EE4620 - Spectral Domain Methods in Electromagnetics

Topic # 5

Introduction to Leaky Wave Antennas

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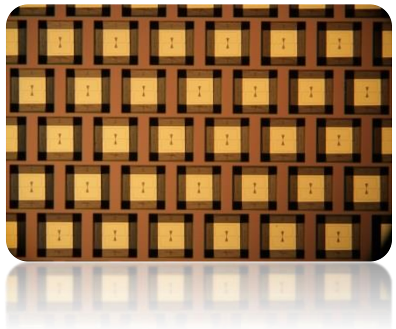
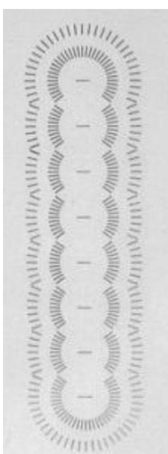
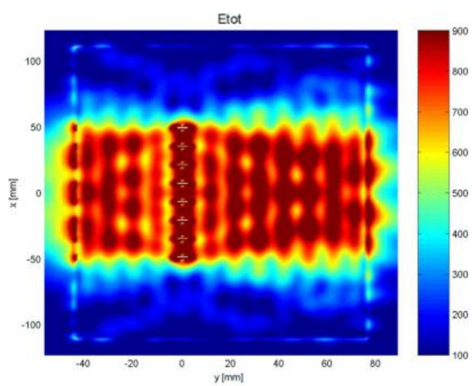
Antennas Printed in Stratified Dielectrics

Dielectric allows using integrated technology (PCB, lithography)



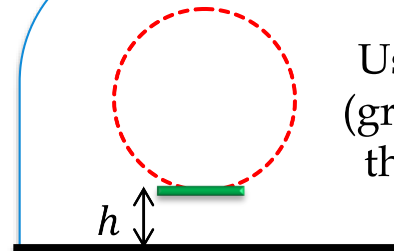
E.g. of a linear array





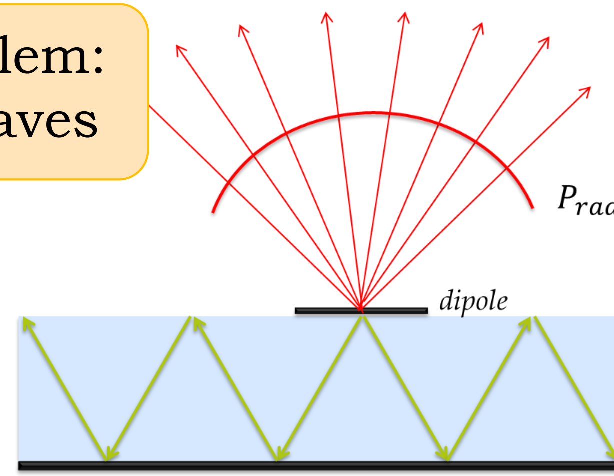
(a)

Main problem: surface waves



Using a back reflector (ground plane) reduces the radiation into the lower region

$$h_{opt} = \lambda/4$$



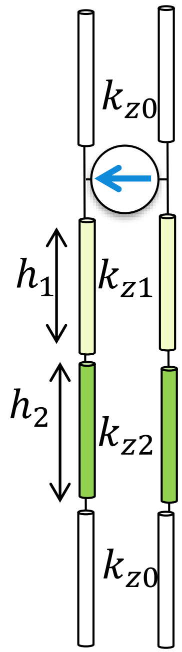
There is a part of the power delivered to the antenna that is radiated inside the dielectric!

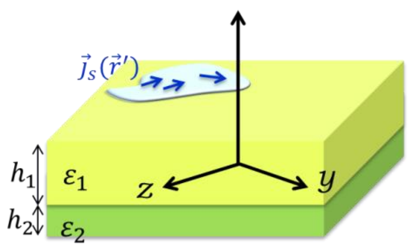
Dyadic Green's Function for Stratified Media

$$\boldsymbol{f}(\vec{r}) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{\boldsymbol{G}}^{fc}(k_x,k_y,z,z')\boldsymbol{C}_s(k_x,k_y)e^{-jk_x x}e^{-jk_y y}dk_x dk_y$$

$$\tilde{\boldsymbol{G}}^{ej} = \begin{bmatrix} -\dfrac{v_{TM}k_x^2+v_{TE}k_y^2}{k_\rho^2} & \dfrac{(v_{TE}-v_{TM})k_xk_y}{k_\rho^2} \\ \dfrac{(v_{TE}-v_{TM})k_xk_y}{k_\rho^2} & -\dfrac{v_{TE}k_x^2+v_{TM}k_y^2}{k_\rho^2} \\ \varsigma\dfrac{k_x}{k}i_{TM} & \varsigma\dfrac{k_y}{k}i_{TM} \end{bmatrix}$$

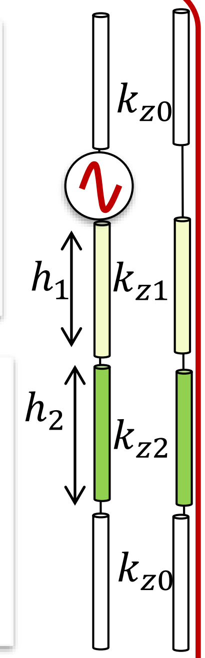
$$\tilde{\boldsymbol{G}}^{hj} = \begin{bmatrix} \dfrac{(i_{TM}-i_{TE})k_xk_y}{k_\rho^2} & \dfrac{i_{TE}k_x^2+i_{TM}k_y^2}{k_\rho^2} \\ \dfrac{i_{TE}k_y^2+i_{TM}k_x^2}{k_\rho^2} & \dfrac{(i_{TE}-i_{TM})k_xk_y}{k_\rho^2} \\ \dfrac{k_y}{\varsigma k}v_{TE} & \dfrac{k_x}{\varsigma k}v_{TE} \end{bmatrix}$$

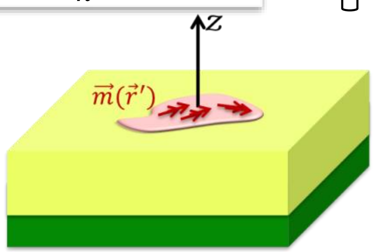




$$\tilde{\boldsymbol{G}}^{hm} = \begin{bmatrix} -\dfrac{i_{TE}k_x^2+i_{TM}k_y^2}{k_\rho^2} & \dfrac{(i_{TM}-i_{TE})k_xk_y}{k_\rho^2} \\ \dfrac{(i_{TM}-i_{TE})k_xk_y}{k_\rho^2} & -\dfrac{i_{TM}k_x^2+i_{TE}k_y^2}{k_\rho^2} \\ \dfrac{k_x}{\varsigma k}v_{TE} & \dfrac{k_y}{\varsigma k}v_{TE} \end{bmatrix}$$

$$\tilde{\boldsymbol{G}}^{em} = \begin{bmatrix} \dfrac{(v_{TM}-v_{TE})k_xk_y}{k_\rho^2} & -\dfrac{v_{TE}k_y^2+v_{TM}k_x^2}{k_\rho^2} \\ \dfrac{v_{TE}k_x^2+v_{TM}k_y^2}{k_\rho^2} & \dfrac{(v_{TE}-v_{TM})k_xk_y}{k_\rho^2} \\ -\varsigma\dfrac{k_y}{k}i_{TM} & \varsigma\dfrac{k_x}{k}i_{TM} \end{bmatrix}$$





$$k_{zi} = \sqrt{k_i^2 - k_x^2 - k_y^2}$$

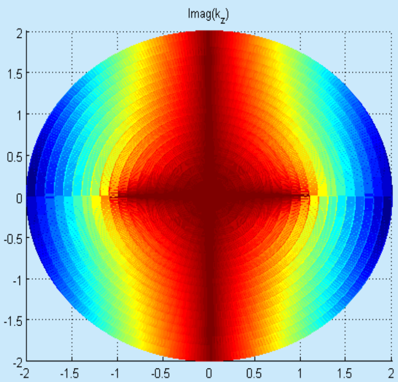
$$Z_{TMi} = \zeta_i k_{zi}/k_i \qquad Z_{TEi} = \zeta_i k_i/k_{zi}$$

Preferred Branch Convention

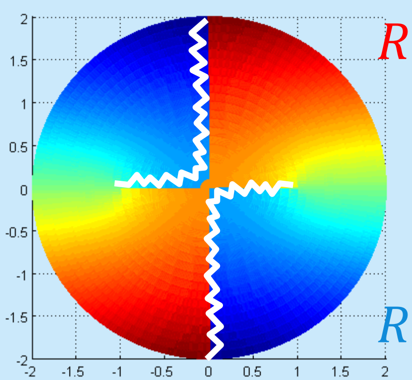
Selection of square root multivalues on the Riemann sheets to obtain a **unique specification of the integrand in the complex plane**

$$k_z = -j\sqrt{-\left(k^2 - k_\rho^2\right)}$$

Top Riemann Sheet:



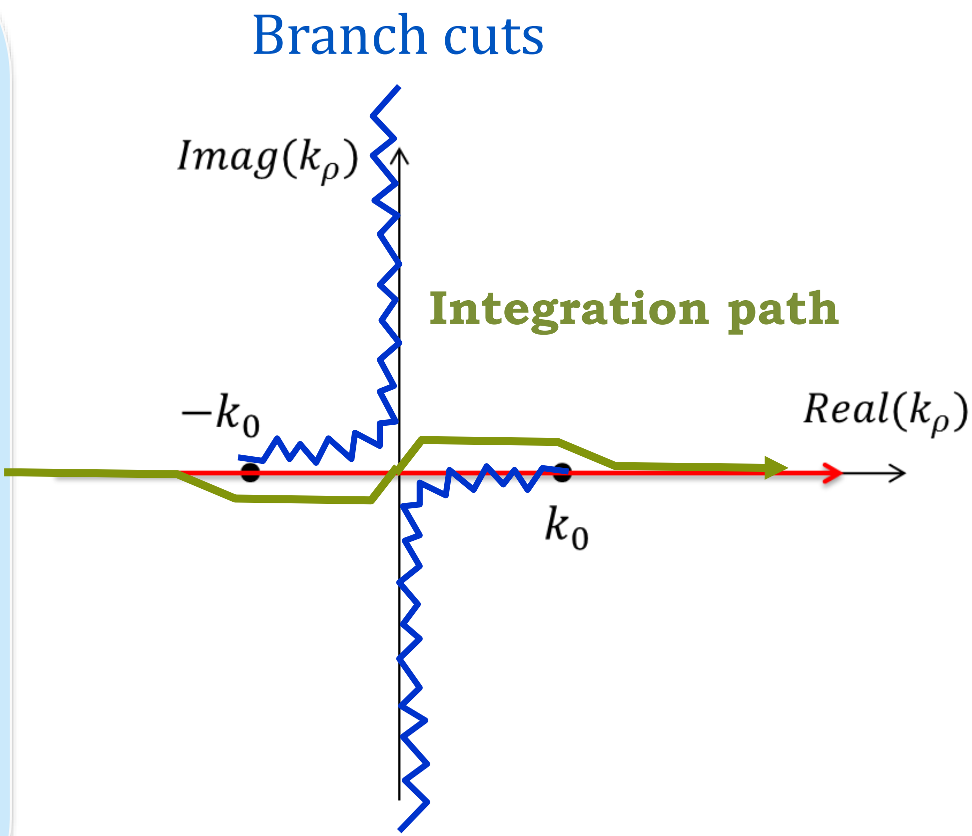
$Imag(k_z) < 0$



$Real(k_z) > 0$

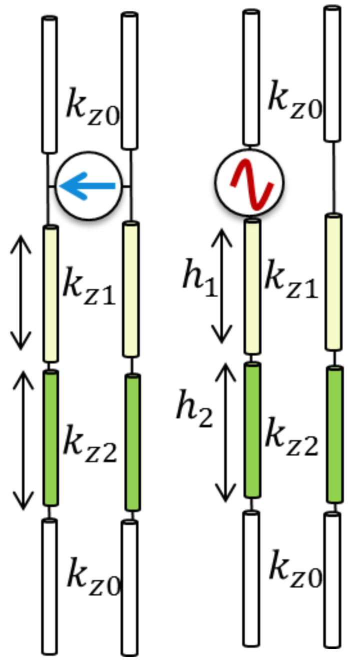
$Real(k_z) < 0$

The radiation condition is verified



Pole Singularities in Stratified Media

Pole singularities in k_ρ arise in dielectric stratifications



$$k_{zi} = \pm\sqrt{k_i^2 - k_\rho^2}$$

The solutions of the transmission lines can be expressed as:

$$v_{TM/TEi}(k_\rho, z) = \frac{N_{TM/TEi}^{v}(k_\rho, z)}{D_{TM/TE}\,(k_\rho)}$$

$$i_{TM/TEi}(k_\rho, z) = \frac{N_{TM/TEi}^{i}\,(k_\rho, z)}{D_{TM/TE}\,(k_\rho)}$$

- Dispersion equation to find transversal propagation constants:

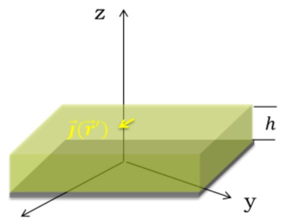
$$D_{TM/TE}\,(k_\rho) = 0 \quad \Rightarrow \quad \boxed{k_{\rho 0} = k_\rho^g - \frac{D(k_\rho^g)}{D'(k_\rho^g)}}$$

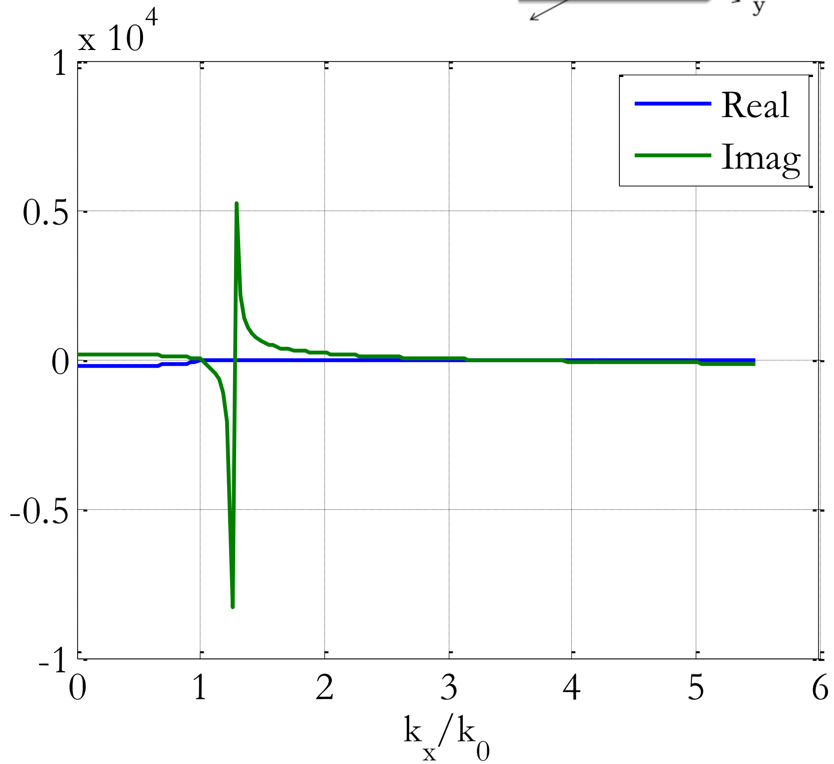
- Residues to find the surface wave field distribution and associated power

$$v_{TM}(k_\rho, z) = \frac{N(k_\rho)}{D(k_\rho)} \quad \Rightarrow \quad \boxed{Res[v_{TM}(k_\rho, z)]\Big|_{k_{\rho i}} = \frac{N(k_{\rho i})}{D'(k_{\rho i})}}$$

Examples of Surface wave poles

Surface Waves



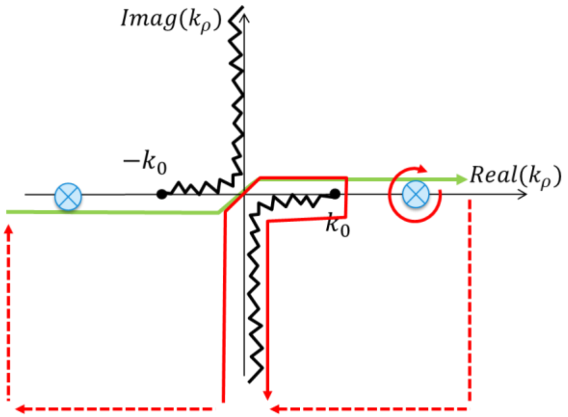


Polar singularity in the real axis
with $k_\rho > k_0$

SW Field Contribution

$$\vec{f}(\vec{r}) \approx \frac{1}{4\pi^2}\int_0^{\pi}\int_{-\infty}^{\infty}\tilde{G}^{fc}(k_\rho,z,z')k_\rho e^{-jk_\rho\rho}k_\rho dk_\rho d\alpha\,\vec{C}_0(k_{\rho c},\phi)$$

Surface wave poles are found on the real axis in the Top Riemann Sheet



$$\vec{f}_{sw}(\vec{r}) = -2\pi j\sum_i Res\left[\frac{e^{\frac{j\pi}{4}}\sqrt{k_\rho}e^{-jk_\rho\rho}}{2\pi\sqrt{2\pi\rho}}\tilde{G}^{fc}(k_\rho,z,z')\vec{C}_0(k_\rho,\phi)\right]\Bigg|_{k_\rho=k_{\rho i}}$$

Field contributions in the form of cylindrical propagating waves inside the stratified dielectrics

Surface Waves

$$k_\rho^{sw} = \beta^{sw} = k_0\sqrt{\epsilon_r^{sw}}$$

$$k_0 < k_\rho^{sw} < k_d$$

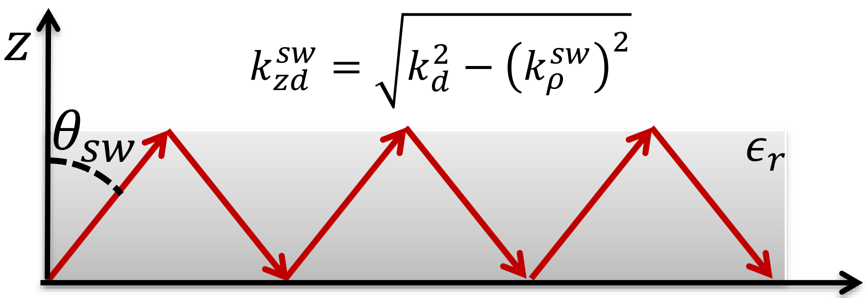
They are also referred as **slow waves**

$$k_\rho^{sw} = \frac{2\pi f}{v_{sw}} > k_0 \qquad v_{sw} < v_0$$

It can be seen as a couple of **homogenous waves propagating inside the dielectric** with a direction characterized by a real angle $\pm\theta_{sw}$:

$$\beta^{sw} = k_d sin\theta_{sw} < k_d \qquad sin\theta_{sw} = \frac{\sqrt{\epsilon_r^{sw}}}{\sqrt{\epsilon_r}}$$

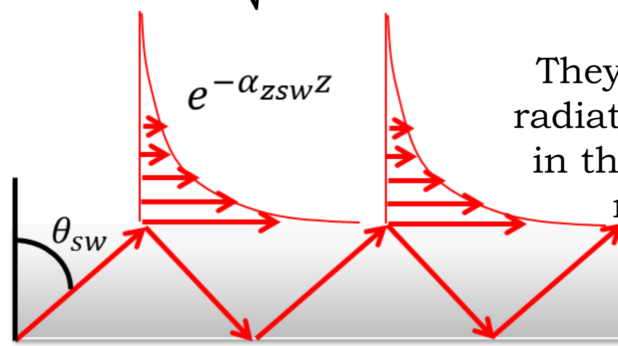
$$k_{zd}^{sw} = \sqrt{k_d^2 - \left(k_\rho^{sw}\right)^2}$$



There is no attenuation, therefore the energy carried by the surface wave will reach *infinity*

It is an **inhomogenous wave in** the air region:

$$k_{z0sw} = -j\sqrt{-\left(k_0^2 - \left(k_\rho^{sw}\right)^2\right)} = -j\alpha_{zsw}$$



They verified the radiation condition in the infinite air medium

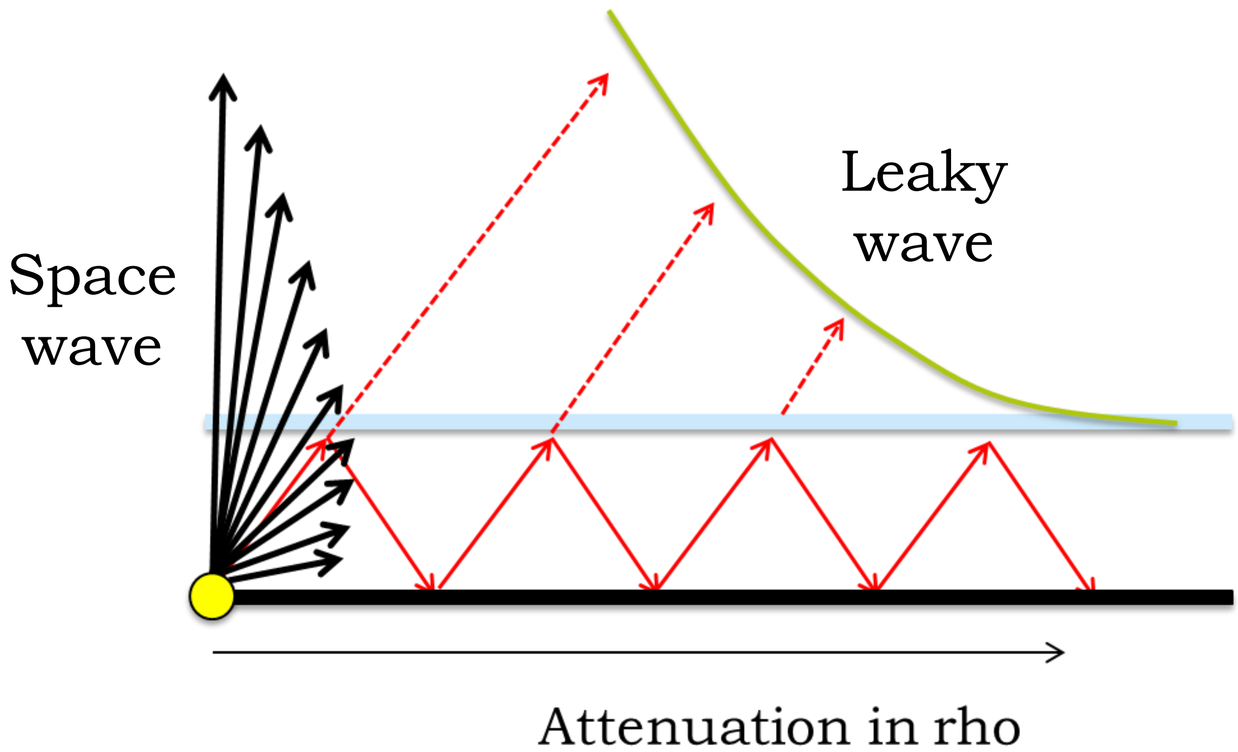
The sw angle is above the critical angle

$$\sqrt{\epsilon_r} sin\theta_{sw} = sin\theta_0$$

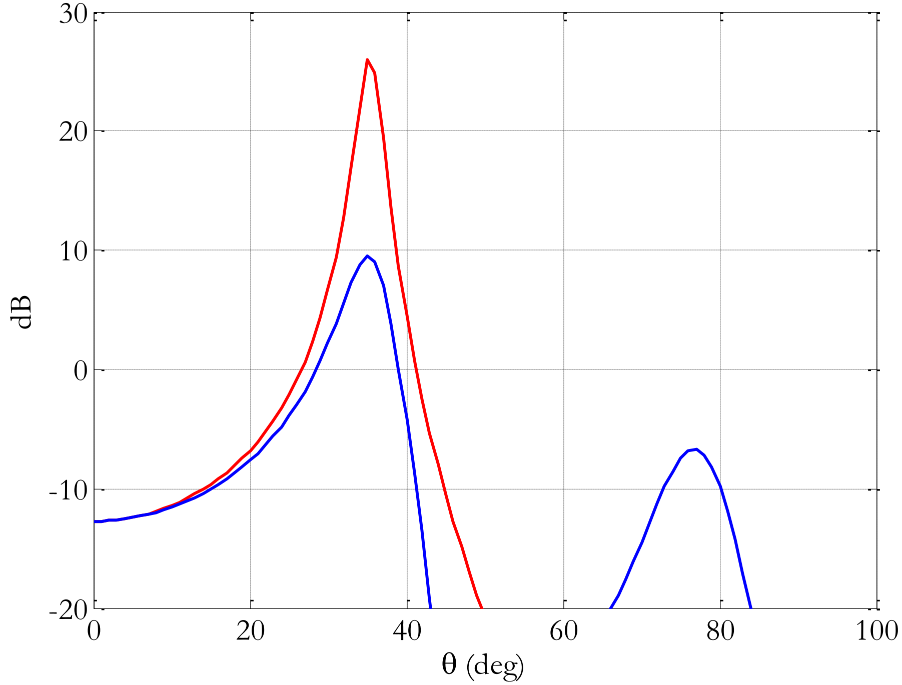
$$\sqrt{\epsilon_{rsw}} = sin\theta_0$$

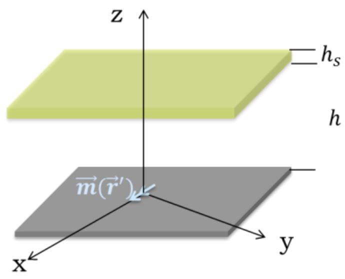
Therefore θ_0 is imaginary

Introduction to leaky waves in stratified media



Leaky Wave Poles





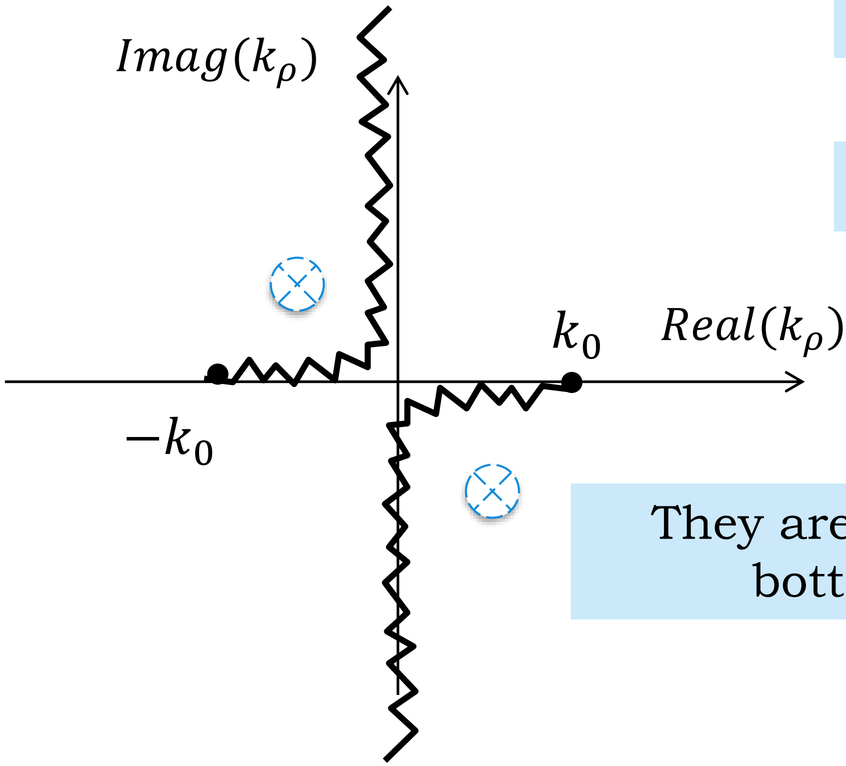
The spectrum seems to peak at a certain location in the visible spectrum, but does not go to infinity

Polar singularity in the complex plane close to the real axis with $Re[k_\rho] < k_0$

Pole Singularity of Leaky Waves

Complex pole singularities: $k_{\rho lw} = \beta_{lw} - j\alpha_{lw}$

They are present only in certain stratifications

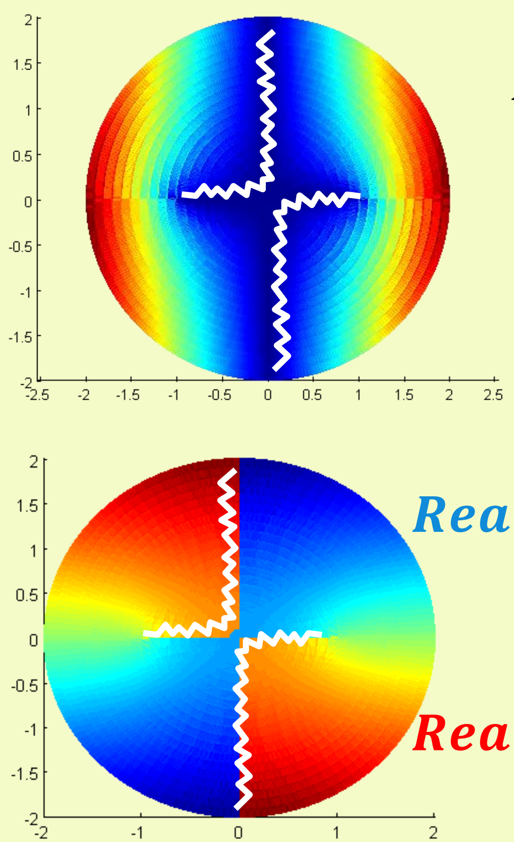


$0 < \beta_{lw} < k_0$

$Im(k_{\rho lw}) < 0$ → They radiate energy into the infinite medium

They are found in the bottom sheet

Bottom Riemann Sheet

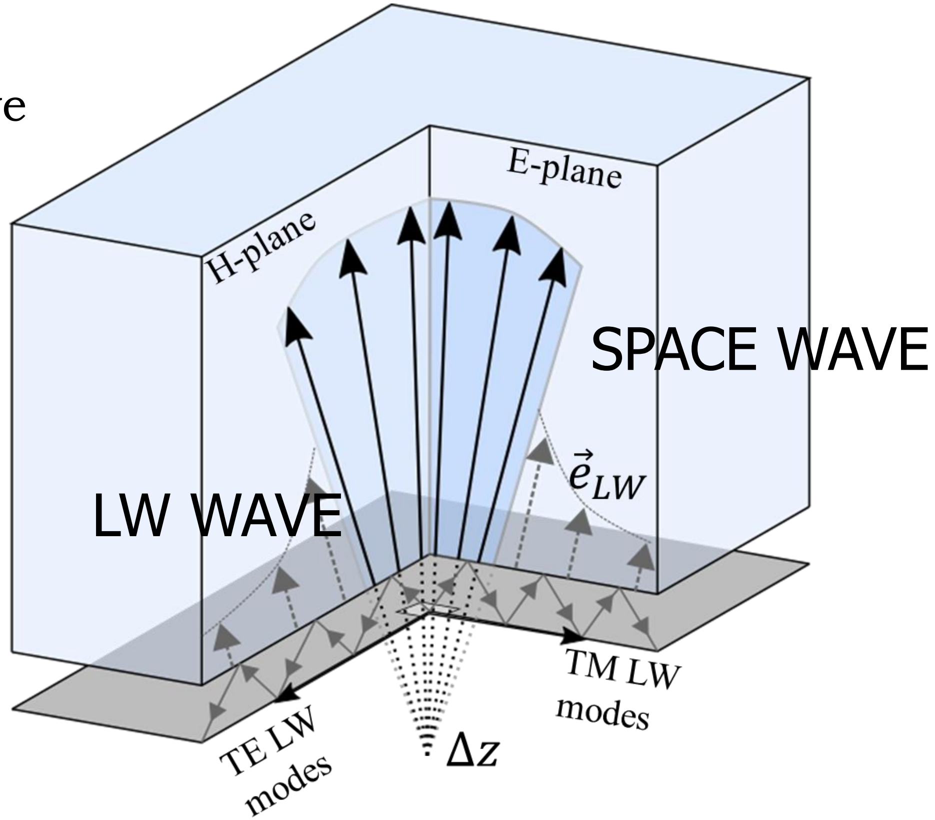


$$k_z = +j\sqrt{-(k^2 - k_\rho^2)}$$

This is opposite to the standard choice

They are present close to the source

They enlarge the effective area of the source



The leaky wave pole is only captured for observation points near the source

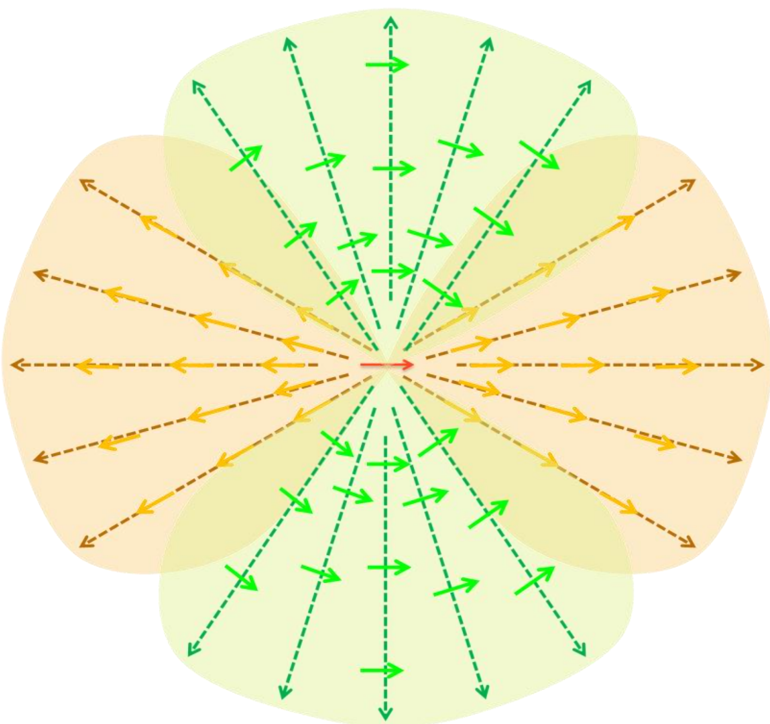
The residue contribution does not arrive to infinity

But it is responsible to the power transferred to the far field of the antenna: **modulation of the SFG in the region around θ_{lw}^{0}**

They can be used to do pattern shaping!

Cylindrical LWs

They are cylindrical waves with the same ϕ-pattern and polarization than those of surface waves

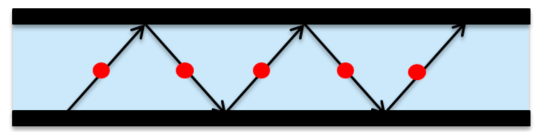


TE Wave

Electric field oriented in the azimuthal direction
Maximum in the Hplane of the antenna

$$E_\phi(\rho, z) \approx -Res\left[v_{TE}\left(k_\rho, z, z'\right)\right]\Big|_{k_{\rho i}} j_x(k_{\rho i}, \phi)\frac{C \sin\phi \, e^{-jk_{\rho i}\rho}}{\sqrt{\rho}}$$

TE Wave



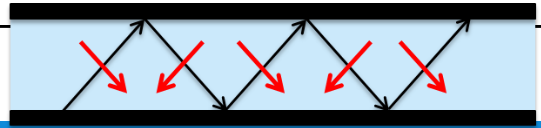
TM Wave

Electric field oriented in the radial and z direction
Maximum in the Eplane of the antenna

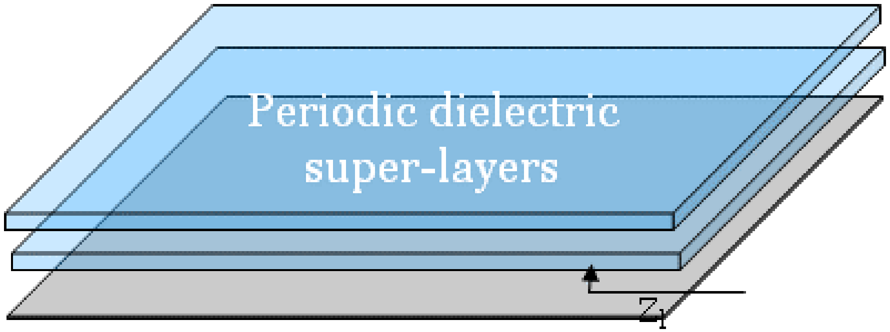
$$E_\rho(\rho, z) \approx Res\left[v_{TM}\left(k_\rho, z, z'\right)\right]\Big|_{k_{\rho i}} j_x(k_{\rho i}, \phi)\frac{C \cos\phi \, e^{-jk_{\rho i}\rho}}{\sqrt{\rho}}$$

$$E_z(\rho, z) \approx -\frac{\varsigma k_{\rho i}}{k} Res\left[i_{TM}\left(k_\rho, z, z'\right)\right]\Big|_{k_{\rho i}} j_x(k_{\rho i}, \phi)\frac{C \cos\phi \, e^{-jk_{\rho i}\rho}}{\sqrt{\rho}}$$

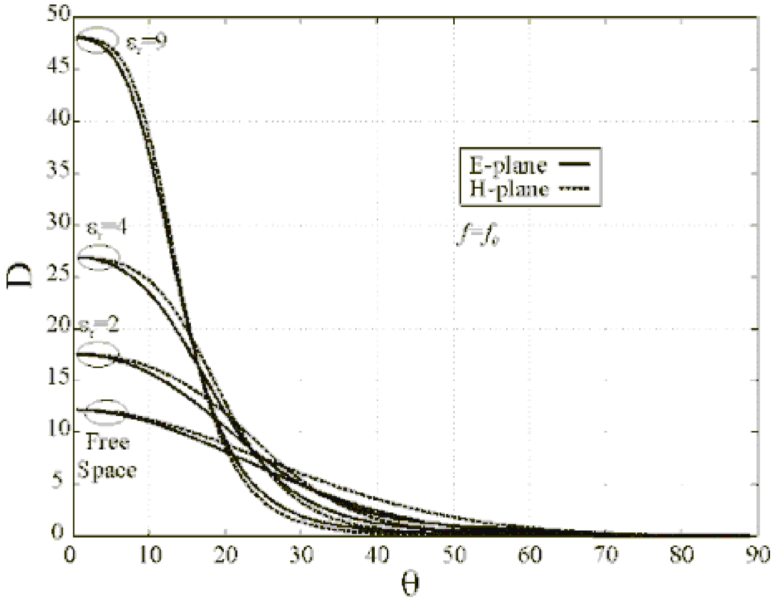
TM Wave



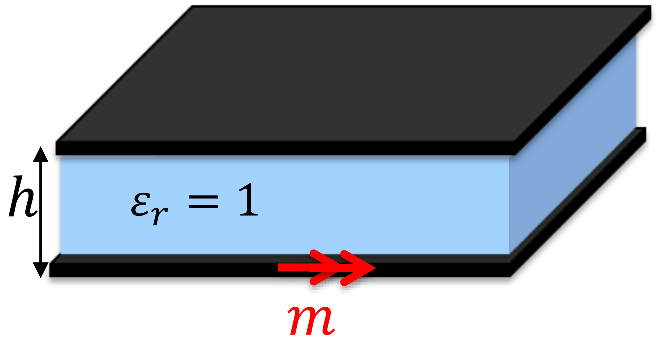
Main Purpose of discussing them is LW Antennas

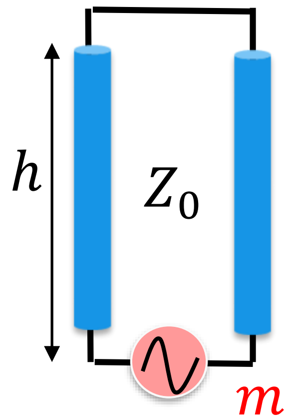


They can be used to enhance the directivity at broadside of small antennas



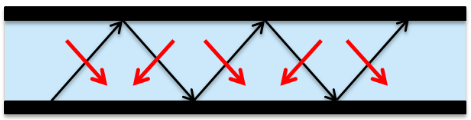
Parallel Plate in Air

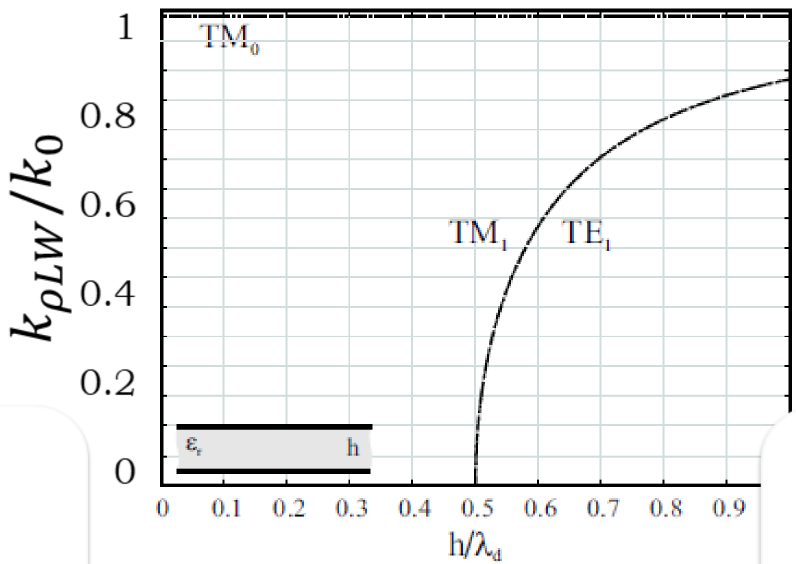




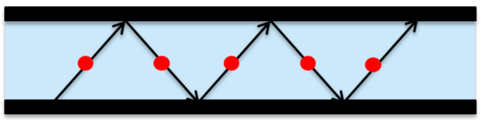
$$D(k_\rho) = jZ_0 \tan(k_{z0}h) = 0$$

TM Wave





TE Wave



for TM $\quad k_{zs}\tan(k_{zs}h) = 0$

$k_{zs} = 0 \qquad \tan(k_{zs}h) = 0$

$k_{\rho_0} = k \qquad k_{zs}h = n\pi$

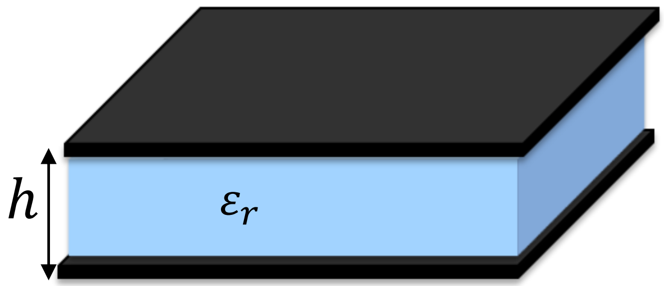
$$k_{\rho_n} = \sqrt{k^2 - \left(\frac{n\pi}{h}\right)^2}$$

for TE $\quad \tan(k_{zs}h) = 0$

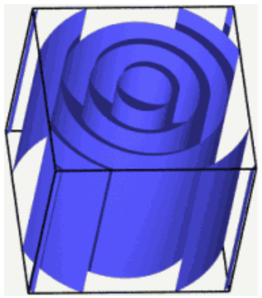
$$k_{zs}h = n\pi$$

$$k_{\rho_n} = \sqrt{k^2 - \left(\frac{n\pi}{h}\right)^2}$$

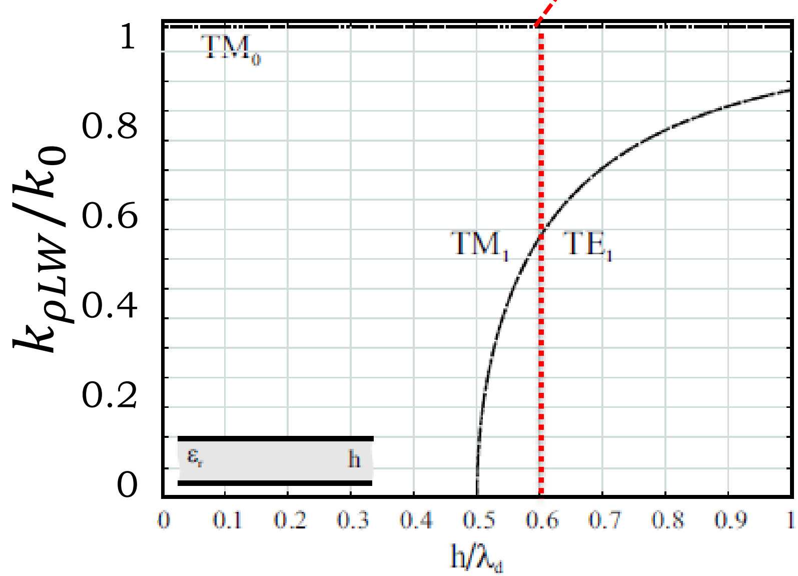
Parallel Plate in Air

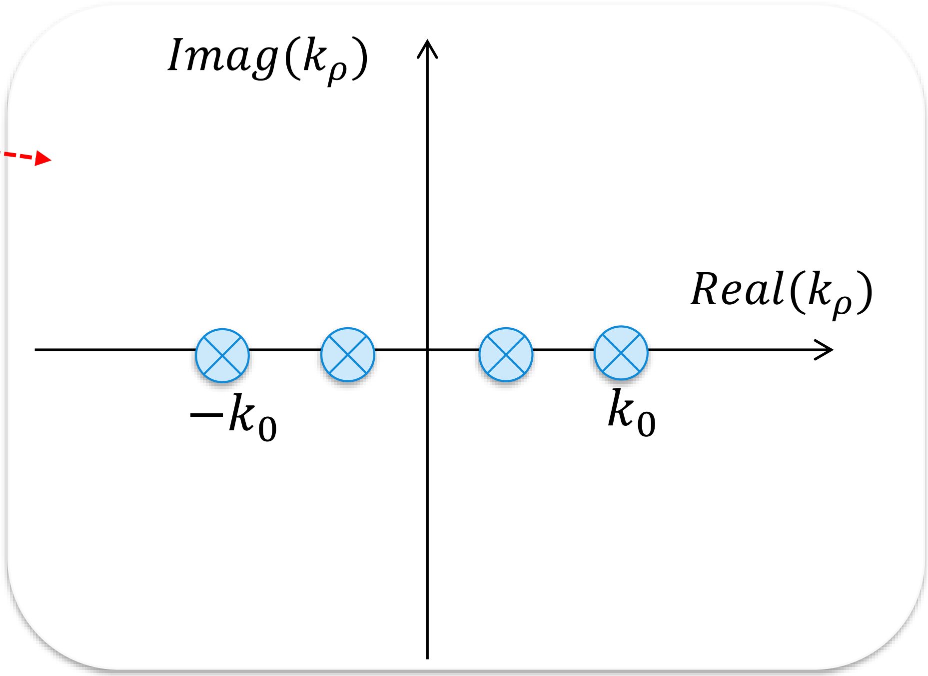


$$\boldsymbol{E} = \boldsymbol{f}(\phi, z)\frac{\boldsymbol{e}^{-j\boldsymbol{k}_{\rho}\boldsymbol{\rho}}}{\sqrt{\boldsymbol{\rho}}}$$



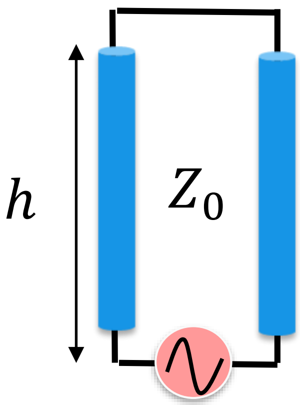
k_ρ-Spectrum





A PPW has no branch singularity, only real poles. These ones are SWs with propagation constant that can be $\leq k_0$

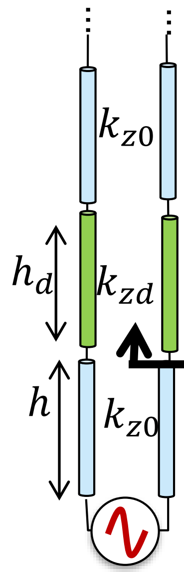
Open Parallel Plate Waveguide



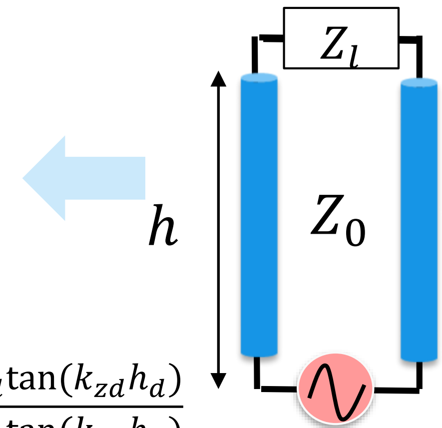
$$Z_0(k_\rho = 0) = \zeta_0$$

$$Z_d(k_\rho = 0) = \frac{\zeta_0}{\epsilon_r}$$

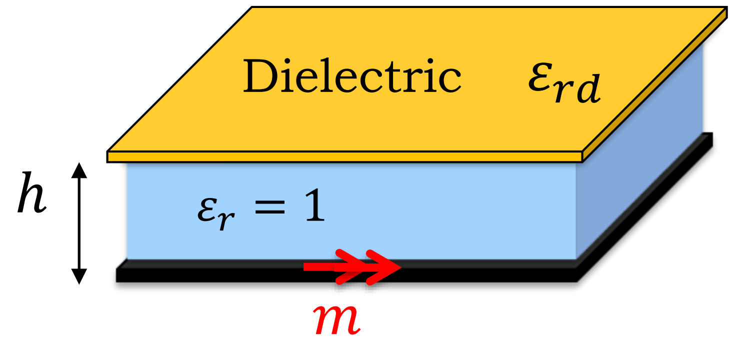
$$Z_0(k_\rho = 0) = \zeta_0$$

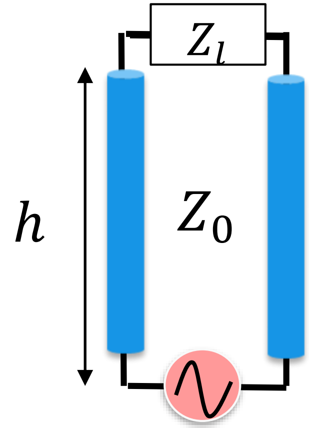


$$Z_l = Z_d \frac{Z_0 + jZ_d \tan(k_{zd} h_d)}{Z_d + jZ_0 \tan(k_{zd} h_d)}$$



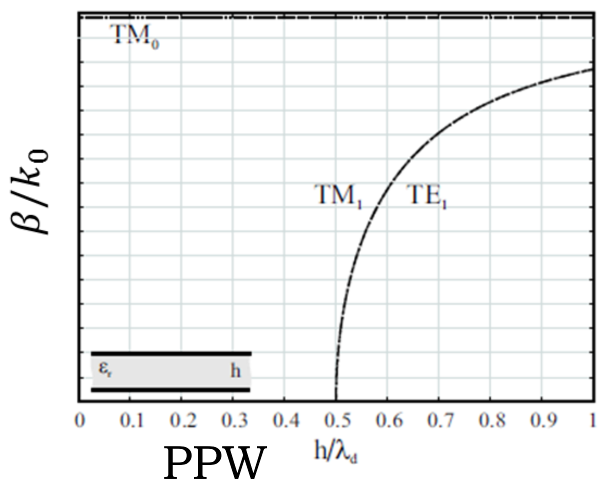
Open Parallel Plate Waveguide





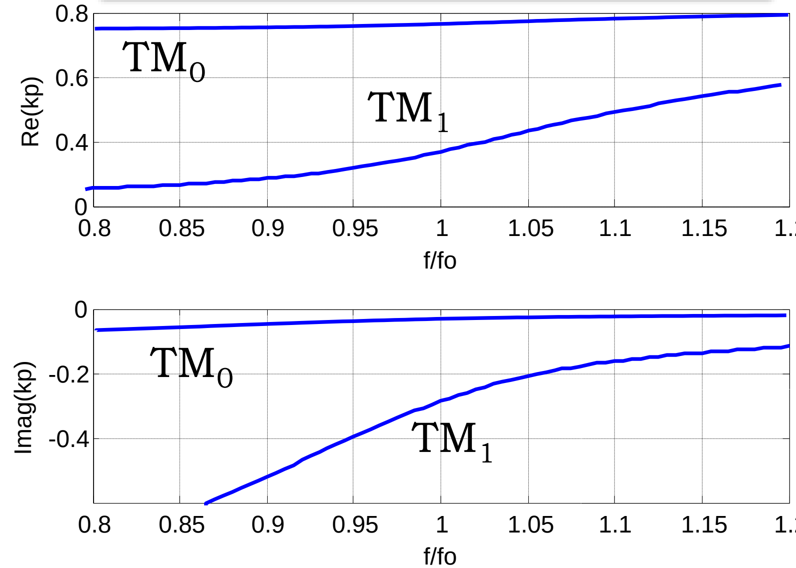
$$i(z = z_s) = Y_{in} = Y_0 \frac{Z_o + jZ_l \tan(k_{z0}h)}{Z_l + jZ_0 \tan(k_{z0}h)}$$

$$D(k_\rho) = jZ_0 \tan(k_{z0}h) = 0$$

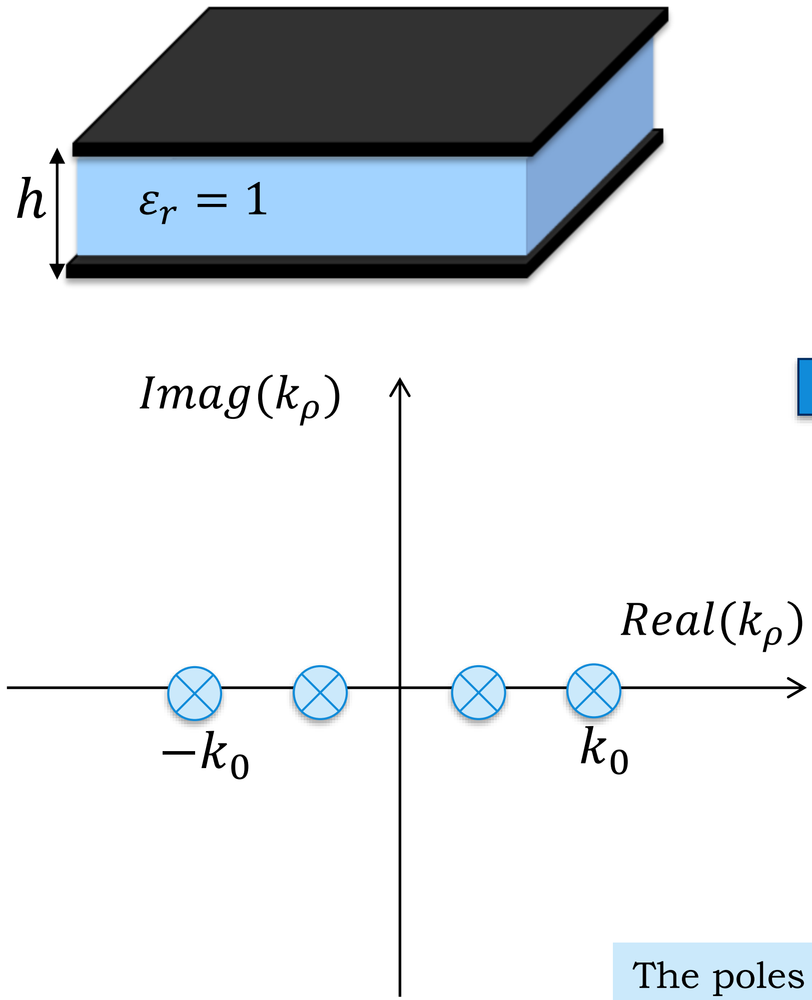


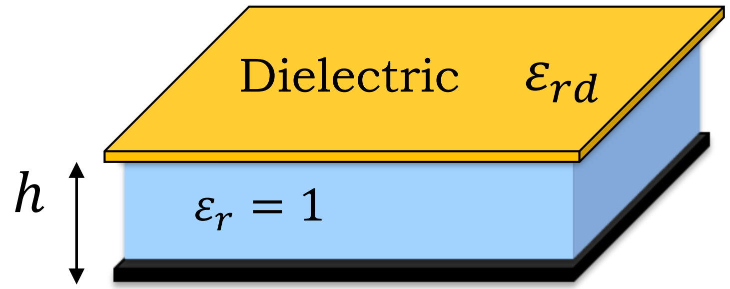
$$Z_l \neq 0$$

$$D(k_\rho) = Z_l + jZ_0 \tan(k_{z0}h) = 0$$

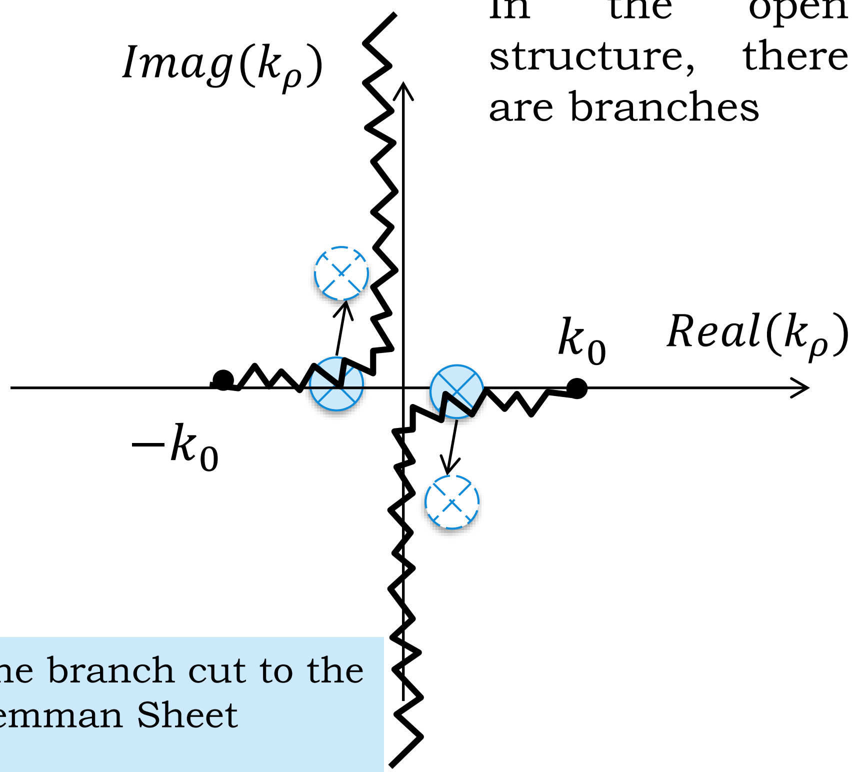


Open Parallel Plate Waveguide



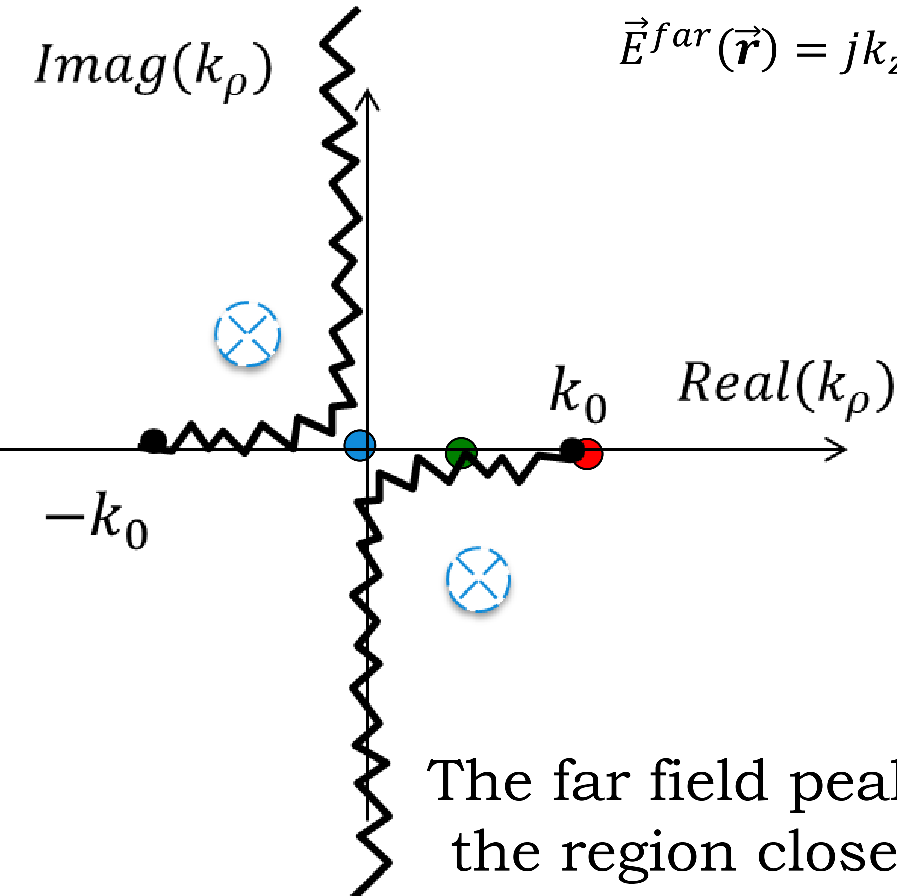


In the open structure, there are branches



The poles cross the branch cut to the bottom Riemman Sheet

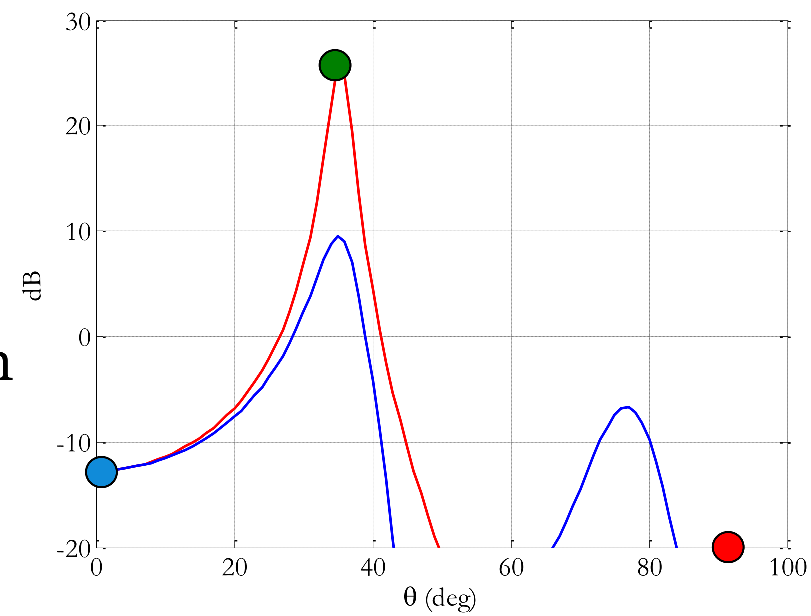
Pattern shaping with leaky waves



$$\vec{E}^{far}(\vec{r}) = jk_{zs}\tilde{\boldsymbol{G}}^{em}(\underbrace{k_{xs}, k_{ys}}_{k_{\rho s} = k_0 sin\theta_s}, z, z')\vec{\boldsymbol{M}}_{eq}(k_{xs}, k_{ys})e^{jk_{zs}|z|}\frac{e^{-jkr}}{2\pi r}$$

Saddle point in the far field

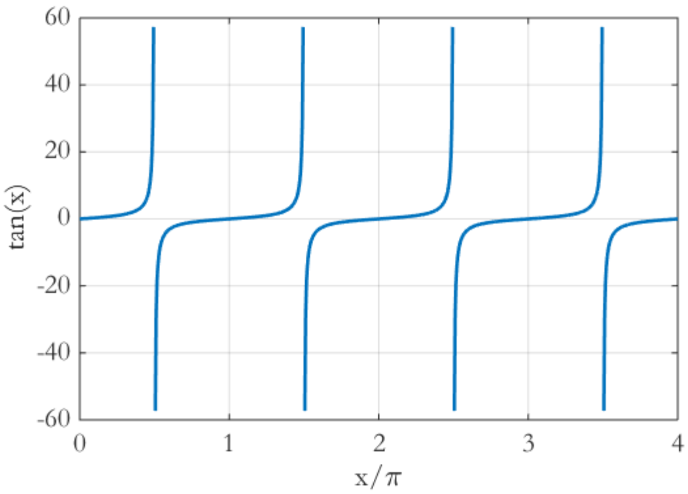
The far field peaks in the region close the LW pole location



Dispersion Equation: Analytical Approximated Solution

$$\boxed{D(k_\rho) = Z_l + jZ_0 \tan(k_{z0}h)}$$

Approximation 1:



The tan function can be approximated linearly around its zeroes for arguments in the surrounding of $x = \pm n\pi$, resorting to

$$\tan(k_{z0}h)_{|x \pm n\pi| \approx 0} \approx k_{z0}h - n\pi$$

n=1

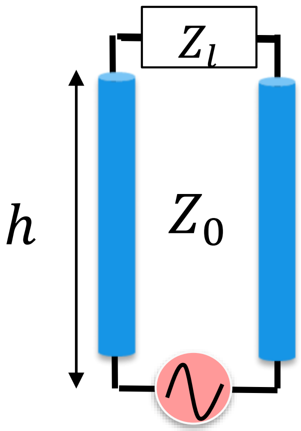
$$\boxed{k_{z0} = j\frac{Z_l}{hZ_0} + \frac{\pi}{h} = \sqrt{k_0^2 - k_\rho^2}}$$

A. Neto and N. Llombart, "Wideband Localization of the Dominant Leaky Wave Poles in Dielectric Covered Antennas," in IEEE Antennas and Wireless Propagation Letters, vol. 5, pp. 549-551, 2006, doi: 10.1109/LAWP.2006.889558.

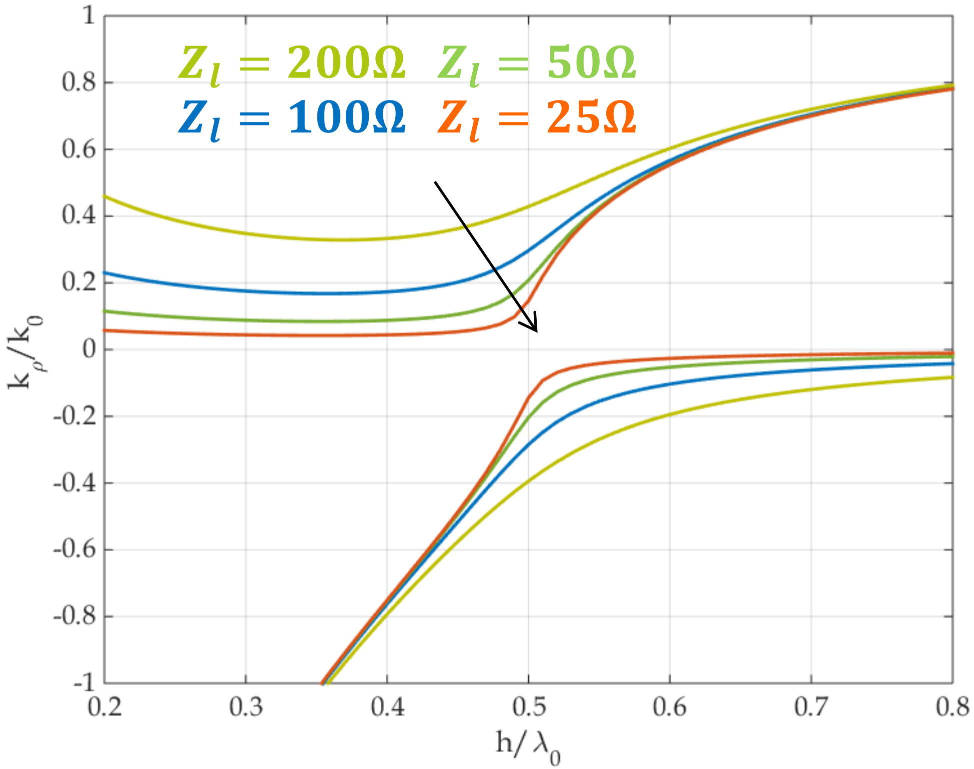
Impact of the cavity top impedance

$$k_{z0} = j\frac{Z_l}{hZ_0} + \frac{\pi}{h} = \sqrt{k_0^2 - k_\rho^2}$$

The propagation constant highly depends on Zl



$$k_\rho = \sqrt{k_0^2 - k_{z0}^2} = \beta - j\alpha$$



$$\beta = k_0 sin\theta_{LW}$$

$$Z_l \downarrow \; \theta_{lw} \downarrow$$

Resonant condition:

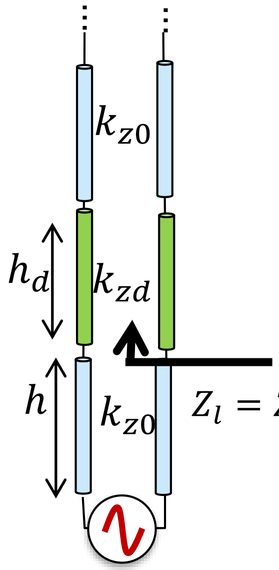
$$h \approx \lambda_0/2$$

Tunning the cavity top impedance

$$Z_0(k_\rho = 0) = \zeta_0$$

$$Z_d(k_\rho = 0) = \frac{\zeta_0}{\epsilon_r}$$

$$Z_0(k_\rho = 0) = \zeta_0$$



$$Z_l = Z_d \frac{Z_0 + jZ_d \tan(k_{zd} h_d)}{Z_d + jZ_0 \tan(k_{zd} h_d)}$$

For a quarter wavelength thick substrate (Z_l tends to zero for large ϵ_r):

$$h_d = \lambda_d/4$$

$$k_\rho = 0$$

$$\Rightarrow \boxed{Z_l = \zeta_0/\epsilon_r}$$

Dispersion Equation: Analytical Solution

$$D(k_\rho) = Z_l + jZ_0 \tan(k_{z0}h)$$

$$k_{z0} = j\frac{Z_l}{hZ_0} + \frac{\pi}{h} = \sqrt{k_0^2 - k_\rho^2}$$

Approximation 2:

$$Z_l = Z_d \frac{Z_0 + jZ_d \tan(k_{zd}h_d)}{Z_d + jZ_0 \tan(k_{zd}h_d)} \rightarrow Z_l \approx \zeta_0/\epsilon_r$$

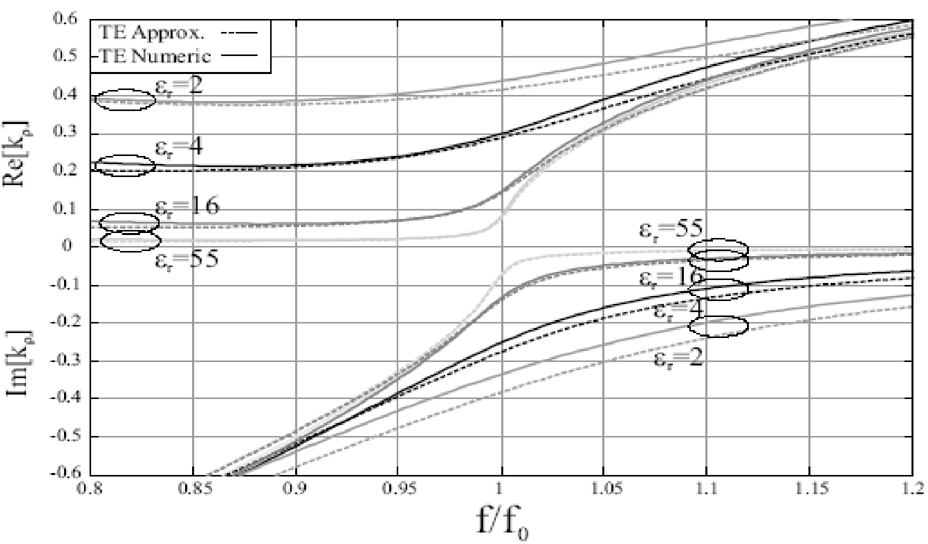
For poles radiating
close to broadside

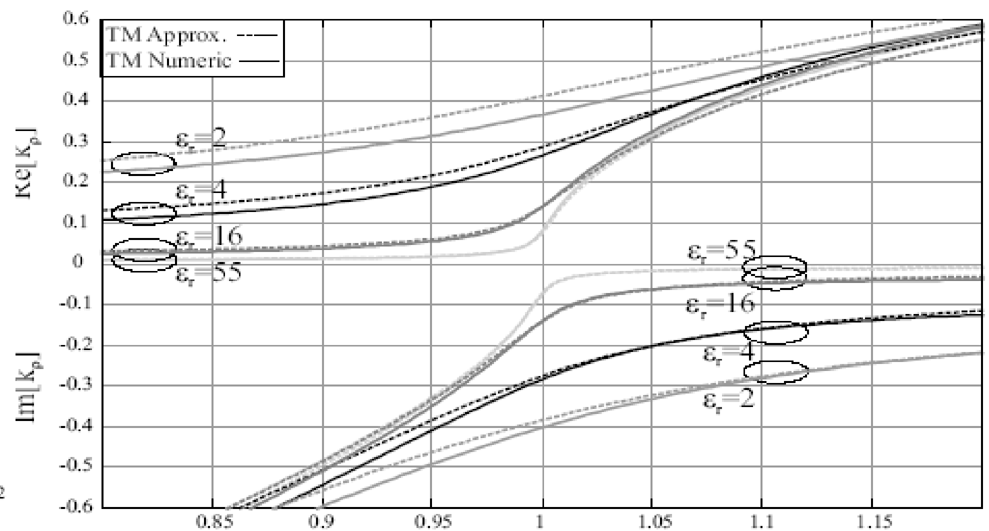
Analytical Approximated Solution

$$k_{z0} = j\frac{\zeta_0}{hZ_0\epsilon_r} + \frac{\pi}{h} = \sqrt{k_0^2 - k_\rho^2}$$

$$Z_{TE} = \zeta_i k_i / k_{zi} \qquad\qquad Z_{TM} = \zeta_i k_{zi} / k_i$$

$$k_{z0}^{TE} = k_0\left(\frac{1}{2\bar{h}} + j\frac{1}{4\bar{h}^2\pi\epsilon_r}\right) \qquad \bar{h} = h/\lambda_0 \qquad k_{z0}^{TM} = k_0\left(\frac{1}{2\bar{h}} + j\frac{1}{\pi\epsilon_r}\right)$$





$$\varepsilon_r \uparrow \quad \theta_{lw} \downarrow \quad \alpha_{lw} \downarrow$$

Leaky Waves

$$k_\rho^{lw} = \beta^{lw} - j\alpha^{lw}$$

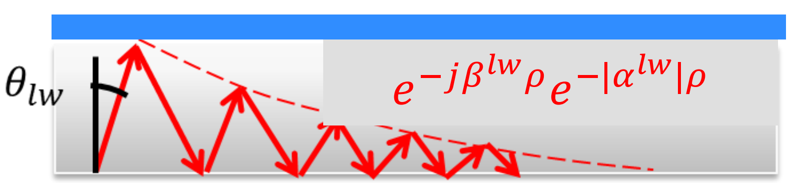
$$\beta^{lw} < k_0$$

They are also referred as **fast waves**

$$k_\rho^{lw} = \frac{2\pi f}{v_{lw}} < k_0 \qquad v_{lw} > v_0$$

It can be seen as a couple of waves propagating with a direction characterized by a real angle $\pm\theta_{lw}$ and an attenuation:

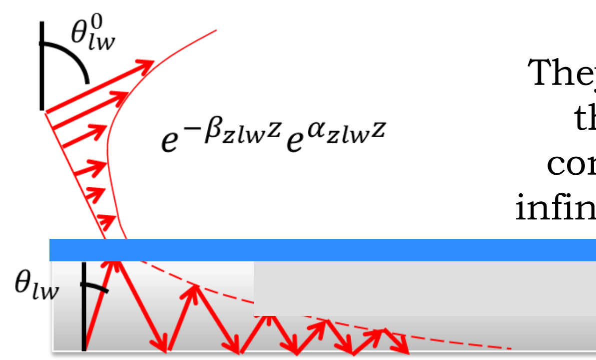
$$\beta^{lw} = k_o sin\theta_{lw} < k_0$$



There is attenuation, therefore the the leaky wave looses energy while propagates

There is also propagation in the air region that can be related to a real angle:

$$\sqrt{\epsilon_r} sin\theta_{lw} = sin\theta_{lw}^0$$

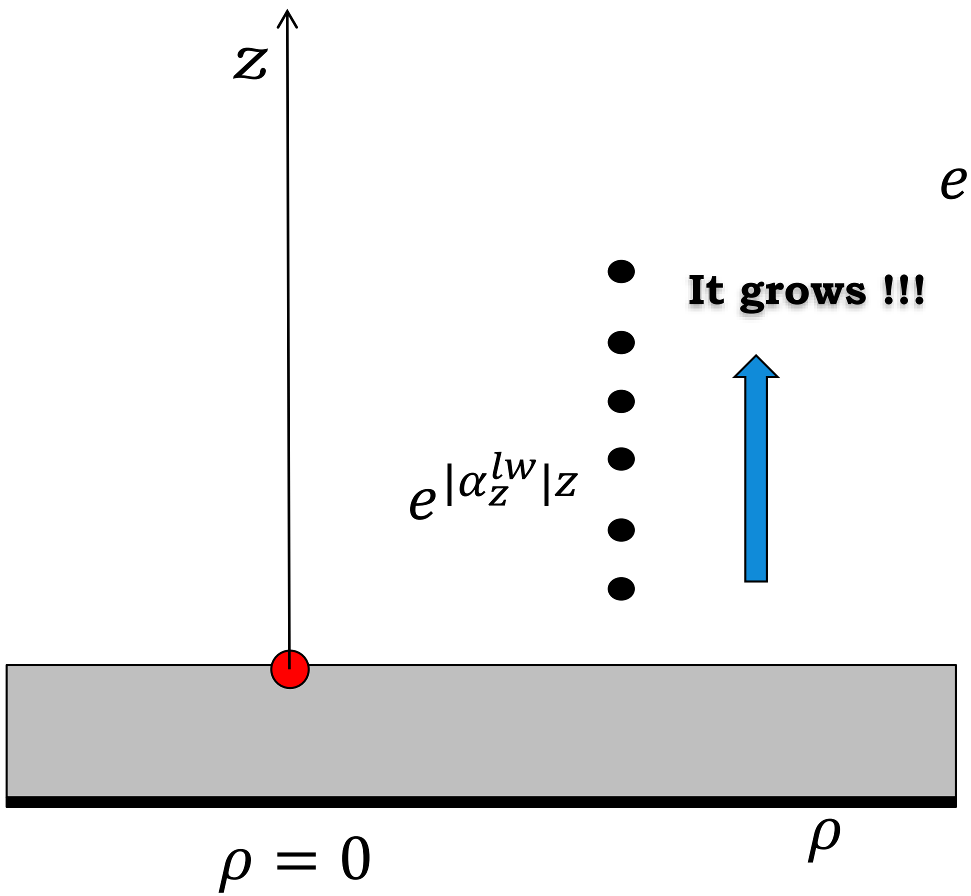


They do not verify the radiation condition in the infinite air medium

$$k_{z0}^{lw} = j\sqrt{-(k_0^2 - k_{\rho lw}^2)} = \beta_{zlw} + j\alpha_{zlw}$$

The difficulty with leaky Waves

$$\vec{f}_{Lw}(\vec{r}) = -2\pi j \sum_i Res\left[\frac{e^{\frac{j\pi}{4}}\sqrt{k_{\rho LW}}\,e^{-jk_{\rho LW}\rho}}{2\pi\sqrt{2\pi\rho}}\, e^{-jk_{zLW}z}\,\tilde{\boldsymbol{G}}^{fc}(k_{\rho LW}, z=0, z')\,\vec{\boldsymbol{C}}_{\boldsymbol{0}}(k_{\rho Lw}, \phi)\right]\Bigg|_{k_\rho = k_{\rho LW}}$$



$$e^{-jk_{zLW}z} = e^{-j\beta_{zLW}z}e^{-j(j\alpha_{zLW})z}$$

$$= e^{-j\beta_{zLW}z}e^{\alpha_{zLW}z}$$

This scared people for decades
Their claimed was they did not exist

Integration path: far observation point

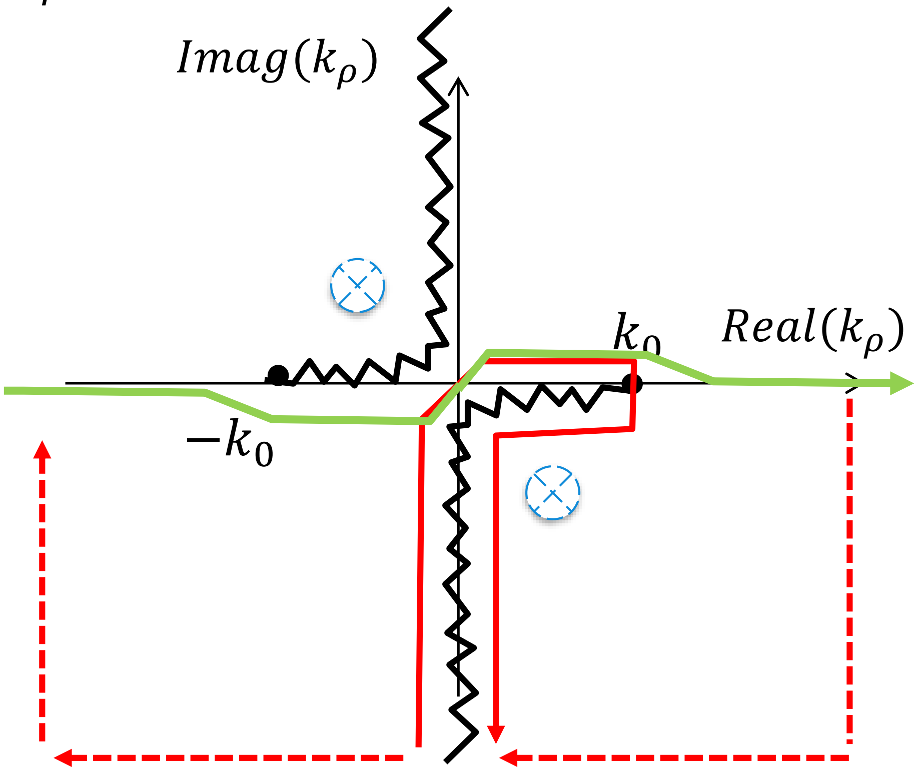
Complex pole singularities (Bottom sheet poles)

$$k_{\rho lw} = \beta_{lw} - j\alpha_{lw} \qquad k_{zlw} = j\sqrt{-(k_0^2 - k_{\rho lw}^2)}$$

Waves that propagate in the transverse direction with attenuation

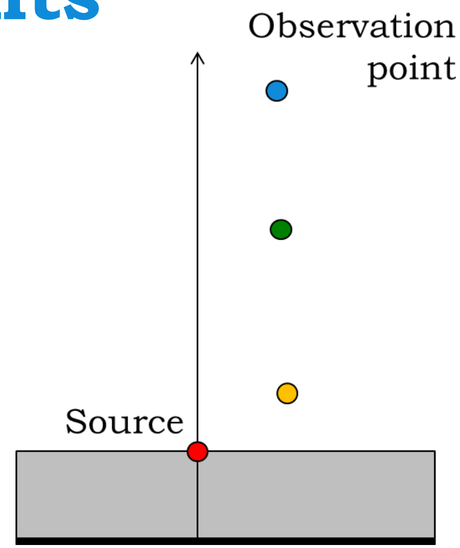
However it is captured in other deformations: near-field!!!

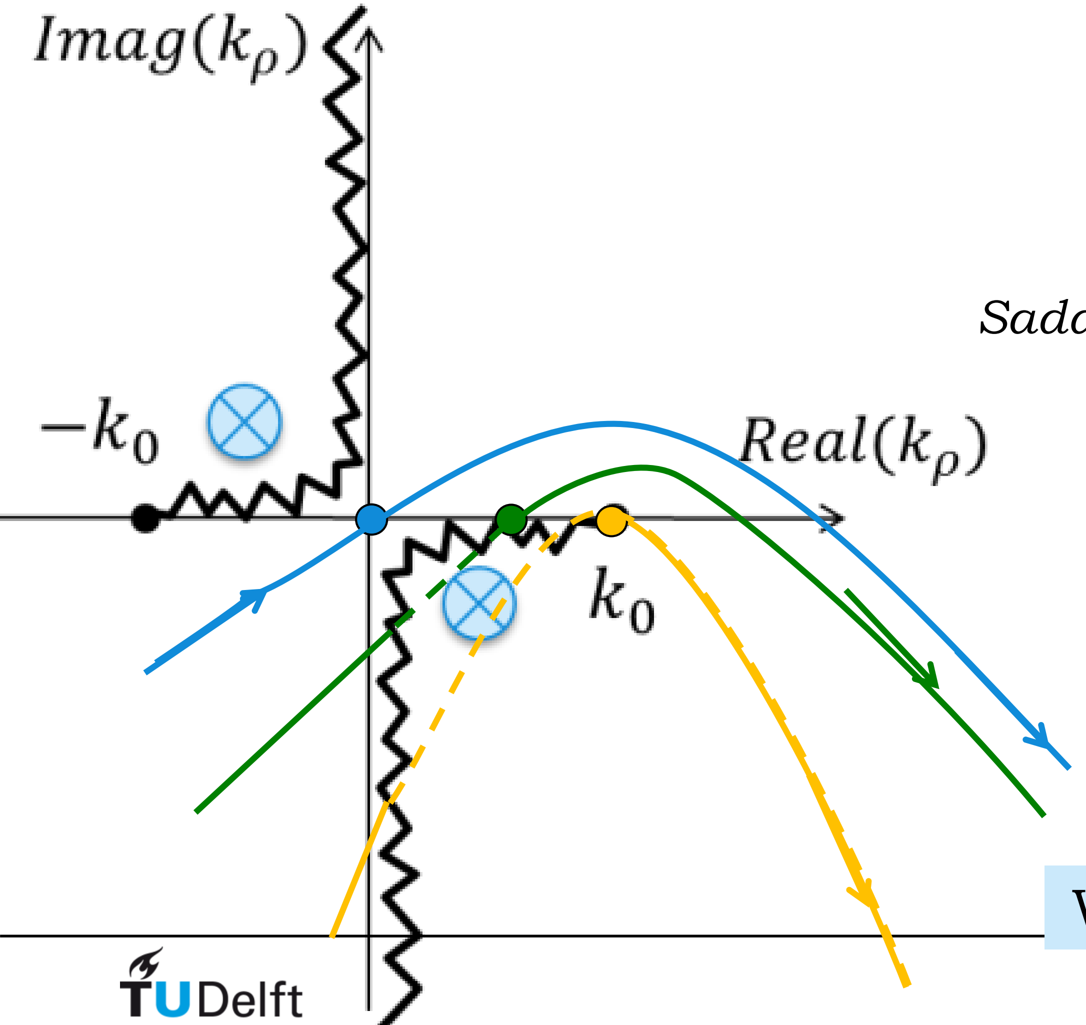
Not captured in the deformation around the branch



Near field observation points

For near field ***steepest descent path*** are the integration paths that guarantee most rapid convergence of the integral





Saddle point exist in these paths

$$k_{\rho 1} = k_0 sin0 = 0$$

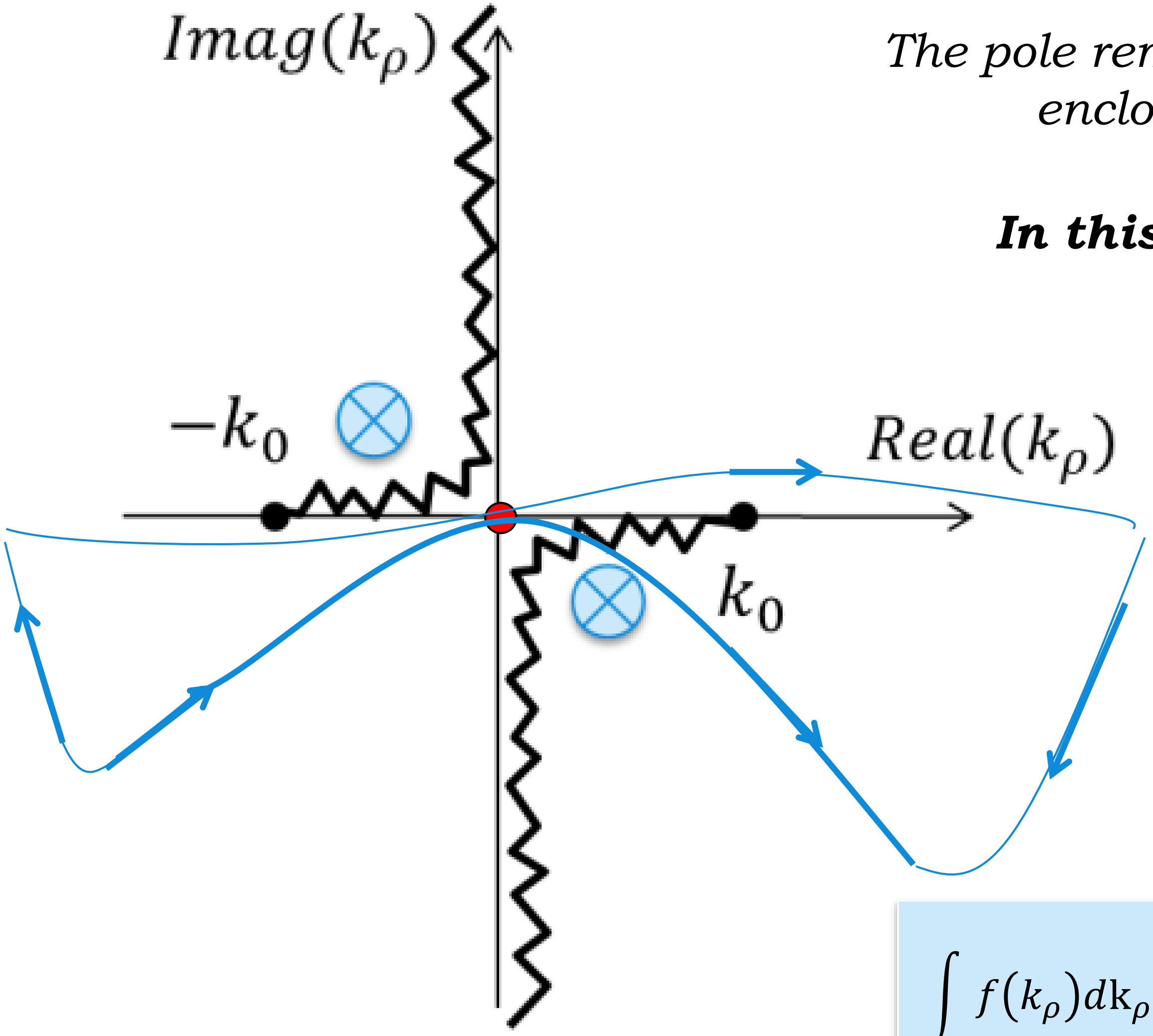
$$k_{\rho 2} = k_0 \sin\frac{\pi}{4} = k_0/\sqrt{2}$$

$$k_{\rho 3} = k_0 \sin\frac{\pi}{2} = k_0$$

When is the LW pole captured?

Deformation on SDP

From the original path to SDP via deformation

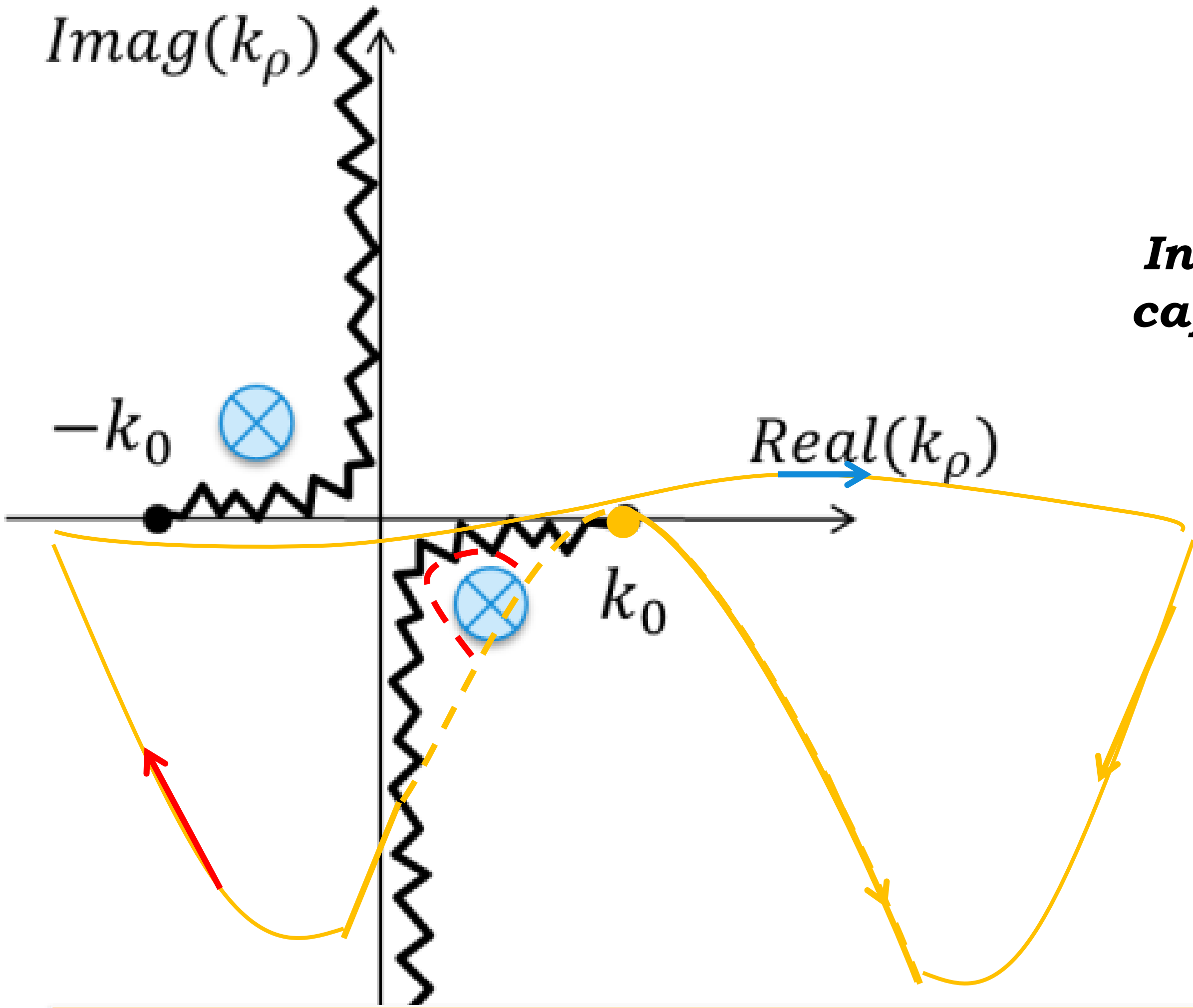


The pole remains outside the enclosed region

In this case no pole is captured

$$\int_R f(k_\rho)dk_\rho = \int_{SDP} \tilde{\boldsymbol{G}}^{fc}(k_\rho, z, z')e^{-j\vec{k}_\rho\cdot\vec{\rho}}\ k_\rho dk_\rho$$

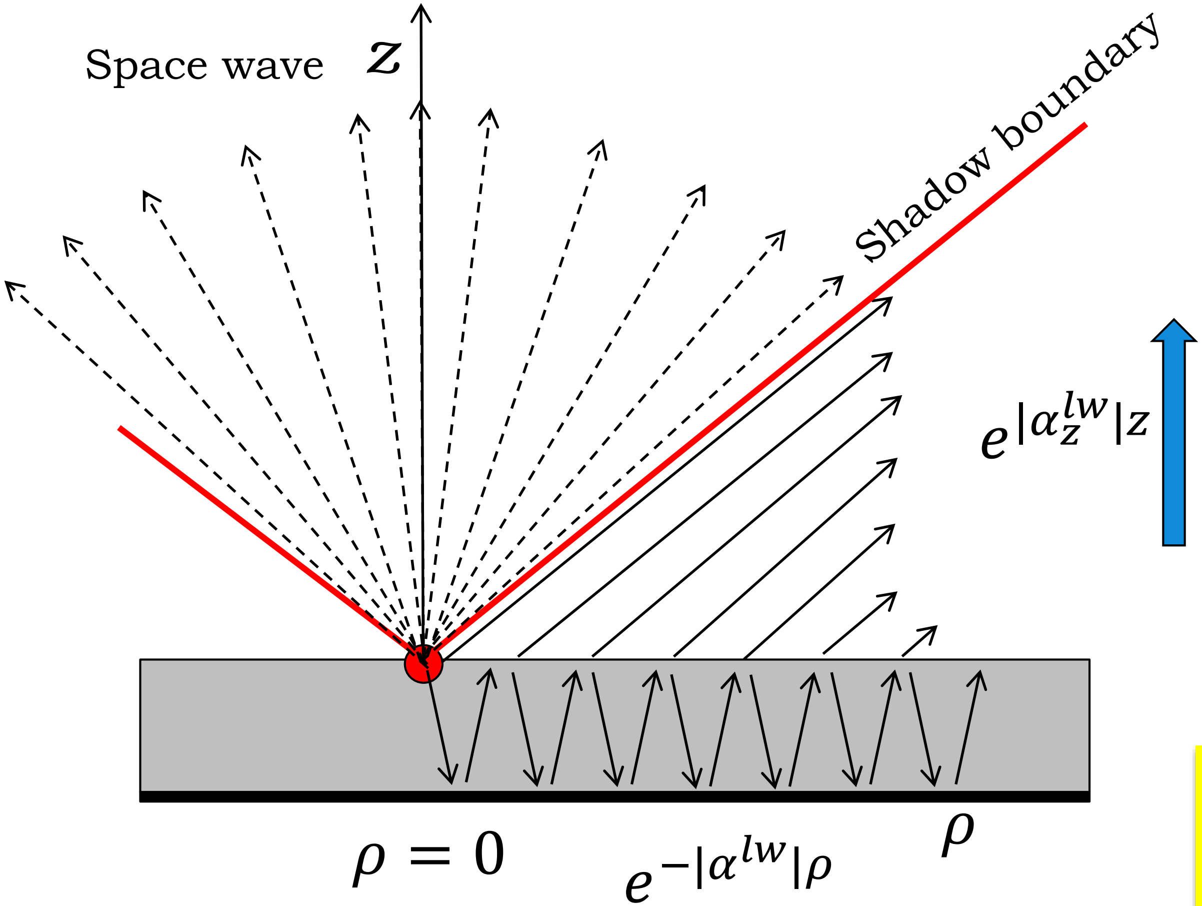
Near field shaping with leaky waves



In this case a pole is capture in the bottom Riemann sheet

$$\int_R f(k_\rho)dk_\rho = \int_{SDP} \widetilde{\boldsymbol{G}}^{fc}(k_\rho, z, z')e^{-j\vec{k}_\rho\cdot\vec{\rho}}\ k_\rho dk_\rho - 2\pi j\, Res\left[\widetilde{\boldsymbol{G}}^{fc}(k_\rho, z, z')e^{-j\vec{k}_\rho\cdot\vec{\rho}}\ k_\rho\right]\Big|_{k_\rho=k_{\rho i}}$$

Existence Region

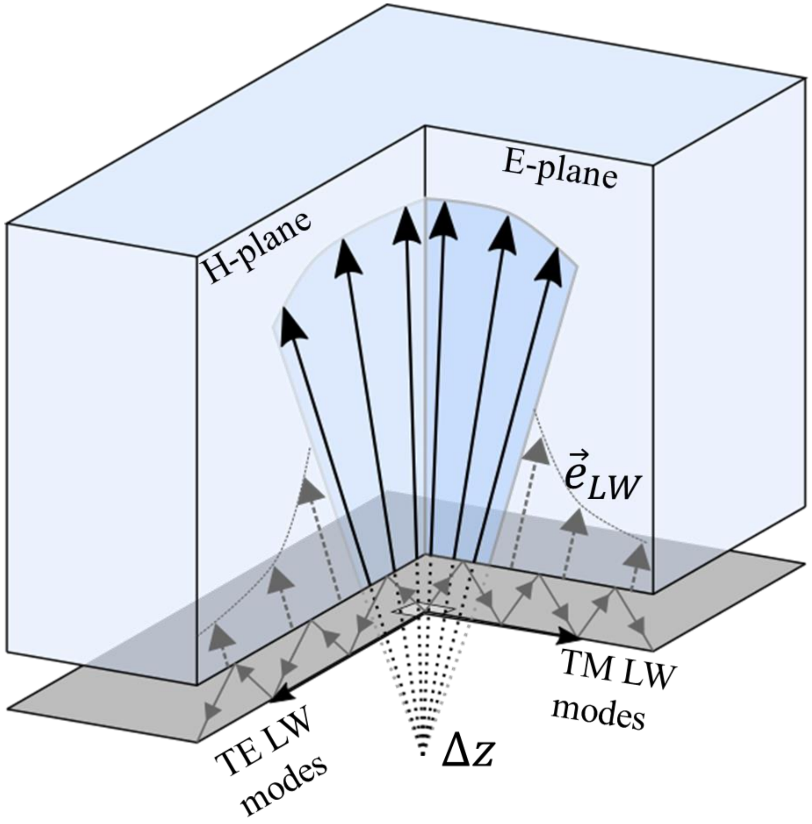


If you take any ρ, and then increase z from zero, the wave becomes larger… until it disappears at the shadow boundary

If you take $z = 0$, and then increase ρ from zero, the wave attenuates exponentially to zero

The leaky wave field contribution is in fact limited to a region of existence.

Existence Region



The leaky wave pole is only captured for observation points near the source

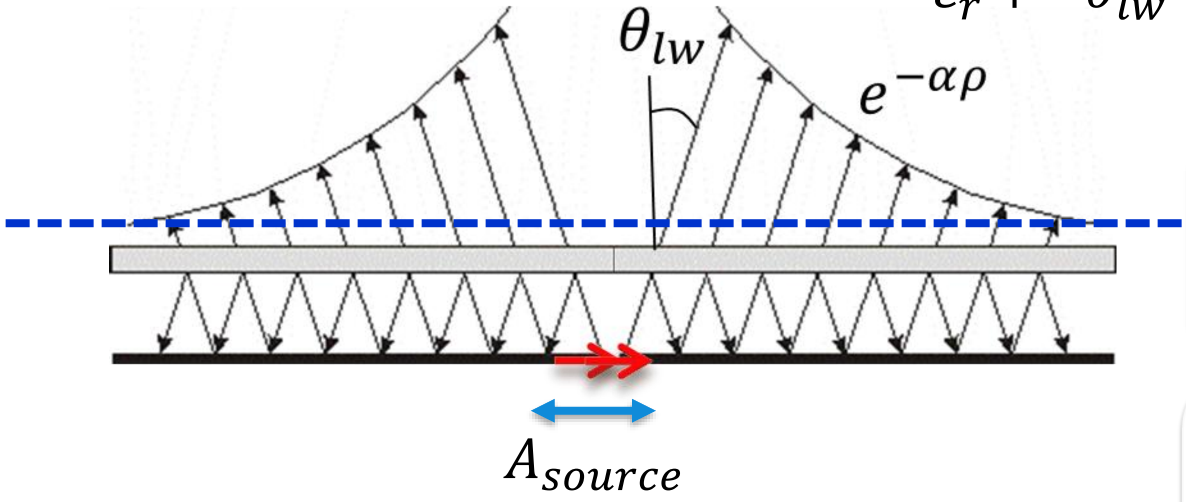
The residue contribution does not arrive to infinity

But it is responsible to the power transferred to the far field of the antenna: **modulation of the SFG in the region around θ_{lw}^0**

They can be used to do pattern shaping!

Enhanced Directivity

$\varepsilon_r \uparrow \quad \theta_{lw} \downarrow \quad \alpha_{lw} \downarrow \quad Dir \uparrow$



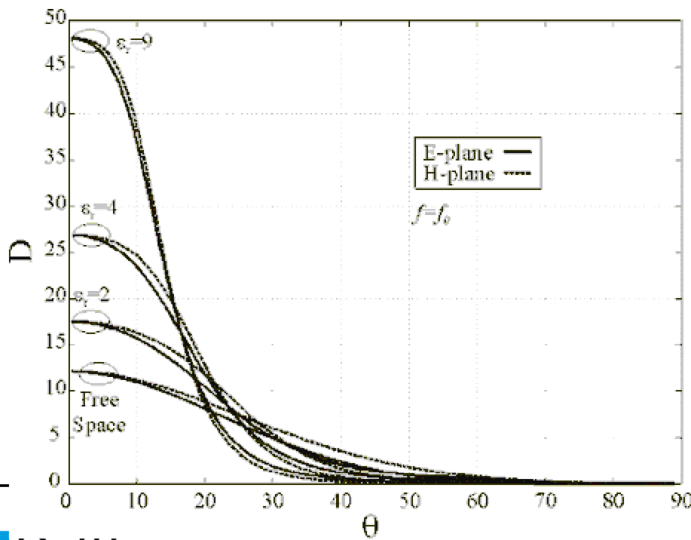
$$E \propto \frac{e^{-j\beta^{lw}\rho}e^{-\alpha^{lw}\rho}}{\sqrt{\rho}}$$

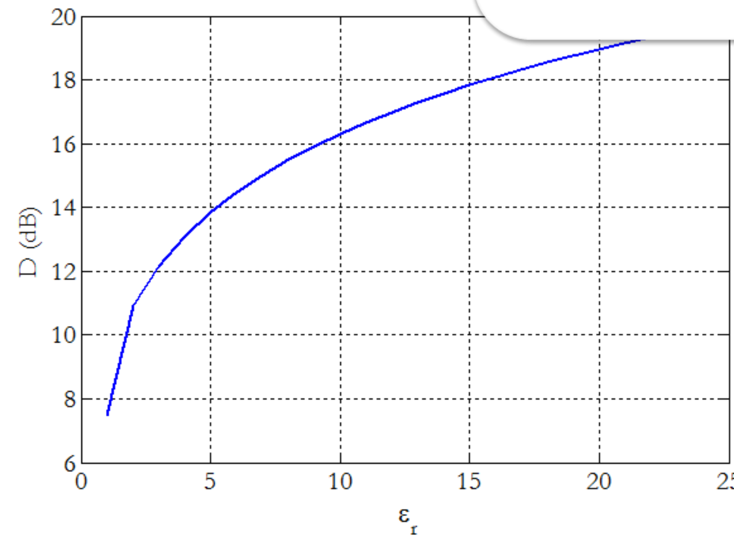
$$A_{eff} \propto \frac{1}{\alpha^2} \gg A_{source}$$

Resonant condition:

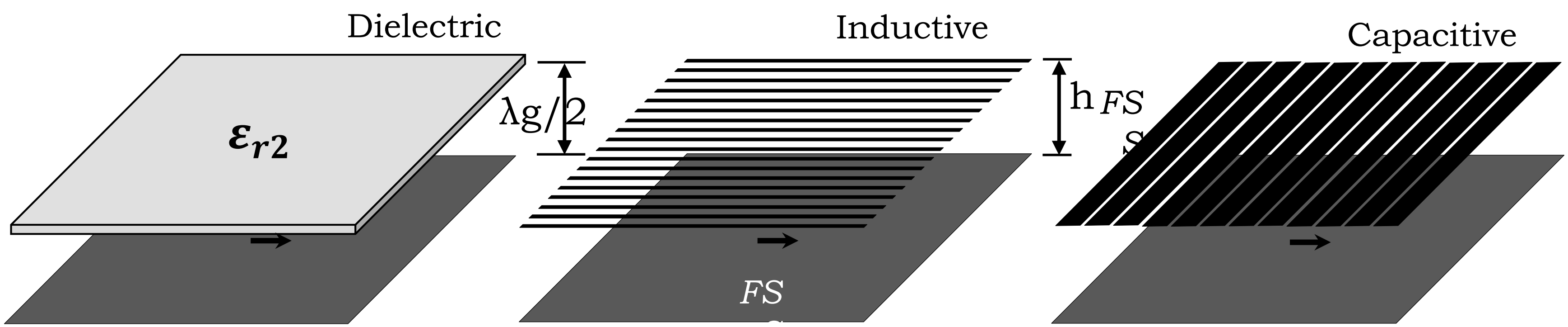
$$h = \frac{\lambda_0}{2\cos\theta_0}$$

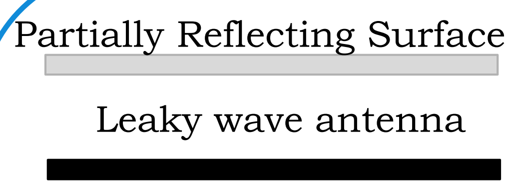
$$h_d = \frac{\lambda_{d2}}{4\cos\theta_d}$$



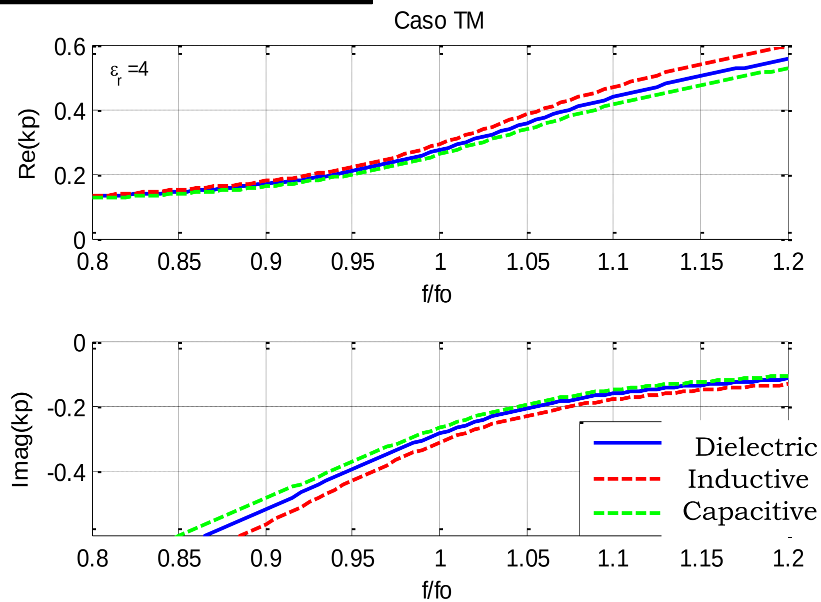


Partially Reflecting Surfaces





FSS and Dielectric are equivalent for broadside radiation



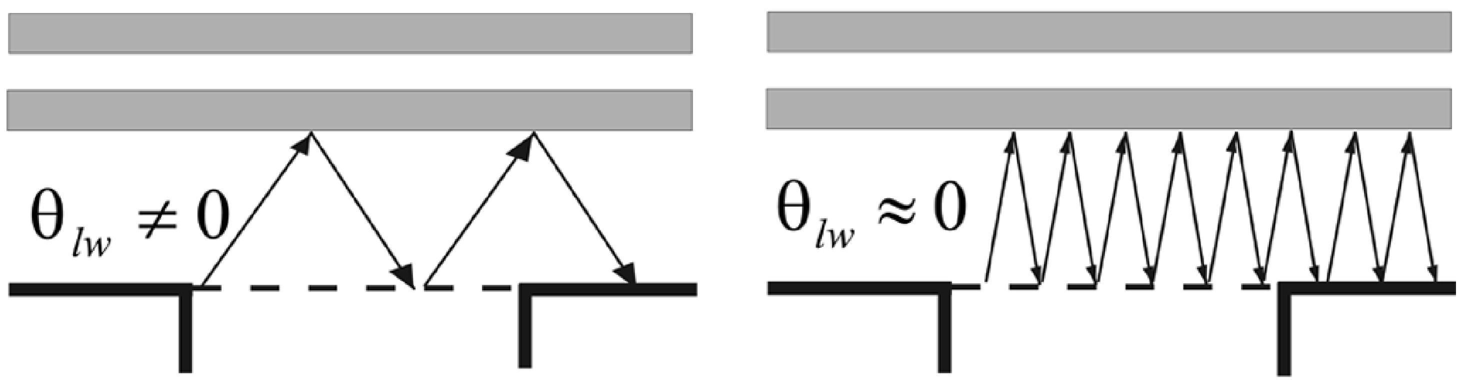
Bandwidth Issues

Input Admittance:

$$Y_{in} = \frac{1}{(2\pi)^2} \iint_{-\infty}^{\infty} |M(k_x, k_y)|^2 G^{hm}(k_x, k_y) dk_x dk_y$$

Highly dominated by the presence of the leaky wave poles $Res\left(G^{hm}(k_x, k_y)\right) \propto \frac{1}{sin\theta_{lw}}$

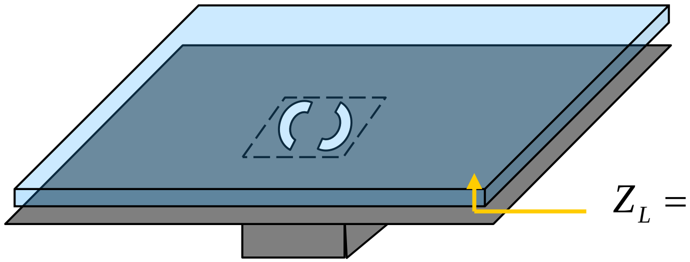
BW $\Leftrightarrow$ $\frac{Y^{ebg}(f_1)}{Y^{ebg}(f_2)} \approx \frac{k_{lw}(f_2)}{k_{lw}(f_1)}$



$\varepsilon_r \uparrow \quad \theta_{lw} \downarrow \quad \alpha_{lw} \downarrow \quad Dir \uparrow \quad BW \downarrow$

A. Neto, N. Llombart, G. Gerini, M. Bonnedal, P. De Maagt, “EBG Enhanced Feeds for the Improvement of the Aperture Efficiency of Reflector Antennas”, IEEE TAP, vol. 55, no. 8, pp.2185-2193, Aug. 2007.

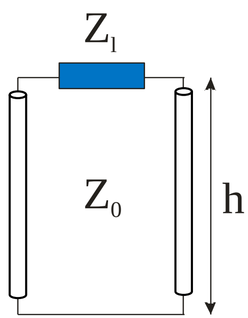
Leaky Wave Lens Feed



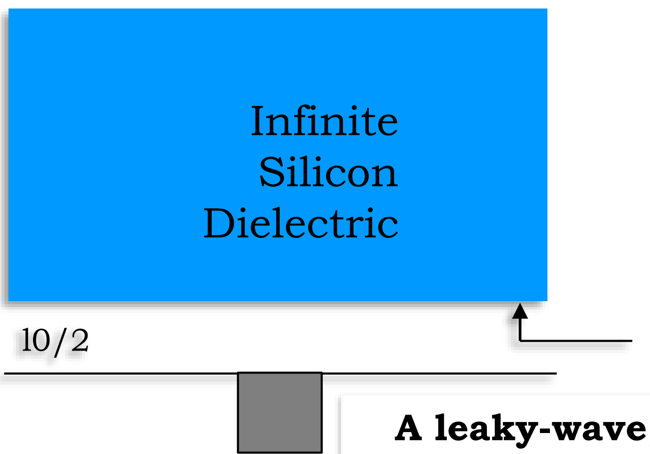
λd/4 Quartz Super/layer

$$Z_L = \frac{\zeta_0}{\varepsilon_r} = \frac{\zeta_0}{3.8}$$

Waveguide Feed

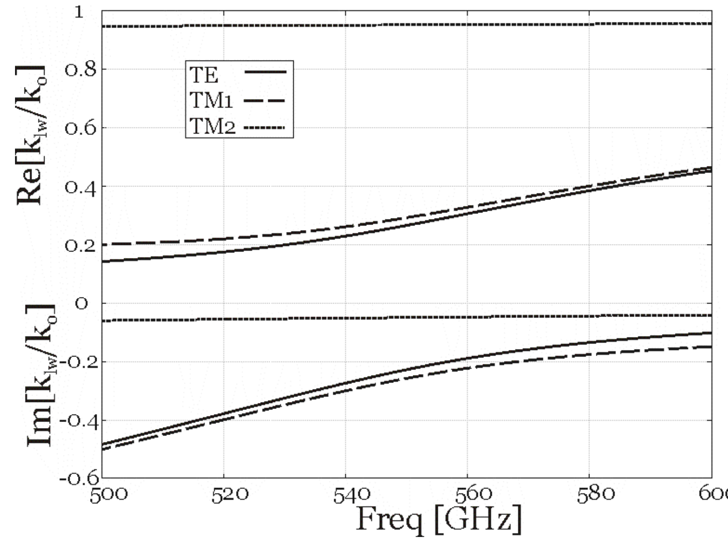


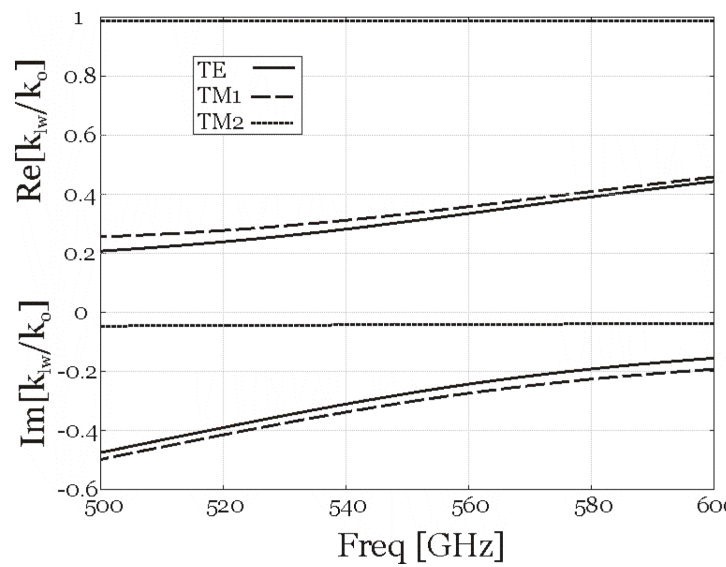
h=λ0/2 Cavity



$$Z_L = \frac{\zeta_0}{\sqrt{\varepsilon_r}} = \frac{\zeta_0}{3.45}$$

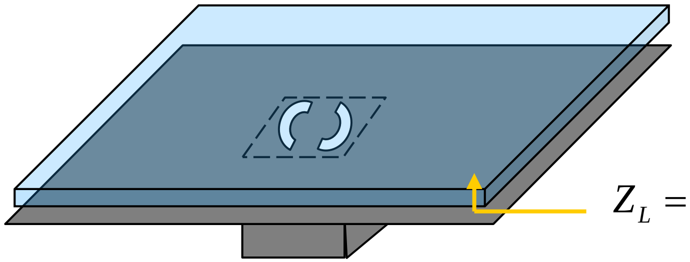
A leaky-wave/EBG cavity can be used to illuminate a lens





Same dispersion diagram than quarter-wavelenght superstrates

Leaky Wave Lens Feed

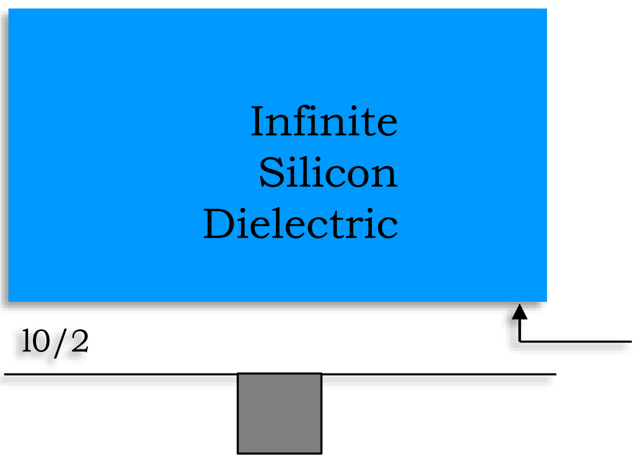


$$Z_L = \frac{\zeta_0}{\varepsilon_r} = \frac{\zeta_0}{3.8}$$

$$D = 4\pi A_{ef}/\lambda_0^2$$

Same effective area given by the same leaky wave mode

ε_r higher directivity for the same bandwidth or leaky wave frequency dispersion

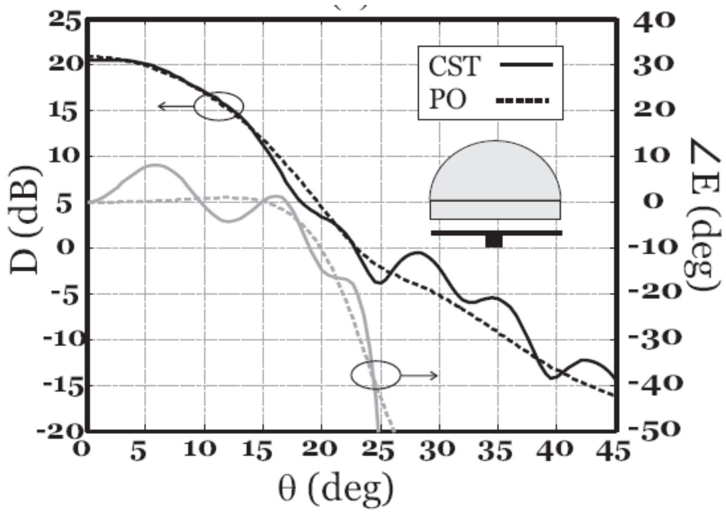


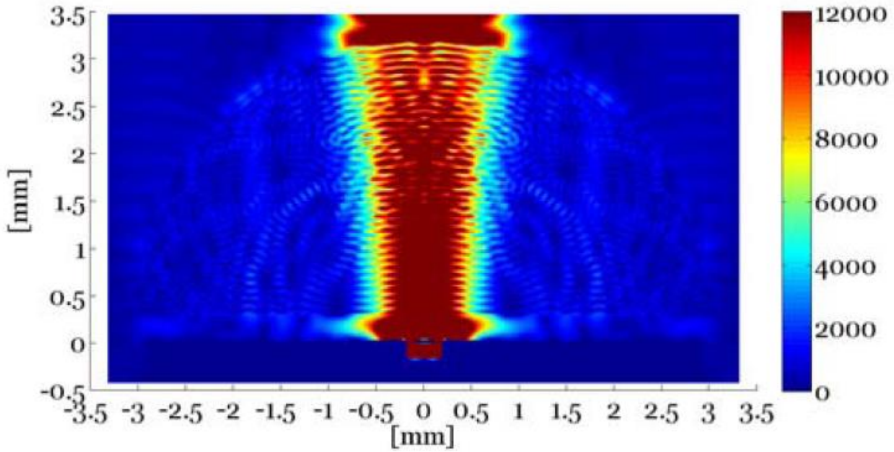
$$Z_L = \frac{\zeta_0}{\sqrt{\varepsilon_r}} = \frac{\zeta_0}{3.45}$$

$$D = 4\pi A_{ef}/\lambda_d^2 = 4\pi A_{ef}\varepsilon_r/\lambda_0^2$$

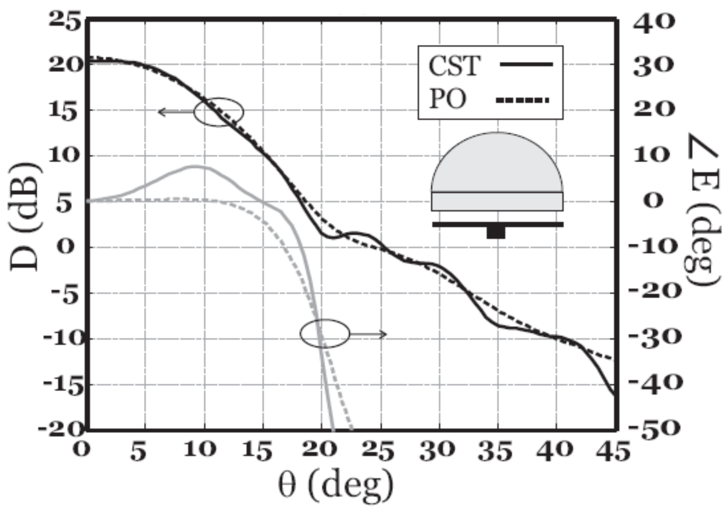
Lens Radiated Fields in standard lenses

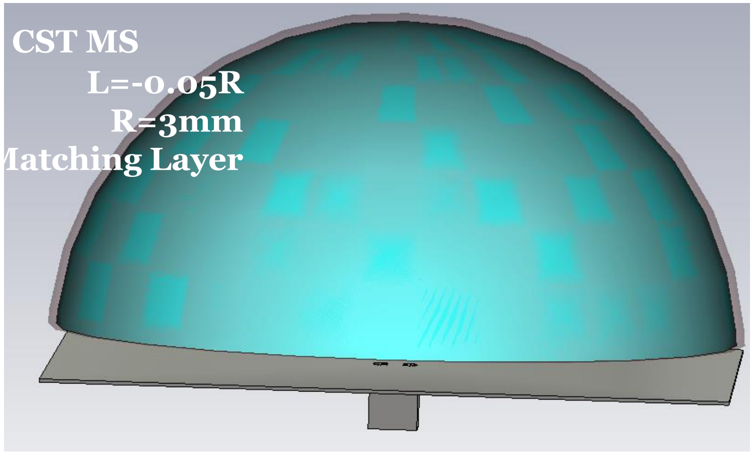
E Plane





H Plane

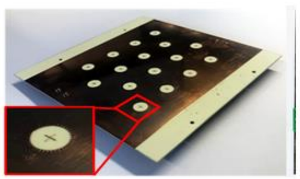




Examples of Lens LW Prototypes

30GHz HDPE/PCB

Scanning Lens Phased Array

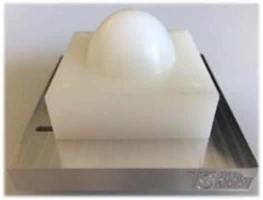


HUAWEI

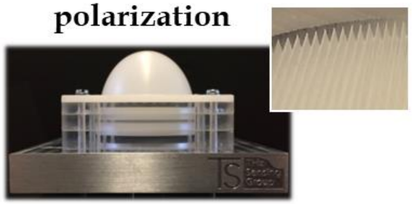
DEMO
www.demo.tudelft.nl

140GHz-220GHz HDPE/TOPAS Prototypes

High-gain wideband LW lens antennas

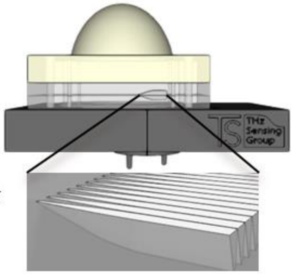


Circular polarization



IMST

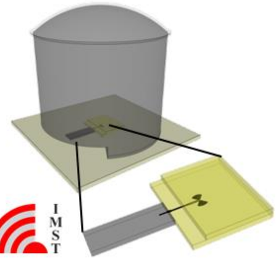
Steering enhancement



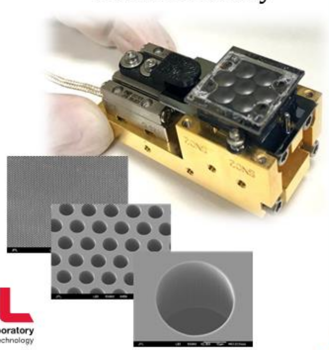
DEMO
www.demo.tudelft.nl

300&500GHz Silicon Prototypes

In-package wideband LW lens antenna



Scanning Lens Phased Array



IMST

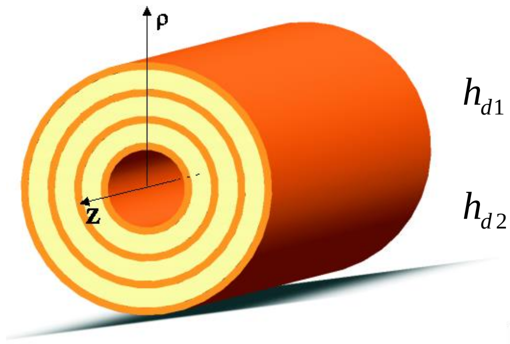
Fraunhofer IAF

JPL
Jet Propulsion Laboratory
California Institute of Technology

erc

Waveguide Applications

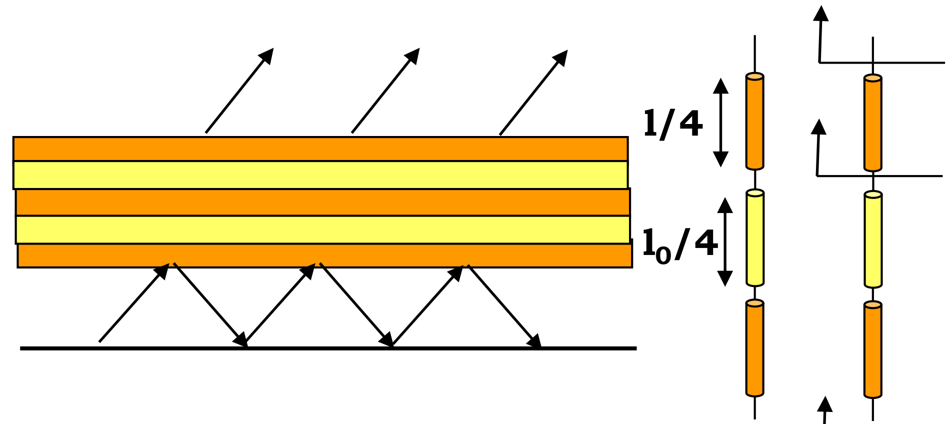
Bragg Fibers



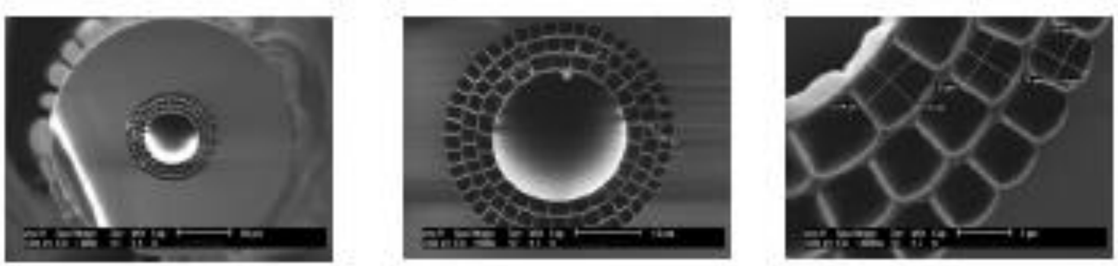
Same Resonant condition than leaky wave antenna:

$$h_{d1} = \frac{\lambda_{d1}}{4\cos\theta_{d1}}$$

$$h_{d2} = \frac{\lambda_{d2}}{4\cos\theta_{d2}}$$



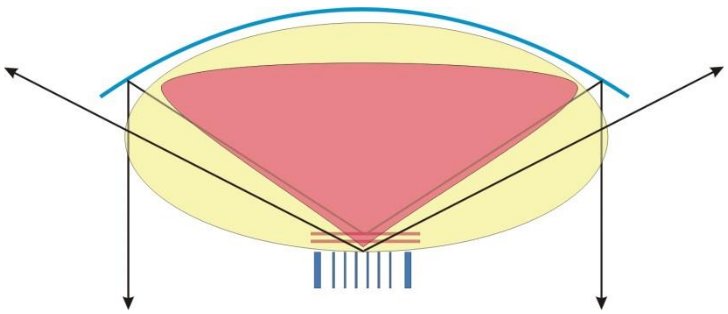
- They are used at near infrared and optical regimes.
- Field distribution similar than a circular waveguide

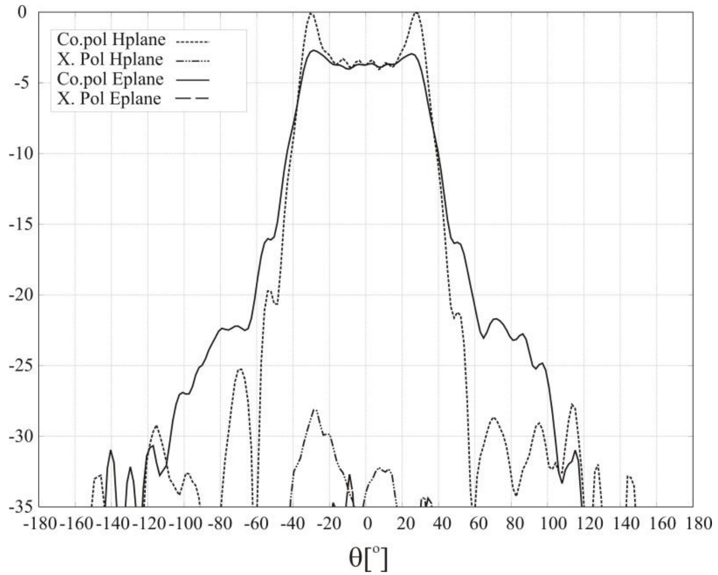


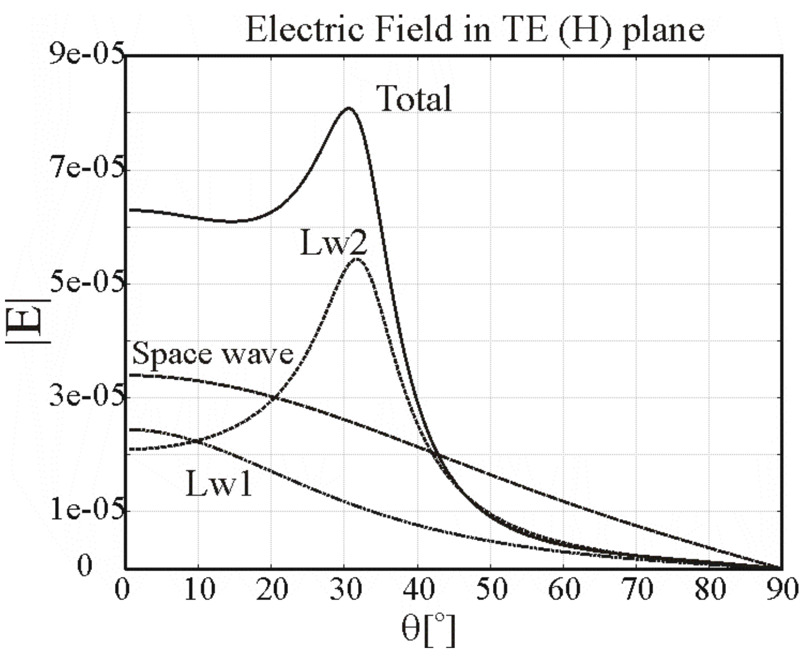
Loss in the order of dB/km

Field Shaping Application

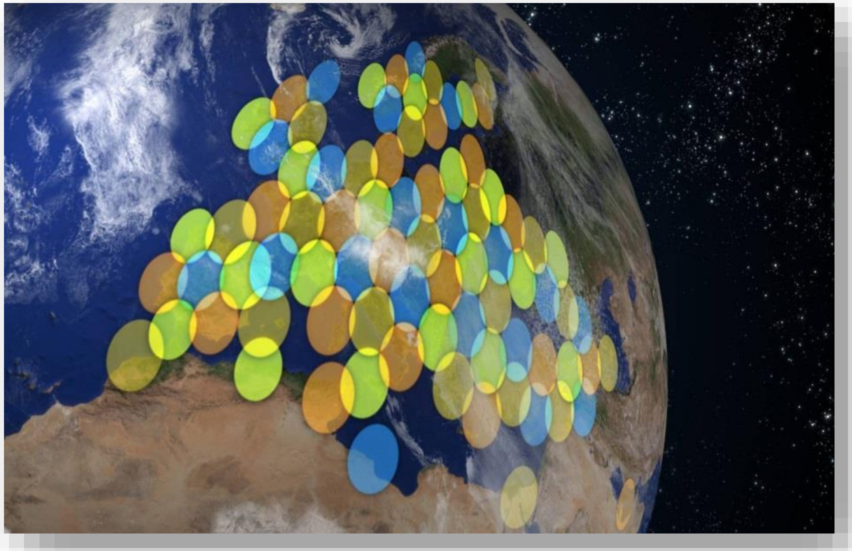
Illumination of reflector
with 90% efficiency



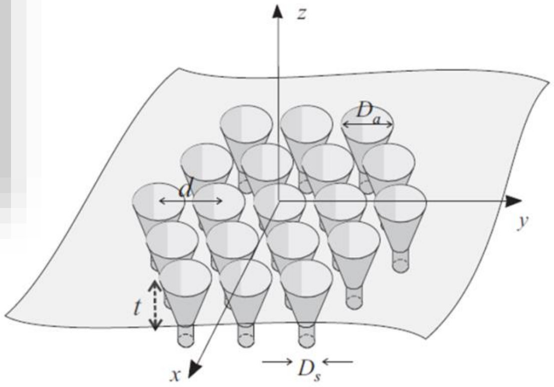




Multi Beam Imaging for Telecom



Ka Band
Telecommunication
Applications
Earth Coverage by using
Multiple Antenna Beams



__Technological Solutions__

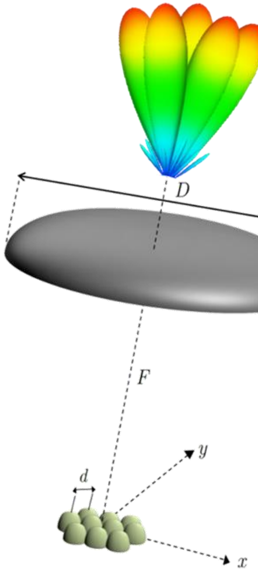
Use of reflectors for high directivity in combination with

1) Phased Arrays generating multiple beams

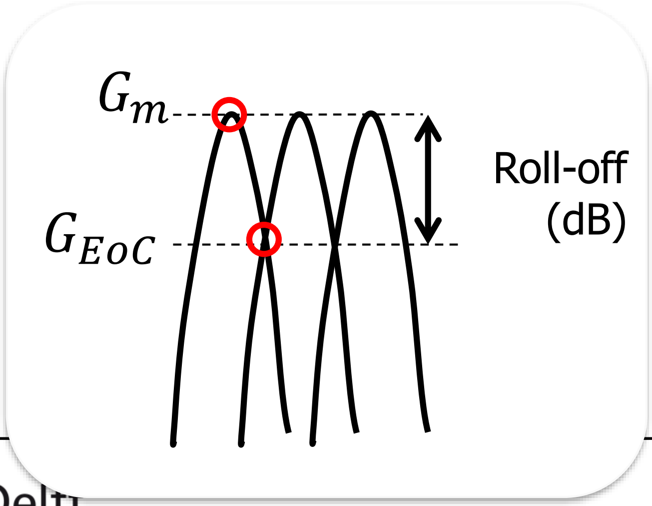
2) Focal Plane Arrays with Single Fed per Beam

Edge of Coverage Gain

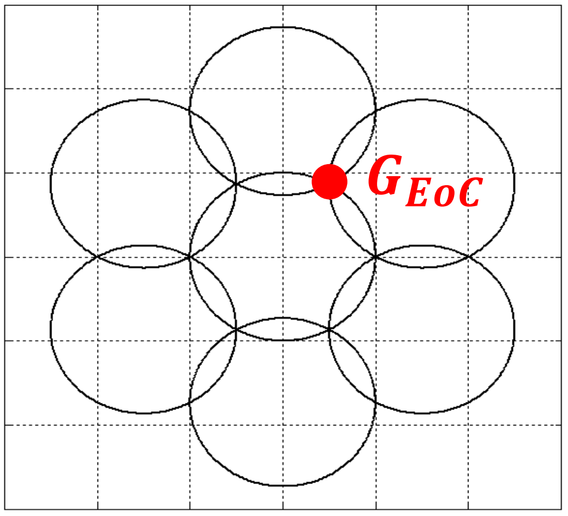
The goal is to maximize the gain at the edge of coverage and keep the inter-beam interferences low



Far Field Beams

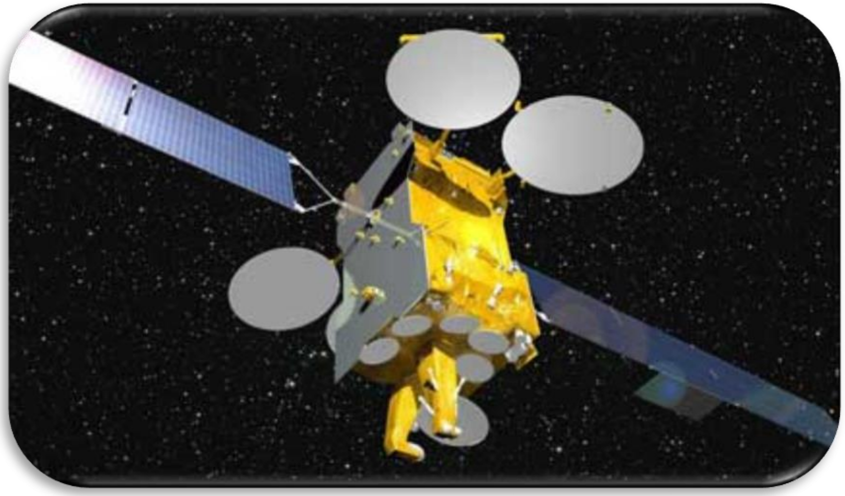


The best packaging is achieve for an hexagonal array

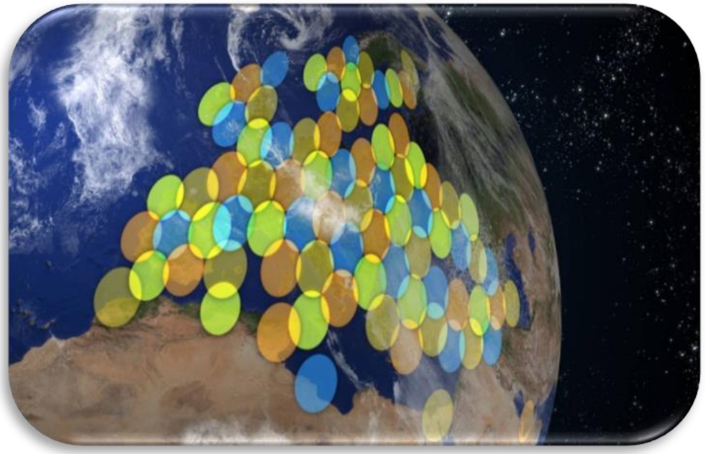


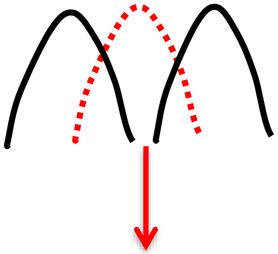
Standard Solution for ka Satellites

Use of 4 reflectors to increase the Geoc with $2\lambda_0 f_\#$ FPA



Diminish roll-off without increasing spill over





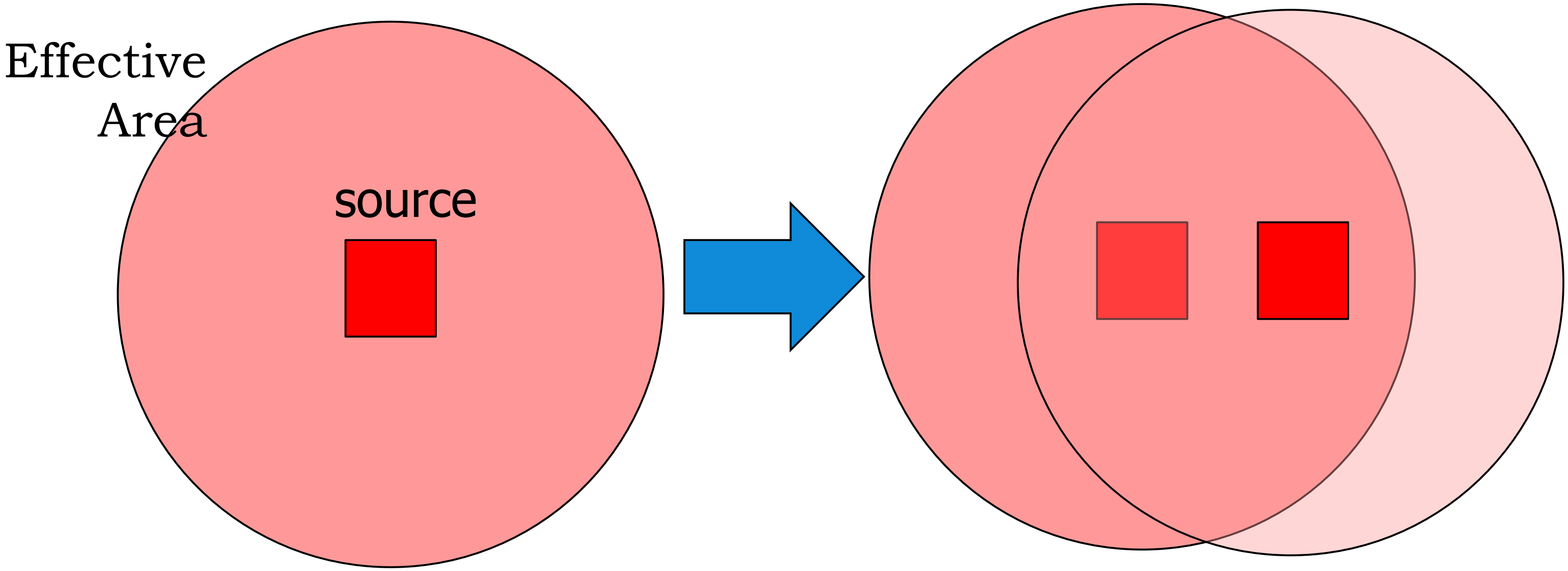
Beam generated by another reflector

$$G_{EoC} \approx D_m + SO + RO = D_m + 3.5dB$$

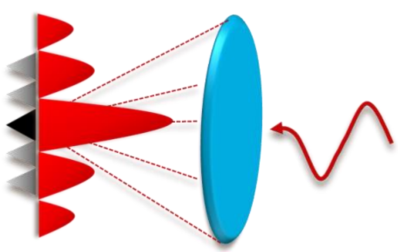
S. Rao, Handbook of Reflector Antennas and Feed Systems

Overlapped Feeds

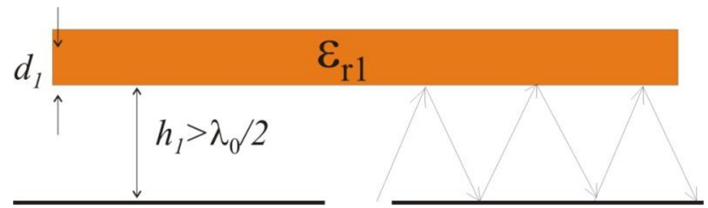
Is it possible to place them closer in the FPA?



Use of Phased arrays: Coherent beamforming of 3x3 or 5x5 sub arrays



Leaky wave/Fabry Perot Antennas

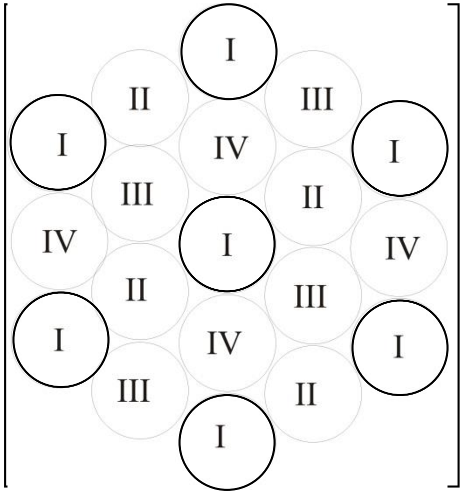


Antennas with directive patterns and ‘small physical areas’

Overlapped Feeds FPA

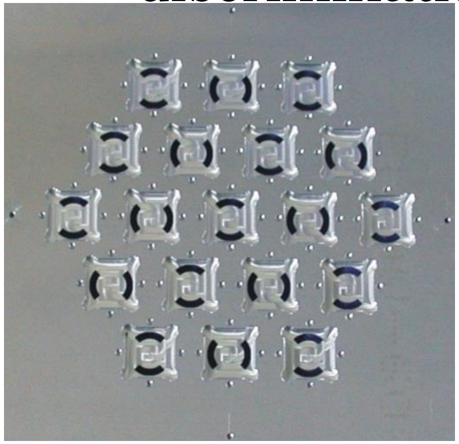
Loss due to the mutual coupling

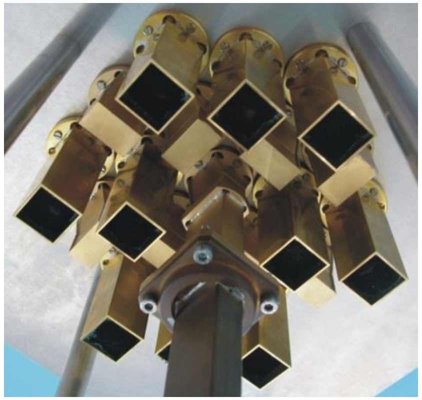
Use of reactive loading to compensate for it: **Equivalent short circuits loads** for neighboring waveguides

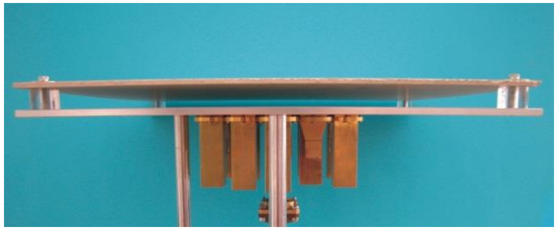


1) Polarization discrimination

2) Frequency discrimination

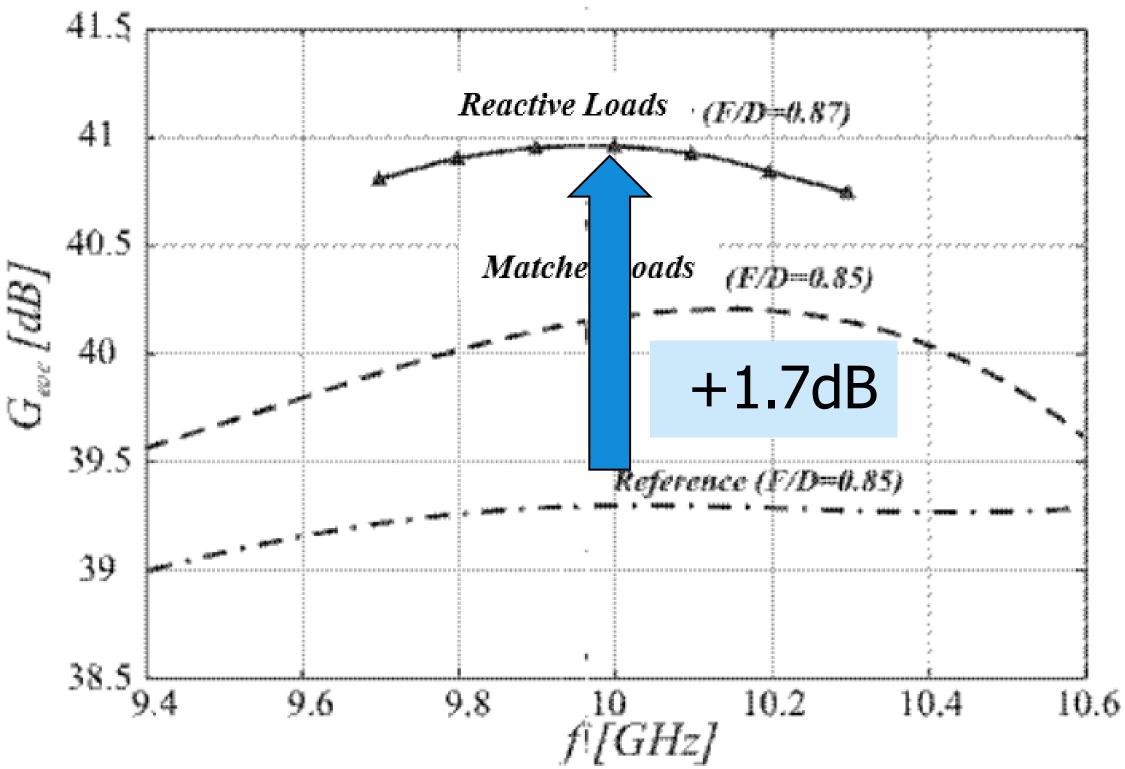






Effectively in-band feeds at double distance ($S_{12} \ll -25dB$)

Reactively Loaded case



10% Bandwidth

Important Points

Stratified GFs contain poles on bottom Riemann sheet

They correspond to leaky waves

These poles are complex and located closed to the real axes on the bottom Riemann sheet

These poles are not captured in deformations around branch, but in other deformations useful to obtain analytic evaluations of the near field

In the near field, the leaky waves are cylindrical waves, similar to surface waves but with an attenuation associated to radiation

Leaky waves can be used to shape the far field of small sources

Related IEEE Papers on LWAs

- D. R. Jackson and A. A. Oliner, "A leaky-wave analysis of the high-gain printed antenna configuration," IEEE Transactions on Antennas and Propagation, vol. 36, no. 7, pp. 905–910, Jul. 1988, doi: 10.1109/8.7194.

- G. Lovat, P. Burghignoli, and D. R. Jackson, "Fundamental properties and optimization of broadside radiation from uniform leaky-wave antennas," IEEE Transactions on Antennas and Propagation, vol. 54, no. 5, pp. 1442–1452, May 2006, doi: 10.1109/TAP.2006.874350

- R. Gardelli, M. Albani, and F. Capolino, "Array thinning by using antennasinaFabry-erot cavity for gainenhancement,"IEEETrans.Antennas Propag., vol. 54, no. 7, pp. 1979–1990, Jul. 2006

- A. Neto, N. Llombart, G. Gerini, M. D. Bonnedal, and P. de Maagt, "EBG Enhanced Feeds for the Improvement of the Aperture Efficiency of Reflector Antennas," IEEE Transactions on Antennas and Propagation, vol. 55, no. 8, pp. 2185–2193, Aug. 2007,

- N. Llombart, G. Chattopadhyay, A. Skalare, and I. Mehdi, "Novel Terahertz Antenna Based on a Silicon Lens Fed by a Leaky Wave Enhanced Waveguide," IEEE Transactions on Antennas and Propagation, vol. 59, no. 6, pp. 2160–2168, Jun. 2011, doi: 10.1109/TAP.2011.2143663.

- M. Arias Campo, D. Blanco, S. Bruni, A. Neto, and N. Llombart, "On the Use of Fly's Eye Lenses with Leaky-Wave Feeds for Wideband Communications," IEEE Transactions on Antennas and Propagation, vol. 68, no. 4, pp. 2480–2493, Apr. 2020,

- M. Alonso-delPino, S. Bosma, C. Jung-Kubiak, G. Chattopadhyay, and N. Llombart, "Wideband Multi-Mode Leaky-Wave Feed for Scanning Lens Phased Array at Submillimeter Wavelengths," IEEE Transactions on Terahertz Science and Technology, 2020,