Analysis of Artificial Dielectric Layers with Finite Conductivity

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Analysis of Artificial Dielectric Layers with Finite Conductivity

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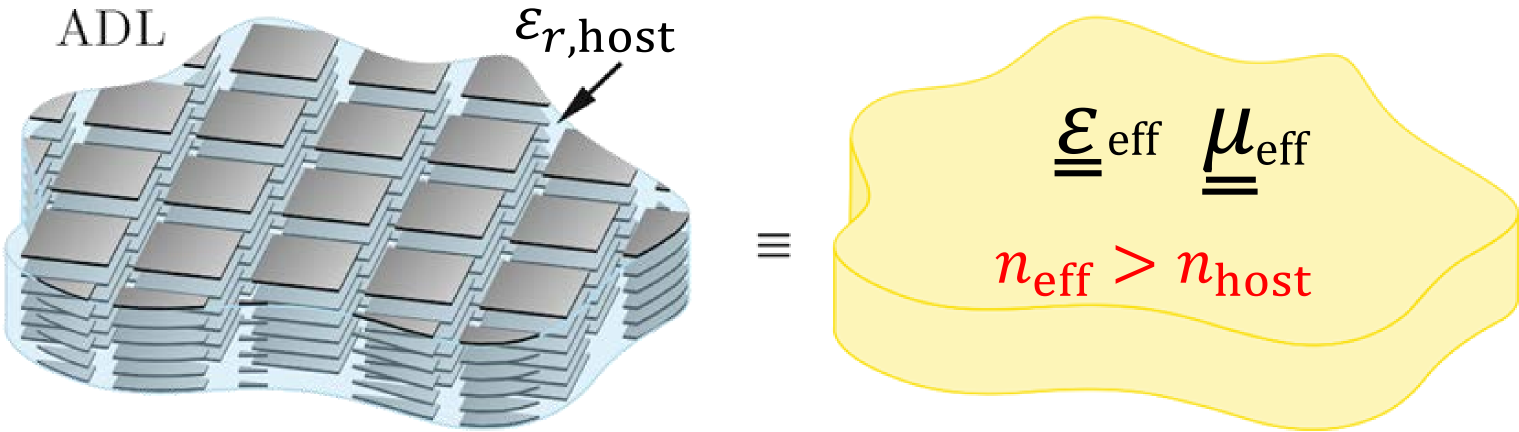
Artificial Dielectric Layers



Sub-wavelength patches

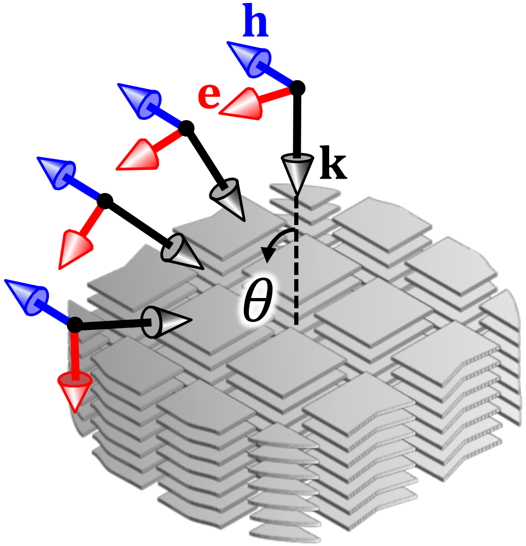
$n_{\text{eff}}(\hat{\mathbf{p}}, \theta)$

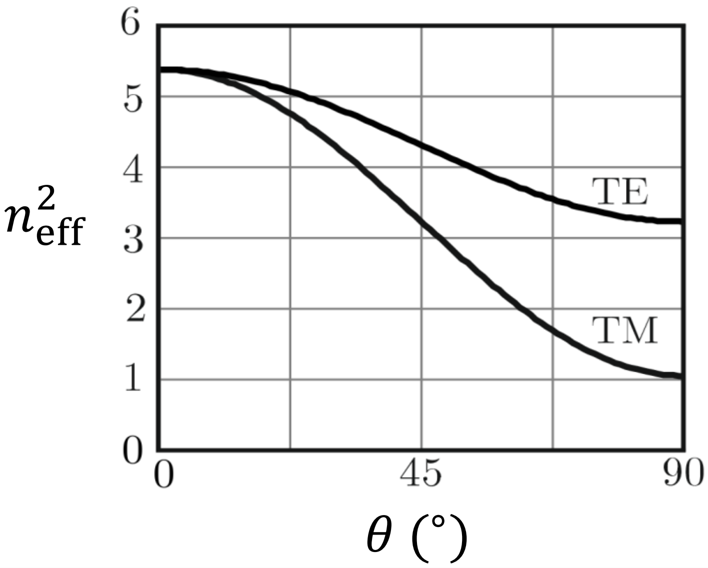
$\hat{\mathbf{p}}$: polarization of the incident plane wave (TE/TM)

θ: angle of incidence

Anisotropy is a key property to avoid surface waves

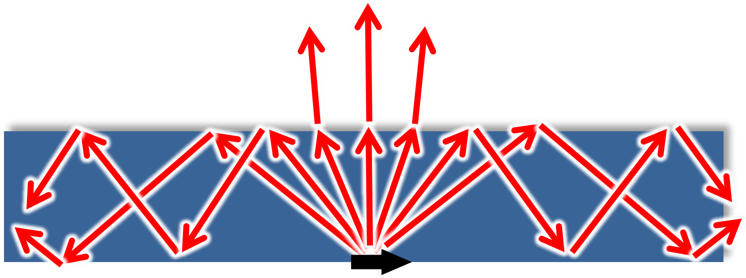
Solution to surface waves





n_{eff} **decreases with angle**

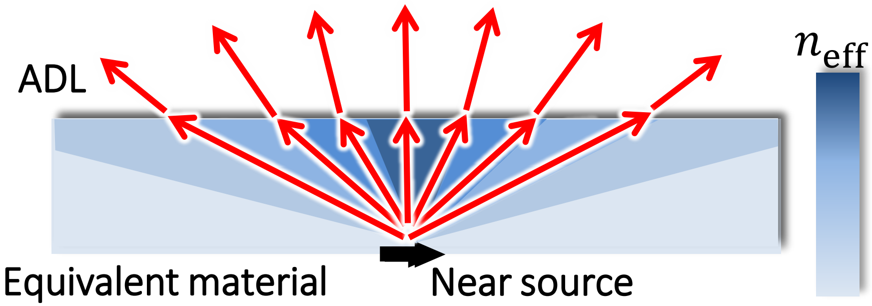
Homogeneous dielectric



☺ High front-to-back ratio

☹ Surface waves

Artificial dielectric

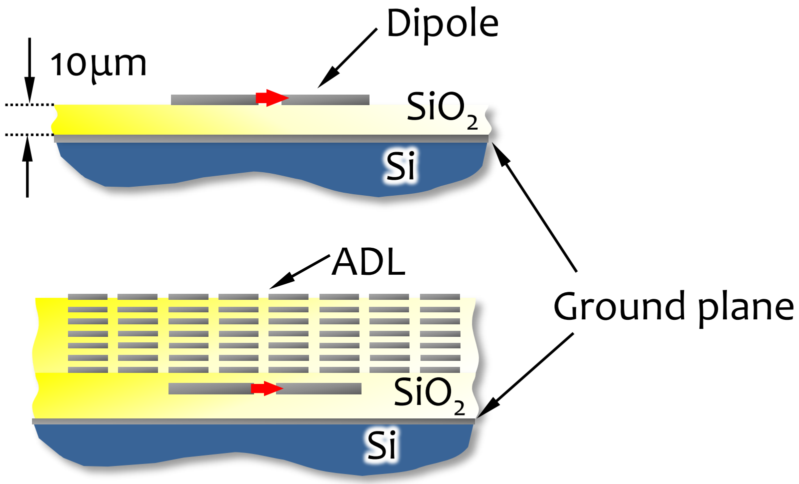


☺ High front-to-back ratio

☺ No surface wave

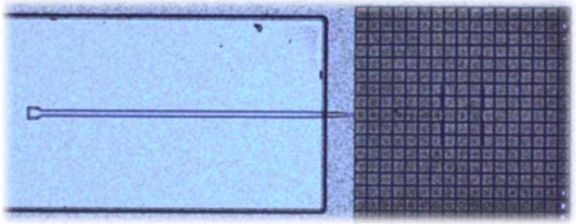
Applications for antennas

Improve efficiency of on-chip antennas

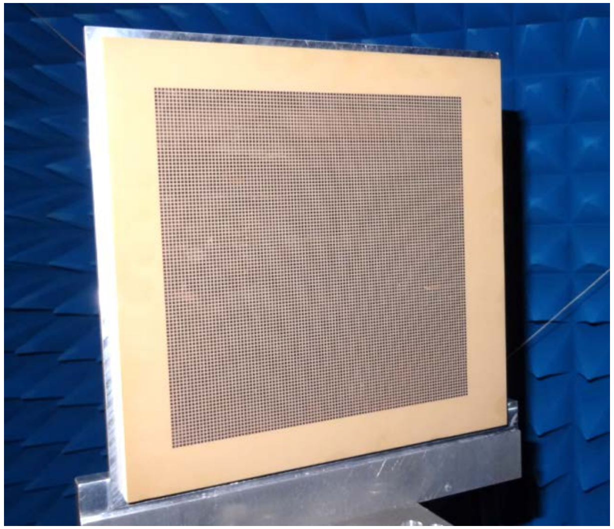


	Dipole alone	With ADL
Input resistance	0.16Ω	10Ω
Bandwidth	1%	10%
Efficiency	36%	87%

300 GHz
prototype



Wide-band wide-scan phased array



6 -15 GHz

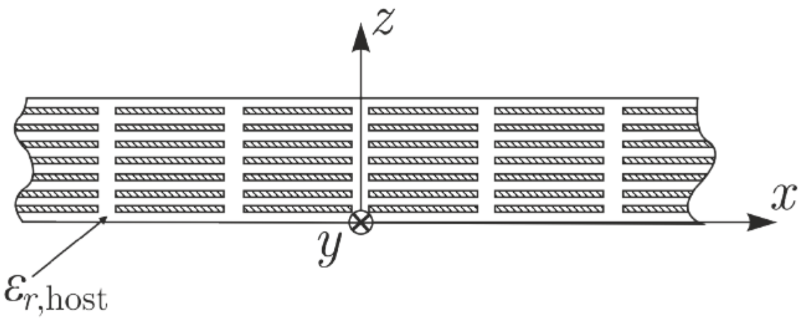
No surface waves

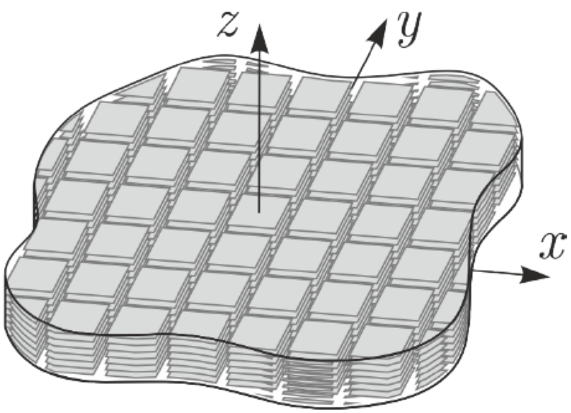
Scan to 60 deg. on H-plane
and 80 deg. on E-plane
with no **scan blindness**

Analysis of ADL

D. Cavallo, W. H. Syed and A. Neto, 'Part-I', *IEEE TAP*, 61-3, 2014
D. Cavallo, W. H. Syed and A. Neto, 'Part-II', *IEEE TAP*, 61-3, 2014

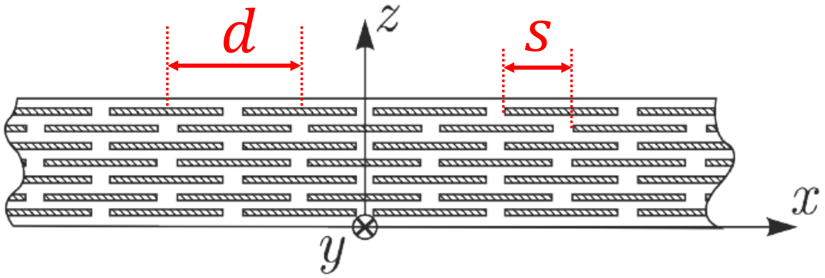
Closed-form expression for **aligned layers**

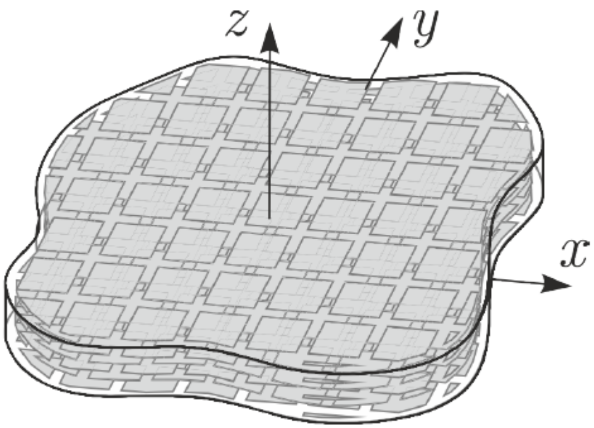




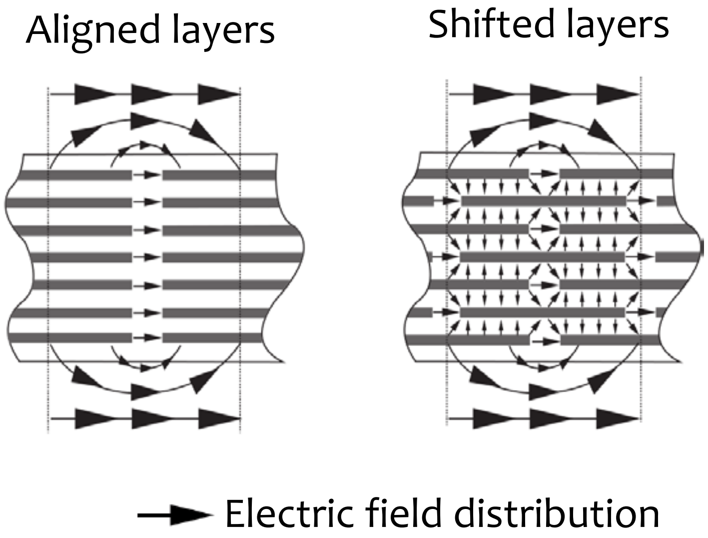
D. Cavallo and C. Felita, *TAP*, 65-10, 2017

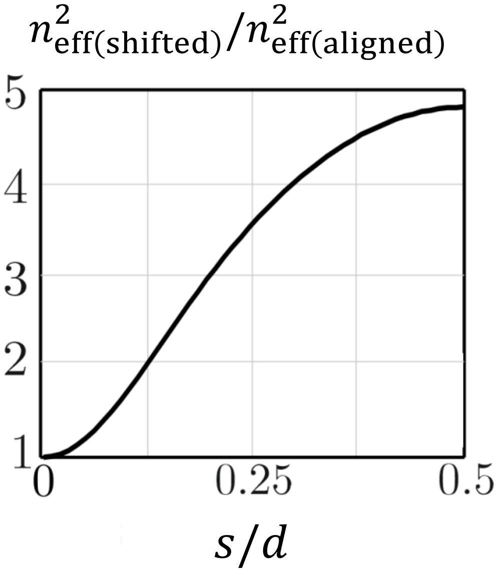
Generalization: **alternatively shifted layers**



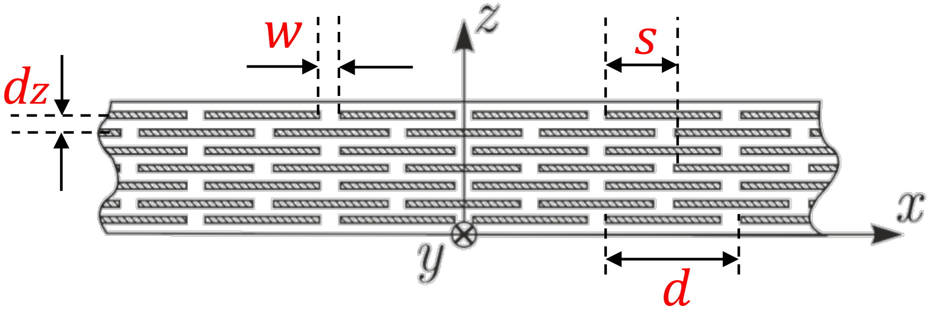


Shift between layers





Much higher equivalent permittivity with shift

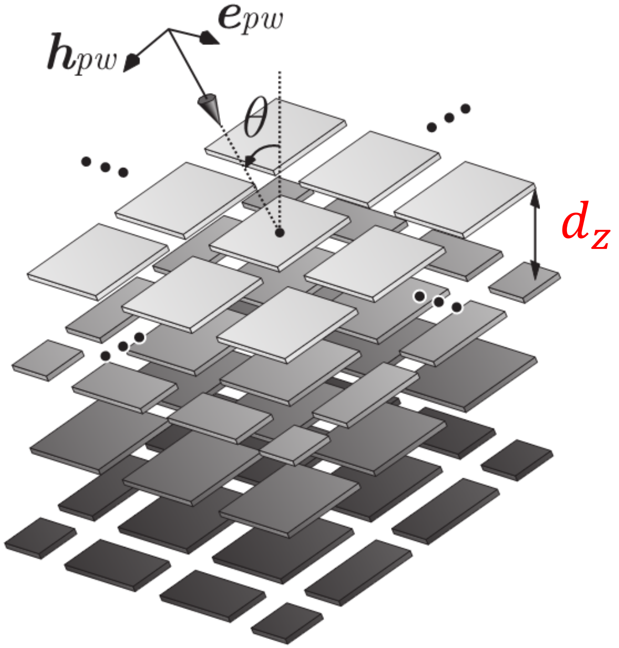


$$n_{\mathrm{eff}} = f(d, w, d_z, s)$$

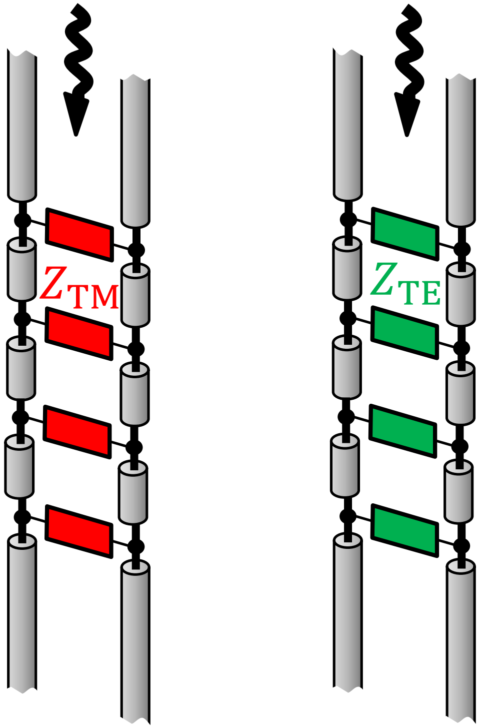
Shift s (key parameter)

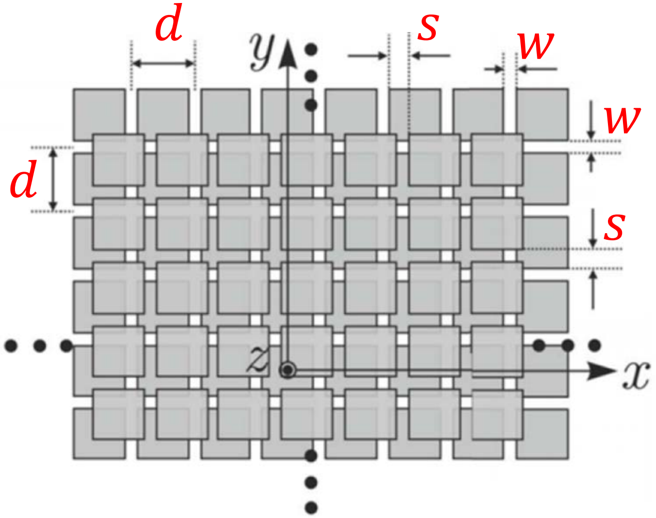
- **More flexible design**
  - Reduced number of layers
  - Reduced overall thickness
- **Extended range of desired permittivity**

Equivalent circuit



TM component **TE component**





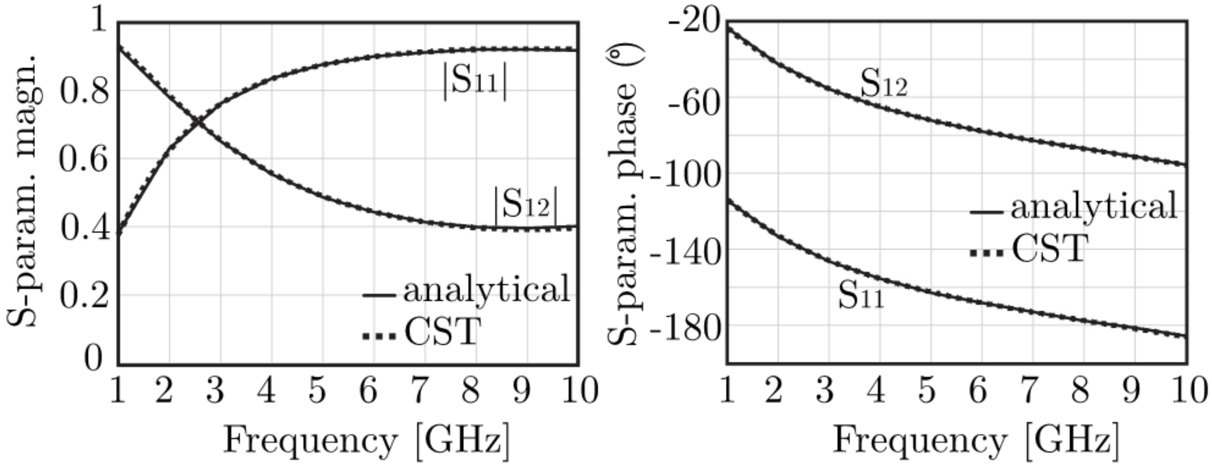
$$Z_{\mathrm{TM}} = -\frac{j}{B_\infty} \qquad Z_{\mathrm{TE}} = -\frac{j}{B_\infty}\frac{1}{1-\frac{\sin^2\theta}{2}}$$

Susceptance B

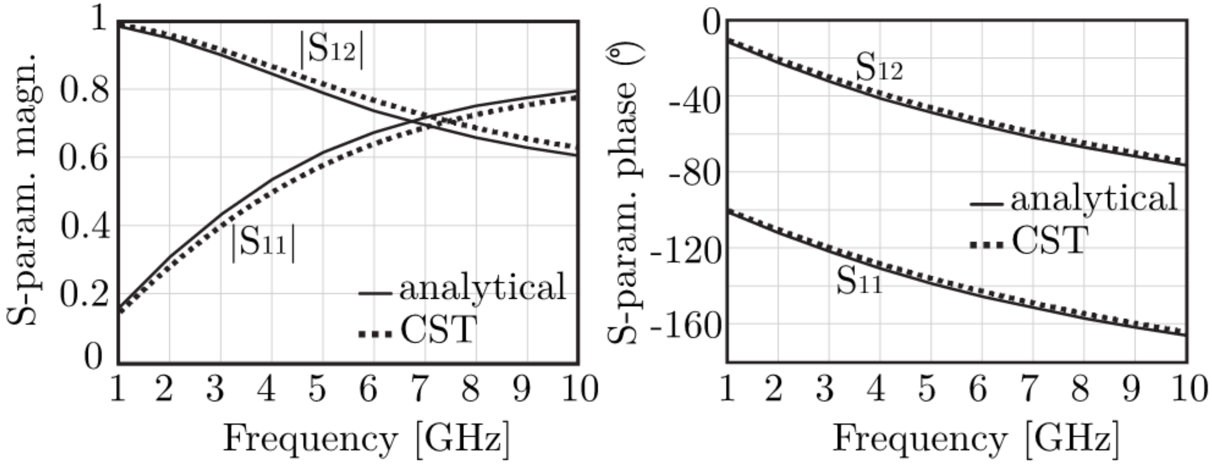
$$B_\infty \approx \underbrace{j\frac{k_0}{\zeta_0}\frac{d}{\pi}\sum_{m\neq 0}\frac{|\mathrm{sinc}(\pi m w/d)|^2}{|m|}}_{\text{Reactance of single layer}}\underbrace{\left(-\cot\left(\frac{-j2\pi|m|d_z}{d}\right)+e^{j2\pi m\, s/d}\csc\left(\frac{-j2\pi|m|d_z}{d}\right)\right)}_{\text{Inter-layer reactive coupling}}$$

Validation formulas

TE incidence, $\theta = 60°$



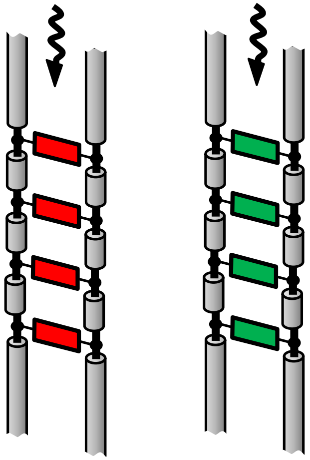
TM incidence, $\theta = 60°$



Plane wave incidence

5 layers

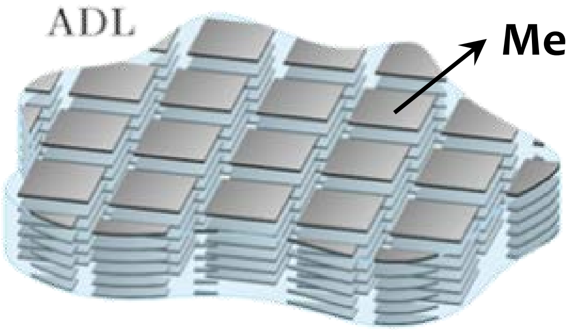
$s_x = s_y = 0.25 d_x$



Equivalent circuit provides S-parameters

- Generic plane wave incidence
- Arbitrary small distance
- Arbitrary number of layers

Ohmic losses in ADLs



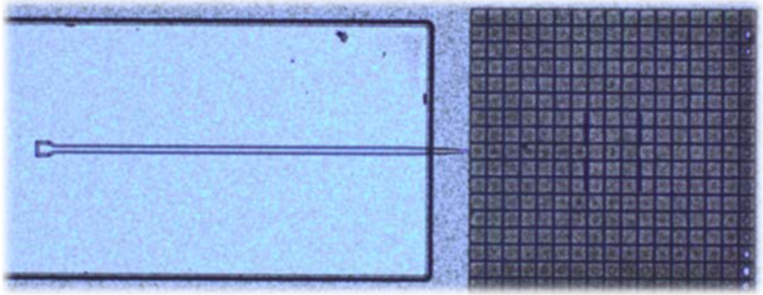
Metal patches (finite conductivity σ)

Most frequent question: **losses?**

Answer: **very low** because the **patches are sub-wavelength**

More quantitative answer: **0.8 dB losses at 300 GHz**

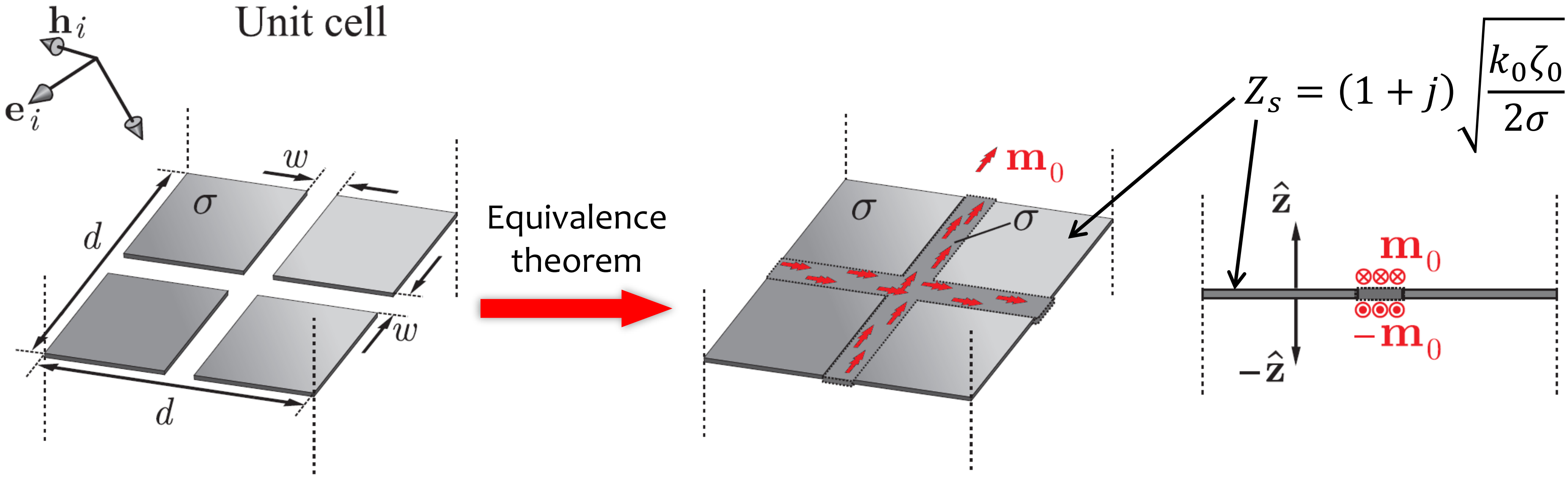
300 GHz prototype



- **However, losses depends on**
  - How the ADL is illuminated
    e.g. **plane wave** or **near source**
  - **Polarization** and **direction** of the incident field

Goal: quantify analytically the losses due to finite conductivity

Generalization to lossy metal

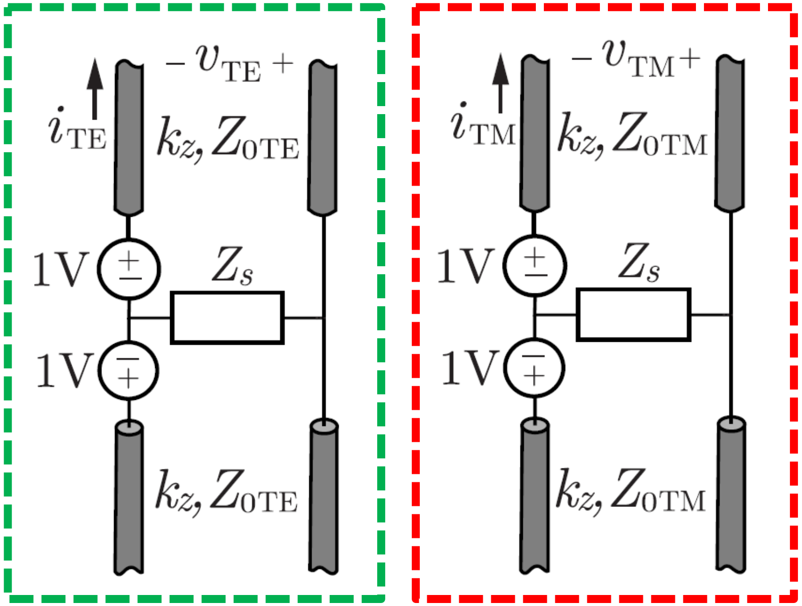


$$Z_s = (1+j)\sqrt{\frac{k_0\zeta_0}{2\sigma}}$$

Integral Equation

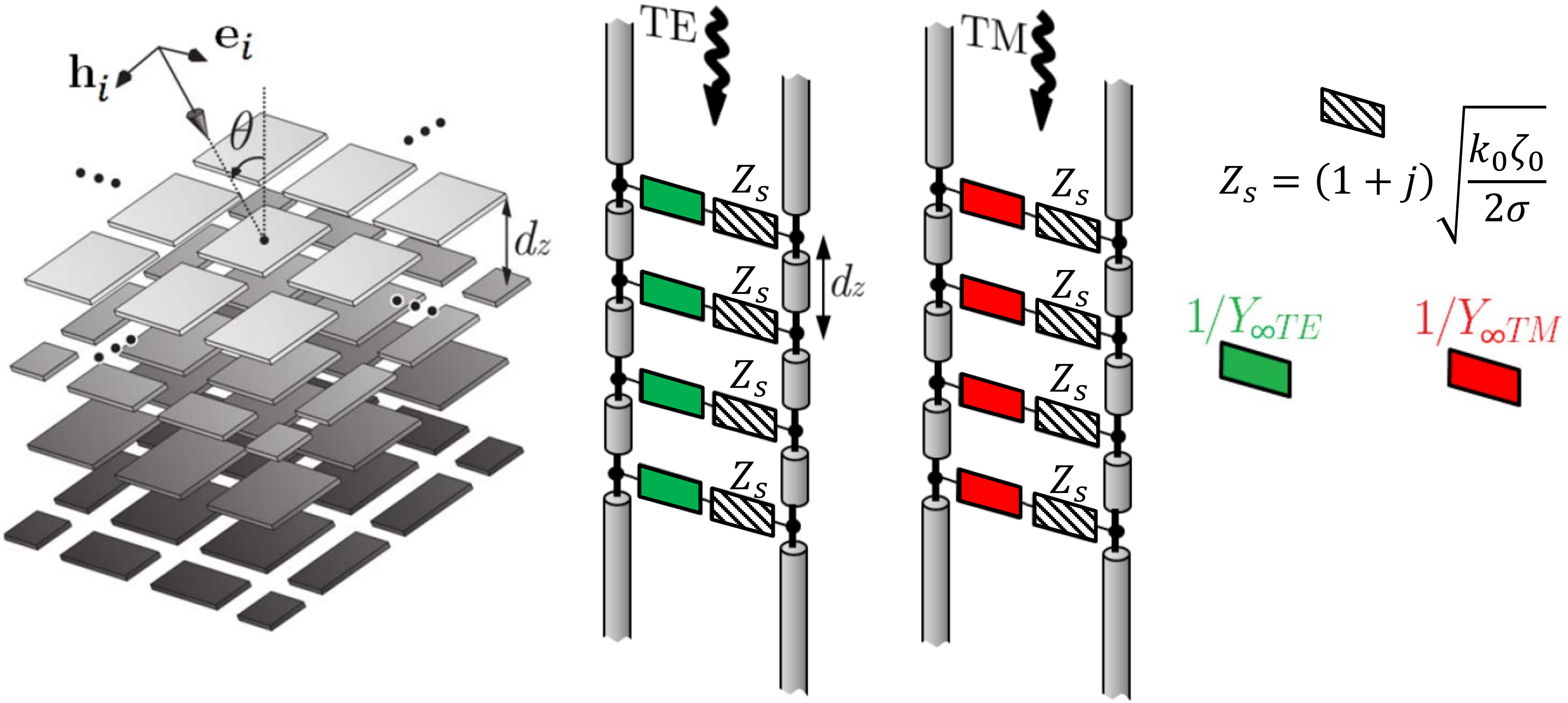
$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} 2\mathbf{m}_0(\boldsymbol{\rho}')\mathbf{g}_{Z_s}(\boldsymbol{\rho}-\boldsymbol{\rho}')d\boldsymbol{\rho}' = -(1+\Gamma)\mathbf{h}_{\mathrm{i}}$$

Equivalent z-transmission lines of the spectral Green's function



M. Albani, A. Mazzinghi and A. Freni, IEEE TAP, 59-11, 2011.

Equivalent circuit for lossy metal



▨ $Z_s = (1+j)\sqrt{\frac{k_0\zeta_0}{2\sigma}}$

🟩 $1/Y_{\infty TE}$

🟥 $1/Y_{\infty TM}$

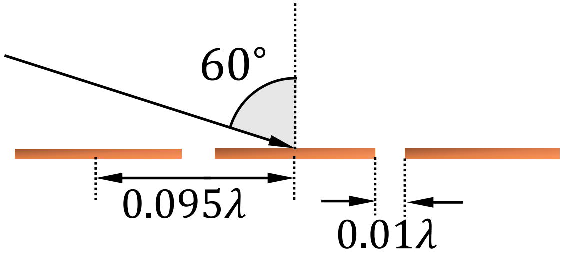
Equivalent layer impedances are in the form

$$Y_{\infty TE} \approx 2\sum_{m_y \neq 0} |\mathrm{sinc}(k_{ym}w/2)|^2 S_\infty \left(\frac{k_{x0}^2}{2k_{ym}^2}\left(\frac{\zeta_0 k_0}{k_{zm}} + 2Z_s S_\infty\right)^{-1} + \left(\frac{\zeta_0 k_{zm}}{k_0} + 2Z_s S_\infty\right)^{-1} \right)$$

$$S_\infty = -j\cot\left(\frac{-j2\pi|m|d_z}{d}\right) + je^{j2\pi m\frac{s}{d}}\csc\left(\frac{-j2\pi|m|d_z}{d}\right)$$

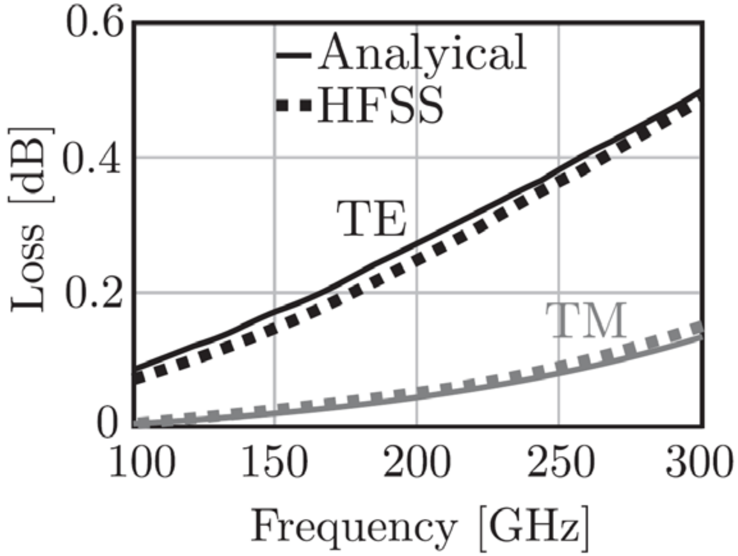
Single layer: losses

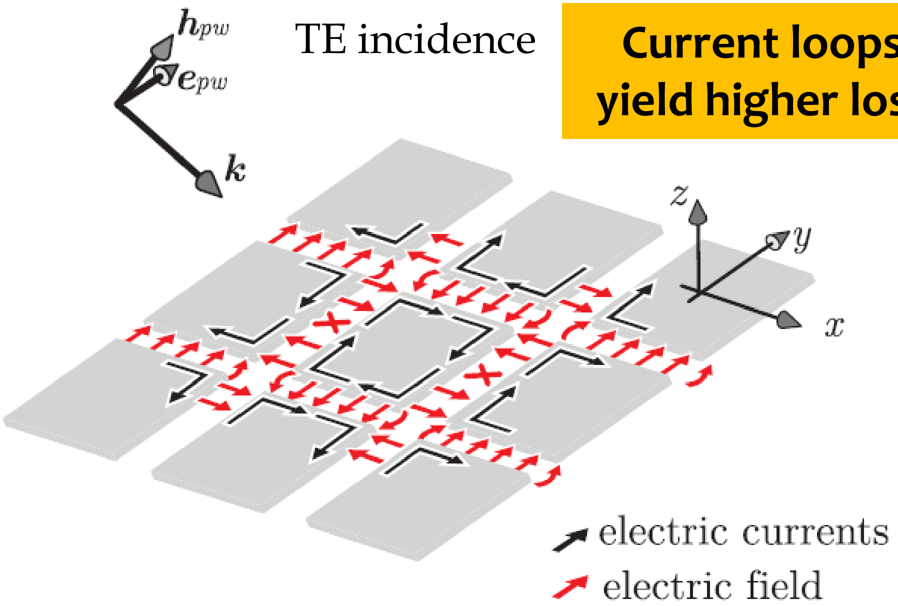
Example



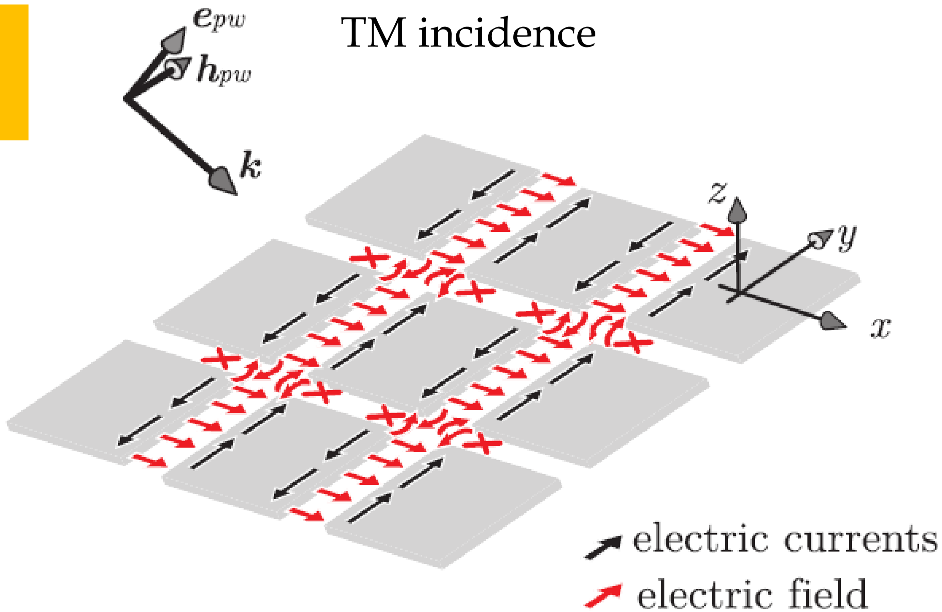
λ@300GHz

$\sigma = 1000 \frac{\mathrm{S}}{\mathrm{m}}$



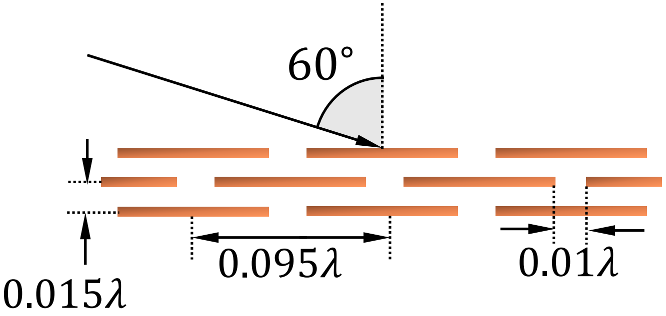

TE incidence

Current loops yield higher loss

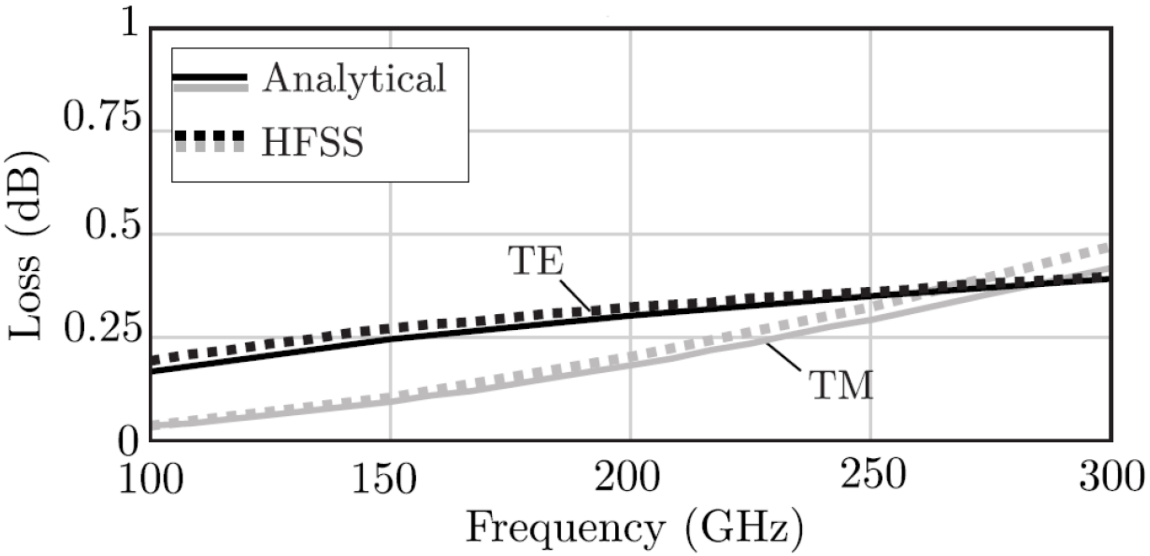

TM incidence

Validation

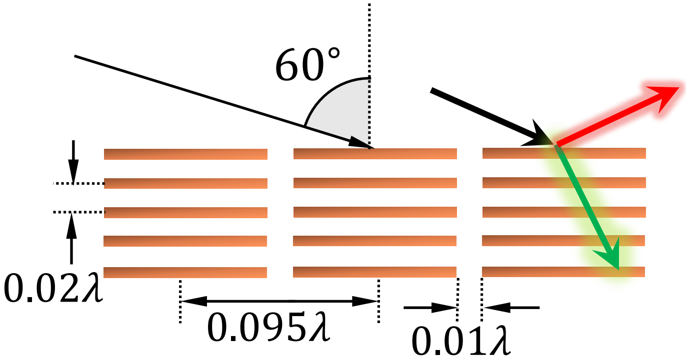
Example 1



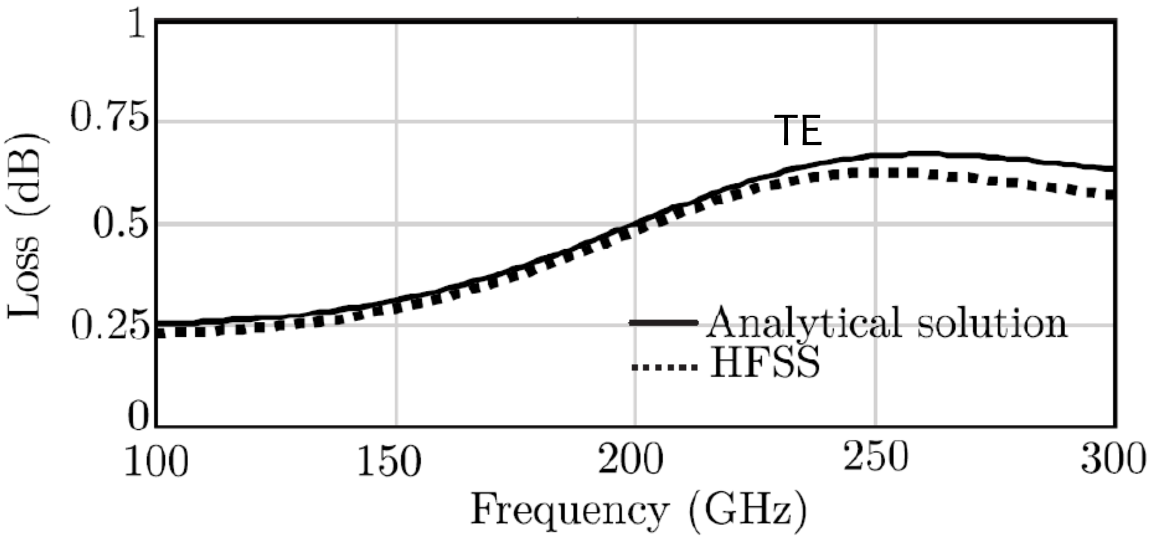
3 layers $\sigma = 1000 \, \frac{\mathrm{S}}{\mathrm{m}}$



Example 2

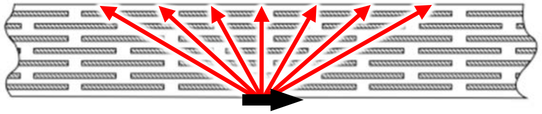


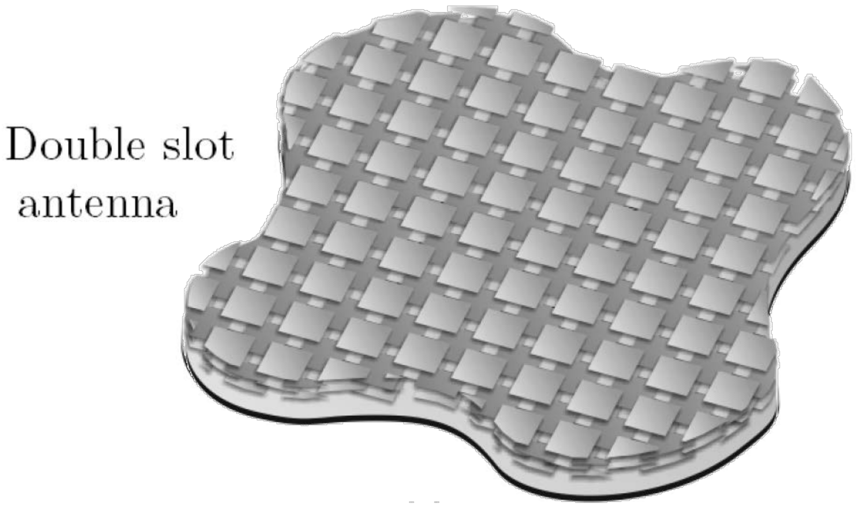
5 layers $\sigma = 10^6 \, \frac{\mathrm{S}}{\mathrm{m}}$



Near source excitation

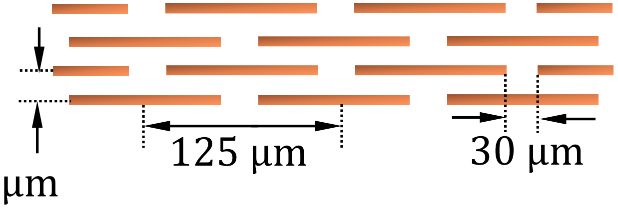
What are the losses for near source illumination?





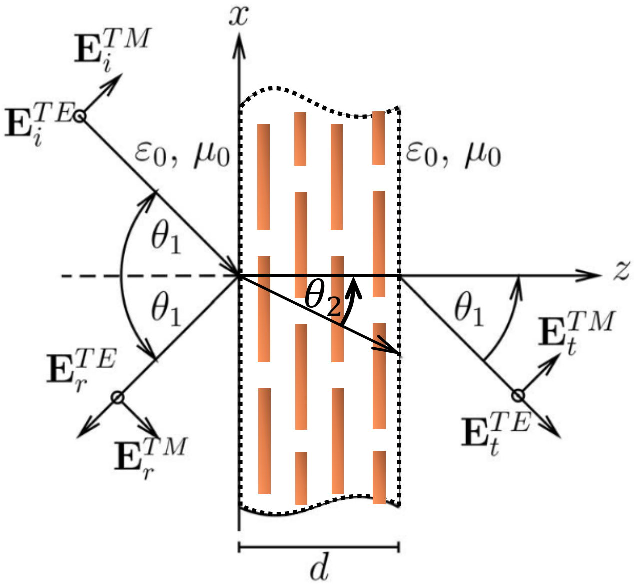
$l_{\text{slot}} = d_{\text{slot}} = 750\mu\text{m}$ $\delta_{\text{slot}} = 100\mu m$
$w_{\text{slot}} = 50\ \mu\text{m}$ $h = 50\mu\text{m}$

4 layers $\sigma = 10^7 \frac{\text{S}}{\text{m}}$



Effective constitutive parameters

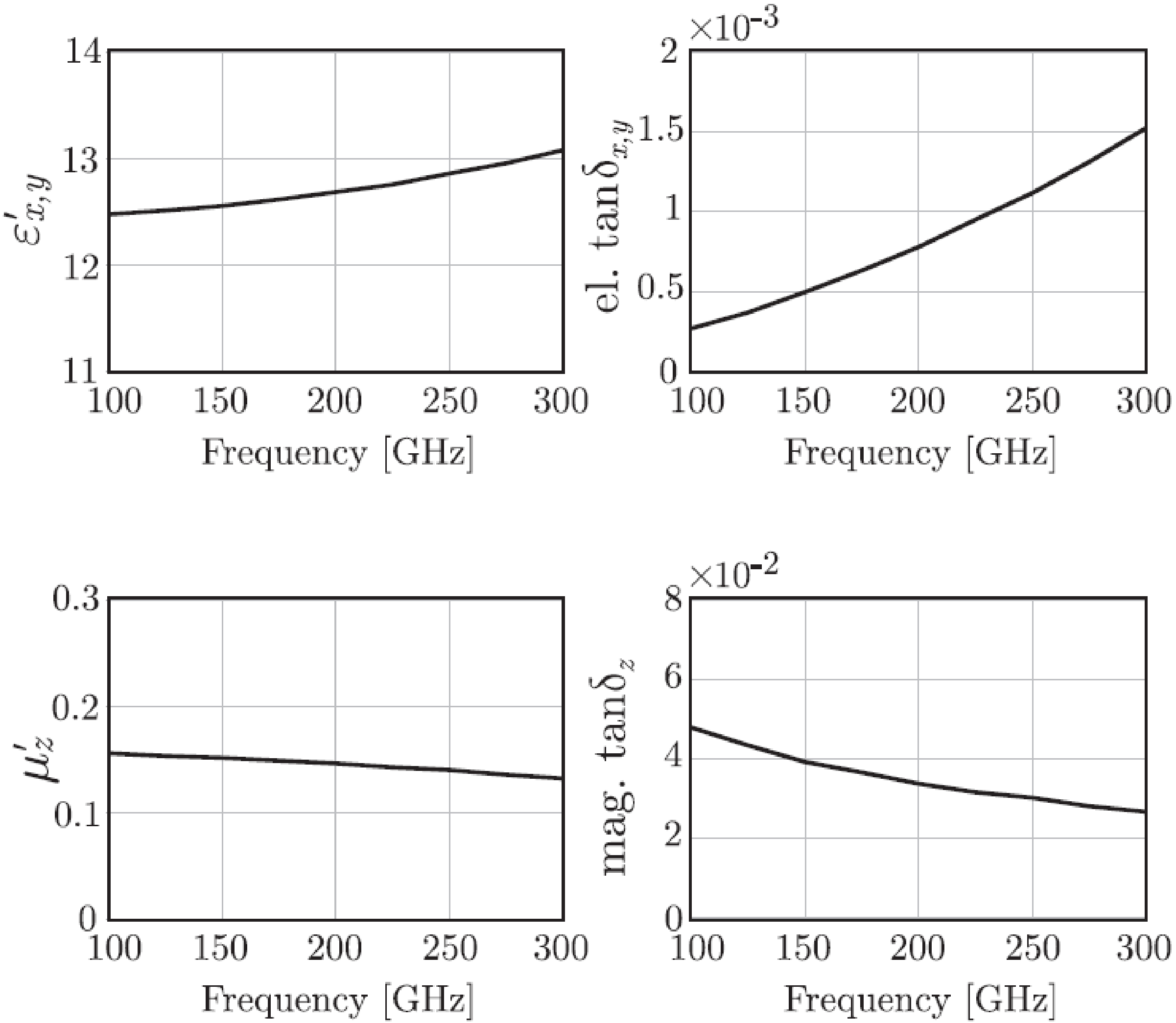
D. Cohen and R. Shavit, IEEE TAP, 63-5, 2015.



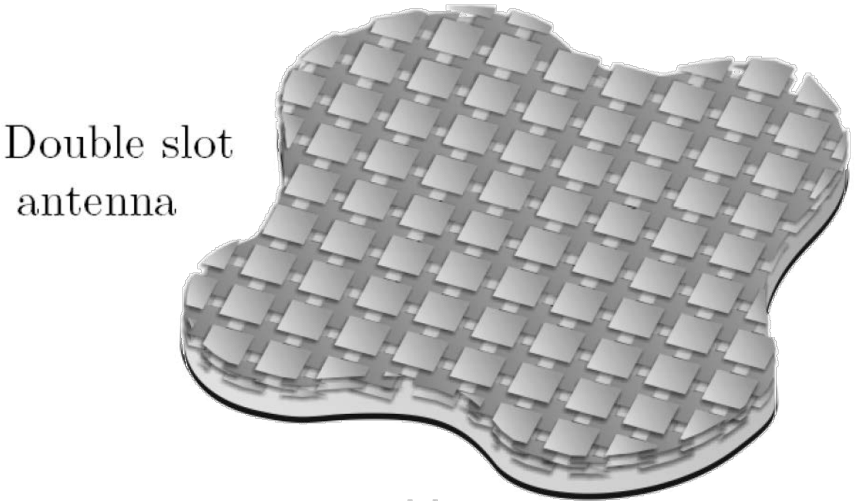
S-parameters

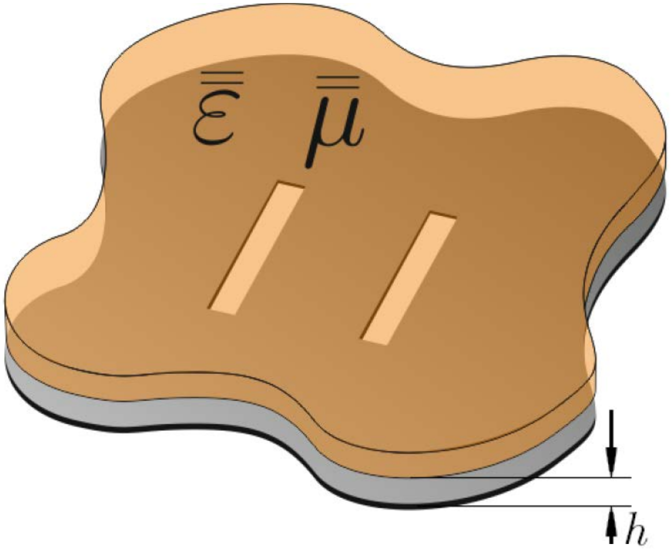
↓

$\underline{\underline{\varepsilon}}_{\text{eff}}$ $\underline{\underline{\mu}}_{\text{eff}}$

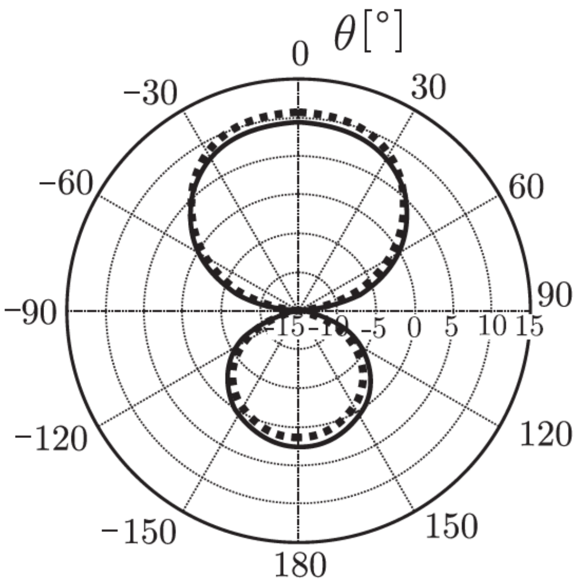


Double slot with ADLs

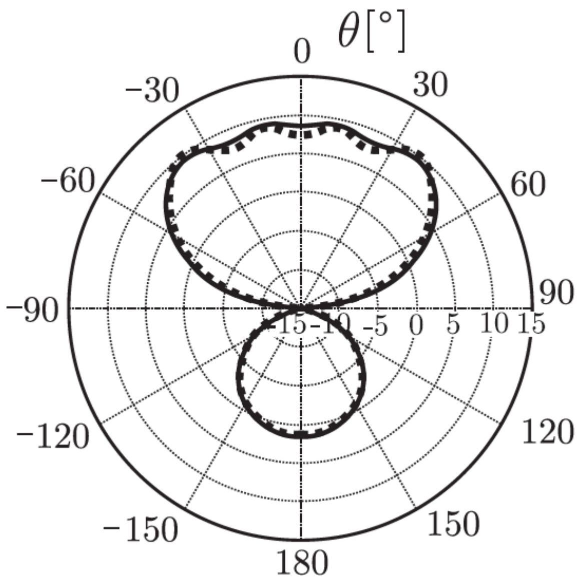




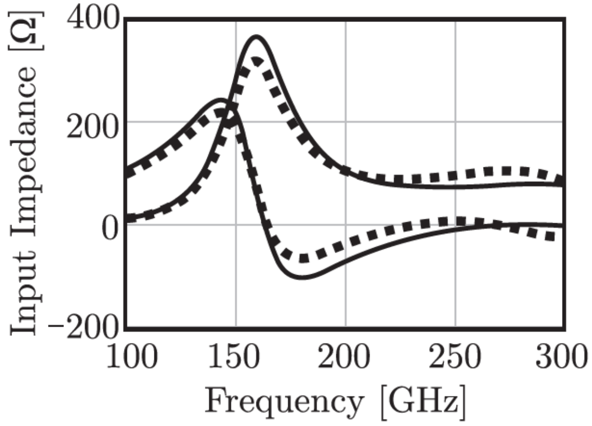
200 GHz



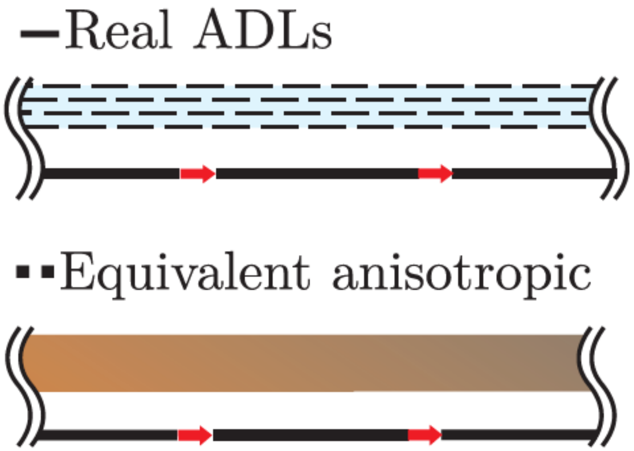
250 GHz

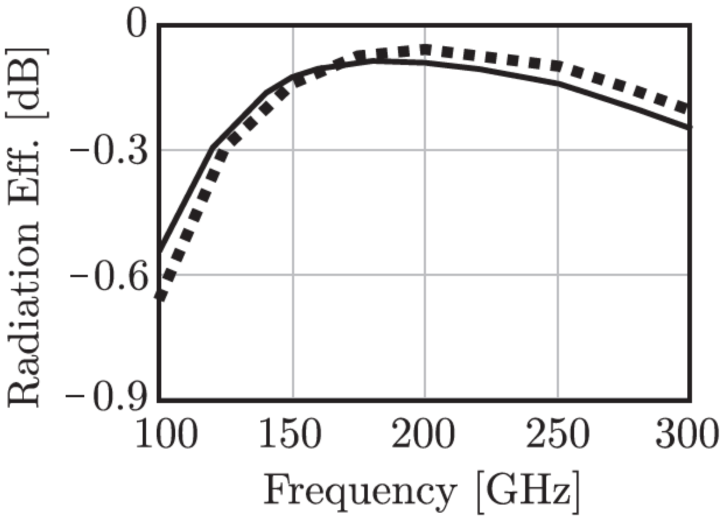


—Real ADLs
▪▪Equivalent anisotropic

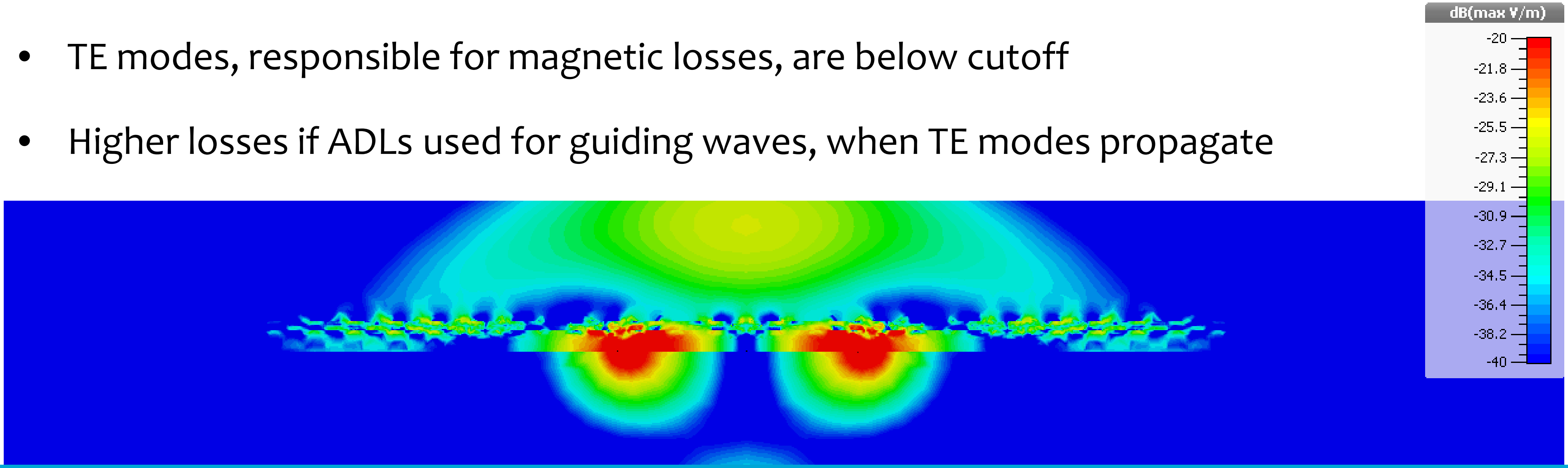


Efficiency of 200GHz antenna





- No TM surface wave propagates in the structure
- TE modes, responsible for magnetic losses, are below cutoff
- Higher losses if ADLs used for guiding waves, when TE modes propagate



Conclusions

ANALYTICAL SPECTRUM OF ARTIFICIAL DIELECTRIC LAYERS (FINITE σ)

- Analytical description of the dissipation losses
- Effective **electric and magnetic** $\tan\delta$ can be retrieved

3 MAIN MESSAGES

1) Magnetic losses much higher than electric one (current loops)

2) Magnetic losses are excited by TE mode propagating in the structure

3) Our applications of ADLs does not involve TE modes (very high efficiency)