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

Lecturers:
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S. Tretyakov, HUT
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Important rooms and times

- **Lecture rooms:**
  - Blue room, Floor 6 North (Monday, Thursday, Friday)
  - ED section meeting room, Floor 3 South (Tuesday and Wednesday)
- **Group rooms:**
  - Lunnerummet (5430), Floor 5 North
  - Antenna groups library, Floor 7 East
  - Seminar room, Floor 7 North
- **Coffee each day 10:30-11:30 and 15:30-16:00 at:**
  - S2 coffee room on floor 6, North
- **Lunches: Each day 12:30-13:30 at Einstein**
  - Included in your registration

Participants

1	Ee Lee	The University of Birmingham
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3	Teck Yiau Lee	The University of Birmingham
4	Mauro Ettorre	Università degli Studi di Siena
5	Massimo Nannetti	Università degli Studi di Siena
6	Bart Morsink	Thales Naval Nederland
7	Simon van den Berg	Thales Naval Nederland
8	Elayachi Moussa	France Telecom
9	Eva Rajo-Iglesias	Universidad Carlos III de Madrid
10	Simone Genovesi	Università di Pisa
11	Tomislav Debogovic	University of Zagreb
12	Marco Mussetta	Politcnico di Milano
13	Daniele Monopoli	Politcnico di Milano
14	Javier L Araque Quijano	Politecnico di Torino
15	Simone Germani	University of Pavia
16	Christian Damm	Darmstadt University of Technology
17	Ulf Carlberg	Chalmers
18	Malcolm Ng Mou Kehn	Chalmers
19	Omid Sotoudeh	Chalmers
20	Jian Yang	Chalmers

Full day Short course at
the 2002, 203, 204, 205 IEEE APS Symposia

Theory and Applications of PBG Structures used as Artificial Magnetic Conductors and Soft and Hard Surfaces

Prof Per-Simon Kildal (www.kildal.se)
Chalmers University of Technology, SWEDEN

Prof Stefano Maci, University of Siena, Italy

Dr Daniel F. Sievenpiper, HRL Laboratories, Malibu, CA

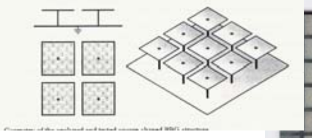
Surfaces with **STOP** or **GO** characteristics -
Artificial Magnetic Conductors and
Soft and **Hard** Surfaces
or
Introduction to Canonical Surfaces

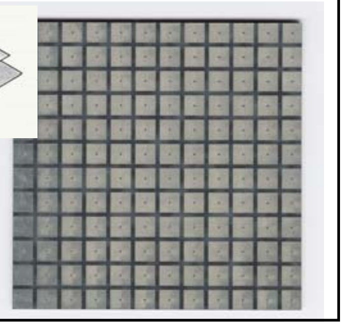
Per-Simon Kildal (www.kildal.se)
Chalmers Univ. of Technology
Gothenburg, SWEDEN

Outline

- 1. Introduction to PBG/EBGs, PMCs, AMCs, and soft and hard surfaces
- 2. Transformation of AMC to soft/hard surface
- 3. Soft and hard surfaces: Principles of operation and realizations
- 4. Brief overview of:
  - TEM waveguides
  - Reduction of blockage from cylinders
  - Examples of applications: soft, hard, AMC
  - Numerical approaches

High impedance surface Sievenpiper &Yablonovitch,1999





High impedance surface
=
Artificial Magnetic Conductor (AMC)

Very good application:

AMC as ground plane for low profile antenna, W. McKinzie 2002

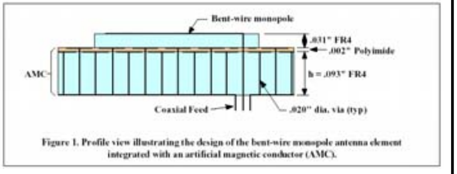


Figure 1. Profile view illustrating the design of the bent-wire monopole antenna element integrated with an artificial magnetic conductor (AMC).

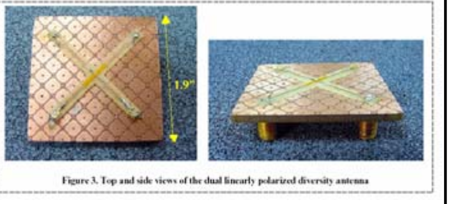


Figure 3. Top and side views of the dual linearly polarized diversity antenna

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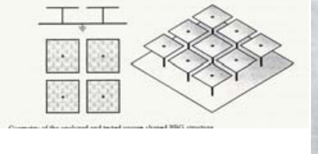
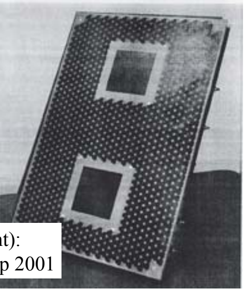
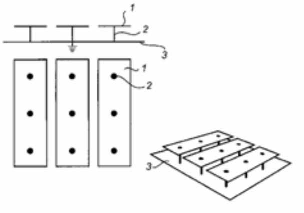
Example of AMC application in base station

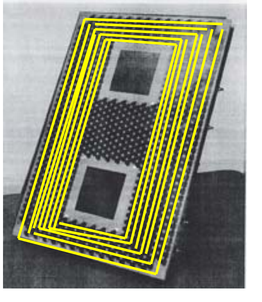




Application (did not give improvement):
Redvik and Derneryd, Estec Workshop 2001

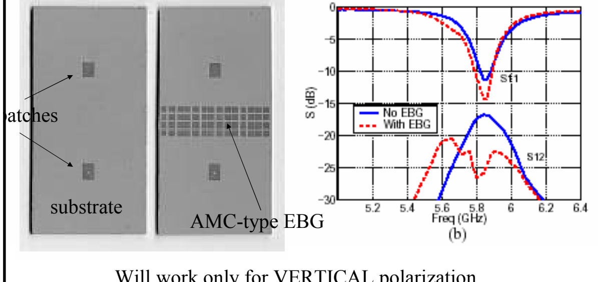
Change to soft strip surface will give improvement





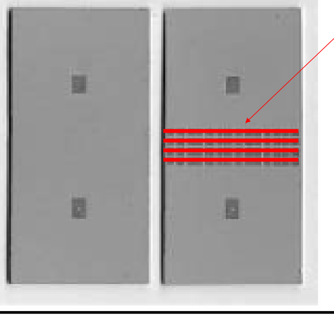
I will in the following explain why.

Example of coupling reduction with AMC-type EBG (Rahmat-Samii, et.al IEEE AP-S 2002)



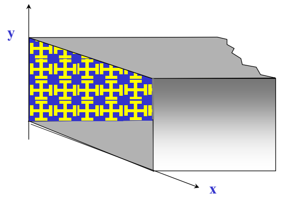
Will work only for VERTICAL polarization

Rahmat-Samii's EBG will give low coupling also for horizontal polarization if it is changed to SOFT surface by using strips



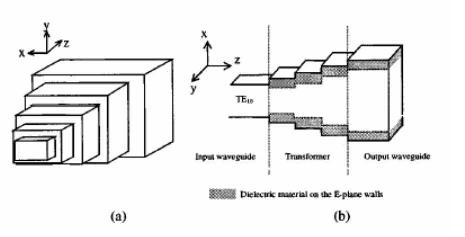
Works for both vertical and horizontal polarizations.

AMC-type EBG for TEM waveguide
F-R Yang, Itoh et al, 1999

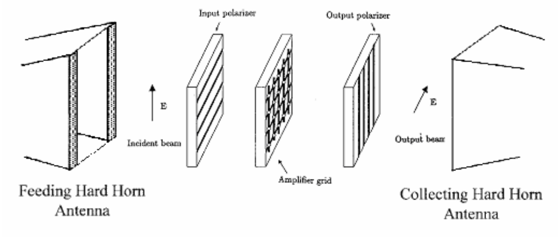


Also called hard waveguide
Others: Higgins et al, Rutledge et al

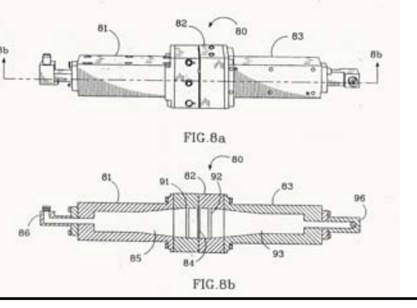
Quasi-TEM or hard horn transition by Ozkar and Mortazawi, 2000



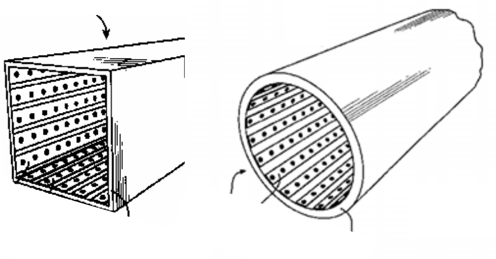
For use in grid amplifiers
Mortazawi et al,
Rutledge et al,



Grid amplifier in hard waveguide
A. Higgins, Hao Xin, Rockwell Scientific, 2001



Examples of dual-polarized quasi-TEM PBG-type hard waveguides



PBG terminology

- Many publications recent years
- ”Strange” terminology coming from photonics area
  - photonic, bandgap, forbidden band
- Acronym PBG is already established
- Now well accepted and better terminology:

EBG = Electromagnetic BandGap

i.e. Artificial narrow-band new structures, often having magnetic properties

- Classical relative:

The corrugated surface = anisotropic PBG surface

Soft and hard surfaces

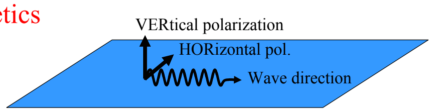
- Defined for electromagnetic waves in 1987-90
- IEEE AP Society distinguished lecturer 1991-94
  - A challenging design tool for the antenna engineer.
- > 100 references to Soft and hard surfaces
- Others have generalized the concept
- Referenced in work on PBG materials

Soft and hard surfaces originate from acoustics and diffraction theory

p is acoustic pressure

Surface	Boundary condition	Wave propagating at surface
Soft	$p = 0$	No
Hard	$\frac{\partial p}{\partial n} = 0$	Yes

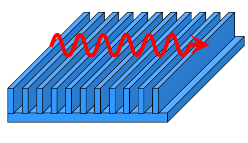
Artificially soft and hard surfaces in electromagnetics



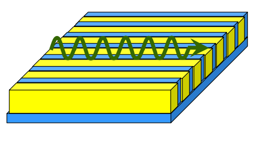
Type of surface	Boundary condition	Wave propagation at surface
Smooth conductor	$E_{HOR} = 0$ $\partial E_{VER}/\partial n = 0$	**STOP for HOR pol.** **GO for VER pol.**
Soft surface	$E_{HOR} = 0$ $E_{VER} = 0$	**STOP for HOR pol.** **STOP for VER pol.**
Hard surface	$\partial E_{HOR}/\partial n = 0$ $\partial E_{VER}/\partial n = 0$	**GO for HOR pol.** **GO for VER pol.**

Realization of soft and hard surfaces with corrugations

Soft STOP surface (left) **Hard GO surface (right)**



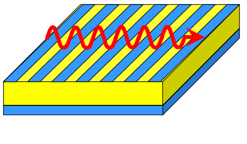
Transverse air-filled corrugations

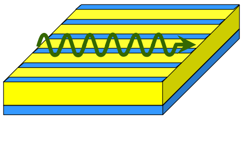


Longitudinal dielectric-filled corrugations

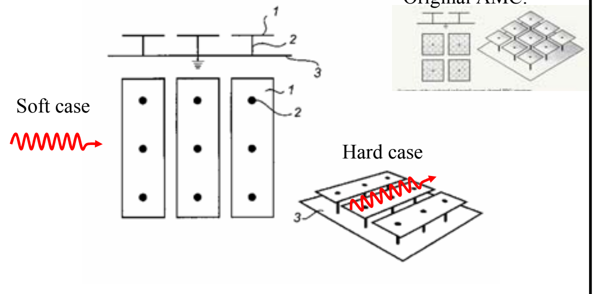
Alternative realizations: Strip-loaded grounded substrate

Soft STOP surface (left) **Hard GO surface (right)**

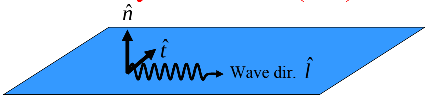




Realizations as strip-like Sievenpiper surfaces



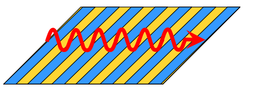
Definitions in terms of surface impedances and boundary conditions (BC)

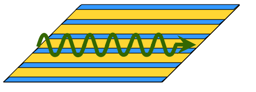


Ideal surface	BC_t & Z_t	BC_l & Z_l	HOR pol E_t	VER pol E_n
PEC	E_t=0, Z_t=0	E_l=0, Z_l=0	**STOP**	**GO**
PMC	H_t=0, Z_t=oo	H_l=0, Z_l=oo	**GO**	**STOP**
Soft	E_t=0, Z_t=0	H_l=0, Z_l=oo	**STOP**	**STOP**
Hard	H_t=0, Z_t=oo	E_l=0, Z_l=0	**GO**	**GO**

PEC/PMC strip model of ideal soft and hard surfaces

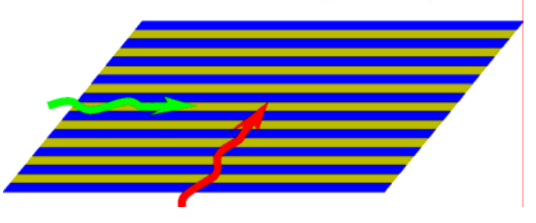
- Ideal soft surface = **STOP** surface
- Ideal hard surface = **GO** surface





strip period $\rightarrow 0$

PEC/PMC strip surface can be either soft or hard, depending on plane of incidence



PBG/EBG terminology regarding surface waves

Surface name: new	Surface name: classical	Polarization: VER	Polarization: HOR
	PEC	**GO**	**STOP**
AMC / PBG / EBG / EMXtal	**PMC**	**STOP**	**GO**
	Soft	**STOP**	**STOP**
	Hard	**GO**	**GO**

New table for comparing surfaces

Canonical Surface		E-field Polarization: VER or TM	E-field Polarization: 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**	

Explanations of Abbreviations

- GO surfaces: Enhances propagation of waves along surface
- STOP surface: Stops propagation of waves along surface
- PEC = Perfect Electric Conductor
- PMC = Perfect Magnetic Conductor
- AMC = Artificial Magnetic Conductor
- PBG = Photonic Bandgap Material
- EBG = Electromagnetic Bandgap Material
- EMXtals = Electromagnetic Crystals

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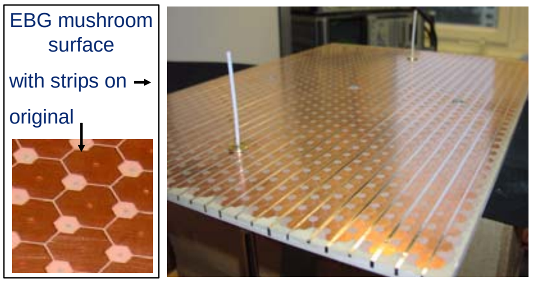
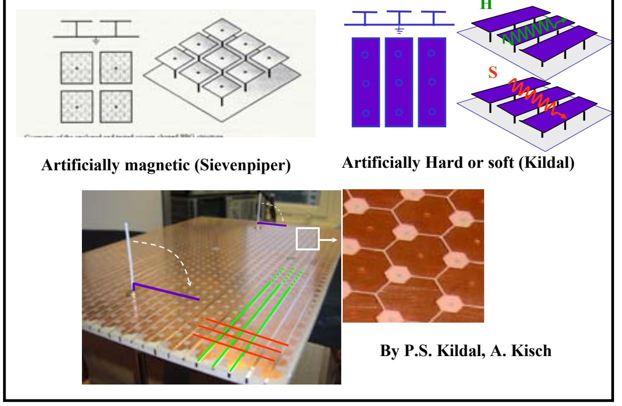
Experimental study of strip-loading an EBG mushroom surface



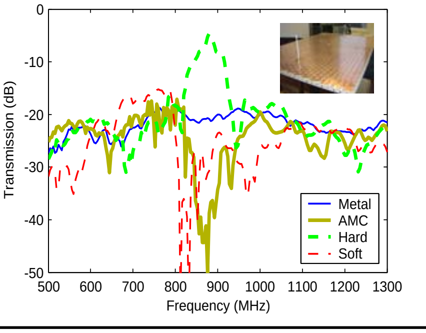


Artificially magnetic (Sievenpiper)

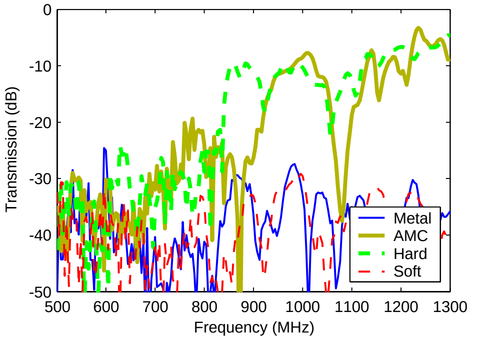
Artificially Hard or soft (Kildal)

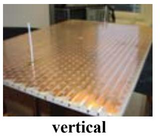
By P.S. Kildal, A. Kisch

Measured transmission between VER monopoles

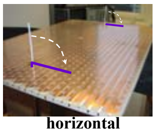


Measured transmission between HOR dipoles

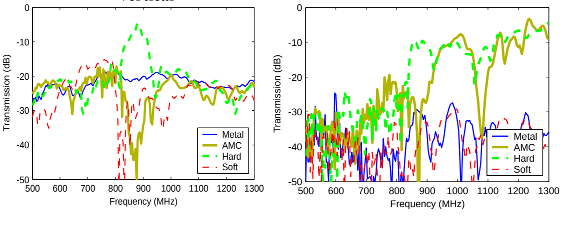




vertical



horizontal



Soft surface gives lowest coupling

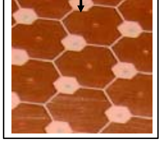
Hard surface gives strongest coupling

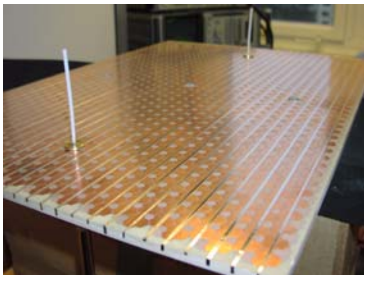
Experimental study of strip-loading an EBG mushroom surface

EBG mushroom surface

with strips on →

original





Computed coupling levels in dB between wire antennas on different infinite ideal surfaces at 900 MHz

	VER monopoles	HOR dipoles	HOR dipoles
	E-plane	H-plane, h=0	H-plane, h=λ/4
PEC	-22, -20	X, -30,x	-26, -26, -26
PMC	X, -30	-20, -20, -21	-14, -13, -14
Soft	-29,x	X, -30,x	-26, -23,x
Hard	-10,x	-10,x,x	-13,x, x
Codes Used	2D MoM, Wire MoM	2D MoM, 3D MoM, Wire MoM	2D MoM, 3D MoM, Wire MoM

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

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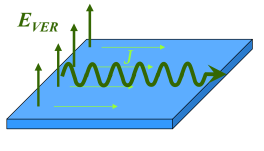
PEC: Wave propagation along surface

VER propagation GOes with

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

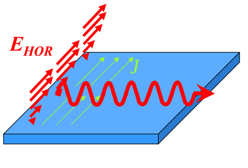
at surface.



HOR polarization STOPs with

$E_{HOR} = 0$

at surface

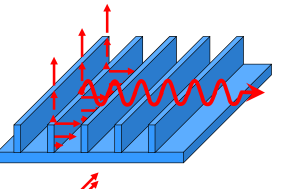


Soft surface: Principle of operation for transverse corrugations (current fences)

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

$E_{VER} = 0$

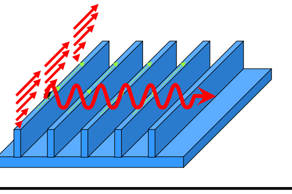
$J_{long} = 0$



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

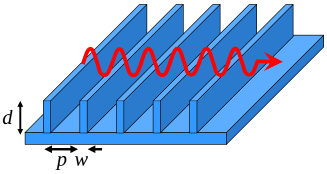
$E_{HOR} = 0$

$J_{transv} = undesturbed$



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*

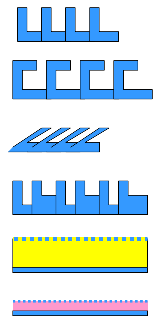
$d < \lambda_c/4$: *surface waves*

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

$d = \lambda_c/4$: *best frequency*

$d > \lambda_c/2$: *surface waves*

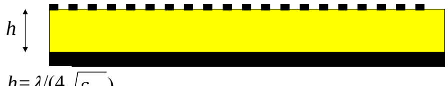
Soft surfaces:
Relative bandwidths of different realizations



- 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

Classical thick



$h=\lambda/(4\sqrt{\varepsilon_{eff}})$

Modern EBG-type thin

$\lambda/(2\sqrt{\varepsilon_{eff}})$

Alternative thin narrower strips

$\lambda/(4\sqrt{\varepsilon_{eff}})$

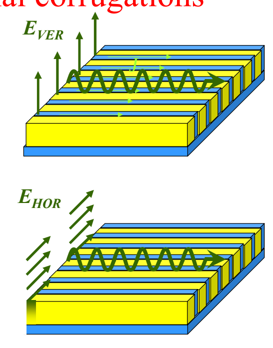
Hard surface: Principle of operation for longitudinal corrugations

E_{VER} sees PEC.

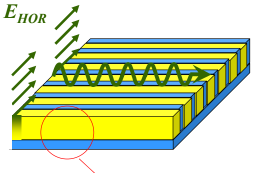
$$\partial E_{HOR}/\partial n = \partial E_{VER}/\partial n = 0$$

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

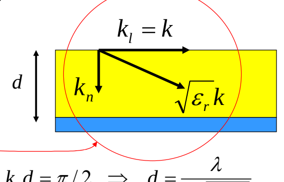
HOR case: Equivalent to grounded slab problem.
Rely on surface wave at cut-off.



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



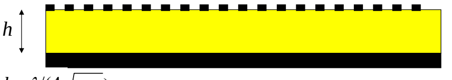
Bandwidth small due to dispersive surface wave near cut-off.



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

Realizations with longitudinal strips
$\varepsilon_{eff}=\varepsilon_r-1$ for hard surface

Classical thick



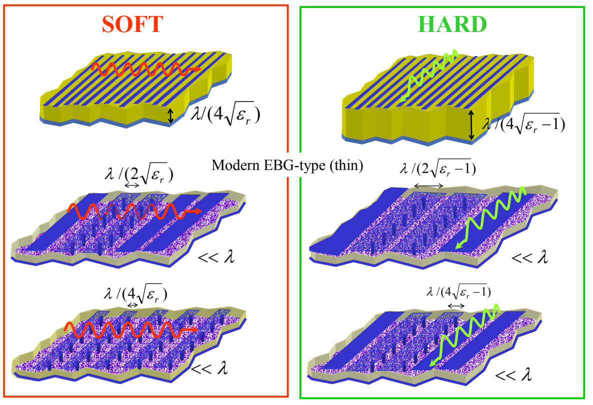
$h=\lambda/(4\sqrt{\varepsilon_{eff}})$

Modern EBG-type thin

$\lambda/(2\sqrt{\varepsilon_{eff}})$

Alternative thin narrower strips

$\lambda/(4\sqrt{\varepsilon_{eff}})$



Outline

- 1. Introduction to PBG/EBGs, PMCs, AMCs, and soft and hard surfaces
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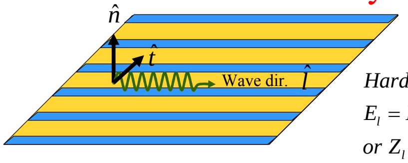
Hard surface supports TEM wave intrinsically



Hard surface defined by

$E_l = H_l = 0$

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

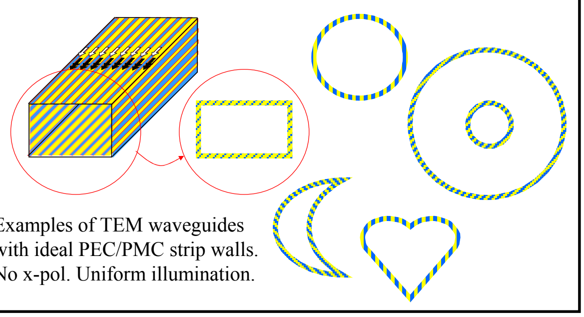
Plane wave in $\hat{l}$ *direction*:

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

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

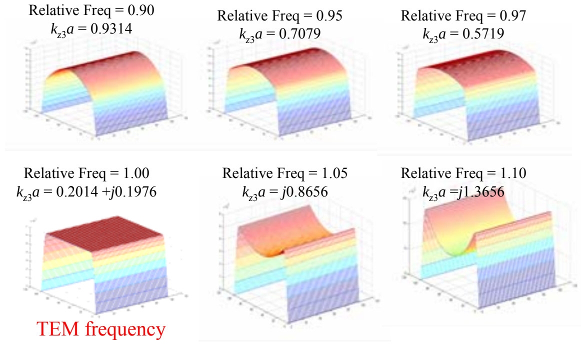
automatically satisfies boundary condition

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

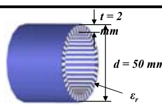


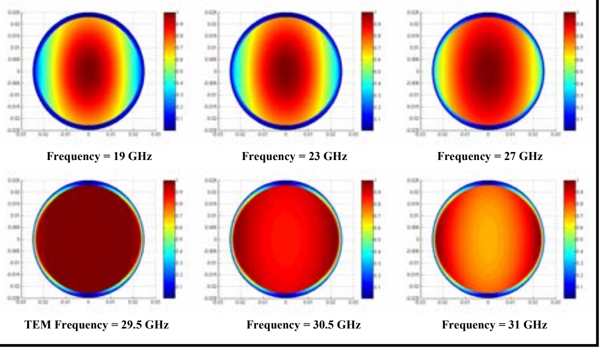
Examples of TEM waveguides with ideal PEC/PMC strip walls. No x-pol. Uniform illumination.

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



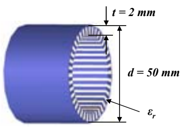
Analytical solution in circular hard corrugated waveguide, D = 5λ



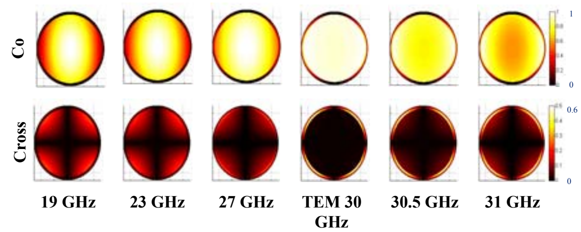


Classical-type model:
Dominant TE_z mode field distribution

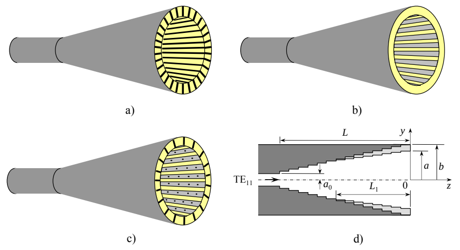
Example: $d = 5\lambda$ at 30 GHz $\varepsilon_r = 2.5$ $f_{TEM} = 30$ GHz



The corrugation period p << λ

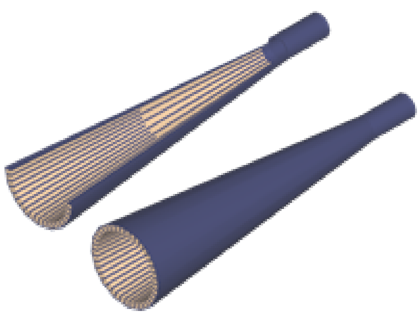


Different hard horn realizations

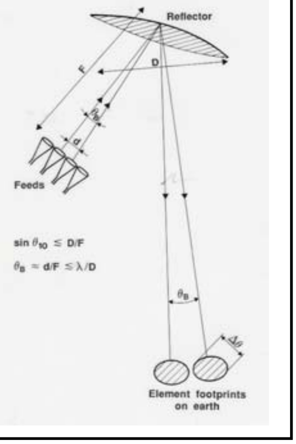


Longitudinally corrugated hard horn

(Sotoudeh, Kildal, Ingvarsson, Mangenot 2004)



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



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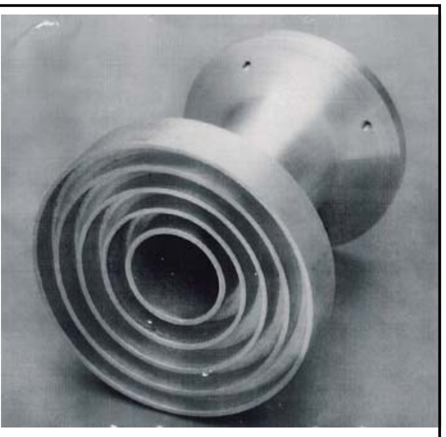
Example of structure which gives siedelobes: Support struts.

Sidelobes can be reduced by HARD surfaces

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



Small antennas on SOFT corrugated ground planes

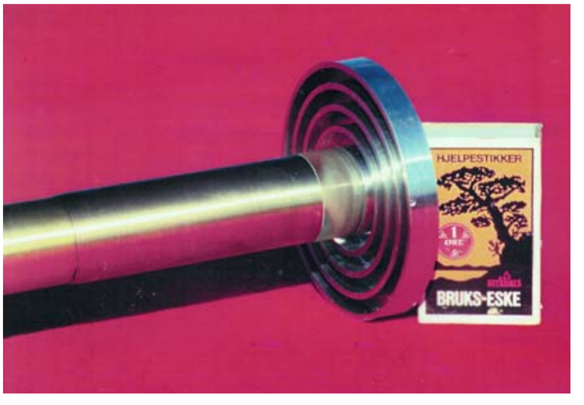
for sidelobe reduction and beam symmetry

(Ying 1996)

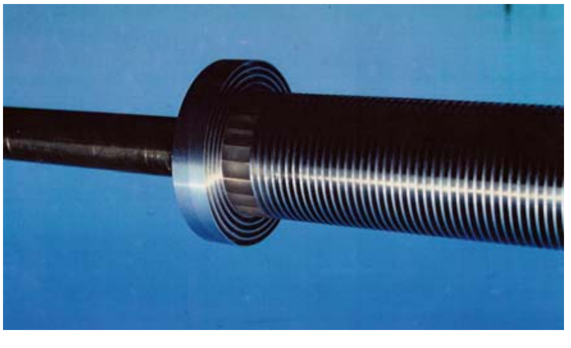
Hat feed with SOFT corrugated hat

in 90 cm reflector,

12 GHz



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



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)

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	