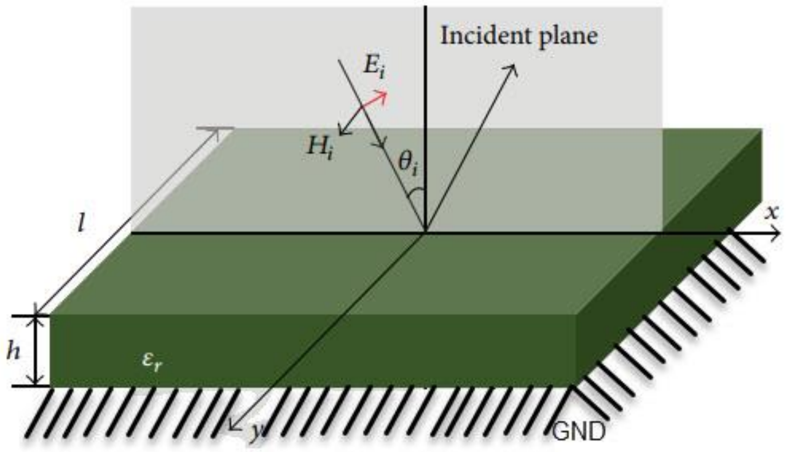
بسم الله الرحمن الرحيم



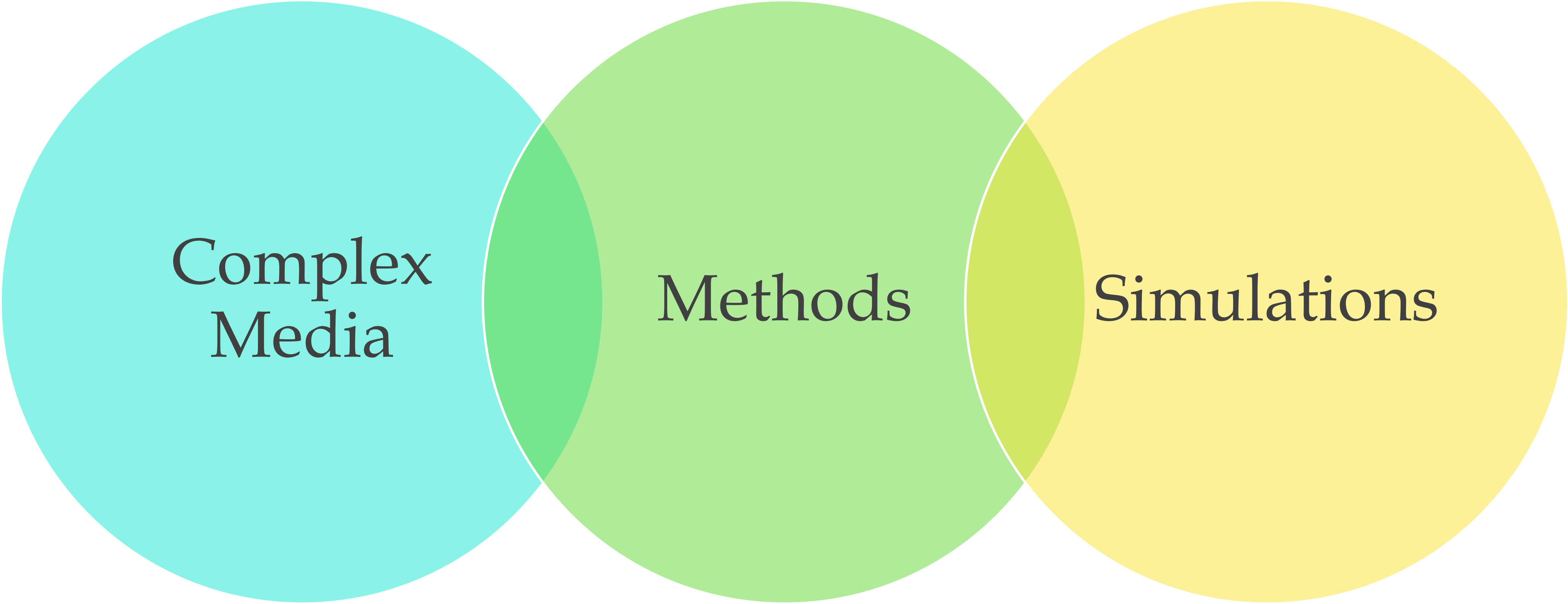
Plane-Wave Reflection from a Grounded Slab of Complex Media

Supervisor: Dr. Seyed Mohammad Hashemi

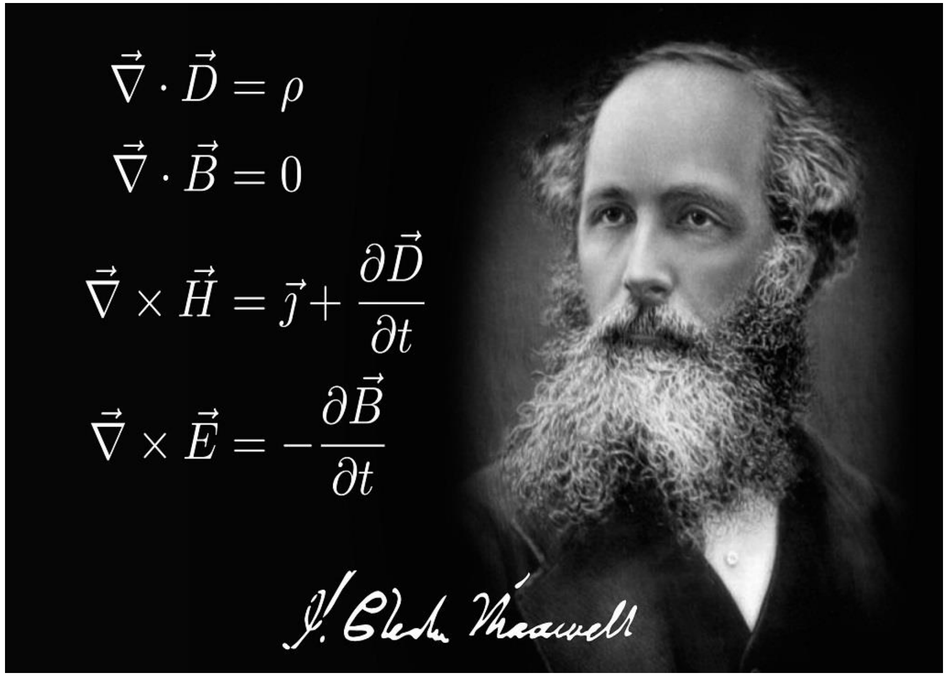
Student: Mohammad Reza Farhadi Nia

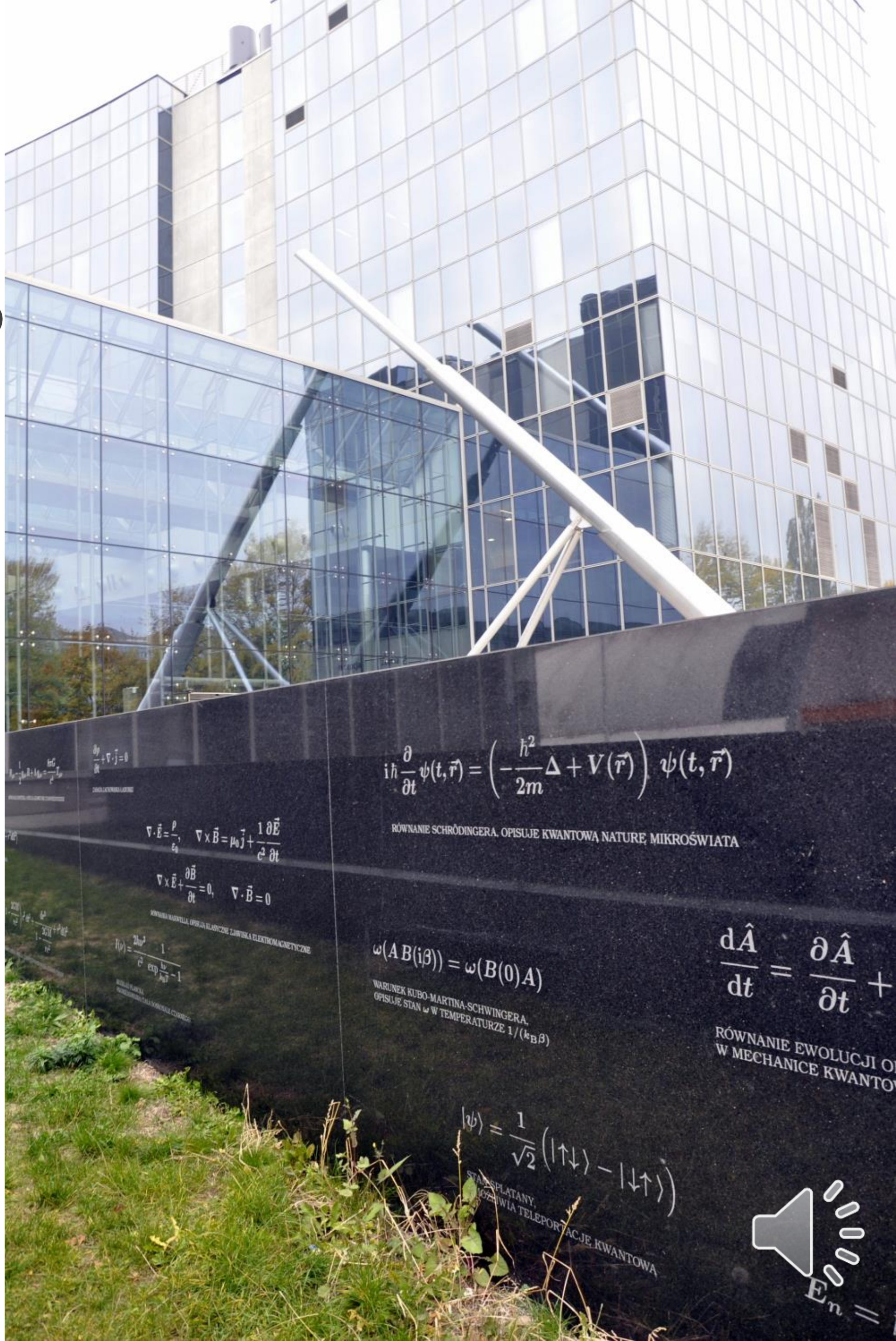
March 2021

PRESENTATION



MAXWELL'S EQUATIONS & CONSTITUTIVE EQUATIONS





Warsaw University

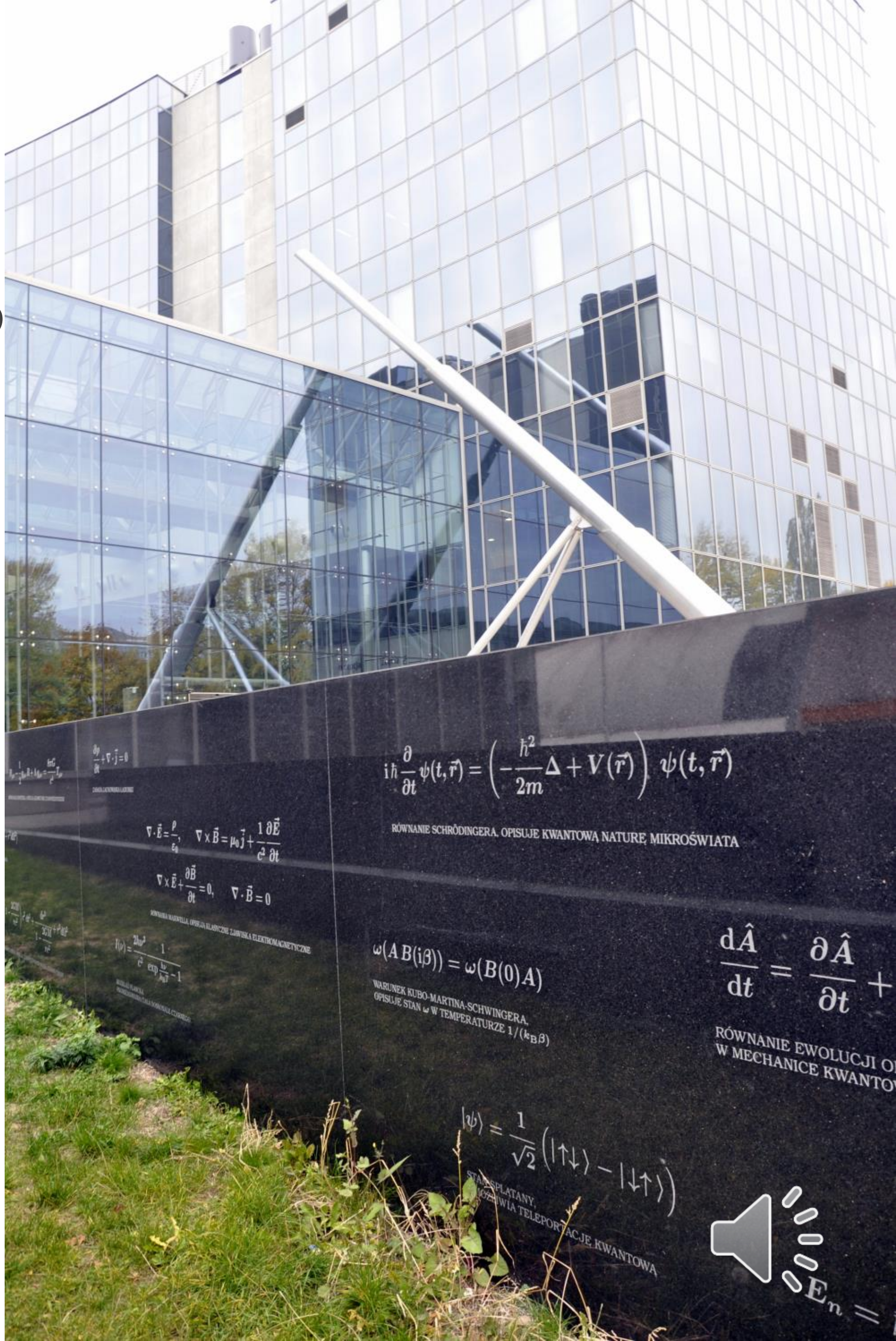
MAXWELL'S EQUATIONS & CONSTITUTIVE EQUATIONS

$$\nabla \times \tilde{\underline{H}}(\underline{r},t) - \frac{\partial}{\partial t}\tilde{\underline{D}}(\underline{r},t) = \tilde{\underline{J}}_e(\underline{r},t)$$

$$\nabla \times \tilde{\underline{E}}(\underline{r},t) + \frac{\partial}{\partial t}\tilde{\underline{B}}(\underline{r},t) = -\tilde{\underline{J}}_m(\underline{r},t)$$

$$\nabla \cdot \tilde{\underline{D}}(\underline{r},t) = \tilde{\underline{\rho}}_e(\underline{r},t)$$

$$\nabla \cdot \tilde{\underline{B}}(\underline{r},t) = -\tilde{\underline{\rho}}_m(\underline{r},t)$$

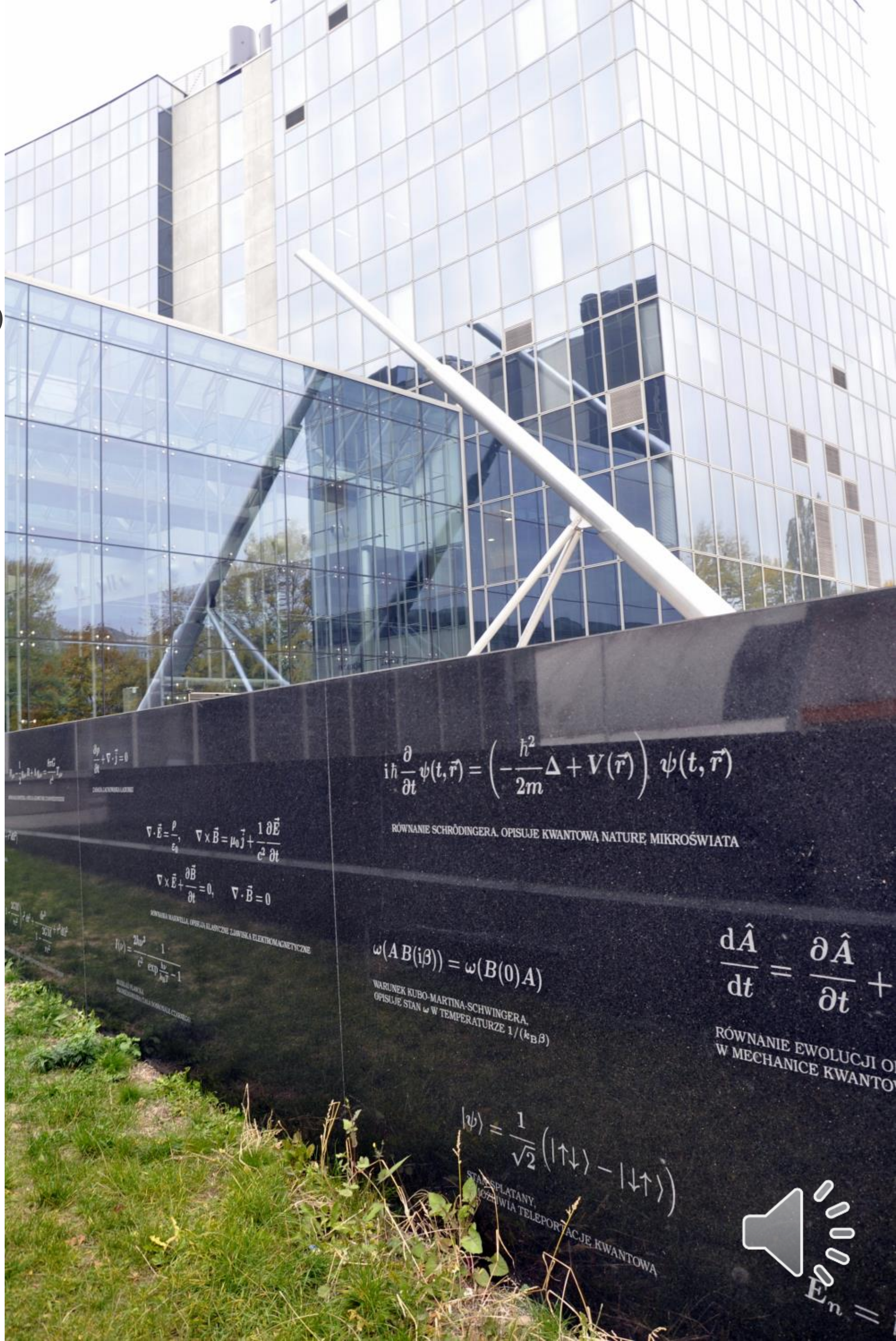


Warsaw University

MAXWELL'S EQUATIONS & CONSTITUTIVE EQUATIONS

$$\underline{\tilde{D}}(\underline{r},t) = F\left\{\underline{\tilde{E}}(\underline{r},t), \underline{\tilde{B}}(\underline{r},t)\right\}$$

$$\underline{\tilde{H}}(\underline{r},t) = G\left\{\underline{\tilde{E}}(\underline{r},t), \underline{\tilde{B}}(\underline{r},t)\right\}$$



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MAXWELL'S EQUATIONS & CONSTITUTIVE EQUATIONS

$$\underline{D}(\underline{r},\omega)=\underline{\underline{\varepsilon}}_{EH}(\underline{r},\omega)\cdot\underline{E}(\underline{r},\omega)+\underline{\underline{\xi}}_{EH}(\underline{r},\omega)\cdot\underline{H}(\underline{r},\omega)$$

$$\underline{B}(\underline{r},\omega)=\underline{\underline{\zeta}}_{EH}(\underline{r},\omega)\cdot\underline{E}(\underline{r},\omega)+\underline{\underline{\mu}}_{EH}(\underline{r},\omega)\cdot\underline{H}(\underline{r},\omega)$$

$$\begin{bmatrix}\underline{D}(\underline{r},\omega)\\ \underline{B}(\underline{r},\omega)\end{bmatrix}=\underline{\underline{K}}_{bi}(\omega)\bullet\begin{bmatrix}\underline{E}(\underline{r},\omega)\\ \underline{H}(\underline{r},\omega)\end{bmatrix}$$

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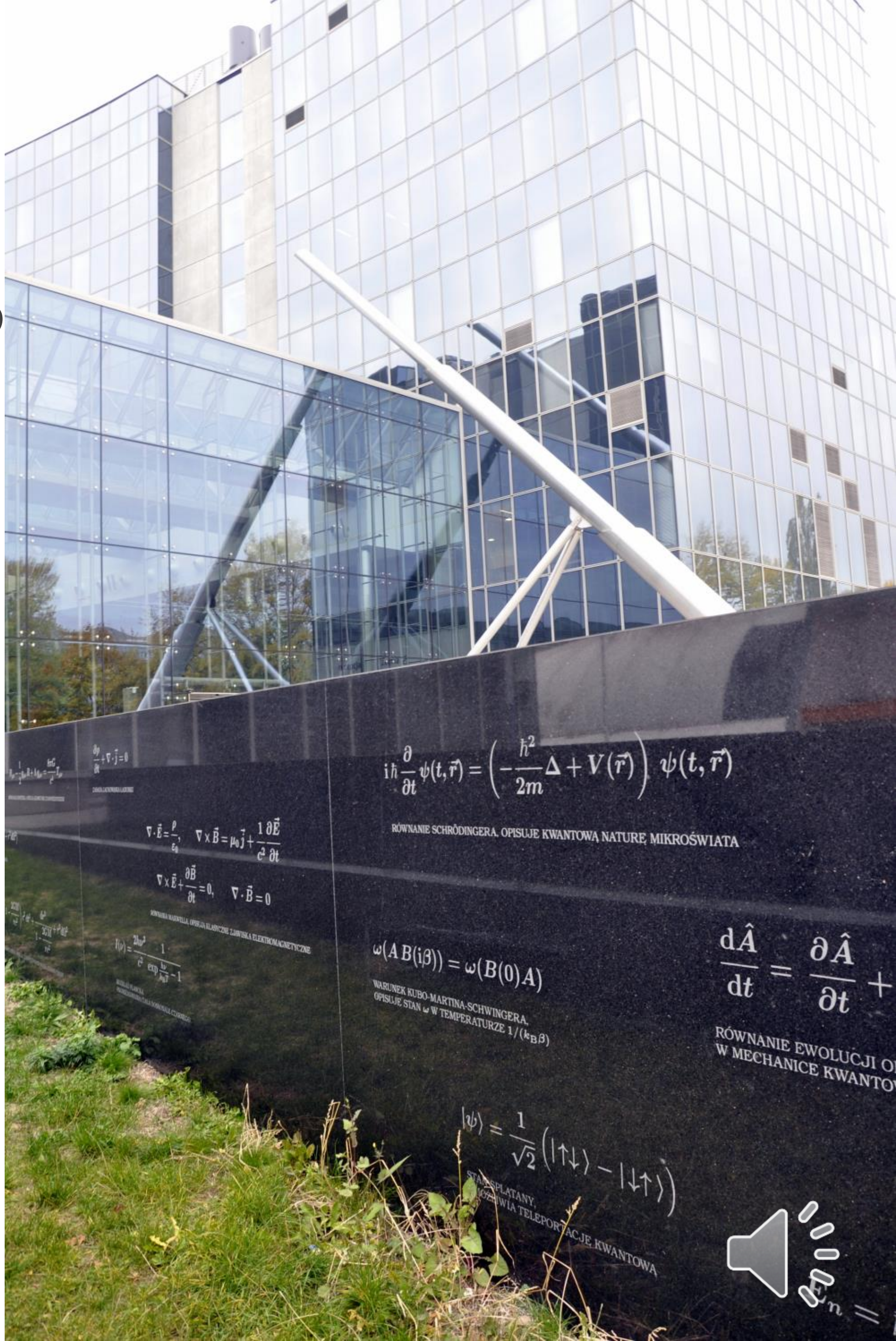
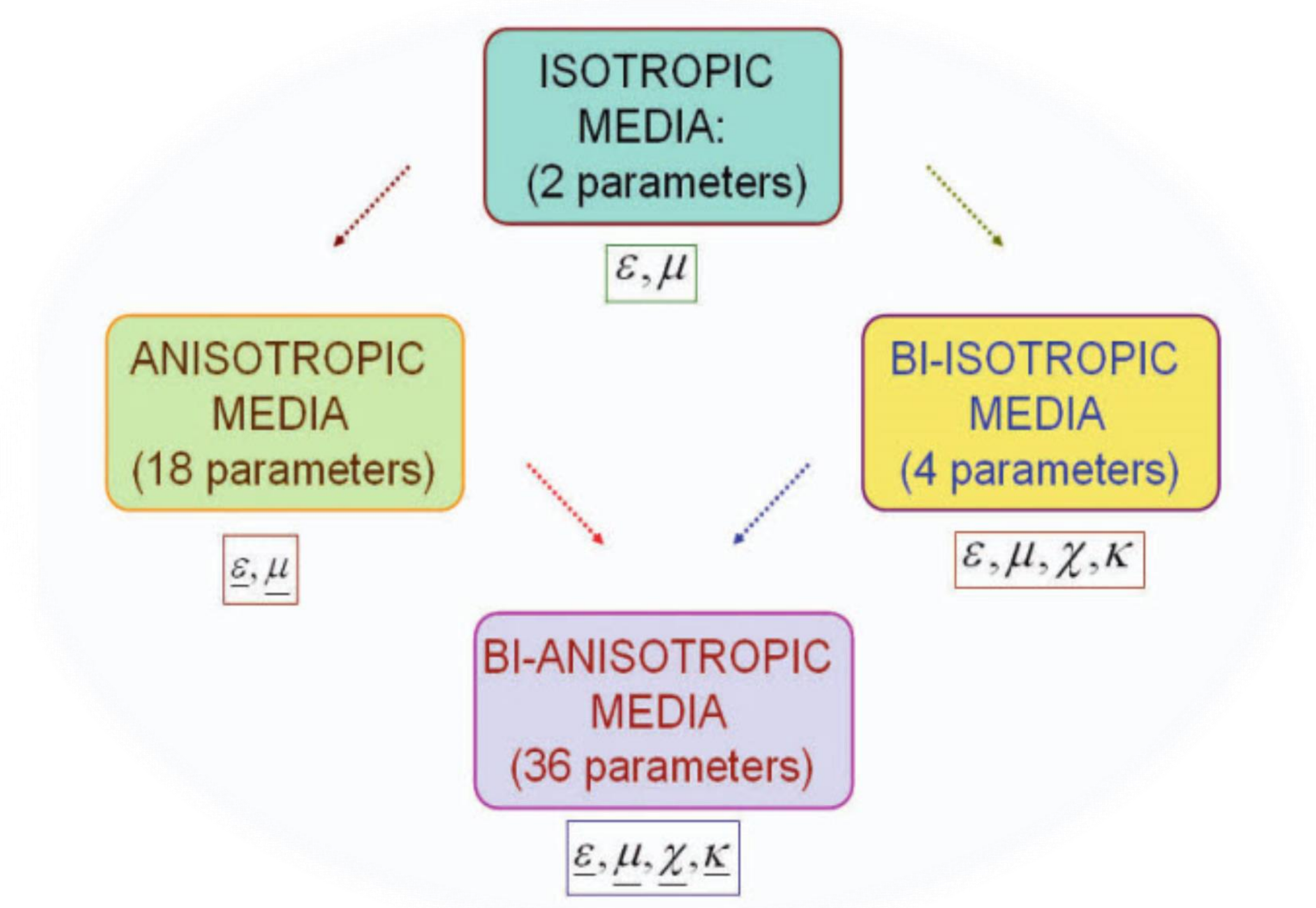


COMPLEX MEDIA

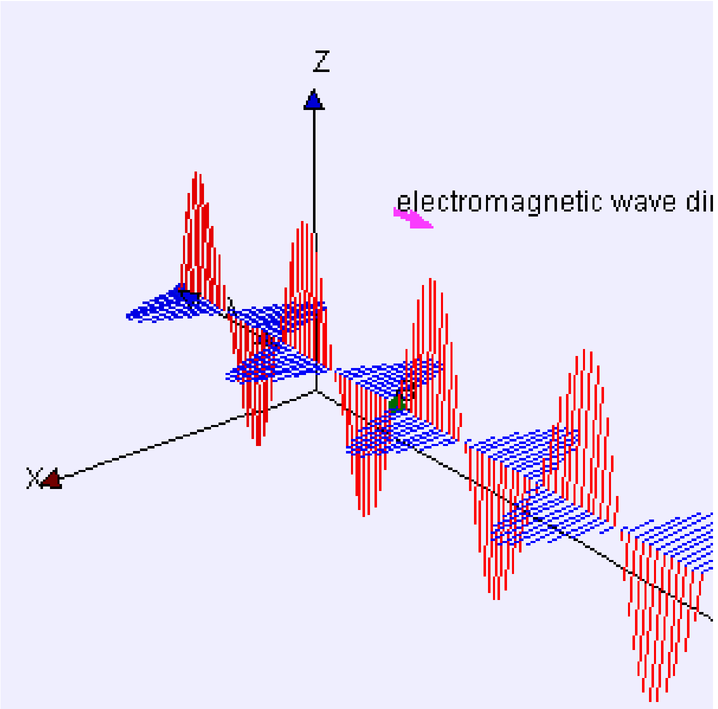
$$\begin{bmatrix} \underline{D}(\underline{r},\omega) \\ \underline{B}(\underline{r},\omega) \end{bmatrix} = \underline{\underline{K}}_{bi}(\omega) \bullet \begin{bmatrix} \underline{E}(\underline{r},\omega) \\ \underline{H}(\underline{r},\omega) \end{bmatrix}$$

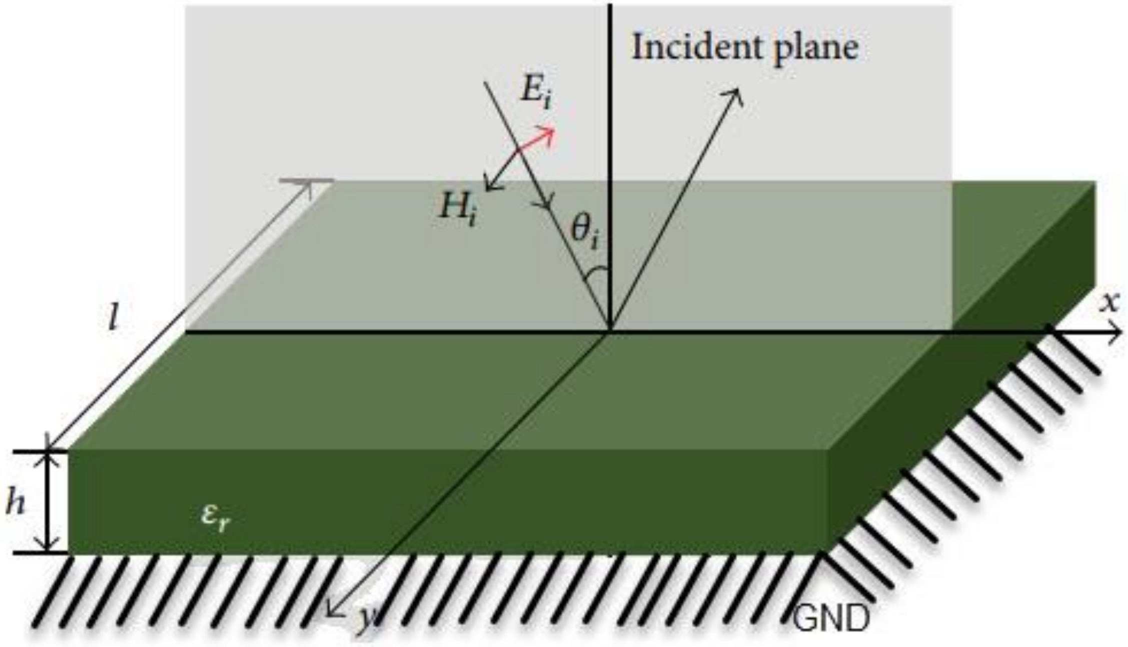
$$\underline{\underline{K}}_{bi}(\omega) = \begin{bmatrix} \underline{\underline{\varepsilon}}_{bi}(\omega) & \underline{\underline{\xi}}_{bi}(\omega) \\ \underline{\underline{\zeta}}_{bi}(\omega) & \underline{\underline{\mu}}_{bi}(\omega) \end{bmatrix} = \begin{bmatrix} \begin{pmatrix} \varepsilon_x(\omega) & \varepsilon_\alpha(\omega) & \varepsilon_\beta(\omega) \\ \varepsilon_\alpha(\omega) & \varepsilon_y(\omega) & \varepsilon_\gamma(\omega) \\ \varepsilon_\beta(\omega) & \varepsilon_\gamma(\omega) & \varepsilon_z(\omega) \end{pmatrix} & \begin{pmatrix} \xi_x(\omega) & \xi_\alpha(\omega) & \xi_\beta(\omega) \\ \xi_\alpha(\omega) & \xi_y(\omega) & \xi_\gamma(\omega) \\ \xi_\beta(\omega) & \xi_\gamma(\omega) & \xi_z(\omega) \end{pmatrix} \\ \begin{pmatrix} \zeta_x(\omega) & \zeta_\alpha(\omega) & \zeta_\beta(\omega) \\ \zeta_\alpha(\omega) & \zeta_y(\omega) & \zeta_\gamma(\omega) \\ \zeta_\beta(\omega) & \zeta_\gamma(\omega) & \zeta_z(\omega) \end{pmatrix} & \begin{pmatrix} \mu_x(\omega) & \mu_\alpha(\omega) & \mu_\beta(\omega) \\ \mu_\alpha(\omega) & \mu_y(\omega) & \mu_\gamma(\omega) \\ \mu_\beta(\omega) & \mu_\gamma(\omega) & \mu_z(\omega) \end{pmatrix} \end{bmatrix}$$

COMPLEX MEDIA

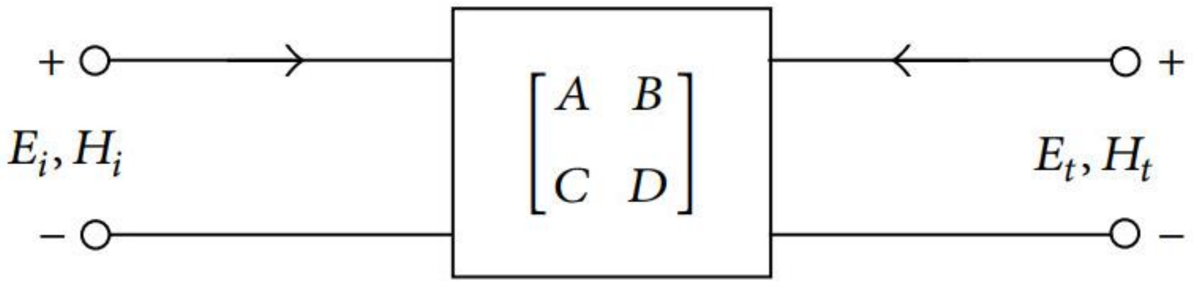


REFLECTION


Z
electromagnetic wave di
X


Incident plane
E_i
H_i
θ_i
l
x
h
ε_r
y
GND

TRANSFORM MATRIX



$$T = \begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \dfrac{Z_2 e^{\gamma_2 d} - Z_1 e^{\gamma_1 d}}{Z_2 - Z_1} & -Z_1 Z_2 \dfrac{e^{\gamma_2 d} - e^{\gamma_1 d}}{Z_2 - Z_1} \\ -\dfrac{e^{\gamma_2 d} - e^{\gamma_1 d}}{Z_1 - Z_2} & \dfrac{Z_1 e^{\gamma_2 d} - Z_2 e^{\gamma_1 d}}{Z_1 - Z_2} \end{pmatrix}$$

$$Z_{1,2} = -\frac{E_{\perp}}{H_{\angle}} = \frac{E_{\angle}}{H_{\perp}}$$

$$\det\left[\underline{\underline{L}}(jk) + j\omega \underline{\underline{K}}_{EH}(\omega) \right] = 0$$

REFLECTION

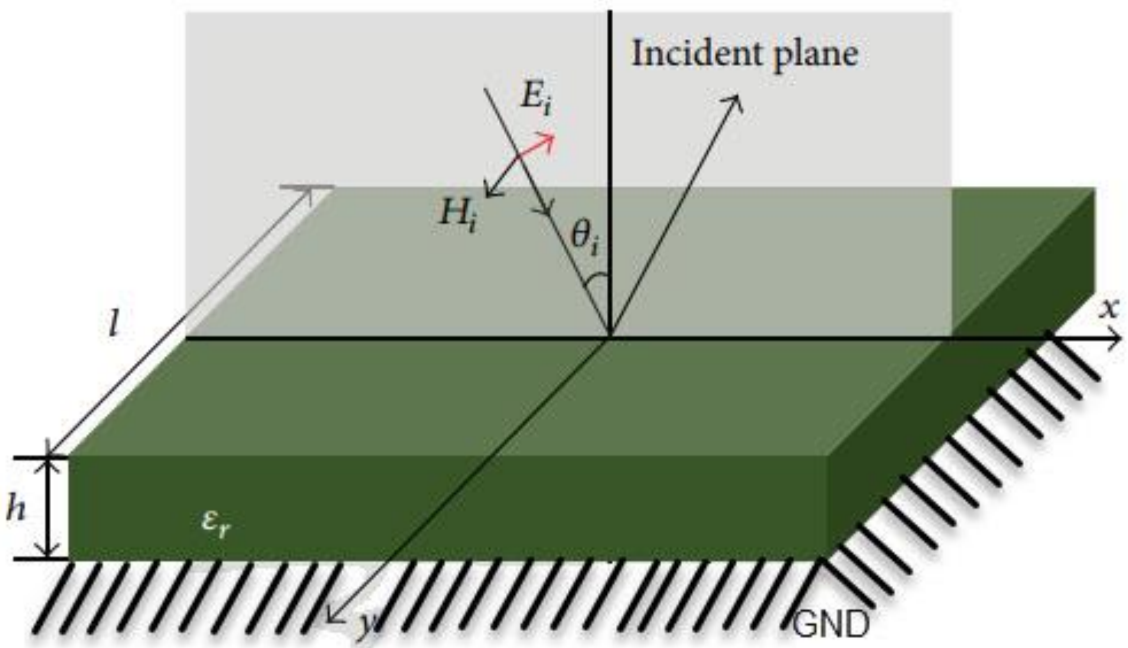
$$\Gamma = s_{11} - \frac{s_{12}s_{21}\Gamma_L}{1+s_{22}\Gamma_L} = \frac{\left(-D^2+\left(A-CZ_0\right)D-2AD+2BC\right)Z_0^2+B\left(A-CZ_0\right)Z_0+B^2}{\left(\left(A+D+CZ_0\right)Z_0+B\right)\left(DZ_0+B\right)}$$

$$Z_{0TE} = \eta_0 \frac{k_0}{\sqrt{k_0-k_x^2}},$$

$$Z_{0TM} = -\eta_0 \frac{\sqrt{k_0-k_x^2}}{k_0},$$

$$k_x = k_0 \sin(\theta_i)$$

$$\Gamma_L = -1$$



ROADMAP

STAGE 01

$$k$$

STAGE 02

$$Z_{1,2}$$

STAGE 03

$$T = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

STAGE 04

$$\Gamma = s_{11} - \frac{s_{12}s_{21}}{1+s_{22}}$$

$$Q.E.D$$

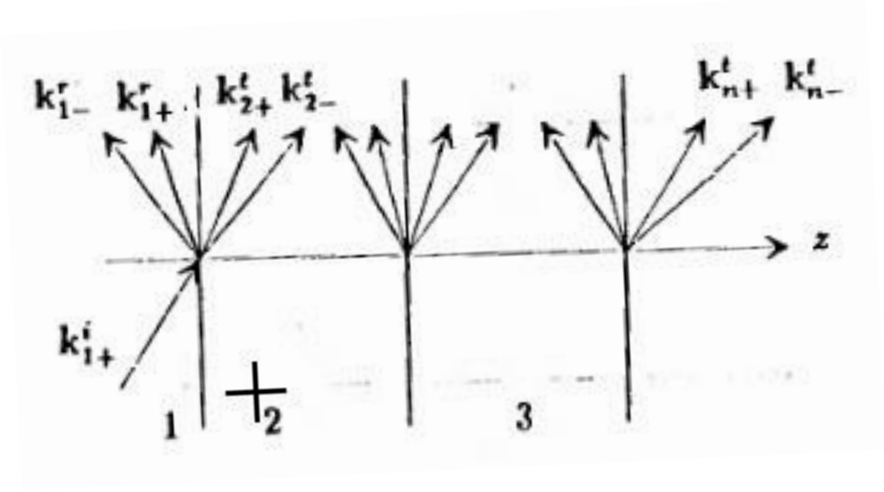
BLOCH IMPEDANCE

$$Z_{TM1} = \frac{E_{1\angle}}{H_{1\perp}} = \frac{E_x}{H_y} = \frac{-(k_x + \omega\zeta_{23})(+k_z - \omega\xi_{12}) - \omega^2\mu_{22}\varepsilon_{13}}{(k_x + \omega\zeta_{23})(-\omega\varepsilon_{11}) - (\omega\varepsilon_{13})(k_z - \omega\zeta_{21})}$$

$$Z_{TE1} = -\frac{E_{1\perp}}{H_{1\angle}} = -\frac{E_y}{H_x} = -\frac{(k_x - \omega\xi_{23})(\omega\mu_{11}) + (\omega\mu_{13})(k_z + \omega\xi_{21})}{(k_x - \omega\xi_{23})(+k_z + \omega\zeta_{12}) + \omega^2\varepsilon_{22}\mu_{13}}$$

OTHER METHOD

$$Z_{in\pm} = \eta_2 \frac{\eta_{3\pm}\cos(\vartheta_2 \mp k_2 L\cos(\vartheta_2) + j\eta_2 \sin(k_2 L\cos(\vartheta_2))}{\eta_2 \cos(\vartheta_2 \pm k_2 L\cos(\vartheta_2) + j\eta_{3\pm} \sin(k_2 L\cos(\vartheta_2))}$$



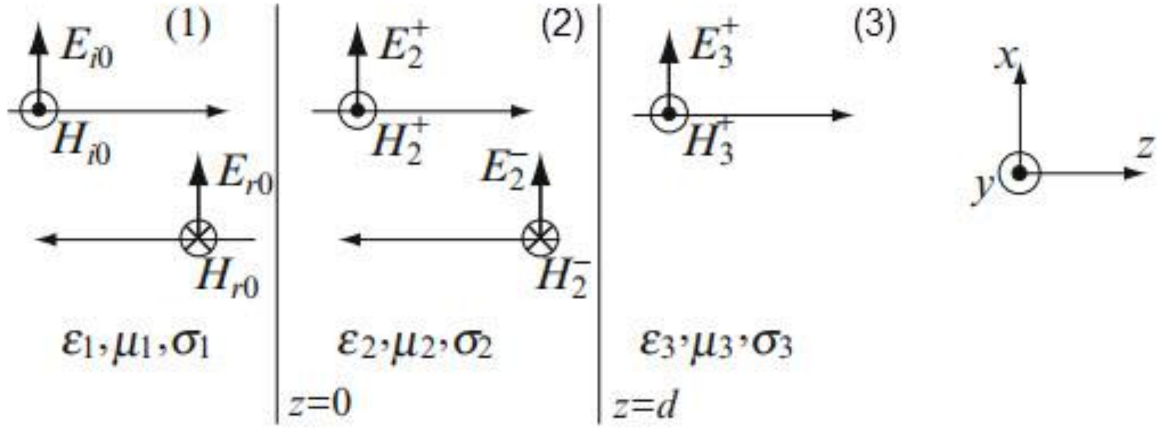
$$R_{\mp\pm} = \eta_2 \frac{Z_{in\pm} - \eta_{1\pm}}{Z_{in\pm} + \eta_{1\mp}} e^{\pm 2j\vartheta}, \Gamma = \left| R_{\mp\pm} \right|$$

$$R_{co} = \eta_2 \frac{Z_{in+}Z_{in-}\cos(2\vartheta_1) - \eta_1^2 + j\eta_1(Z_{in+} - Z_{in-})\sin(\vartheta_1)}{Z_{in+}Z_{in-} + \eta_1^2 + \eta_{1+}Z_{in+} - \eta_{1-}Z_{in-}}$$

$$R_{cross} = -\frac{jZ_{in+}Z_{in-}\sin(2\vartheta_1) + j\eta_1(Z_{in+} - Z_{in-})\cos(\vartheta_1)}{Z_{in+}Z_{in-} + \eta_1^2 + \eta_{1+}Z_{in+} + \eta_{1-}Z_{in-}}$$

OTHER METHOD

$$\begin{bmatrix} -1 & 1 & 1 & 0 \\ \frac{1}{\eta_1} & \frac{1}{\eta_2} & -\frac{1}{\eta_2} & 0 \\ 0 & e^{-\gamma_2 d} & e^{+\gamma_2 d} & -e^{-\gamma_3 d} \\ 0 & \frac{e^{-\gamma_2 d}}{\eta_2} & \frac{e^{+\gamma_2 d}}{\eta_2} & -\frac{e^{-\gamma_3 d}}{\eta_3} \end{bmatrix} \begin{bmatrix} E_{ro} \\ E_2^+ \\ E_2^- \\ E_3^+ \end{bmatrix} = \begin{bmatrix} E_{io} \\ \frac{E_{io}}{\eta_1} \\ 0 \\ 0 \end{bmatrix}$$

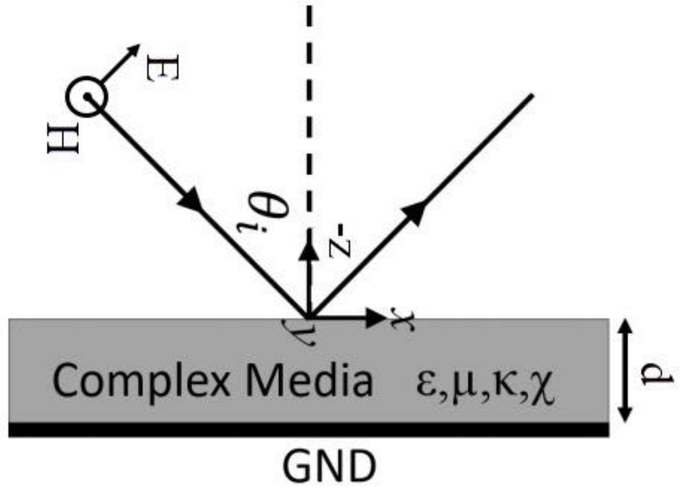


$$\Gamma_{slab} = \frac{E_{ro}}{E_{io}} = \frac{\Gamma_{12} + \Gamma_{23} e^{-2\gamma_2 d}}{1 + \Gamma_{12} \cdot \Gamma_{23} e^{-2\gamma_2 d}}$$

$$\Gamma_{ij} = \frac{\eta_j - \eta_i}{\eta_j + \eta_i}$$

OTHER METHOD

$$\begin{bmatrix} -1 & 1 & 1 & 0 \\ \dfrac{\cos(\theta_i)}{\eta_1} & \dfrac{\cos(\theta_j)}{\eta_2} & -\dfrac{\cos(\theta_j)}{\eta_2} & 0 \\ 0 & e^{-\gamma_2 d\cos(\theta_j)} & e^{+\gamma_2 d\cos(\theta_j)} & -e^{-\gamma_3 d\cos(\theta_k)} \\ 0 & \dfrac{\cos(\theta_j)}{\eta_2} e^{+\gamma_2 d\cos(\theta_j)} & -\dfrac{\cos(\theta_j)}{\eta_2} e^{+\gamma_2 d\cos(\theta_j)} & \dfrac{\cos(\theta_k)}{\eta_3} e^{-\gamma_3 d\cos(\theta_k)} \end{bmatrix} \begin{bmatrix} E_{ro} \\ E_2^+ \\ E_2^- \\ E_3^+ \end{bmatrix} = \begin{bmatrix} E_{io} \\ \dfrac{\cos(\theta_i)}{\eta_1} E_{io} \\ 0 \\ 0 \end{bmatrix}$$

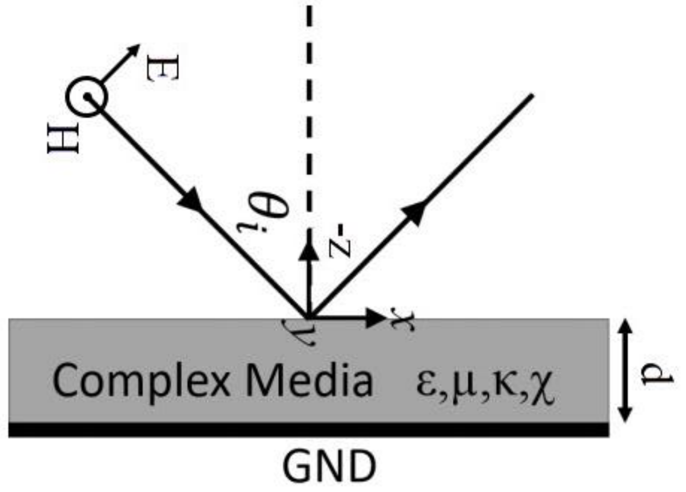


- $$\Gamma_{TE,slab} = \frac{E_{ro}}{E_{io}} = \frac{\Gamma_{12} + \Gamma_{23} e^{-2\gamma_2 d}}{1 + \Gamma_{12} \cdot \Gamma_{23} e^{-2\gamma_2 d}}$$

$$\eta_{l,TE} = \frac{\eta_l}{\cos(\theta_s)}, d' = d\cos(\theta_j), l = 1, 2, 3, s = i, j, k$$

OTHER METHOD

$$\begin{bmatrix} \cos(\theta_i) & \cos(\theta_j) & \cos(\theta_j) & 0 \\ \frac{-1}{\eta_1} & \frac{1}{\eta_2} & \frac{1}{\eta_2} & 0 \\ 0 & \cos(\theta_j)e^{-\gamma_2 d\cos(\theta_j)} & -\cos(\theta_j)e^{+\gamma_2 d\cos(\theta_j)} & -\cos(\theta_k)e^{-\gamma_3 d\cos(\theta_k)} \\ 0 & \frac{e^{+\gamma_2 d\cos(\theta_j)}}{\eta_2} & \frac{e^{+\gamma_2 d\cos(\theta_i)}}{\eta_2} & \frac{e^{-\gamma_3 d\cos(\theta_k)}}{\eta_3} \end{bmatrix} \begin{bmatrix} E_{ro} \\ E_2^+ \\ E_2^- \\ E_3^+ \end{bmatrix} = \begin{bmatrix} E_{io}\cos(\theta_i) \\ \frac{E_{io}}{\eta_1} \\ 0 \\ 0 \end{bmatrix}$$



- $$\Gamma_{TM,slab} = -\frac{E_{ro}}{E_{io}} = \frac{\Gamma_{12} + \Gamma_{23}e^{-2\gamma_2 d}}{1+\Gamma_{12}\cdot\Gamma_{23}e^{-2\gamma_2 d}}$$ $\eta_{l,TM} = \eta_l \cos(\theta_s), d' = d\cos(\theta_j), l = 1,2,3, s = i,j,k$

NORMAL INCIDENT

$$d = 10mm$$

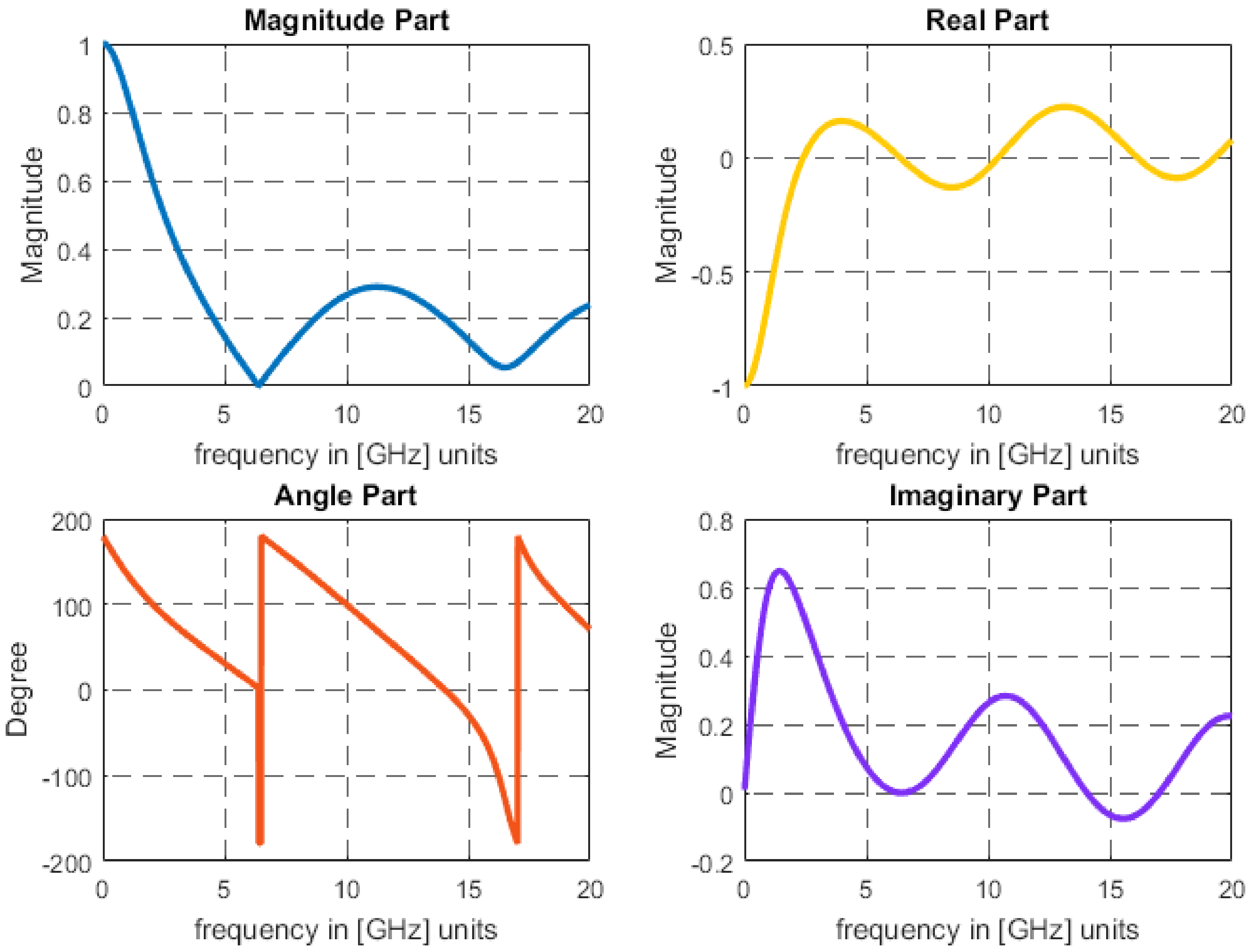
$$1 < \varepsilon_r < 3 \rightarrow \varepsilon_r = 1.42$$

$$1 < \mu_r < 5 \rightarrow \mu_r = 1.97$$

$$0.2 < \sigma[\frac{s}{m}] < 0.5 \rightarrow \sigma = 0.42[\frac{s}{m}]$$

$$\Gamma = 7.4884 \times 10^{-7}$$

$$f = 6.497[GHz]$$



NORMAL INCIDENT

$$d = 10mm$$

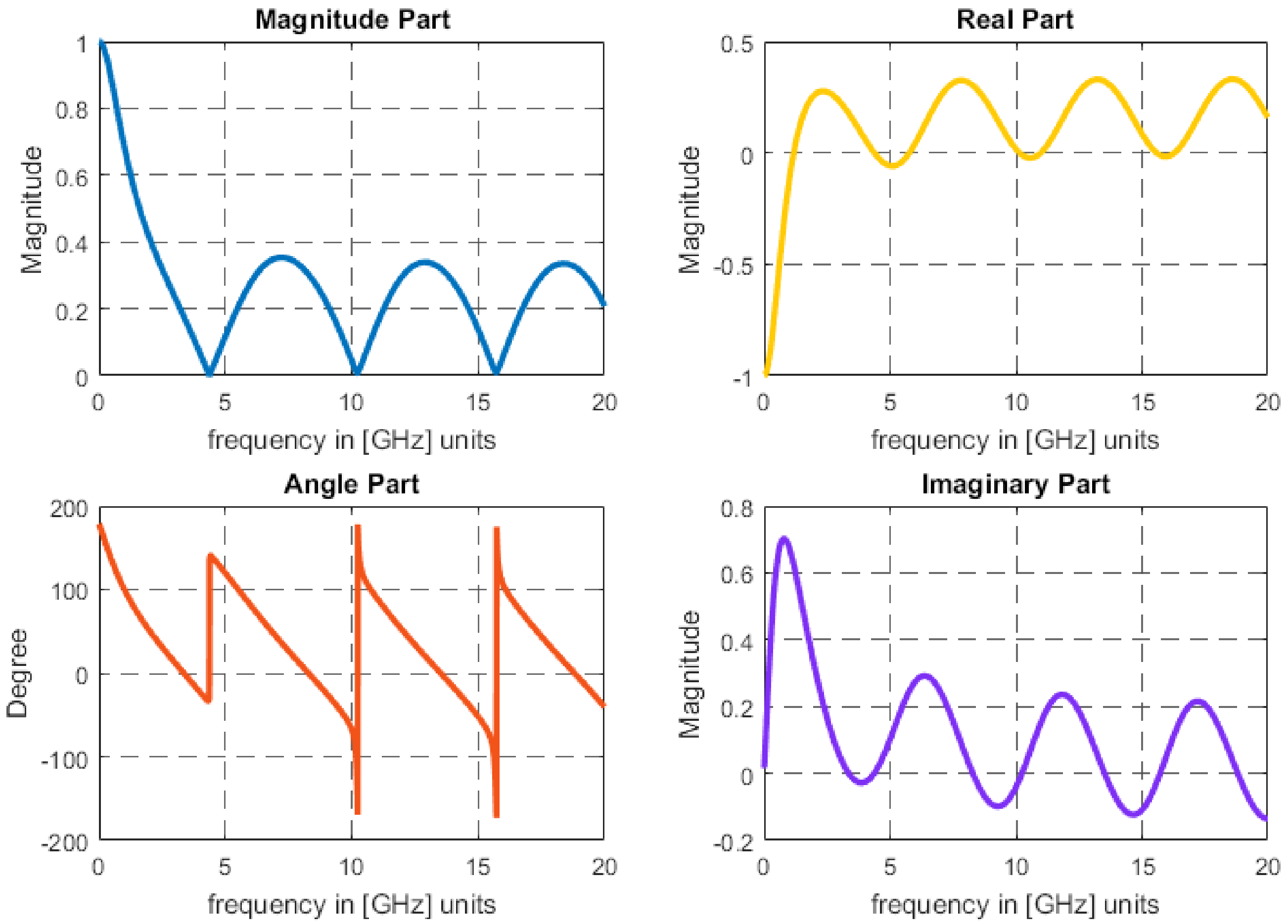
$$\varepsilon_r = 2.010$$

$$\mu_r = 3.924$$

$$\sigma = 0.33[\frac{s}{m}]$$

$$\Gamma = 2.0172 \times 10^{-6}$$

$$f = 4.331[GHz]$$



RUN TIME

Profile Summary (Total time: 3227.789 s)

Generated 27-Feb-2021 23:02:16 using performance time.

Function Name	Calls	Total Time (s)	Self Time* (s)	Total Time Plot (dark band = self time)
iteration	1	3227.789	5.802	
iteration>Mininmize	2498631	3221.987	1459.402	
iteration>Mininmize/Coefficient	2498631	949.229	949.229	
iteration>Mininmize/Eta	4997262	407.941	407.941	
iteration>Mininmize/Constant	2498631	291.960	291.960	
iteration>Mininmize/Gamma	2498631	113.454	113.454	

***Self time** is the time spent in a function excluding any time spent in child functions. The time includes any overhead time resulting from the profiling process.

Start Profiling Run this code:

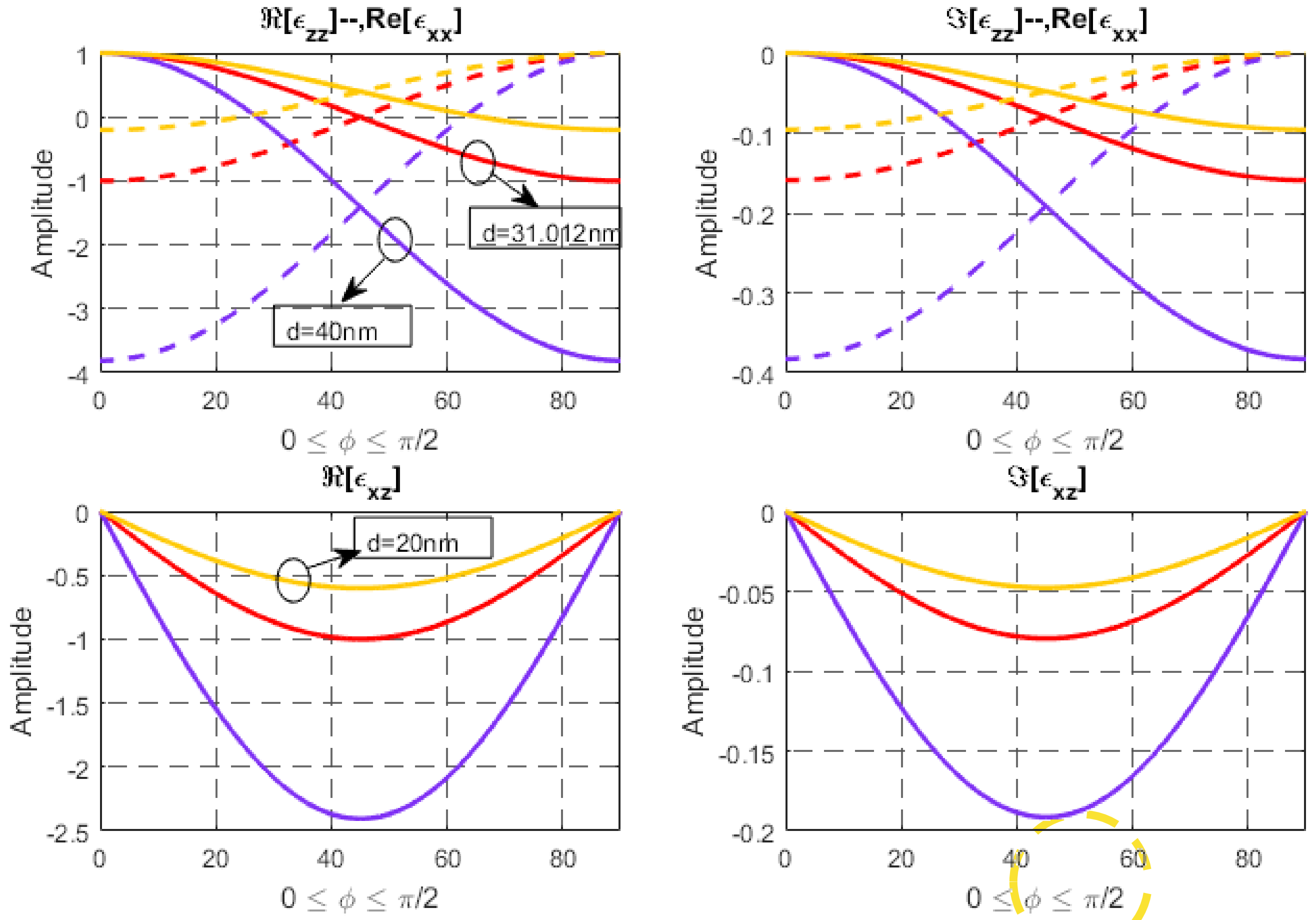
Profile Summary

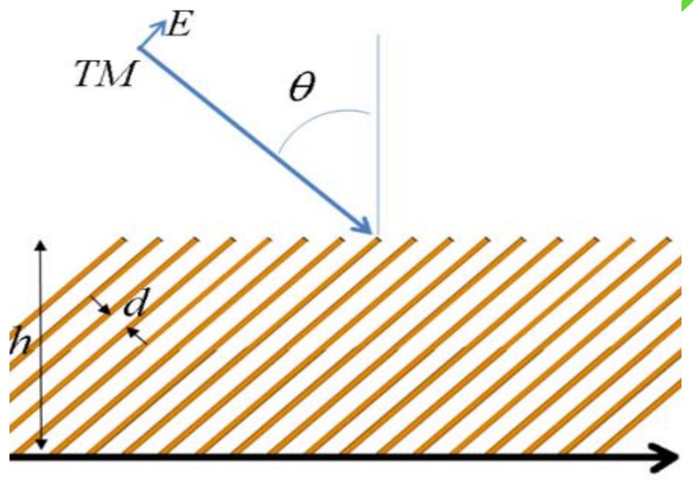
Generated 20-Oct-2020 18:59:09 using performance time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
iteration	1	12226.921 s	94.610 s	
iteration>Mininmize	21715539	12152.564 s	3337.686 s	
iteration>Mininmize/Coefficient	21715539	3772.695 s	3772.695 s	
iteration>Mininmize/Eta	43431078	2485.976 s	2485.976 s	
iteration>Mininmize/Constant	21715539	1835.795 s	1835.795 s	
iteration>Mininmize/Gamma	21715539	720.412 s	720.412 s	

Self time is the time spent in a function excluding the time spent in its child functions. Self time also includes overhead resulting from the process of profiling.

ARTICLE





Article: S. M. Hashemi and I. S. Nefedov

$$d = 31.012nm$$

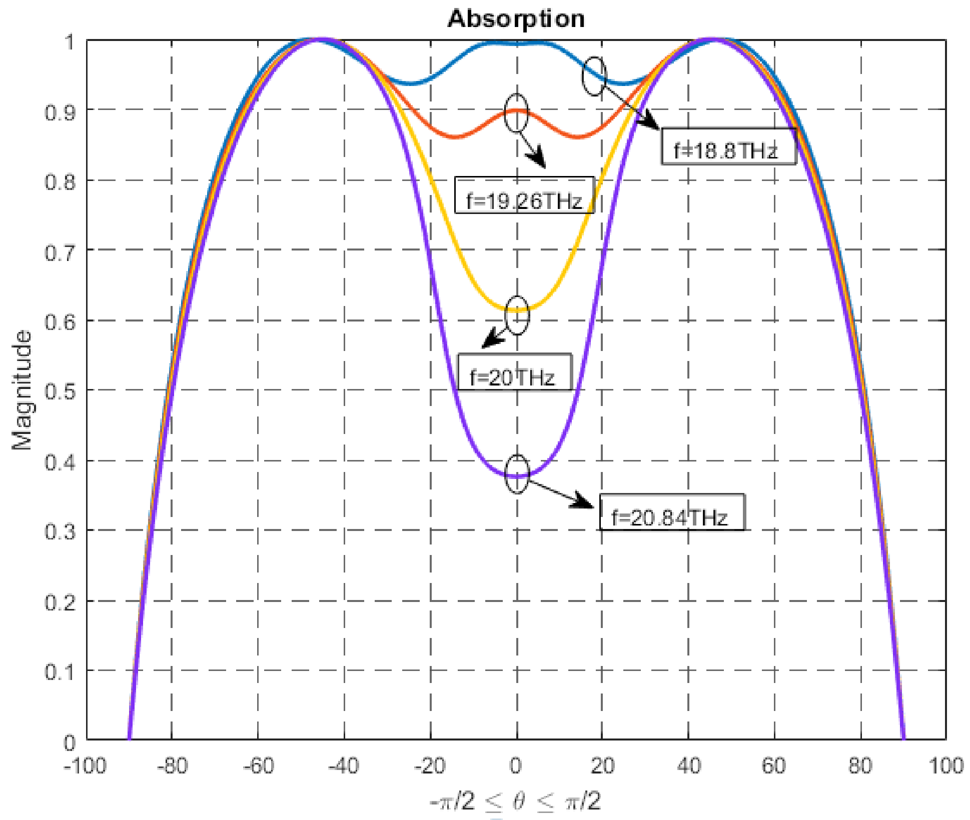
$$h = 0.1\lambda_0$$

$$\theta = 45^\circ$$

$$\varphi = 45^\circ$$

COMPARISON

SIMULATION



ARTICLE

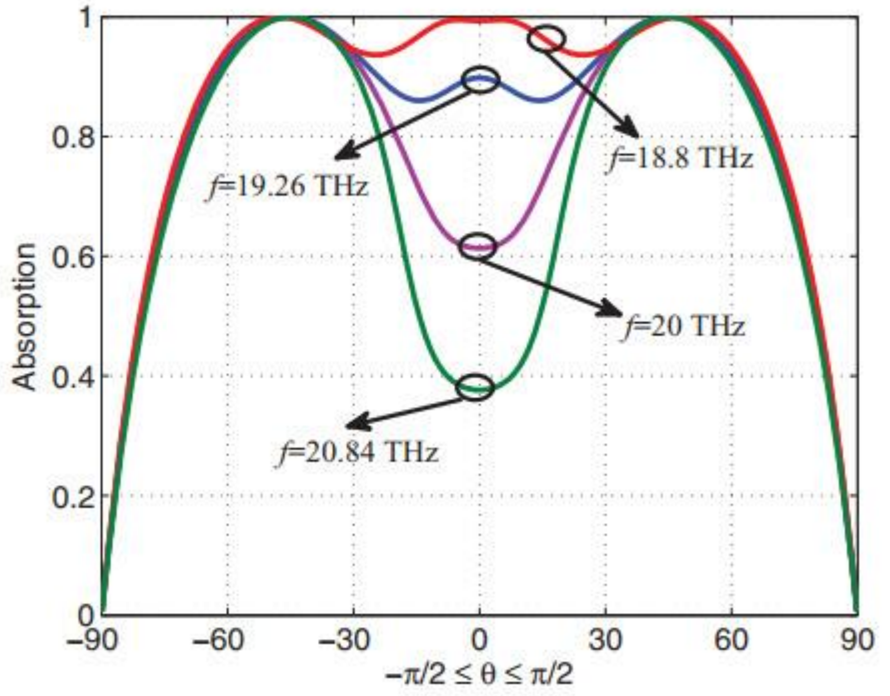
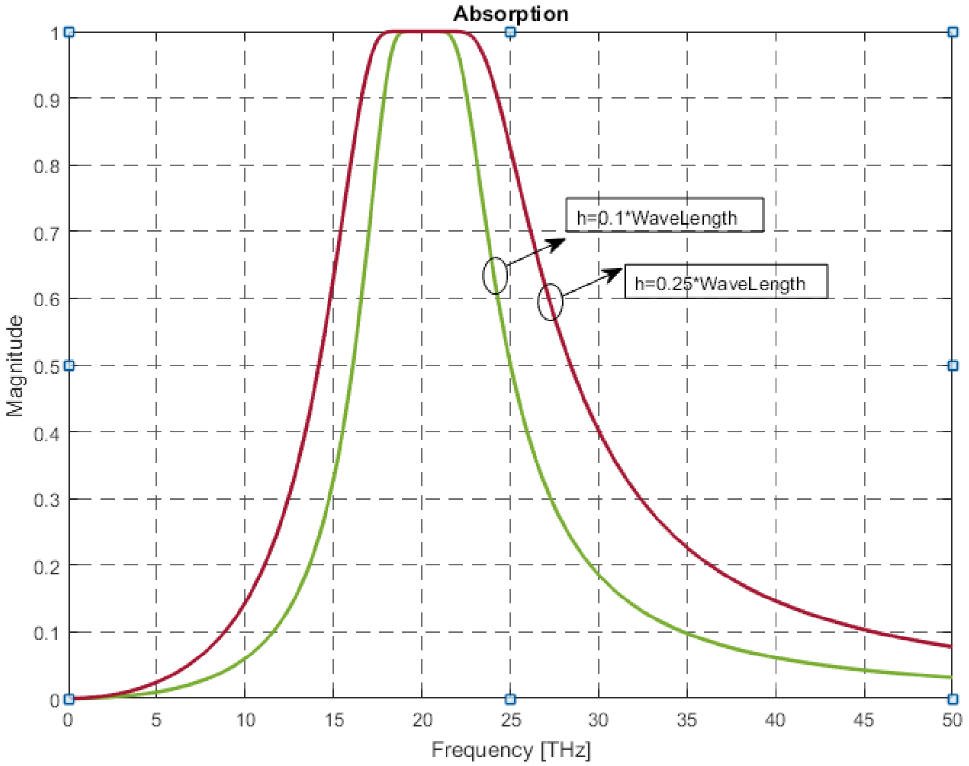


FIG. 9. (Color online) Absorption versus the incidence angle.

COMPARISON

SIMULATION



ARTICLE

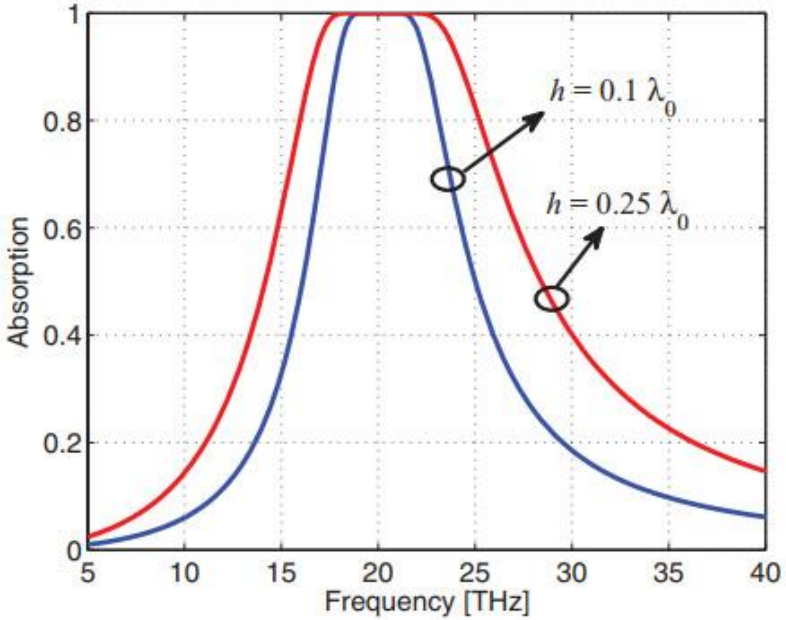
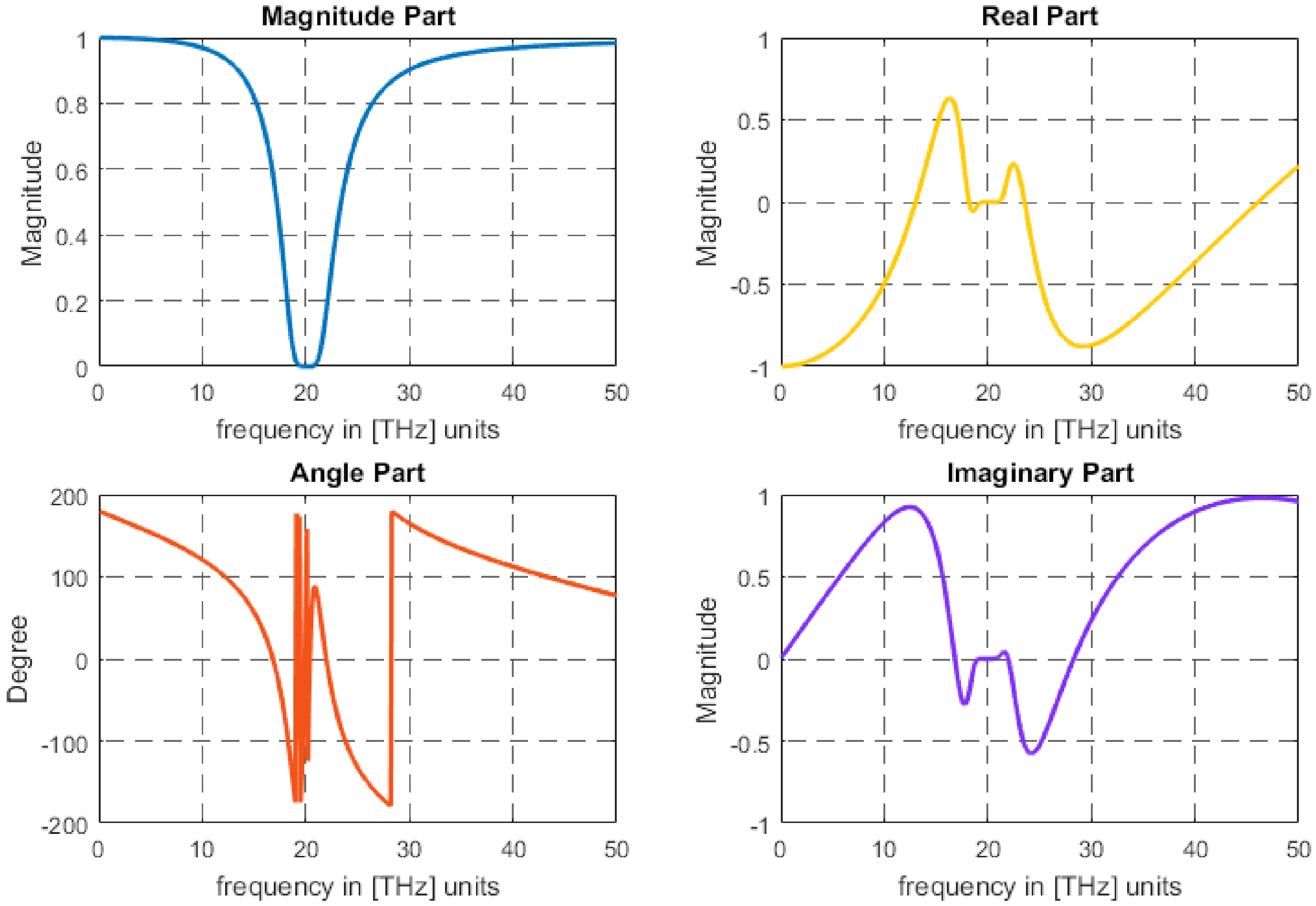


FIG. 8. (Color online) Absorption versus frequency calculated for different thicknesses of the slab. The incidence angle is 45°, the tilt angle is 45°, and λ_0 is the wavelength in free space corresponding to f_0.

COMPARISON


Magnitude Part
Magnitude
frequency in [THz] units
Real Part
Magnitude
frequency in [THz] units
Angle Part
Degree
frequency in [THz] units
Imaginary Part
Magnitude
frequency in [THz] units

APP & FUTURE

- Absorber
- Array Antenna
- Analysis

 …

- Nonhomogeneous
- Nonlinear
- Homogenization

…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