European School of Antennas

Short course: **Artificial EBG surfaces and metamaterials**

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Canonical surfaces

Canonical Surface		E-field Polarization	
		VER or TM	HOR or TE
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT	STOP	STOP
	HARD	GO	GO
PMC-type EBG	grazing	STOP	STOP
	close to normal	PMC	

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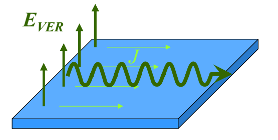
  - TEM waveguides
  - Reduction of blockage from cylinders
  - Examples of applications: soft, hard, AMC
  - Numerical approaches

PEC: Wave propagation along surface

VER propagation GOes with

$$\partial E_{VER} / \partial n = 0$$

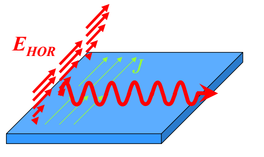
at surface.



HOR polarization STOPs with

$$E_{HOR} = 0$$

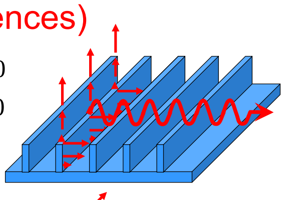
at surface



Soft surface: Principle of operation for transverse corrugations (current fences)

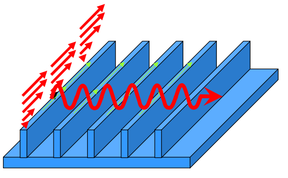
E_{VER} sees AMC (transformation from short-circuit to open-circuit in grooves)

$$E_{VER} = 0$$
$$J_{long} = 0$$



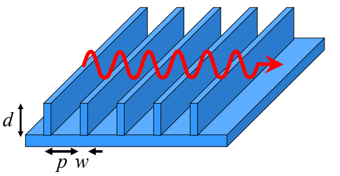
E_{HOR} sees PEC. No penetration into grooves.

$$E_{HOR} = 0$$
$$J_{transv} = undesturbed$$



Soft surface: Bandwidth is limited by surface waves

Ideally large 2:1 bandwidth



$p < \lambda / 2, \quad p / w < 2$

λ_c = wavelength in corrugations

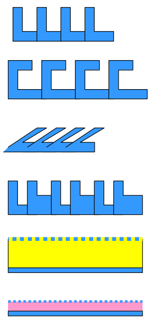
$d < \lambda_c / 4$: surface waves

$\lambda_c / 4 < d < \lambda_c / 2$: no surface waves, i.e. STOP band

$d = \lambda_c / 4$: best frequency

$d > \lambda_c / 2$: surface waves

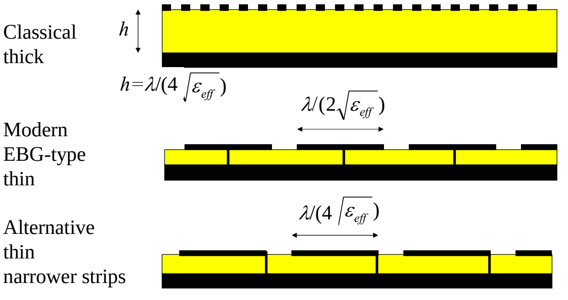
Soft surfaces:
Relative bandwidths of different realizations



- Conventional, up to 1.8
- Cavity-loaded up to 2.4
- Tilted, typically 1.5
- Dual-depth = two narrow bands
- Strip-loaded dielectric up to 1.2 (problem with surface waves)
- Magnetic coating with transverse metal strips, >>1, but lossy

Realizations with transvers strips

$\varepsilon_{eff}=\varepsilon_r$ for soft surface



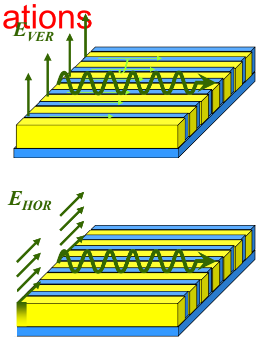
Hard surface: Principle of operation for longitudinal corrugations

E_{VER} sees PEC.

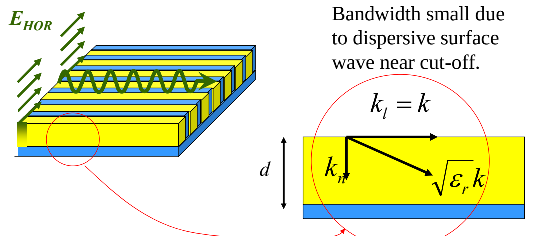
$$\partial E_{HOR}/\partial n = \partial E_{VER}/\partial n = 0$$

E_{HOR} sees AMC at TEM freq. (transformation from short-circuit to open-circuit in slab)

HOR case: Equivalent to grounded slab problem. Rely on surface wave at cut-off.



Hard surface:
We MUST have dielectric filling to get field transformation

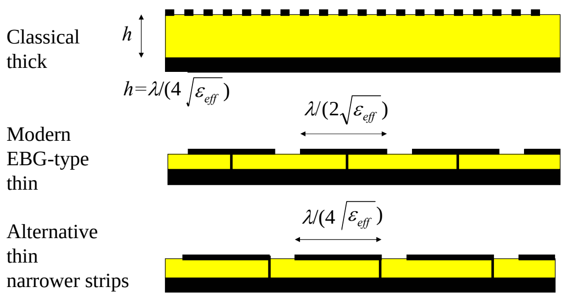


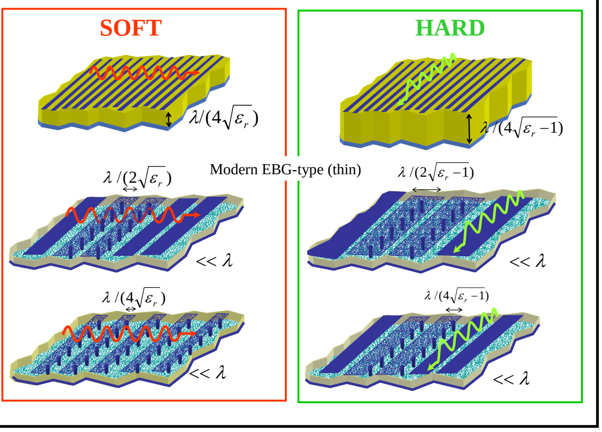
Bandwidth small due to dispersive surface wave near cut-off.

$$AMC\ (TEM\ \ frequency)\ if\ k_n d = \pi/2 \quad \Rightarrow \quad d = \frac{\lambda}{4\sqrt{e_r - 1}}$$

Realizations with longitudinal strips

$\varepsilon_{eff}=\varepsilon_r-1$ for hard surface





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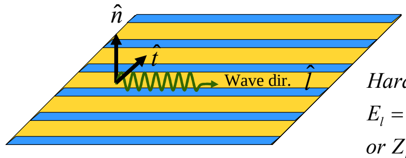
Hard surface supports TEM wave intrinsically



Hard surface defined by

$E_l = H_l = 0$

$or\ Z_l = 0,\ Z_t = \infty$

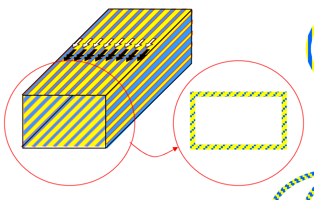
Plane wave in $\hat{l}$ direction:

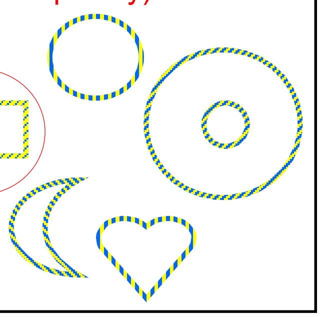
$$\vec{E} = \left[E_n\hat{n} + E_t\hat{t}\right]e^{-jkl}$$

$$\vec{H} = \left[H_n\hat{n} + H_t\hat{t}\right]e^{-jkl} = \left[Z_0E_t\hat{n} - Z_0E_n\hat{t}\right]e^{-jkl}$$

automatically satisfies boundary condition

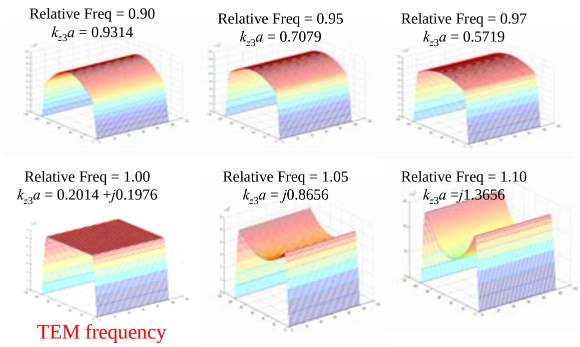
Hard surface: Hard cylinders of any cross-sectional shape are TEM waveguides (at center frequency)





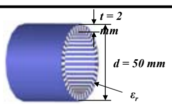
Examples od TEM waveguides with ideal PEC/PMC strip walls. No x-pol. Uniform illumination.

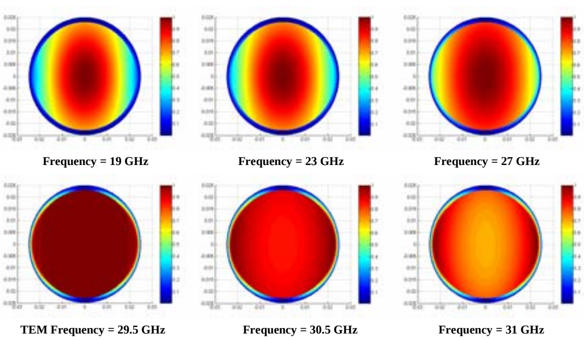
Analytical field solution in rectangular hard quasi TEM dielectric-loaded waveguide



TEM frequency

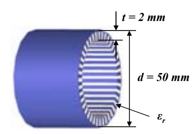
Analytical solution in circular hard corrugated waveguide, D = 5λ



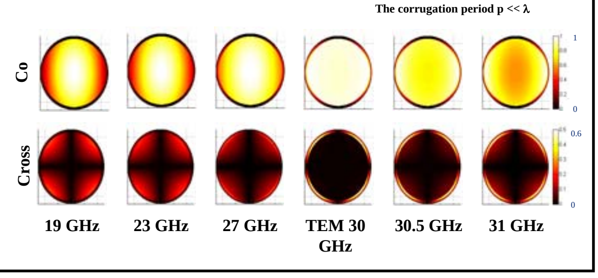


Classical-type model: Dominant TE_z mode field distribution

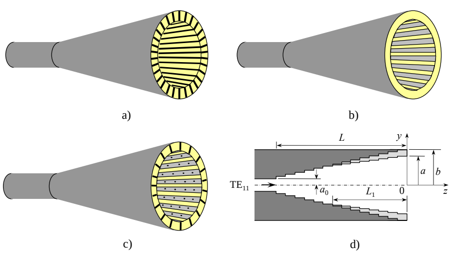
Example: $d = 5\lambda$ at 30 GHz $\varepsilon_r = 2.5$ f_{TEM} = 30 GHz



The corrugation period p << λ

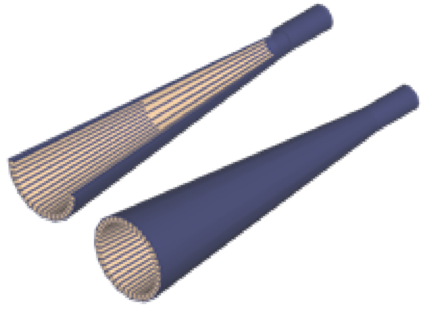


Different hard horn realizations

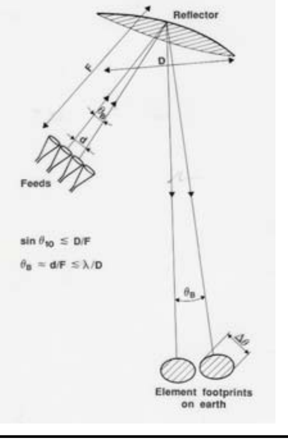


Longitudinally corrugated hard horn

(Sotoudeh, Kildal, Ingvarsson, Mangenot 2004)



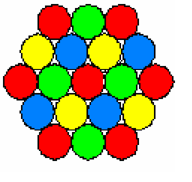
Application of hard horns in cluster feeds for satellite antennas with multiple beams



Example of layout of footprints (4-cell frequency reuse plan and 4 reflectors)

Requirements to:

- **Directivity in each lobe**
- **Directivity in weakest point**
- **Beam isolation**: Co and cross polar side-lobe levels in the neighboring beams with same frequency



Hard horn dimensions for cluster feed

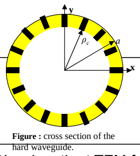
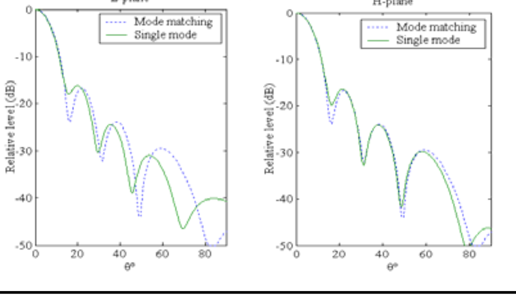


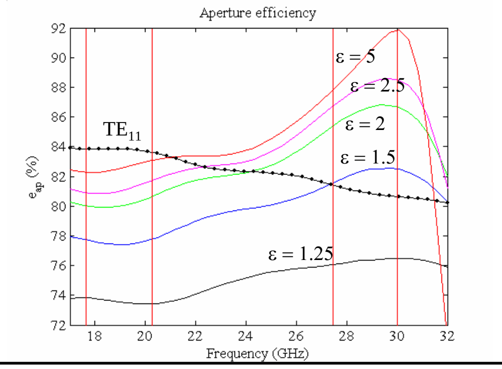
Figure : cross section of the hard waveguide.

	Dimensions	
	wavelengths	mm
Wavelength at TEM frequency of horn (31.8 GHz)	λ	9.4 mm
Horn outer diameter	5 λ	47 mm
Horn length	15 λ	142 mm
Relative permittivity of dielectric material in horn walls	ε = 1.5	ε = 1.5
Reflector diameter	140 λ	1320 mm
Reflector focal length	143 λ	1350 mm

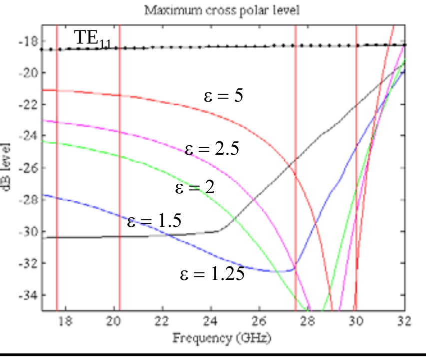
Radiation patterns of 5λ hard horn by single mode aperture integration and mode matching program



Aperture efficiency of hard horn and smooth horn of finite lengths



Maximum crosspolar sidelobe level



Requirements and results multibeam antenna with hard horn cluster

	Requirements	Hard horn results (over the whole band)
End of coverage directive gain	> 39.5 dBi	> 40 dBi
Co-polar beam isolation relative to weakest useful point	> 25 dB	> 26 dB
Cross-polar beam isolation relative to weakest useful point	> 27 dB	>> 27 dB
XPD	< -27 dB	< -27 dB
Reflection coefficient at feed port	<-27 dB	< -25 dB*

Example: Miniaturized hard waveguides in dual-frequency array (aperture reuse)

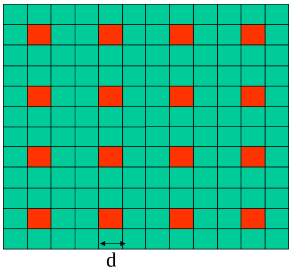


Figure shows array element locations at different frequencies f. Full scan implies element spacing < 0.5 λ at both frequencies

$\mathbf{f_{low}}$

$\mathbf{f_{high} = 3f_{low}}$

Strongly miniaturized elements needed at $\mathbf{f_{low}}$ **: d = 0.16 λ**

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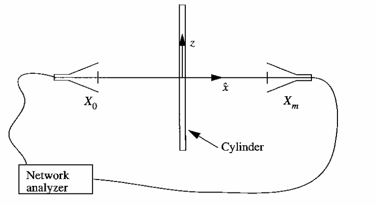
Example of structure which gives siedelobes: Support struts.

Sidelobes can be reduced by HARD surfaces

Reduce scattering from structure around antenna

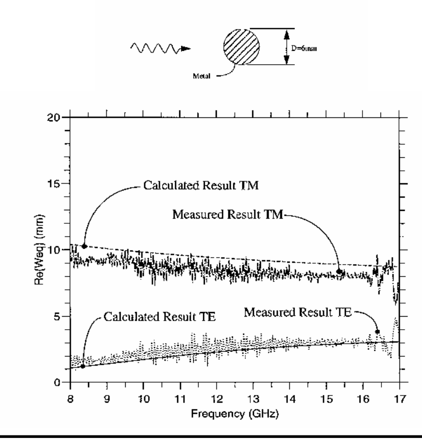
Setup for measuring forward scattering from cylindrical objects



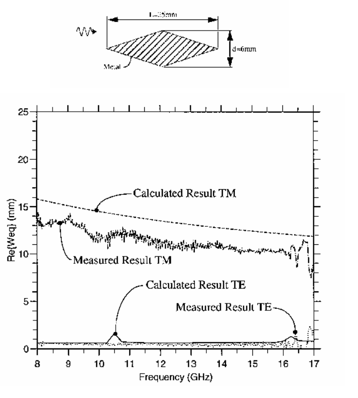
Forward scattering is characterized in terms of an Induced Field Ratio or an Equivalent Blockage Width.

Equivalent blockage width for circular strut.

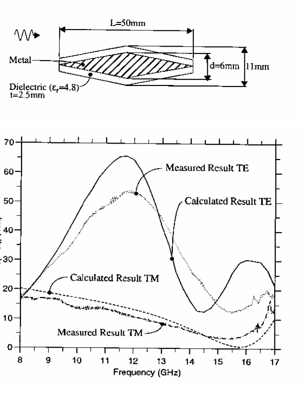
Real part is most important !



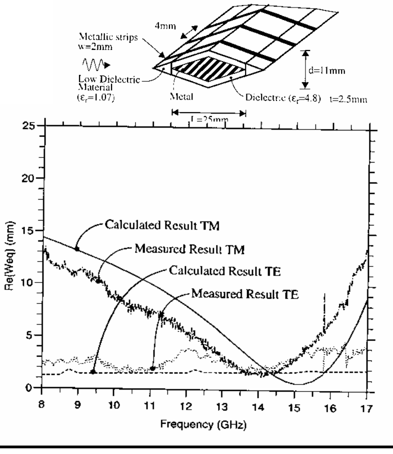
Step 1: Make good hard TE case better by changing shape



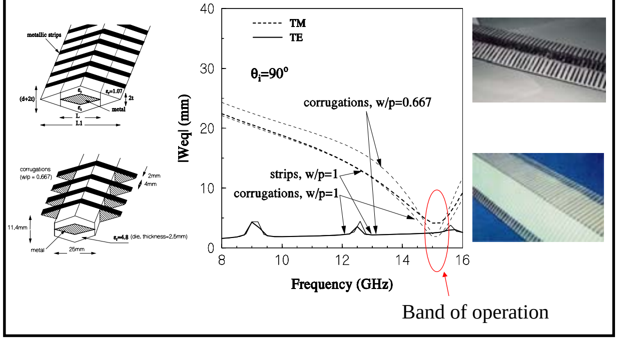
Step 2: Apply dielectric coating to make TM case hard and good.



Step 3: Apply strip-loading to make both TE and TM cases hard and good

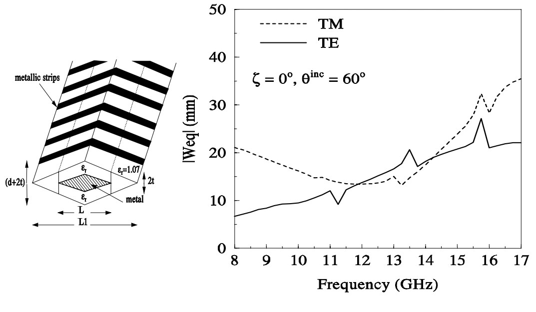


Modeling strips or corrugations with asymptotic boundary conditions

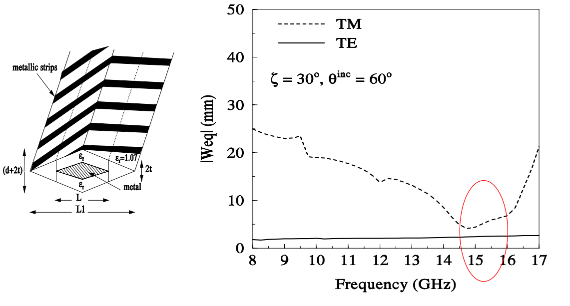


In reality wave has oblique incidence. What then?

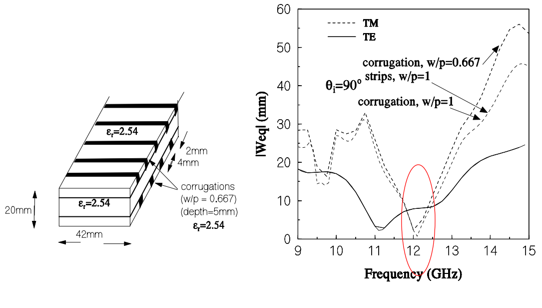
Computed results for obliques incidence are worse



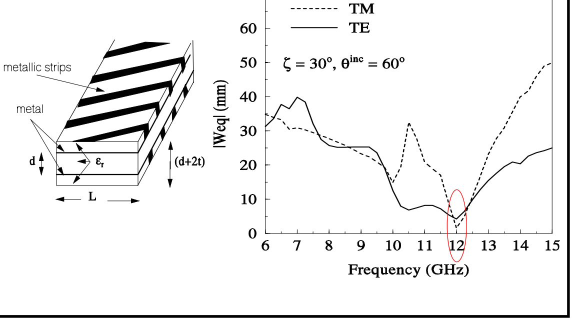
Tilted strips solves the problem



Thick blockage-free struts



Tilted struts for oblique incidence



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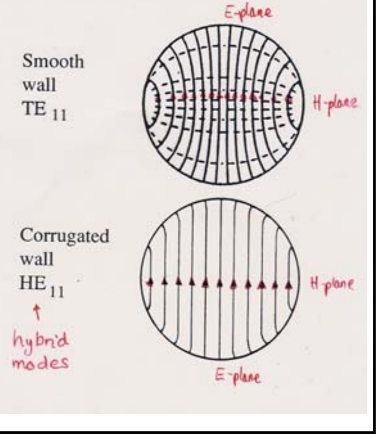
Example of corrugated horn with lens

Corrugated horns were used in earth stations like this one

Circular waveguide with PEC wall:

With soft wall:

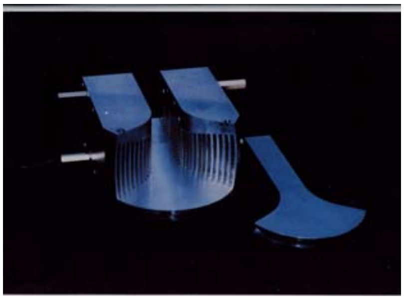
No x-pol, field zero at wall in all planes, known from corrugated horns



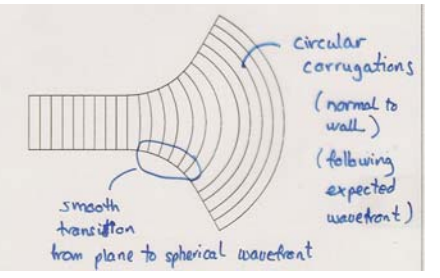
Example of corrugated horn with lens

Realization of SOFT horn by strip-loaded dielectric slab (E. Lier)

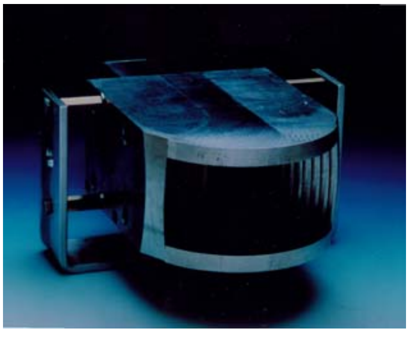
Example of corrugated sector horn



Sector horn: Corrugations should follow curvature of expected wavefront



Example of corrugated sector horn



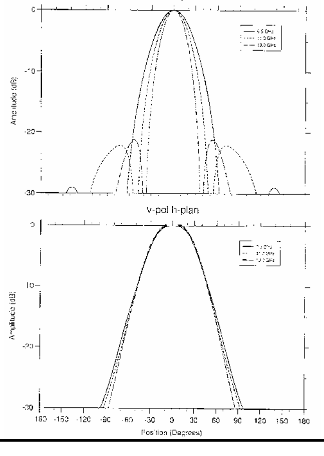
Characteristics of wide angle sector horn

Beam width in horizontal plane is flare-angle controlled:
wide lobe, almost no frequency dependence.

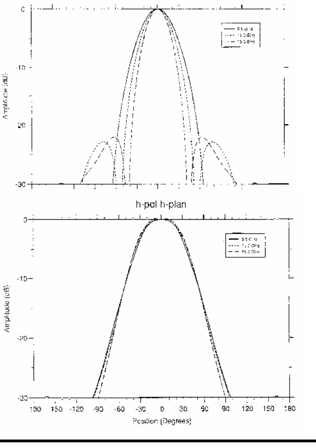
Beam width in vertical plane is aperture-controlled:

$$\theta_{3dB} = \frac{f_0}{f}\theta_0$$

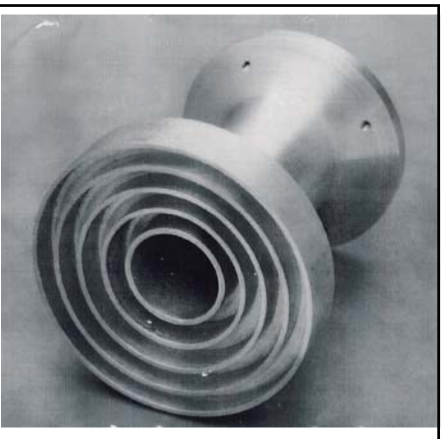
Corrugated sector horn: Theoretical radiation patterns for vertical polarization, vertical and horizontal planes



Corrugated sector horn: Theoretical radiation patterns for horizontal polarization, vertical and horizontal planes



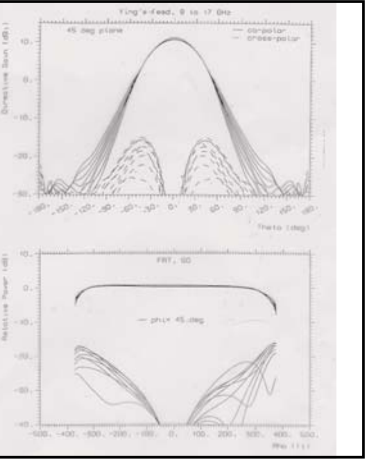
Broadband SOFT corrugated primary feed (Ying, A. Kishk and P-S. Kildal, 1995)



Ying's SOFT feed:

Constant beamwidth over 0.9-1.7 GHz

Aperture-field when used in arecibo three-reflector system

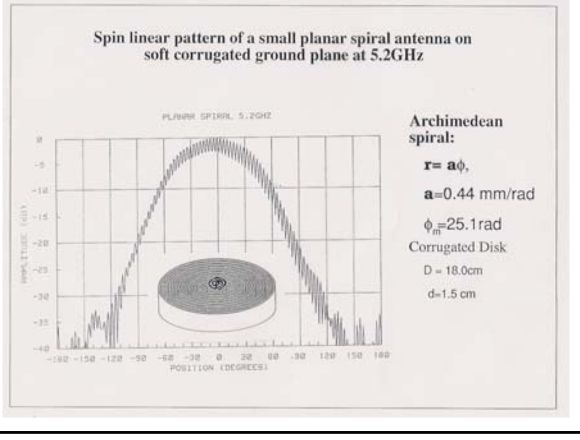


Realization of SOFT horn by strip-loaded dielectric slab (E. Lier, 1988)

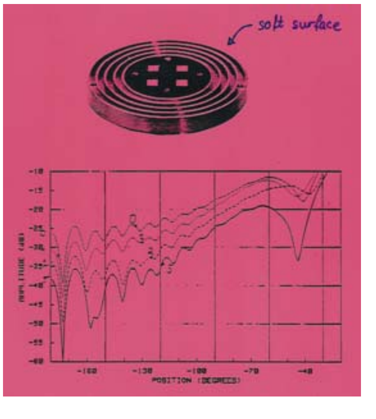
Small antennas on SOFT corrugated ground planes

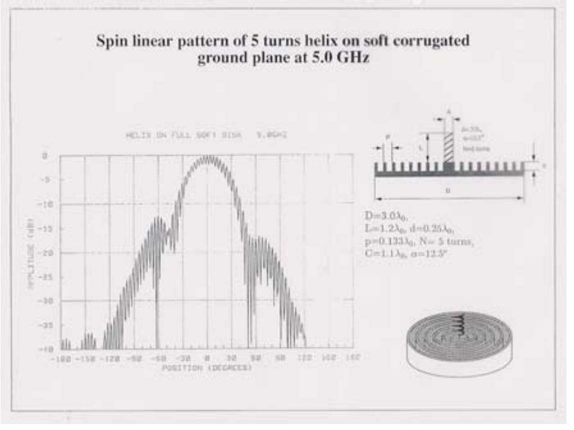
for sidelobe reduction and beam symmetry

(Ying 1996)



Sidelobe reduction versus number of surrounding SOFT corrugations for small microstrip array



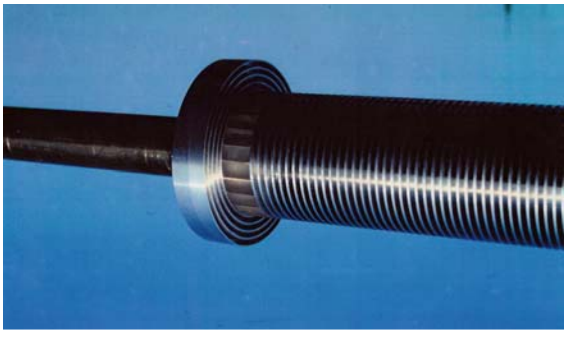


Hat feed with SOFT corrugated hat

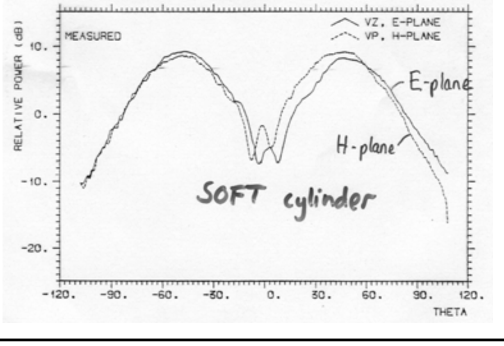
in 90 cm reflector,

12 GHz

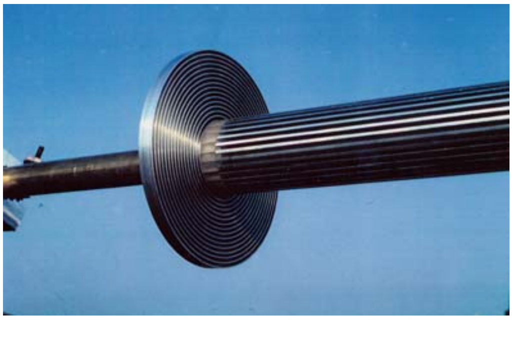
Measurements of hat feed with SOFT hat and SOFT corrugated neck (support tube)



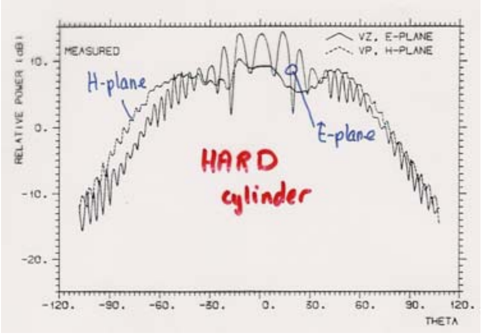
Measured patterns of hat feed with SOFT hat and SOFT corrugated neck (support tube)



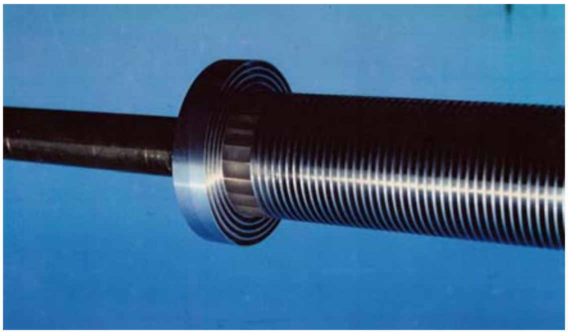
Measurements of hat feed with SOFT hat and longitudinally corrugated HARD neck



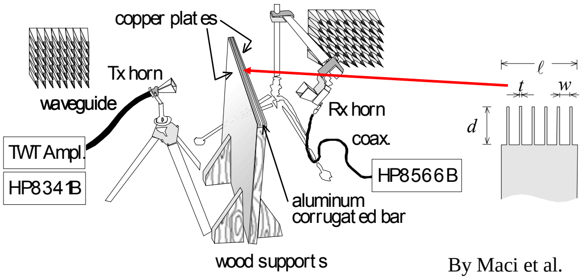
Measured patterns of hat feed with SOFT hat and longitudinally corrugated HARD neck



Measurements of hat feed with SOFT hat and SOFT corrugated neck (support tube)

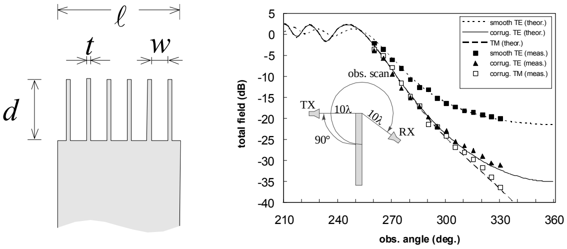


Reduction of diffraction from edge in shield



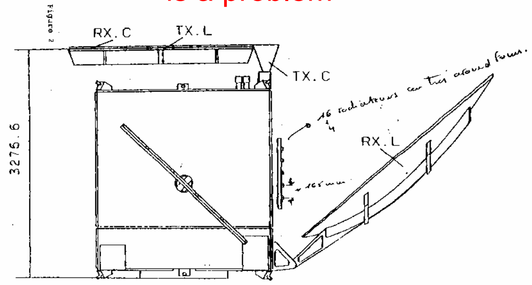
By Maci et al.

Reduction of diffraction from edge in shield, results



Satellite with many antennas:

Coupling & interference between antennas is a problem

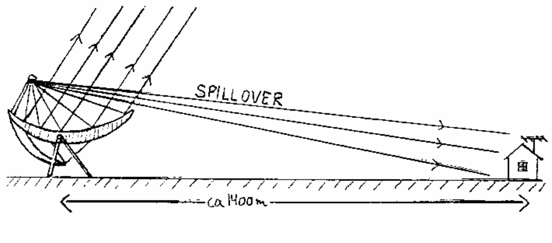


Example: EISCAT VHF cylindrical reflector antenna.

High power radar for ionospheric research

Example: Spillover lobes illuminate house 1.4 km away.

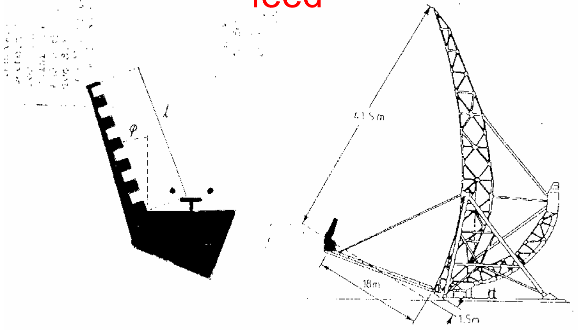
How to reduce spillover lobes?



EISCAT line feed

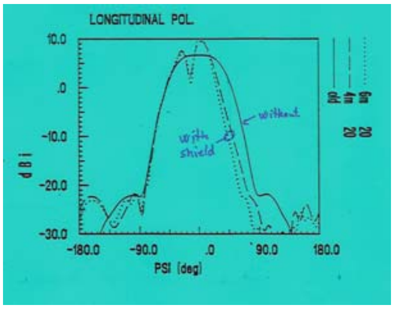
Solution?

Corrugated soft wall along line feed



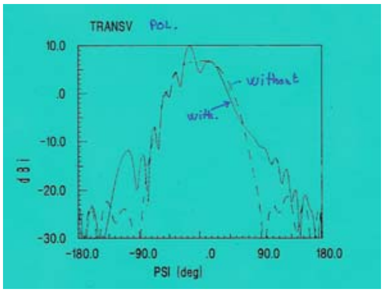
Horizontal polarization with smooth wall: Improved

Radiation pattern of line feed.



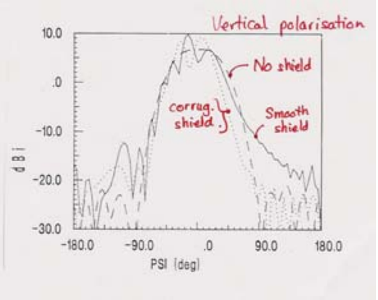
Vertical polarization with smooth wall: Worse

Radiation pattern of line feed.

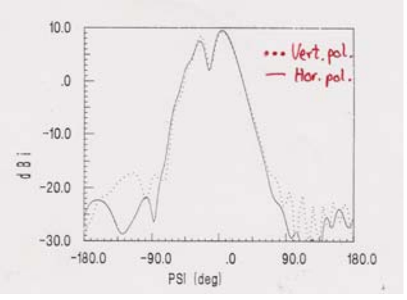


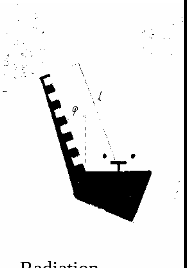
Vertical polarization with smooth and corrugated wall: Corrugated wall OK.

Radiation pattern of line feed.



Both polarizations: Corrugated wall





Radiation pattern of line feed.

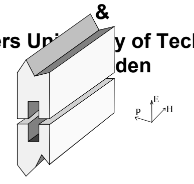
Soft transverse corrugations and chokes used in EMC and to reduce sidelobes of antennas

Dr. Jan Carlsson

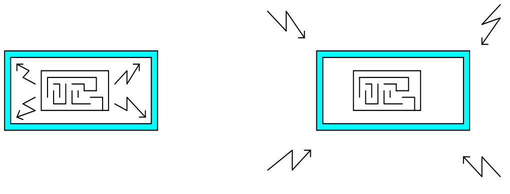
SP Swedish National Testing and Research Institute, Sweden

&

Chalmers University of Technology, Sweden

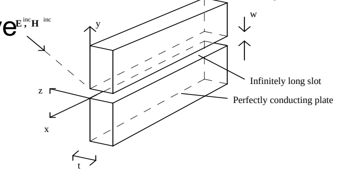


Introduction – EMC applications



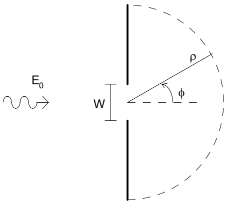
Infinitely long slot in a ground plane

- … can be used as a model for narrow apertures, i.e. when the length is large in terms of the wavelength
- … can be treated as a 2D-problem, easy to solve

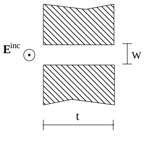


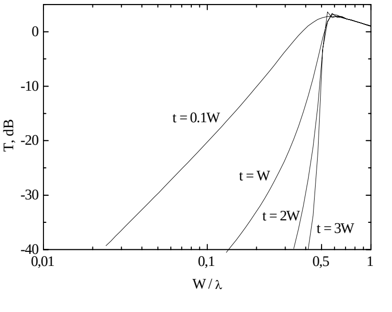
Transmission coefficient

$$T = \frac{P^{trans}}{P^{inc}} = \frac{\rho}{WE_0^2}\int_{-\pi/2}^{\pi/2} \left|E(\phi)\right|^2 d\phi$$

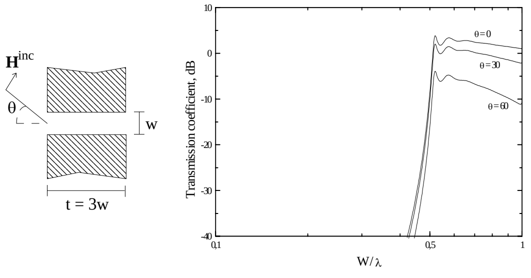


Transmission coefficient, TM-polarization

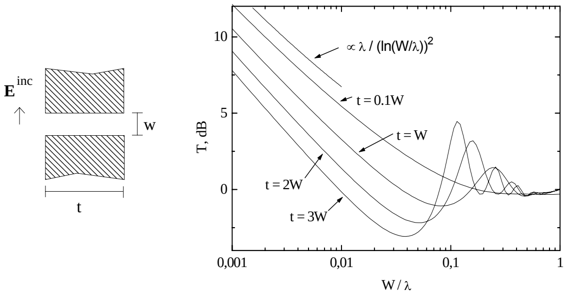




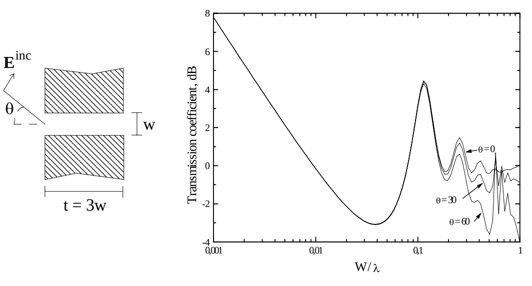
Transmission coefficient, TM-polarization



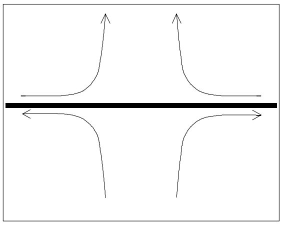
Transmission coefficient,TE-polarization



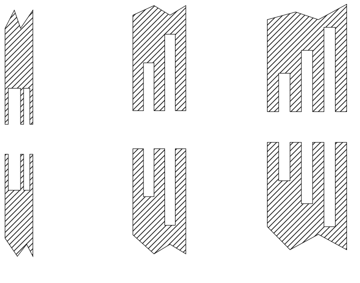
Transmission coefficient,TE-polarization



Transmission reduction, TE-polarization

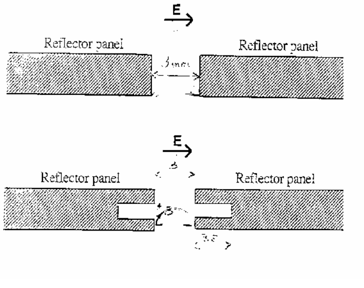


Soft surfaces applied to slots



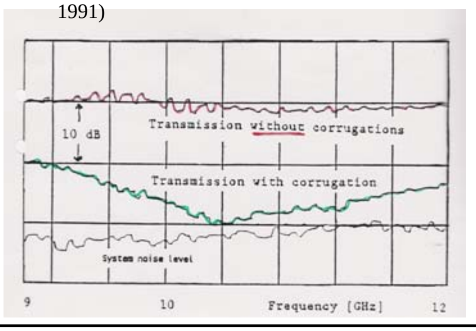
Have been used in reflector antennas

Soft panel edges (Kildal and Napier 1991)

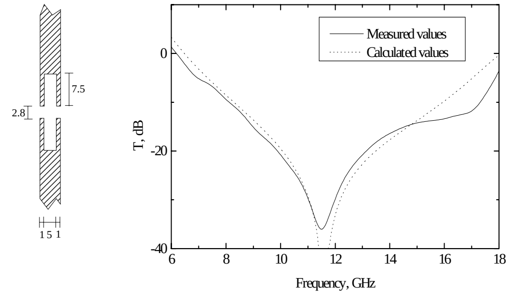


Experimental verification of reduced transmission

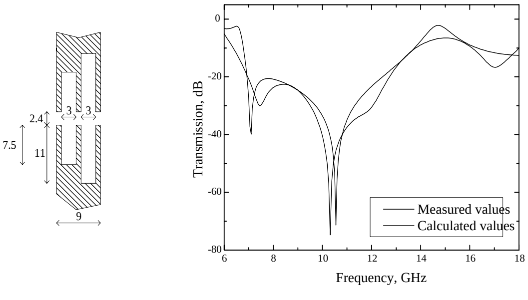
Soft panel edges (Kildal and Napier 1991)



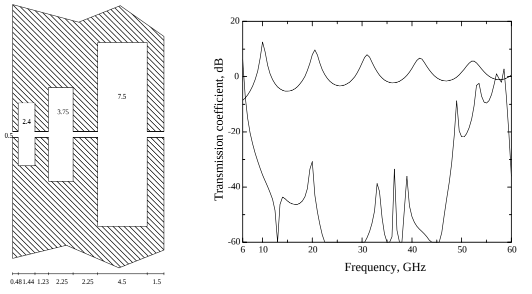
Comparison with measurements



Comparison with measurements



Broadband corrugated slot



Applications

Soft surfaces:

- Shielding
  EMC + sidelobe control
  - reduce transmission through gaps
  - polarization-independent shields
  - reduce coupling along surfaces and over corners
- Feeds
  - soft horns for low sidelobes and cross-polarizatiob and symmetric beam

Hard surfaces:

- Reduce sidelobes due to structure
  - masts, struts
  - spaceframe radomes
- Reduce radar cross-section (monostatic and bistatic)
- Array antennas
  - compact hard horn elements
  - waveguide simulators for dual polarization and broadside radiation

New table for comparing surfaces

Canonical Surface		E-field Polarization	
		VER or TM	HOR or TE
PEC		GO	STOP
PMC		STOP	GO
PEC/PMC Strip grid	SOFT	STOP	STOP
	HARD	GO	GO
PMC-type EBG	grazing	STOP	STOP
	close to normal	PMC	

General rule: How to reduce effect of metallic structure/surface on radiation pattern

Ca-se	E-field is VER rel. to surface	E-field is HOR rel. to surface	Desired surface treatment
1	Good	Bad	Hard GO
2	Bad	Good	Soft STOP
3	Bad	Bad	Transform to case 1 or 2 by changing shape

Determine first which structural part causes the high sidelobe, and for which polarization. Then, perform the surface treatment according to the table.

Four-step design procedure for antennas using soft-hard surfaces

1. Conceptual intuitive design
2. Initial analysis/design based on ideal PEC/PMC strip model
3. Studies of fundamental bandwidth limitations using asymptotic strip/corrugation boundary conditions (zero period).
4. Modeling details (fringe fields) using finite period.

Overview of analysis models

- Physical approach (conceptual)
- PEC/PMC strip models
- Impedance boundary conditions (not useable for hard surfaces)
- Asymptotic (homogenized) boundary conditions for strips and corrugations assume anisotropic but homogenous layer (very accurate for small corrugation periods)
- Exact modeling (slow convergence, small cell/segment sizes)

Missing capabilities of commercial computer codes

- finite arbitrary shaped PMCs
- ideal PEC/PMC strip surfaces (soft/hard surfaces)
- asymptotic strip and corrugation boundary conditions to avoid small cells/large contours

Conclusions

- Large similarities between EBG surfaces, AMC and soft and hard surfaces
- Soft and hard surfaces can be made THIN by using EBG technology in the form of strips
- PEC/PMC strip model:
  - represents ideal soft or hard surfaces
  - useful tool in analytical and numerical work
- Asymptotic BC for strips and corrugations
  - Useful tool in analytical and numerical work
- New applications are waiting:
  - Grid amplifier, hard horns, compact waveguides for use in multifrequency arrays
  - Waveguide simulators

Some contributors to Soft and Hard surfaces

- Dr Erik Lier, colleague from ELAB days
- Chalmers: Ying Zhinong, Zvonimir Sipus, Silvia Raffaelli, Jian Yang
- Prof Ahmed Kishk, Univ Mississippi
- Prof Stefano Maci, Tiberio, Univ of Siena
- Prof Guiliano Manara, Univ of Pisa
- Prof Freni, Univ of Florence
- Prof Ismo Lindell, Viitanen, Helsinki Univ
- Dr Aiden Higgins, Dr Hao Xin, Rockwell Scientific
- Prof Makoto Ando, Tokyo Institute of Technology
- Dr Dan Sievenpiper, HRL Lab
- Prof Rutledge, Caltech
- Prof Mortazawi, N Carolina State Univ
- Dr Ali, Univ Cent Florida
- Singapore, Korea, China and more