ACE course: Artificial EBG surfaces and meta-materials

Design of Hard Horn antennas

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Cluster-fed multi-beam antennas for Ka-band

4 reflector system

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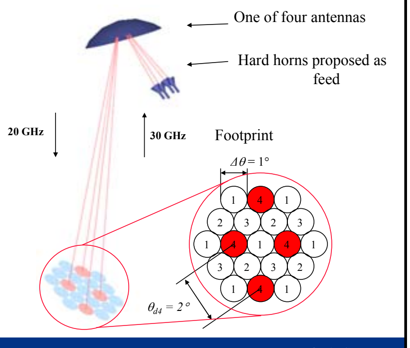


4 cell reuse scheme

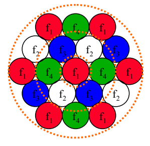
<u>Beam isolation</u>:

Max relative co - pol and x - pol between the neighboring beams

and

Max x - pol in own beam

4-cell frequency re-use plan



System requirements

Downlink	Tx: 17.7 – 20.2 GHz
Uplink	Rx: 27.5-30 GHz
End of Coverage directivity	39.5 dBi
XPD within own beam	< -27 dB
Co-polar beam isolation relative to weakest useful point	>25 dB
Cross-polar beam isolation relative to weakest useful point	>27 dB
Reflection coefficient at feed port	< -27 dB
Polarization between frequency bands	Dual polarization system, individual beams remain single polarized.
Polarization within each band	Dual, linear or circular
Operating frequency band	Tx and Rx

Feed candidates

Classical:
- Smooth walled horn
- Potter/dual mode horn
- Transversally corrugated horns
- Dielectric loaded horns
- High efficiency horns

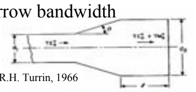
- Hard horns

Smooth walled horns

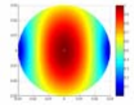
- TE_{11} mode
- Difference in E- and H-plane
- High X-pol
- Medium efficiency
- Wide bandwidth

Potter/dual mode horns

- TE_{11} + TM_{11} modes
- Equal E - and H – planes: Low X - pol
- Low efficiency
- Narrow bandwidth

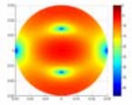


R.H. Turrin, 1966



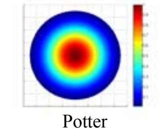
TE_{11}

+



TM_{11}

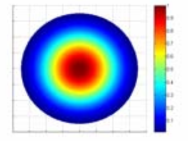
=



Potter

Transversally corrugated horns

- Hybrid HE_{11} mode
- Equal E - and H - planes
- Low X - pol
- Very low efficiency
- Wide bandwidth

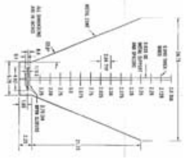


Hybrid HE_{11}

Dielectric loaded horns

- Dual mode horns
- Dielectric core filled horns
- Rods along the axis

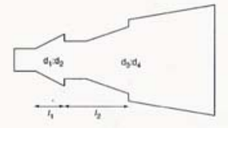
- Narrow bandwidth



Wong et. Al. 1983

High efficiency horns

- Multimode
- Complex step geometry
- High efficiency (ex. 90 %)
- Low X - pol
- Narrow bandwidth



Bhattacharyya et al 2002

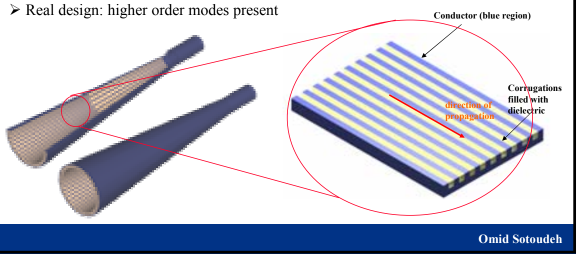
The hard horn

- High efficiency
- Low X – pol
- Wide bandwidth
- Complex geometry
- Ideal singel mode design: Supports only dominant quasi-TEM mode
- Real design: higher order modes present

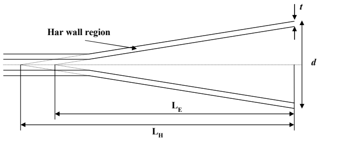
Hard surface = GO surface

Supports quasi-TEM waves

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



Simple single mode hard horns

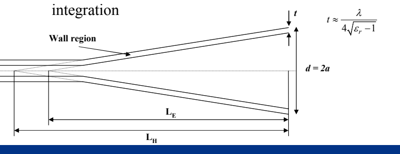


Analysed using asymptotic models

1. Classial type model: based on waveguide modal theory and homogenization of the corrugted wall, (Asymptotic Corrugation Boundary Conditions, ACBC, i.e. corrugation period, p → 0)
   - Fast and rather accurate.
   - Useful for initial parametric studies and design
2. Mode-matching program, also ACBC.
   - Higher order modes taken into consideration
   - Very accurate for fine tuning and design detail.

Classical-type model

- Homogenization of the corrugated wall, ACBC
- Dominant TE_z mode in cylindrical hard waveguides
- Different (classical-type) phase factors for E- and H- planes
- Huygens' equivalence and aperture integration



Hard horn analysis: Waveguide modes

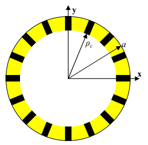
Waveguide modal theory + Asymptotic corrugation boundary condition, ACBC (i.e. corrugation period is zero)

TE characteristic equation:

$$\mu\sqrt{\varepsilon_r\beta_0^2-\beta_z^2}\left[-J_2(\kappa_1)+\frac{J_1(\kappa_1)}{\kappa_1}\right]T_1-\mu_c\sqrt{\beta_0^2-\beta_z^2}\,J_1(\kappa_1)T_2=0$$

$$T_1=-J_1(\kappa_3)Y_0(\kappa_2)+J_0(\kappa_2)Y_1(\kappa_3)$$
$$T_2=J_1(\kappa_3)Y_1(\kappa_2)-J_1(\kappa_2)Y_1(\kappa_3)$$

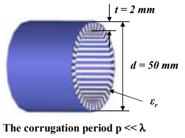
$$\kappa_1=\rho_c\sqrt{\beta_0^2-\beta_z^2},\ \kappa_2=\rho_c\sqrt{\varepsilon_r\beta_0^2-\beta_z^2},\ \kappa_3=a\sqrt{\varepsilon_r\beta_0^2-\beta_z^2}$$



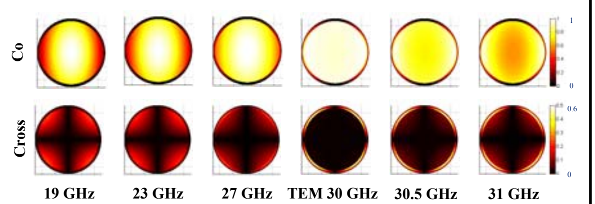
$\beta_0 = 2\pi/\lambda$ wave number in free space
β_z z-dir wave number in horn
a waveguide radius
ρ_c radius of corrugations

Classical-type model: Dominant TE_z mode field distribution

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



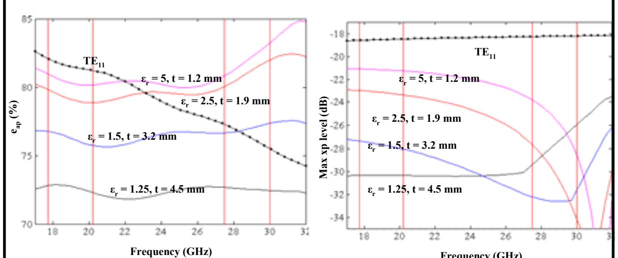
The corrugation period p << λ



Hard horn analysis: Waveguide modes

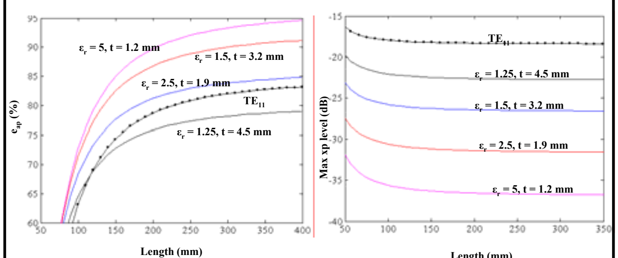
Example

$d = 5\lambda_{TEM}$, $L_H = 15\ \lambda_{TEM}$, $f_{TEM} = 31.8$ GHz



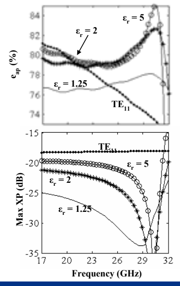
Hard horn analysis: Waveguide modes

$d = 5\lambda_{TEM}$, $f = f_{TEM} = 31.8$ GHz

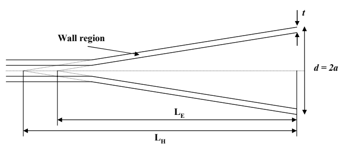


Classical-type model: $d = 5\lambda$ at 17.7 GHz $f_{TEM} = 30.5$ GHz
Example

As function of frequency



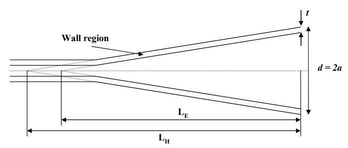
Permittivity ε_r	t (mm)	Lengths L_H = 423.4 mm L_E
1.25	4.8	375.5 mm
2	2.4	399.2 mm
5	1.2	411.2 mm

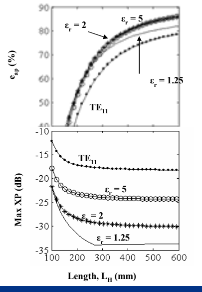


Classical-type model: $d = 5\lambda$ at 17.7 GHz $f_{TEM} = 30.5$ GHz

As function of length
***f* = 28.75 GHz**

Permittivity ε_r	t (mm)
1.25	4.8
2	2.4
5	1.2





Hard horn analysis: Waveguide modes

- Diameter and ε_r fixed
- Characteristic equation → Wall thickness
- Aperture fields
- Horn length modeled by phase factor

$d = 5\lambda_{TEM}$, $f_{TEM} = 31.8$ GHz

Relative permittivity in the corrugations, ε_r	Wall thickness t (mm)
1.25	4.5
1.50	3.2
2.50	1.9
5.00	1.2

Mode-matching code

- Homogenization of the corrugated wall, ACBC
- Cascaded cylindrical sections
- Several higher order modes for each section
- Aperture integration. Method of factorization treats outer surfaces of horn as a metal cylinder.

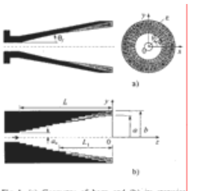
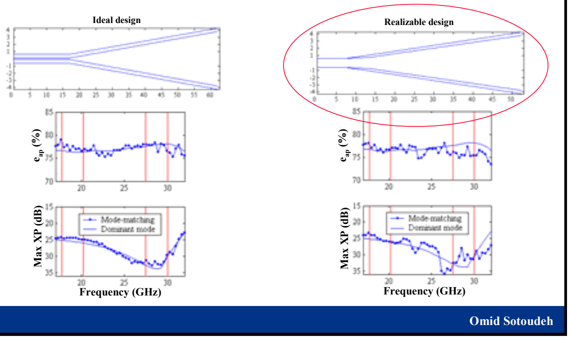


Fig. 1. (a) Geometry of horn and (b) its stepwise representation.

S. Skobelev, P.-S. Kildal 2001

Another example of comparison mode-matching – classical-type

$\varepsilon_r = 1.25$, $d = 5\lambda$ at 17.7 GHz, $f_{TEM} = 30.5$ GHz
$L_H = 25\lambda$ at 17.7 GHz ≈ 424 mm $L_E = 376$ mm

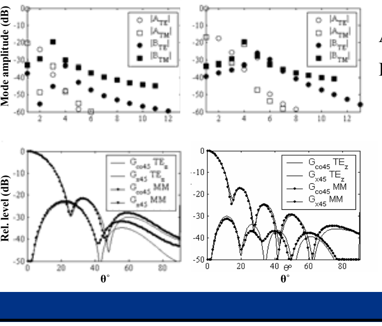


Mode-matching: study of higher order modes

$d = 50$ mm, $\varepsilon_r = 2.5$, $t = 2$ mm, $f_{TEM} = 30$ GHz, $L_H = 250$ mm, $L_E = 230$ mm

Modes at aperture

Patterns



A: Incident

B: Reflected

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Conclusion
Single mode horns

- Simple dominant mode model accurate enough for parametric studies of the single mode hard horn.
  - Also very efficienct for initial design, and finding of the limitations.
- Mode-matching used for final tuning of the design.
  - Very fast compared to the full 3D FEM analysis.
- Single mode hard horns may be designed to operate with

  Medium efficiency and low crosspolarization
  or
  High efficiency and low crosspolarization

  Bandwidth depends on sevral parameters

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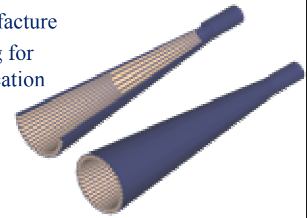
Multimode hard horn design
Motivation

Classical hard horn design:

Difficult to manufacture
Becomes too long for our present application



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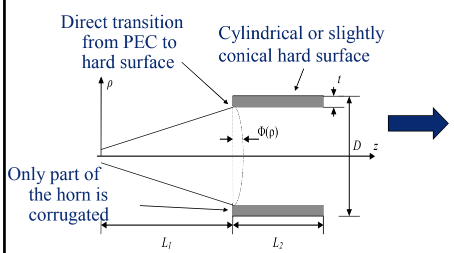
Initial studies

Based on simple manufacturing – very simple geometry



Possible for small radii < 4-5λ
Larger apertures need a long PEC section

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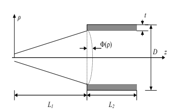
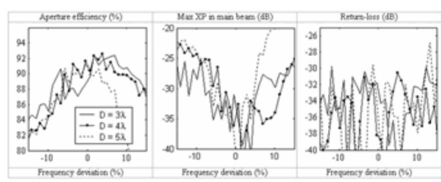
Geometrical parameters (mm) λ = 10 mm, ε_r = 2.5					Bandwidth maximum XP and aperture efficiency		
D	L_1	L_2	t	f_{TEM} (GHz)	< -30 dB, ∀θ	< -30 dB, main beam	Efficiency > 88 %
30	127.9	35.5	1.55	38.6	12.5 %	14 %	15.5 %
40	145.0	68.0	1.70	36.0	13.5 %	16 %	17.5 %
50	156.8	110.4	1.84	32.7	9 %	11%	12 %





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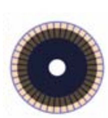
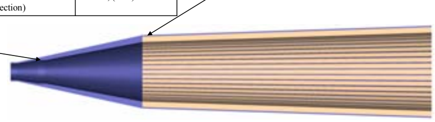
Multimode horn parameters

Parameter	Value
Aperture diameter	d = 65 mm
Wall thickness **Corresponding TEM frequency**	t = 4 mm f_{TEM} ≈ 37.2 GHz
Total length	300.5 mm
Relative permittivity in the corrugated wall region	ε_r = 1.24
Number of corrugations	40
Corrugation tooth thickness	v = 1 mm
Corrugation period: At air interface, (at start of the hard section)	p = π*d / N ≈ 4.48 mm, (3.39 mm)
Corrugation opening: At air interface, (at start of the hard section)	$w = p - v$ ≈ 3.48 mm, (2.39 mm)
w/p: At air interface, (at start of the hard section)	≈ 0.78, (0.71)



Direct transition

Step for widening of the higher band



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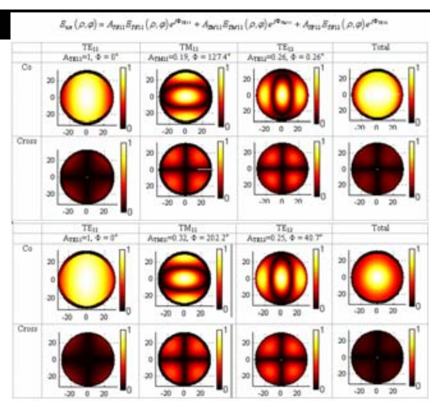

Calculated at 19 GHz

Calculated at 29 GHz

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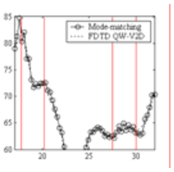
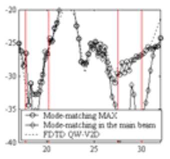
Performance

Aperture efficiency (%)



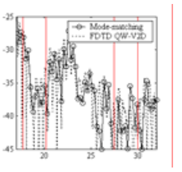
Frequency (GHz)

Max cross-polar level (dB)



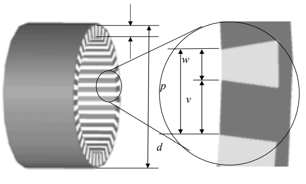
Frequency (GHz)

Return-loss (dB)



Frequency (GHz)

Analysis of corrugation number and shape



Variation of number of corrugations, N d = 75 mm, v = 1 mm, t = 4.9 mm				Variation of ridge width, v d = 75 mm, N = 40, t = 4.9 mm		
N = 36 p = 6.1 mm w = 5.1 mm w/p = 0.84	N = 40 p = 5.5 mm w = 4.5 mm w/p = 0.82	N = 60 p = 3.7 mm w = 2.7 mm w/p = 0.73	N = 80 p = 2.8 mm w = 1.8 mm w/p = 0.64	v = 1 mm p = 5.5 mm w = 4.5 mm w/p = 0.82	v = 2 mm p = 5.5 mm w = 3.5 mm w/p = 0.64	v = 4 mm p = 5.5 mm w = 1.5 mm w/p = 0.27

Theory of BOR, Body of revolution

Aperture fields: vertical polarization

Total:

$$\mathbf{E}(\rho,\phi)=\sum_{n=1}^{\infty}a_n(\rho)\sin(n\phi)\hat{\boldsymbol{\rho}}+\sum_{n=1}^{\infty}c_n(\rho)\cos(n\phi)\hat{\boldsymbol{\varphi}}$$

$$a_n(\rho)=\frac{1}{\pi}\int_0^{2\pi}E_\rho(\rho,\phi)\sin(n\phi)\,d\phi$$

$$c_n(\rho)=\frac{1}{\pi}\int_0^{2\pi}E_\phi(\rho,\phi)\cos(n\phi)\,d\phi$$

BOR_1 component:

$$\mathbf{E}^{\mathbf{BOR}_1}(\rho,\phi)=E^{BOR1}_{E-plane}(\rho)\sin(\phi)\hat{\boldsymbol{\theta}}+E^{BOR1}_{H-plane}(\rho)\cos(\phi)\hat{\boldsymbol{\varphi}}$$

$$E^{BOR1}_{E-plane}(\rho)=\frac{1}{\pi}\int_0^{2\pi}E_\theta(\rho,\phi)\sin(\phi)\,d\phi$$

$$E^{BOR1}_{H-plane}(\rho)=\frac{1}{\pi}\int_0^{2\pi}E_\phi(\rho,\phi)\cos(\phi)\,d\phi$$

Theory of BOR, Body of revolution

Far-fields: vertical polarization

Total:

$$\mathbf{G}(\theta,\phi)=\sum_{n=1}^{\infty}a_n(\theta)\sin(n\phi)\hat{\boldsymbol{\theta}}+\sum_{n=1}^{\infty}c_n(\theta)\cos(n\phi)\hat{\boldsymbol{\varphi}}$$

$$a_n(\theta)=\frac{1}{\pi}\int_0^{2\pi}G_\theta(\theta,\phi)\sin(n\phi)\,d\phi$$

$$c_n(\theta)=\frac{1}{\pi}\int_0^{2\pi}G_\phi(\theta,\phi)\cos(n\phi)\,d\phi$$

BOR_1 component:

$$\mathbf{G}^{\mathbf{BOR}_1}(\theta,\phi)=G^{BOR1}_{E-plane}(\theta)\sin(\phi)\hat{\boldsymbol{\theta}}+G^{BOR1}_{H-plane}(\theta)\cos(\phi)\hat{\boldsymbol{\varphi}}$$

$$G^{BOR1}_{E-plane}(\theta)=\frac{1}{\pi}\int_0^{2\pi}G_\theta(\theta,\phi)\sin(\phi)\,d\phi$$

$$G^{BOR1}_{H-plane}(\theta)=\frac{1}{\pi}\int_0^{2\pi}G_\phi(\theta,\phi)\cos(\phi)\,d\phi$$

Theory of BOR, Body of revolution

BOR_1 relations for RHCP

Far-field functions

$$G^{BOR1}_{co-RHCP}(\theta,\phi) = G^{BOR1}_{co45}(\theta) - G^{BOR1}_{xp45}(\theta)\cos 2\phi$$
$$G^{BOR1}_{xp-RHCP}(\theta,\phi) = G^{BOR1}_{xp45}(\theta)\sin(2\phi)e^{-2j\phi}$$

$$G^{BOR1}_{co45}(\theta) = \frac{1}{2}\left[G^{BOR1}_{E-plane}(\theta) + G^{BOR1}_{H-plane}(\theta)\right]$$
$$G^{BOR1}_{xp45}(\theta) = \frac{1}{2}\left[G^{BOR1}_{E-plane}(\theta) - G^{BOR1}_{H-plane}(\theta)\right]$$

Aperture field functions

$$E^{BOR1}_{co-RHCP}(\rho,\phi) = E^{BOR1}_{co45}(\rho) - E^{BOR1}_{xp45}(\rho)\cos 2\phi$$
$$E^{BOR1}_{xp-RHCP}(\rho,\phi) = E^{BOR1}_{xp45}(\rho)\sin(2\phi)e^{-2j\phi}$$

$$E^{BOR1}_{co45}(\rho) = \frac{1}{2}\left[E^{BOR1}_{E-plane}(\rho) + E^{BOR1}_{H-plane}(\rho)\right]$$
$$E^{BOR1}_{xp45}(\rho) = \frac{1}{2}\left[E^{BOR1}_{E-plane}(\rho) - E^{BOR1}_{H-plane}(\rho)\right]$$

(see e.g. Kildal's textbook, Foundations of Antennas)

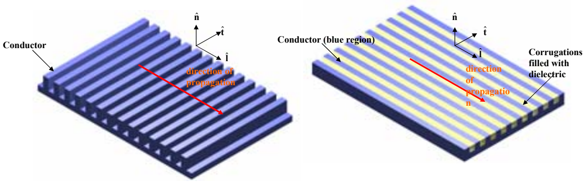
Hard and Soft surfaces

Soft surface: STOP

$$Z_l = -\frac{E_l}{H_t} = \infty \qquad Z_t = \frac{E_t}{H_l} = 0$$

Hard surface: GO

$$Z_l = -\frac{E_l}{H_t} = 0 \qquad Z_t = \frac{E_t}{H_l} = \infty$$



Horn types and their radiation patterns <u>at center frequency</u>

Horn types	Aperture distribution	
	E-plane	H-plane
Ideal hard		
Corrugated hard		
Ideal soft or dual mode		
Corrugated soft		
Smooth walled, TE_{11} mode		

BOR reflector model: BOR_1 analysis model

- The first order φ - variation is used.
- Far field function: $\vec{\mathbf{G}}(\theta,\phi) = G_{E-plane}(\theta)\sin\phi\hat{\theta} + G_{H-plane}(\theta)\cos\phi\hat{\phi}$
- BOR_1 antenna: Co- and x - pol far-field patterns for linear pol in $\phi = 45°$ plane, are the same for circular pol in all planes.

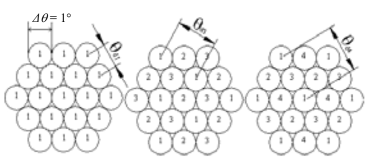
BOR reflector model

Three different cases

$\theta_{d1} = \Delta\theta$ $\quad F_1 = 286.5\ \lambda$

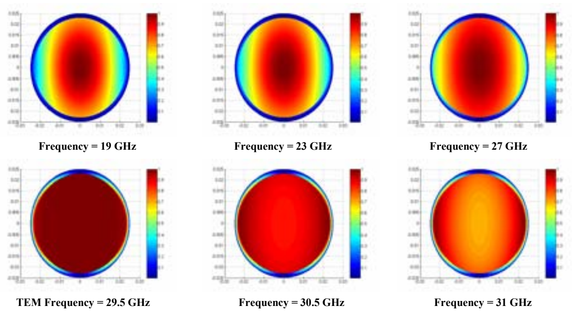
$\theta_{d3} = \sqrt{3}\Delta\theta$ $\quad F_3 = 165.3\ \lambda$

$\theta_{d4} = 2\Delta\theta$ $\quad F_4 = 143.2\ \lambda$



1 reflector system 3 reflector system 4 reflector system

The hard horn: 5λ horns, $\varepsilon_r = 2.5$



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Beam isolation: D = 87λ

Horn type	1 Reflector case (dB)	3 Reflector case (dB)	4 Reflector case (dB)
co-polar level, Desired < -25 dB			
Ideal hard	-19.7	-26.2	-23.8
Hard corrugated	-18.9	-26.5	-25.2
Ideal soft, dual mode	-17.0	-25.5	-29.2
Soft corrugated	-16.4	-22.7	-26.7
Smooth (TE11)	-18.3	-27.8	-29.5
Max cross-polar level in the neighbouring beam relative to co-polar level at the weakest point Required <-27 dB			
Hard corrugated	-46.0	-44.2	-45.9
Smooth (TE11)	-32.5	-28.0	-28.5
Max cross-polar level at the weakest point relative to co-polar level at the weakest point Required <-27 dB			
Hard corrugated	-36.5	-31.3	-31.4
Smooth (TE11)	-23.4	-16.6	-15.6

CHALMERS

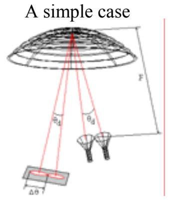
Cluster fed multi beam antenna CFMBA
The design problem

Beams must overlap → small horn diameter

Low spillover → large horn diameter

Low cross polarisation

A simple case



Requires: A high efficiency horn for 20/30 GHz

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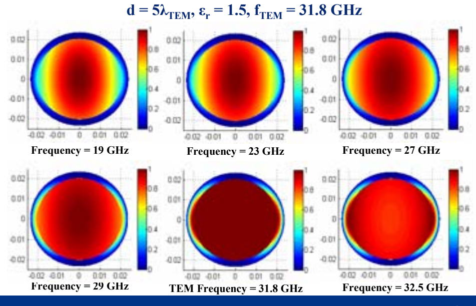
Hard horn analysis: Waveguide modes

Asymptotic hard horn model, A2HS

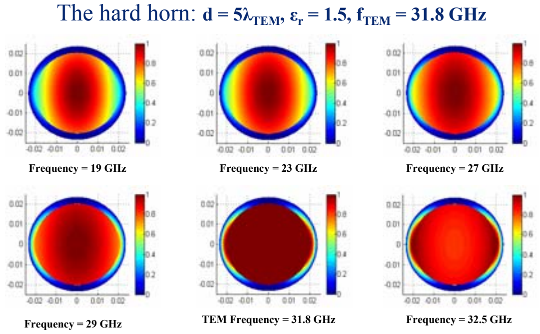
$d = 5\lambda_{TEM}$, $\varepsilon_r = 1.5$, $f_{TEM} = 31.8$ GHz



Summary of work

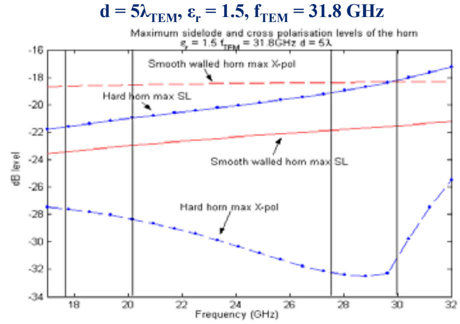
- Trade-off study of feeds
  - Litteratur study
  - Comparison of ideal horns in BOR reflector model
  - Study of hard horns using G1DMULT
  - Study of overlapping sub-arrays
- Hard horn analysis and design
  - Wave guide modes + asymptotic method, A2HS + BOR
  - Mode-Matching, S2MP + BOR
  - Corrugation number, FEM
- CF-MBA analysis
  - BOR + A2HS
  - BOR + S2MP
- Final horn design

The hard horn: $d = 5\lambda_{TEM}$, $\varepsilon_r = 1.5$, $f_{TEM} = 31.8$ GHz



The hard horn: Max SL and XP

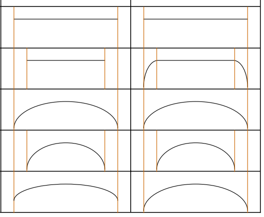
$d = 5\lambda_{TEM}$, $\varepsilon_r = 1.5$, $f_{TEM} = 31.8$ GHz



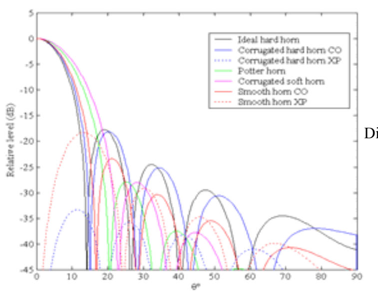
Comparison of horns in a BOR reflector model at centre frequency for one feed per beam MBA

Horn types and their radiation patterns at center frequency

Horn types	Aperture distribution	
	E-plane	H-plane
Ideal hard		
Corrugated hard		
Ideal soft or dual mode		
Corrugated soft		
Smooth walled, TE_{11} mode		



Horn types and their radiation patterns



Horns physical diameter:
d = 5λ

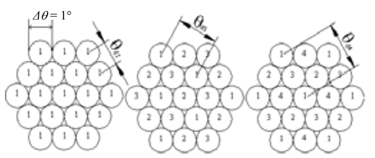
Dielectric in the corrugations:
$\varepsilon_r = 2.44$
↓
Wall thickness ~ 0.21λ

Three different reflector cases

$\theta_{d1} = \Delta\theta$ $F_1 = 286.5\ \lambda$

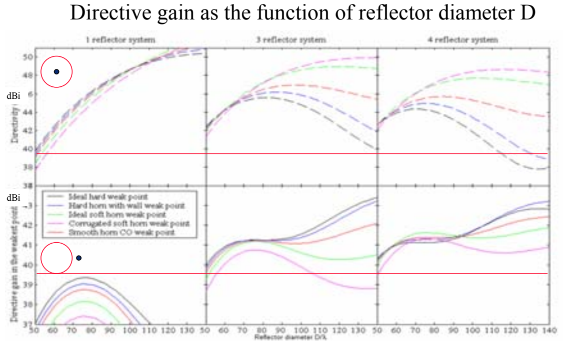
$\theta_{d3} = \sqrt{3}\Delta\theta$ $F_3 = 165.3\ \lambda$

$\theta_{d4} = 2\Delta\theta$ $F_4 = 143.2\ \lambda$



1 reflector system 3 reflector system 4 reflector system

Directive gain as the function of reflector diameter D



Beam isolation: D = 87λ

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Bandwidth of the hard horn in a BOR reflector model

The hard horn: 5λ horns