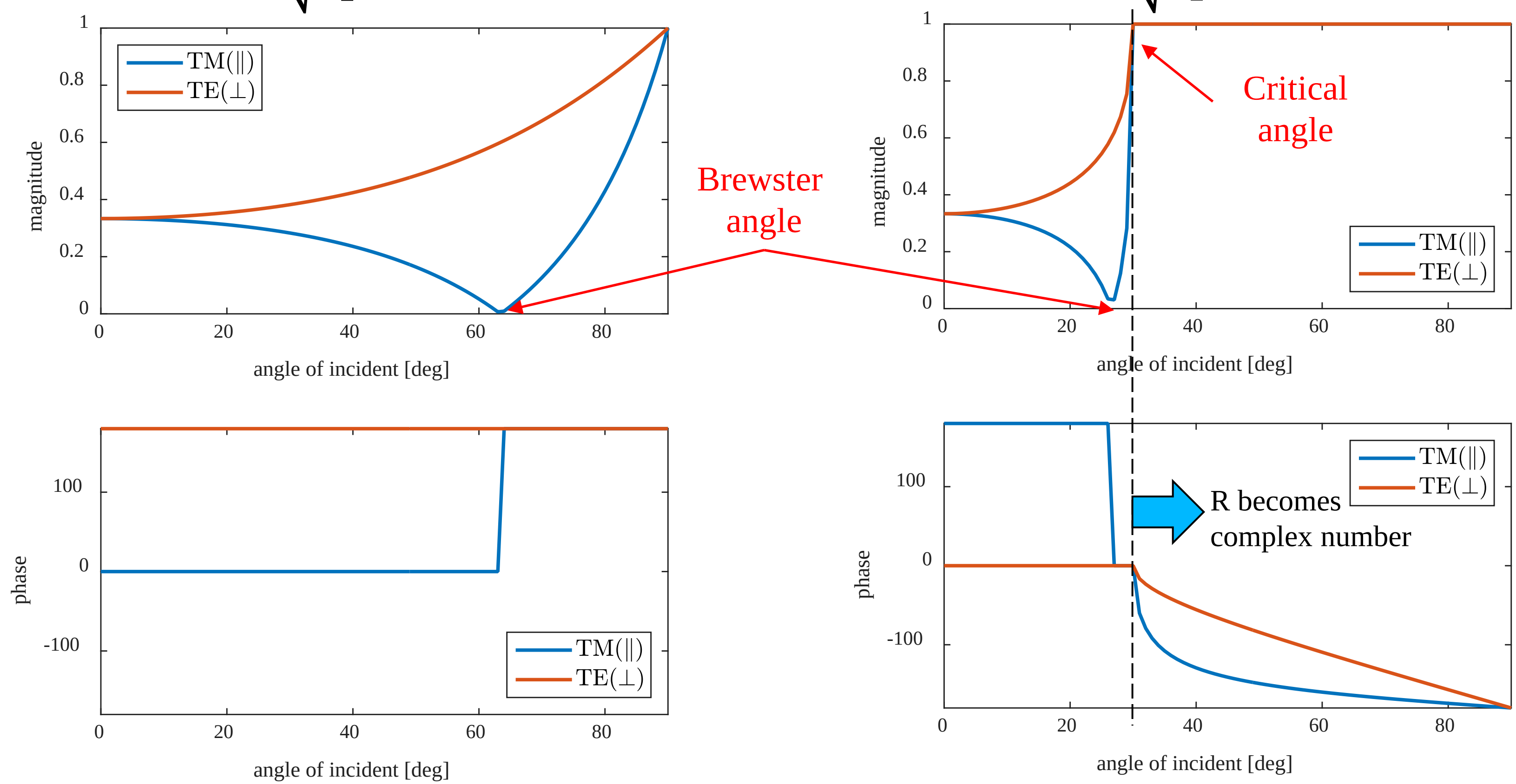
- Two typical cases

$$\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} = 2$$



$$\sqrt{\frac{\varepsilon_2}{\varepsilon_1}} = \frac{1}{2}$$





Material Constants

- Complex permittivity of interior construction materials

$$\delta = \varepsilon + \frac{\sigma}{\mathrm{j}\omega} = \varepsilon_0 \delta_r \qquad \delta_r = \varepsilon_r - \mathrm{j}\frac{\sigma}{\omega \varepsilon_0}$$

δ_r, measured

	1 GHz	**57.5 GHz**	**70 GHz**	**78.5 GHz**	**95.9 GHz**
Concrete	7-j0.85	6.5-j0.43	–	–	6.2-j0.34
Lightweight concrete	2-j0.5	–	–	–	–
Floorboard (synthetic resin)	–	3.91-j0.33	–	3.64-j0.37	3.16-j0.39
Plaster board	–	2.25-j0.03	2.43-j0.04	2.37-j0.1	2.25-j0.06
Ceiling board (rock wool)	1.2-j0.01	1.59-j0.01	–	1.56-j0.02	1.56-j0.04
Glass	6.76-j0.09	6.76-j0.16	6.76-j0.17	6.76-j0.18	6.76-j0.19
Fibreglass	1.2-j0.1	–	–	–	–

Rec. ITU-R P.1238-6

Material Constants

- Model parameters for the relative permittivity (ε_r) and conductivity (σ) of building materials

$$\sigma = c \cdot f^{d} \quad \text{where f [GHz]}$$

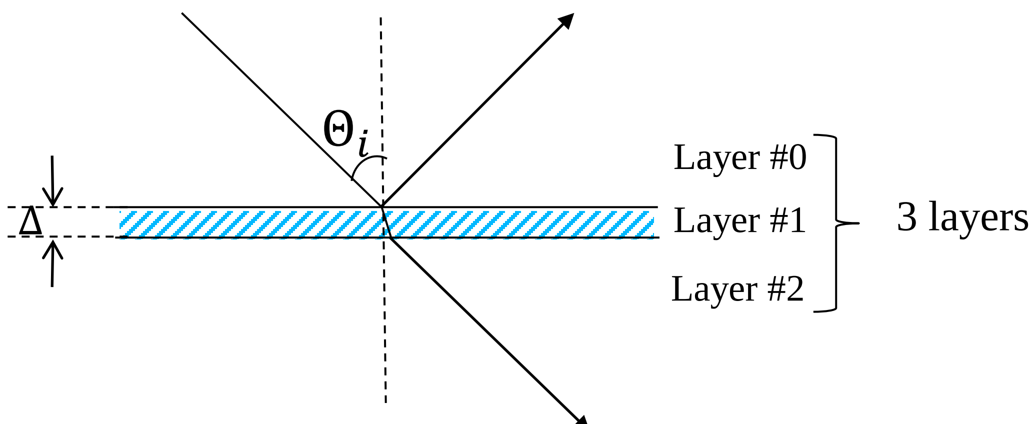
Material class	Relative permittivity	Conductivity		Frequency range (GHz)
		c	*d*	
Concrete	5.31	0.0326	0.8095	1-100
Brick	3.75	0.038	0.0	1-10
Plasterboard	2.94	0.0116	0.7076	1-100
Wood	1.99	0.0047	1.0718	0.001-100
Glass	6.27	0.0043	1.1925	0.1-100
Ceiling board	1.50	0.0005	1.1634	1-100
Chipboard	2.58	0.0217	0.7800	1-100
Floorboard	3.66	0.0044	1.3515	50-100
Metal	1	10^7	0.0	1-100

Rec. ITU-R P.1238-6

Layered Dielectric Structures

- It occurs when a user inside a building is communicating with an outdoor BS, or in a picocell where the Mobile Station (MS) and the BS are in different rooms
- In that case, we are interested in the attenuation and phase shift of a wave transmitted through a wall
- The simplest and practically most important case occurs when a dielectric layer is surrounded on both sides by air

3-Layered Dielectric Structure



R: reflection coefficient (#0→#1)

3-Layered Dielectric Structures

- The reflection and transmission coefficients can be determined by summation of the partial waves, resulting in a total transmission coefficient
- 3-layer case

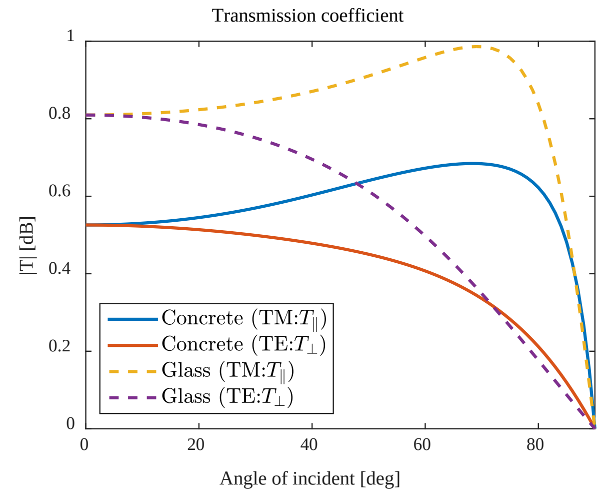
Reflection coefficient

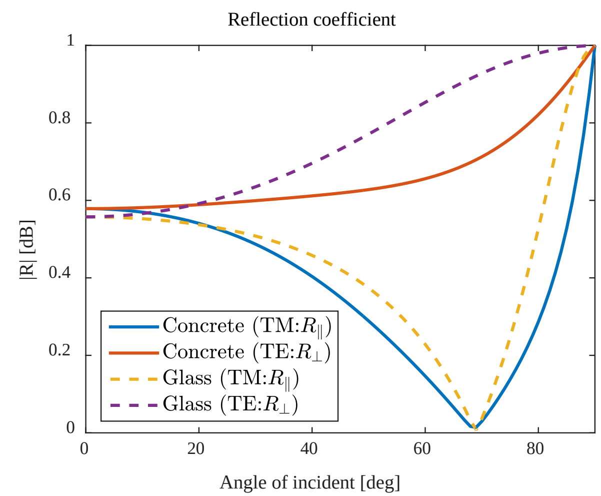
$$R_{3-\text{layered}} = \frac{1 - e^{-j2\alpha}}{1 - R^2 e^{-j2\alpha}} R$$

Transmission coefficient

$$T_{3-\text{layered}} = \frac{(1 - R^2)\, e^{-j\alpha}}{1 - R^2 e^{-j2\alpha}}$$

$$\alpha = \frac{2\pi}{\lambda_0} \Delta \sqrt{\delta_r - \sin^2 \Theta_i}$$





f_c =2 GHz

concrete
$\delta_r = 6.5 - j0.43$
$\Delta = 10$cm

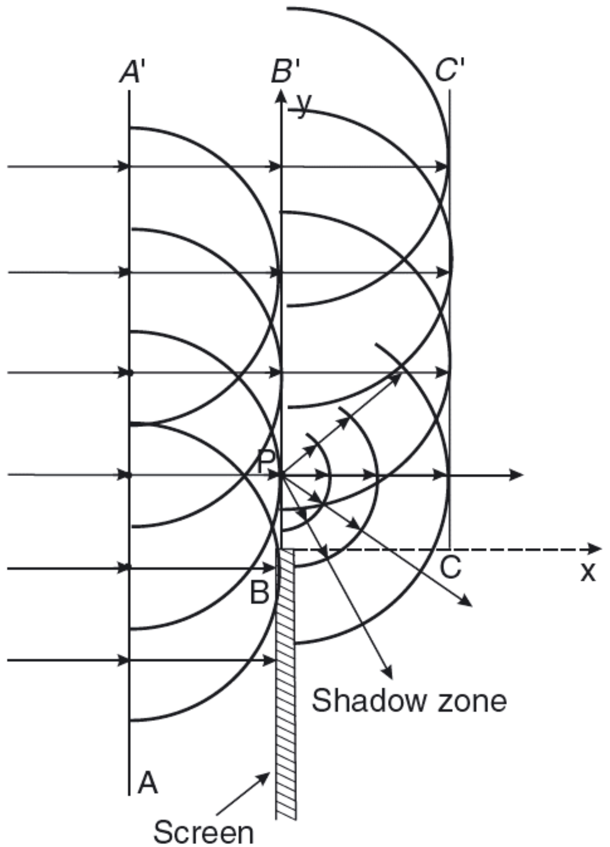
glass
$\delta_r = 6.76 - j0.16$
$\Delta = 1$cm

Diffraction

- When obstructed by a surface that has sharp irregularities (edges)
- Diffraction can be explained by Huygen's principle: all points on a wavefront can be considered as point sources for the production of secondary wavelets

Diffraction by Single Screen

- A homogeneous plane wave by a semi-infinite screen
- Diffraction coefficient for shadowed region



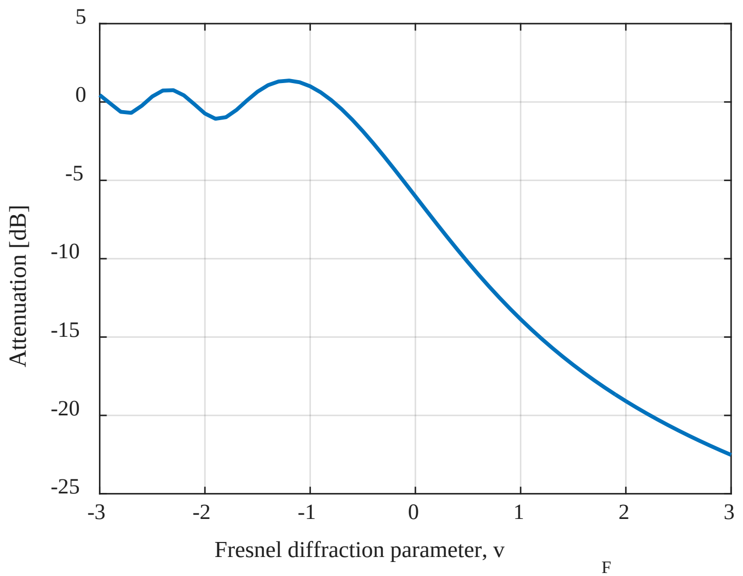
Diffraction coefficient

$$\boxed{J = \left(\frac{1}{2} - \frac{1+\mathrm{j}}{2} F(\nu_F)\right)}$$

Fresnel Integral

$$F(\nu_F) = \int_0^{\nu_F} \exp\left(-\mathrm{j}\frac{\pi t^2}{2}\right) dt$$

Diffraction parameter $\nu_F = -2y/\sqrt{\lambda x}$

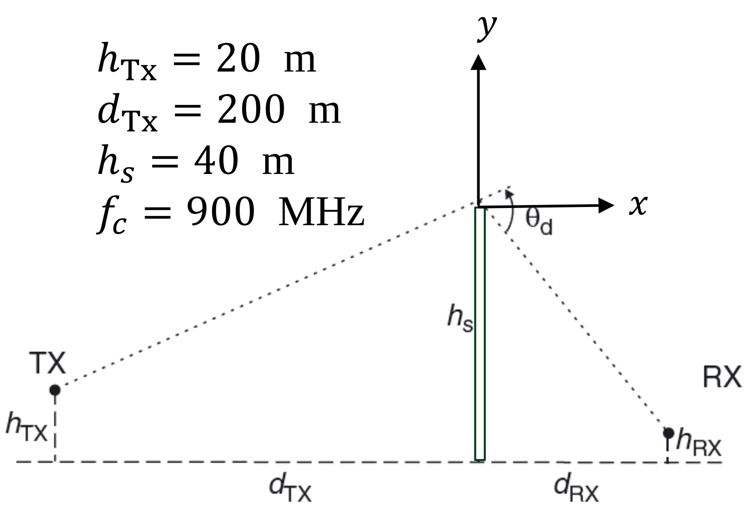


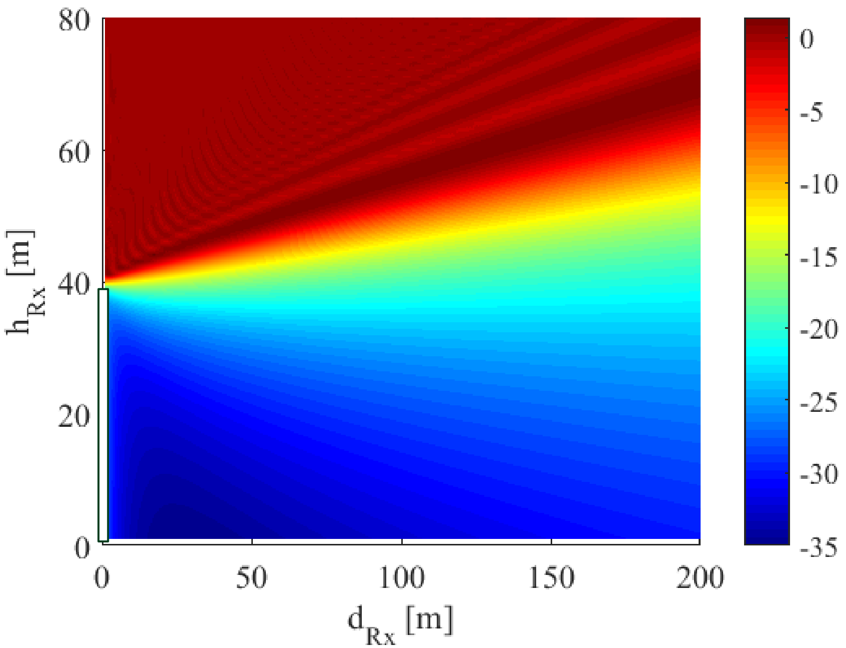
R. Vaughan and J. B. Andersen, Channels, Propagation and Antennas for Mobile Communications, IEE Press (2003).

Diffraction by Single Screen

- Diffraction coefficient for shadowed region

$$h_{\mathrm{Tx}} = 20 \;\; \mathrm{m}$$
$$d_{\mathrm{Tx}} = 200 \;\; \mathrm{m}$$
$$h_s = 40 \;\; \mathrm{m}$$
$$f_c = 900 \;\; \mathrm{MHz}$$





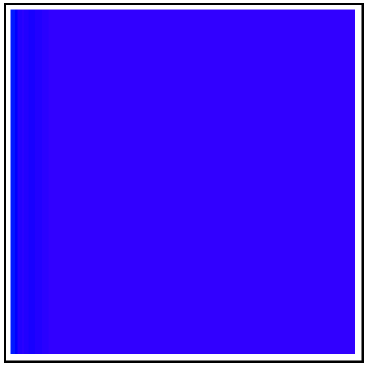
$$\nu_F = -2y/\sqrt{\lambda x} \approx h_s \sqrt{\frac{2(d_{\mathrm{Tx}} + d_{\mathrm{Rx}})}{\lambda d_{\mathrm{Tx}} d_{\mathrm{Rx}}}} = \theta_d \sqrt{\frac{2 d_{\mathrm{Tx}} d_{\mathrm{Rx}}}{\lambda (d_{\mathrm{Tx}} + d_{\mathrm{Rx}})}}$$

Fresnel diffraction parameter

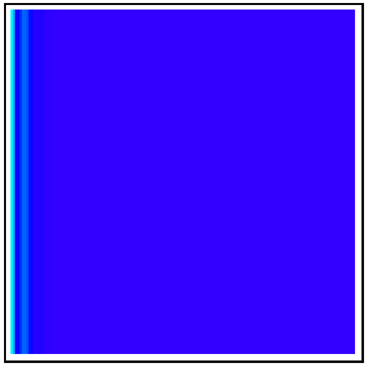
$$\theta_d = \tan^{-1}\left(\frac{h_s - h_{\mathrm{Tx}}}{d_{\mathrm{Tx}}}\right) + \tan^{-1}\left(\frac{h_s - h_{\mathrm{Rx}}}{d_{\mathrm{Rx}}}\right)$$

Examples

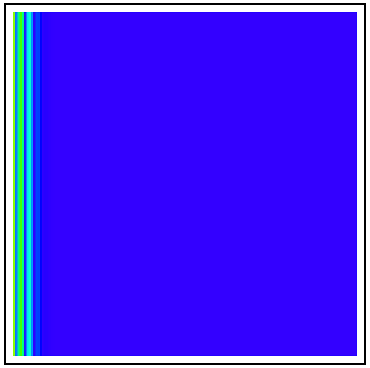
$f = f_0$



$f = 2f_0$

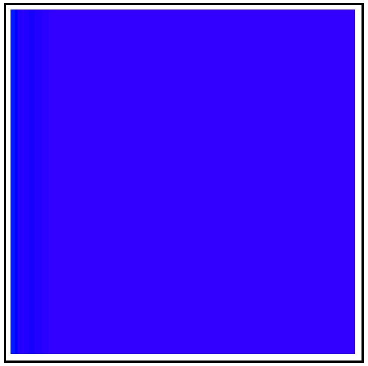


$f = 4f_0$

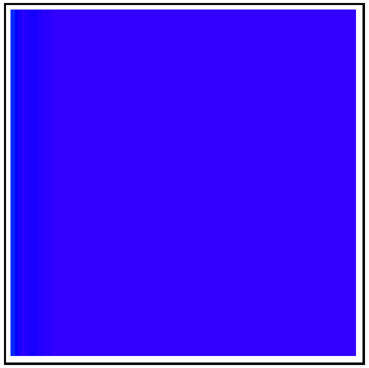


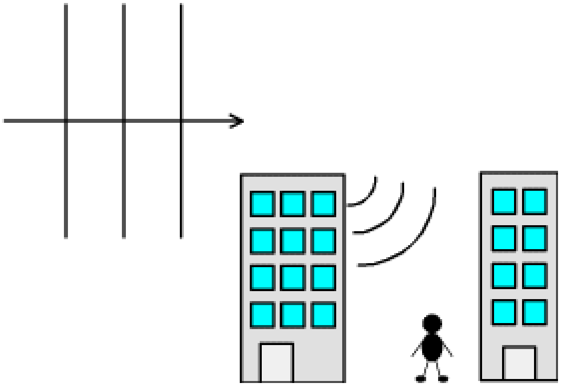
http://www.takuichi.net/hobby/edu/em/diffraction/te/lf_hf.html

TE



TM





http://www.takuichi.net/hobby/edu/em/diffraction/index-j.html

Fresnel Zones

- The impact of an obstacle can also be assessed qualitatively, and intuitively, by the concept of *Fresnel zones*
- The n-th Fresnel zone is the region inside an ellipsoid defined by the locus of points where the distance $(a + b)$ is larger than the direct path between T and R $(d_1 + d_2)$ by an integer multiple of $\lambda/2$
- When $d_1, d_2 \gg R_n$, Fresnel zone can be approximated by

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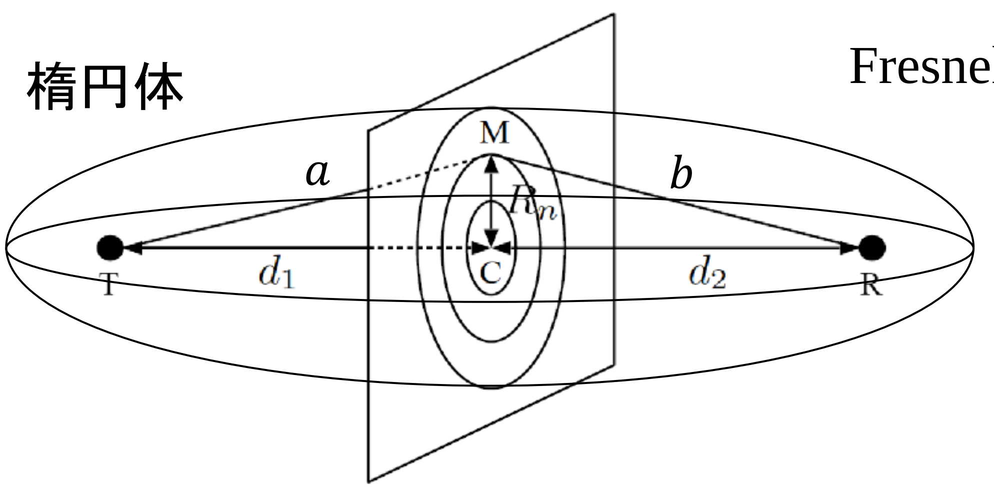


Fresnel Zone $$R_n \approx \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

Fresnel Zones Clearance

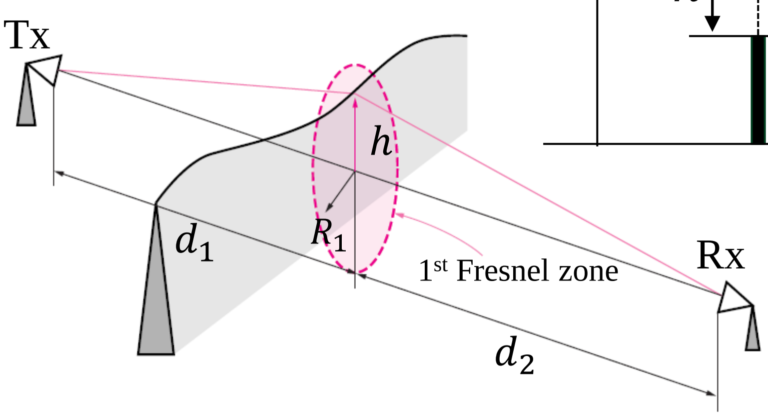
- Contributions within the first zone are all in phase, so any absorbing obstructions which do not enter this zone will have little effect on the received signal
- The Fresnel zone clearance (h/R_n) can be expressed by diffraction parameter v_F as

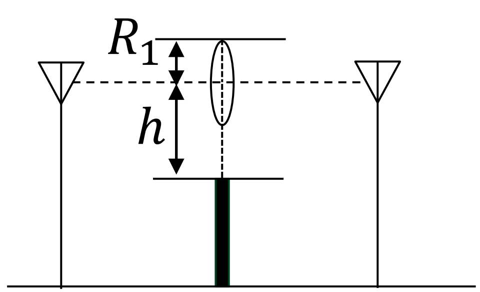
$$v_F \approx h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}} = \frac{h}{R_1}\sqrt{2}$$

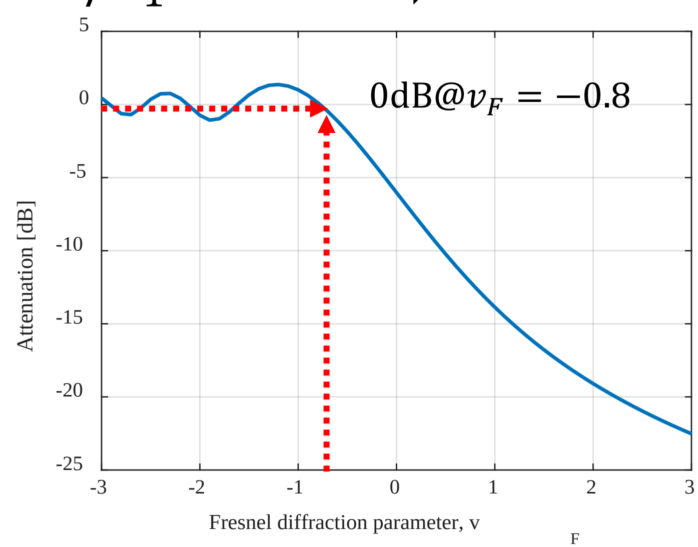
For first Fresnel zone

$$h/R_1 = v_F/\sqrt{2}$$

$$h/R_1 \approx -0.6 \Rightarrow \text{Att. 0dB}$$

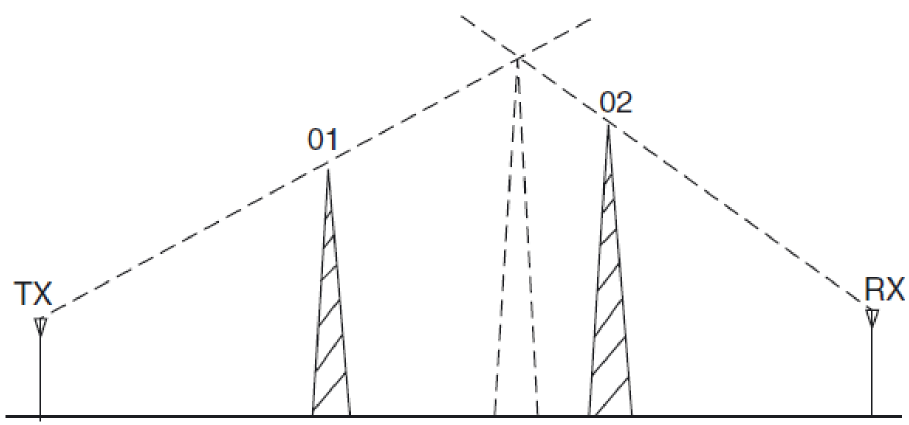






Diffraction by Multiple Screens

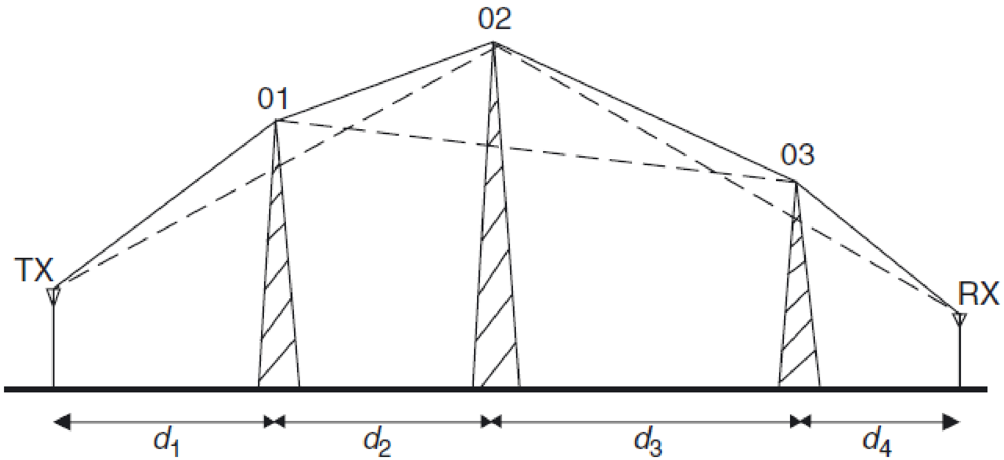
- The situations where *multiple IOs* are located between TX and RX are usually encountered → no exact solutions are available
- Bullington’s Method
  - Replaces the multiple screens by a single, “equivalent” screen
  - The field resulting from diffraction at this single screen can be computed according to previous method → “simple”
  - Most of the physically existing screens do not impact the location of the equivalent screen → tends to give optimistic predictions of the received power



Equivalent screen

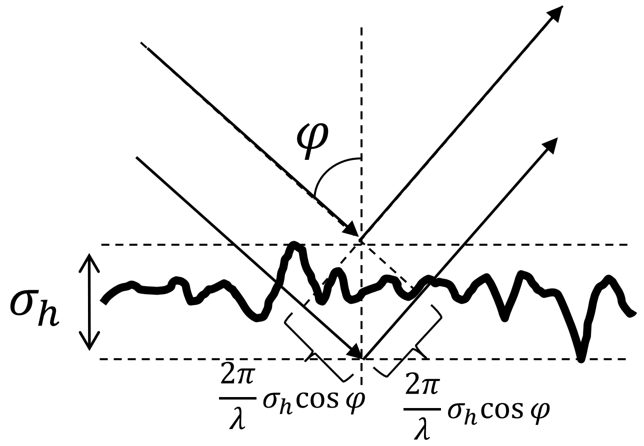
Diffraction by Multiple Screens

- The Epstein–Petersen Method
  - This approach computes the diffraction losses for each screen separately
  - Attenuations by the different screens are then added up (on a logarithmic scale) → includes the effects of all screens
  - The inaccuracies caused by this “far-field assumption” can be reduced considerably by the slope diffraction method



Scattering

- Occurs when the medium has objects that are smaller or comparable to the wavelength (small objects, rough surfaces and other irregularities on the channel)
- Causes the transmitter energy to be radiated in many direction e.g. forage, street sign, lampposts
- Surface roughness criteria



$$\Delta\phi = \frac{4\pi}{\lambda}\sigma_h \cos\varphi$$: Rayleigh roughness

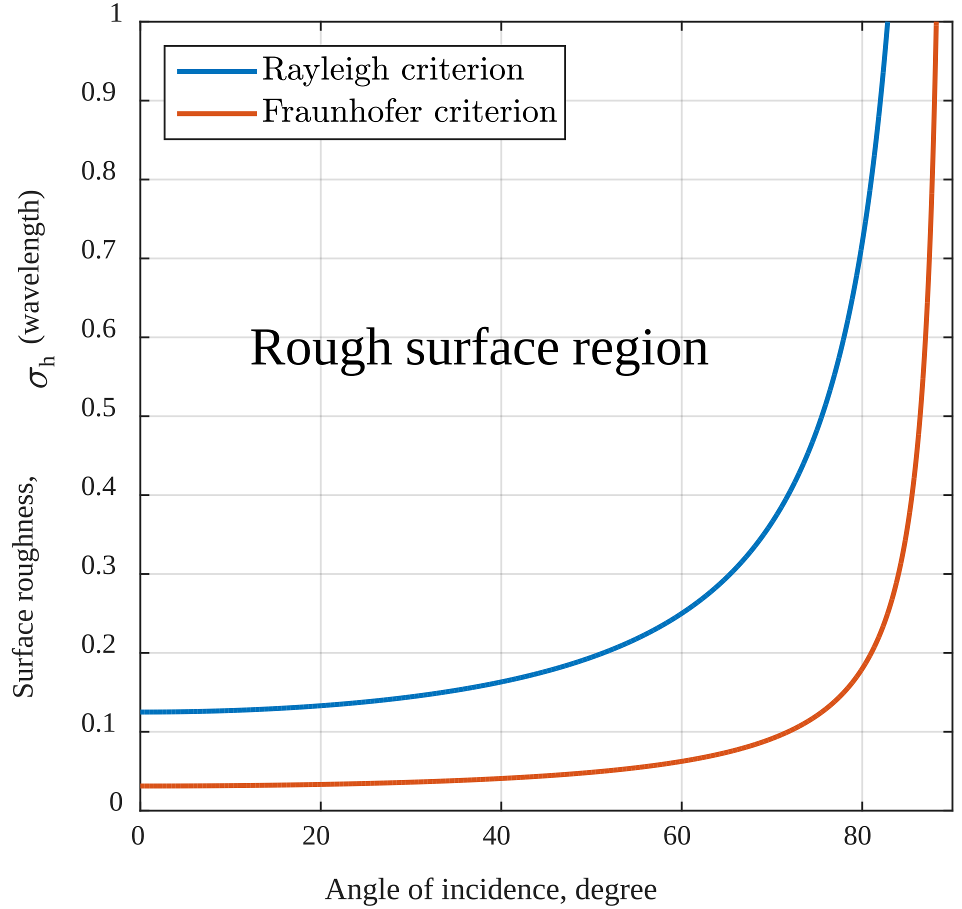
$$\Delta\phi > \frac{\pi}{2} \Rightarrow \sigma_h > \frac{\lambda}{8\cos\varphi}$$ Rayleigh criterion

$$\Delta\phi > \frac{\pi}{8} \Rightarrow \sigma_h > \frac{\lambda}{32\cos\varphi}$$ Fraunhofer criterion

σ_h: standard deviation of height distribution

Scattering

- Surface roughness criteria
  Surfaces above the curve cannot be accurately modelled using the Fresnel reflection coefficient alone



Scattering

- Scattering coefficients by Kirchhoff theory

$$\rho_s = \exp\left(-\frac{1}{2}(\Delta\phi)^2\right) = \exp\left(-\frac{1}{2}\left(4\pi\frac{\sigma_h}{\lambda}\cos\varphi\right)^2\right)$$