ANTENNAS VCE Virtual Center of Excellence

ACE – Antenna Center of Excellence

The European School of Antennas

Course:
"HIGH-FREQUENCY TECHNIQUES
AND TRAVELLING-WAVE ANTENNAS"

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LEAKY-WAVE ANTENNAS: APPLICATIONS

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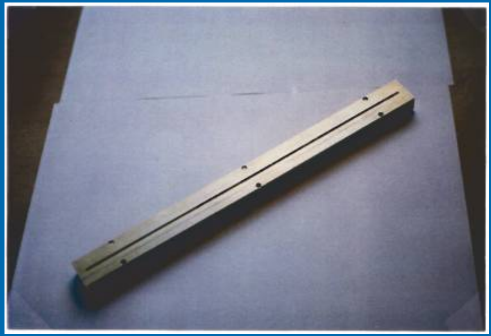
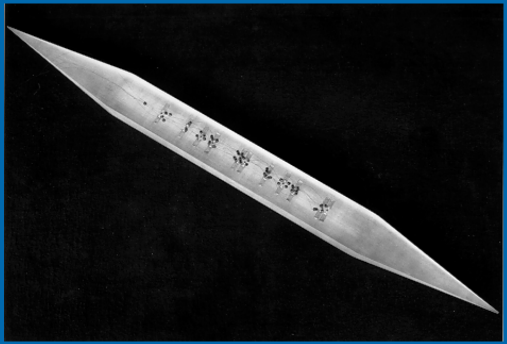
Index

Overview of LWA structures

A classification based on the relevant unperturbed waveguides …

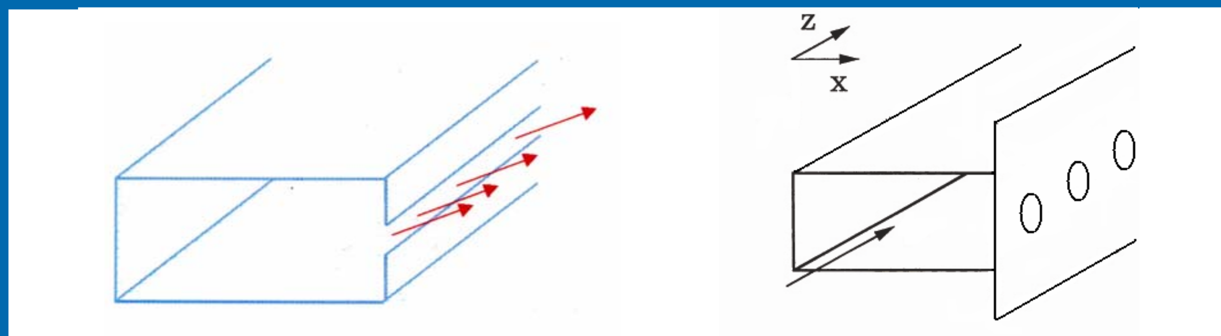




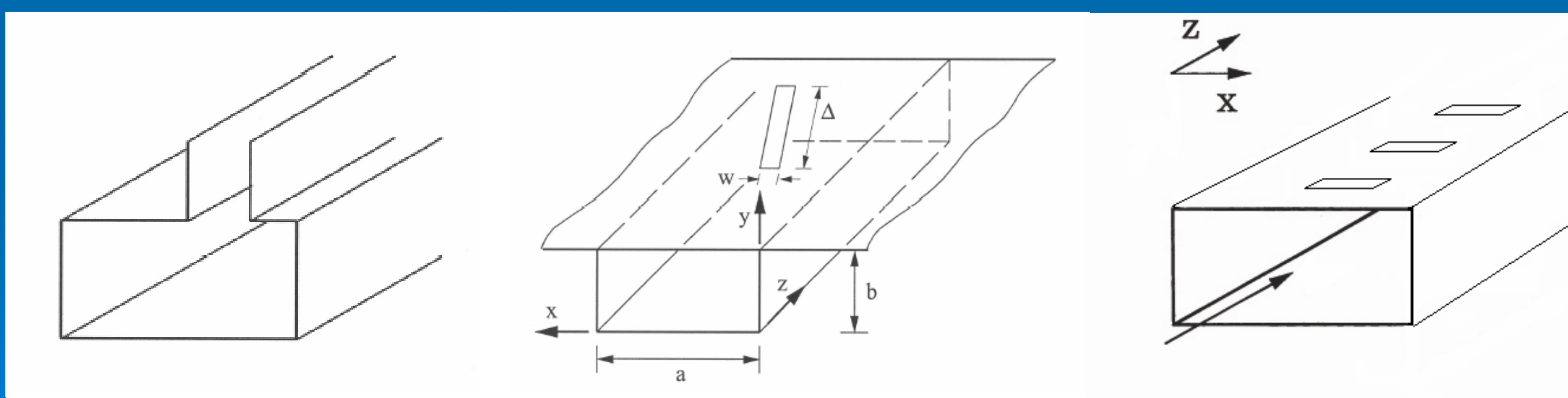
- I – LWAs from metallic waveguides
  (rectangular guides, modified rectangular guides, other metallic guides, parallel-plate structures)
- II – LWAs from metallic/dielectric waveguides
- III – LWAs from printed lines
- IV – LWAs from dielectric guides
- V – LWAs from planar layered guides

Examples (Ia)

LWAs based on metallic rectangular guides (RG)



Side-wall slitted-RG and holey-RG LWAs

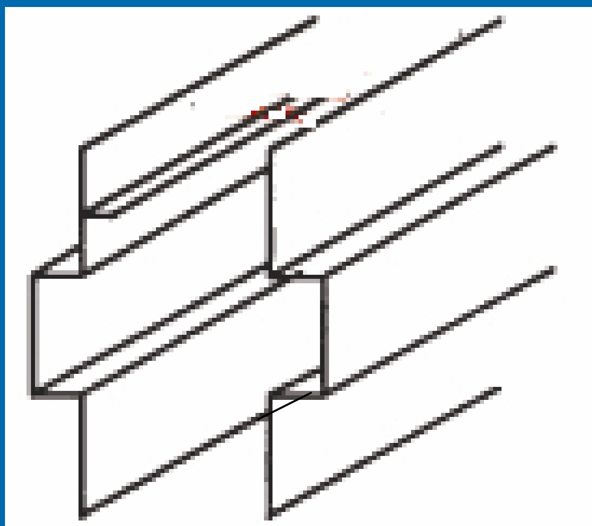


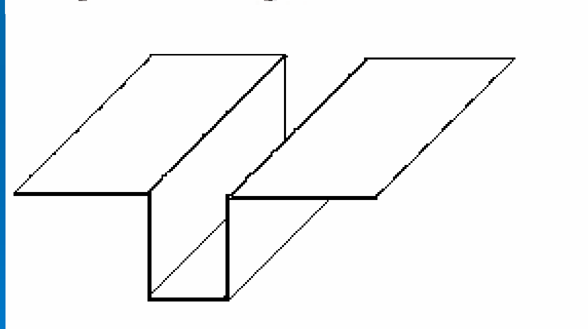
Top-wall stub-loaded, slitted, and slotted-RG LWAs

[Studies by Hines, Rumsey, Walter, Goldstone, Oliner, Hyneman, Balanis, Kyoto Group, Rome Group, etc.]

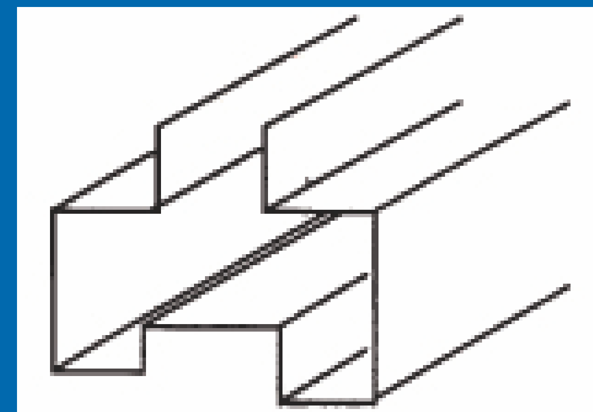
Examples (Ib)

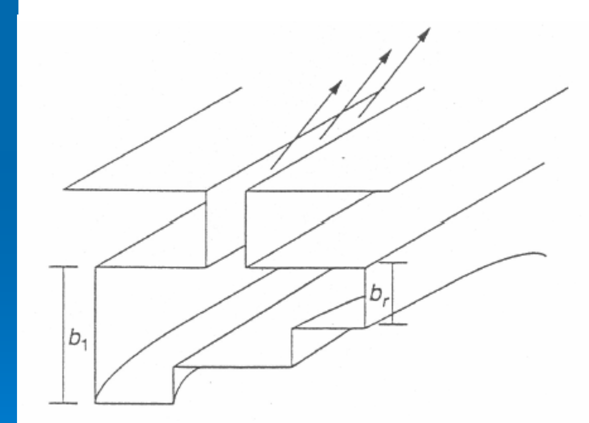
LWAs based on metallic modified rectangular guides





Slitted groove-guide & Channel-guide LWAs





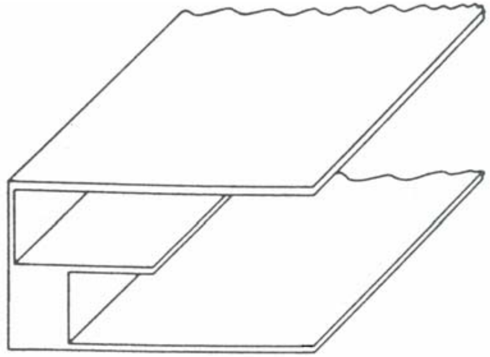
Asymmetrical-ridge & Stepped-guide LWAs

[Studies by Oliner, Kyoto Group, Guglielmi, Rome Group, etc.]

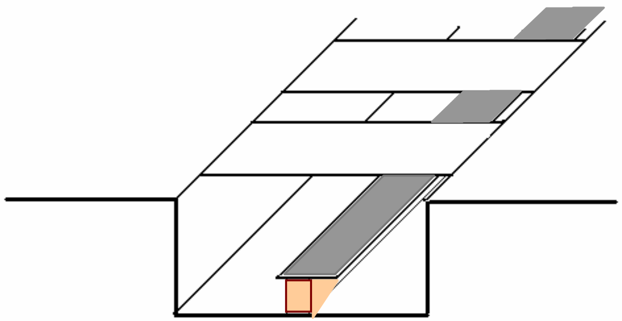
Examples (Ic)

LWAs based on other metallic guides

Slitted circular-guide LWA



Asymmetrical trough-guide LWA

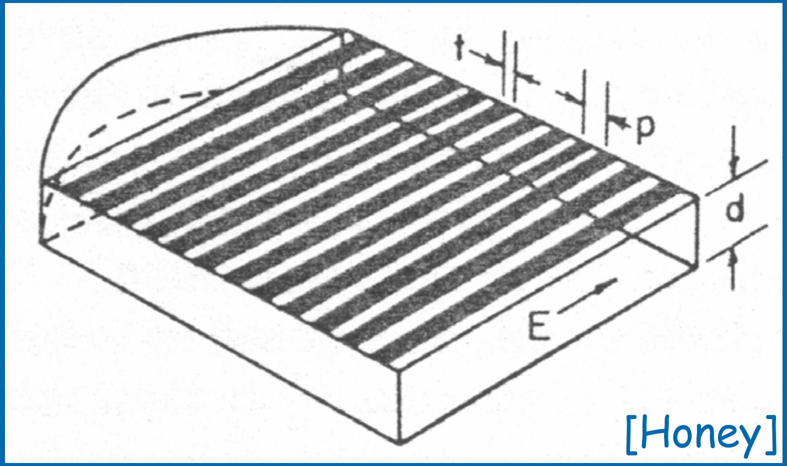


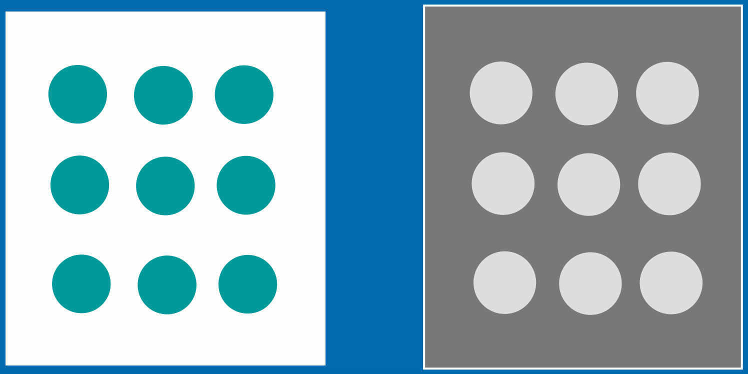
Coaxially-fed slotted LWA

[Studies by Harrington, Goldstone, Oliner, Rumsey, Rotman, Honey, etc.]

Examples (Id)

LWAs based on parallel-plate structures





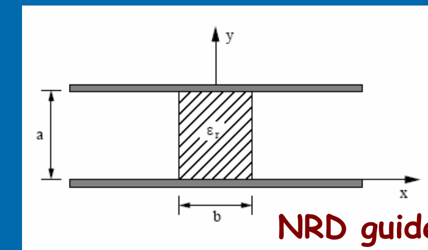
Inductive-grid LWAs

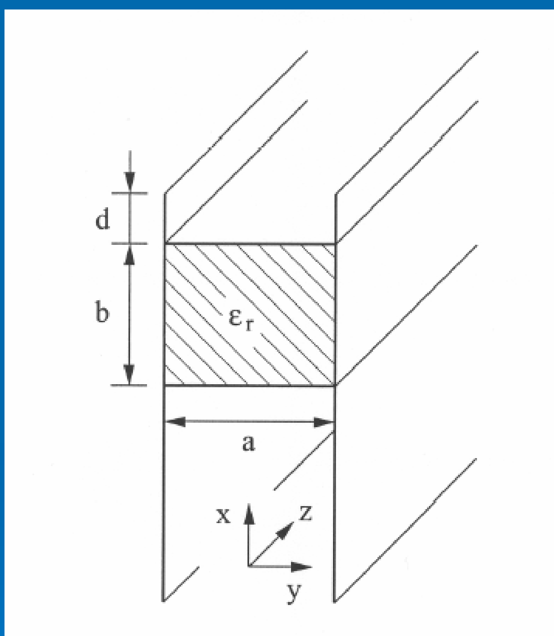
Holey-plate & mushroom LWAs

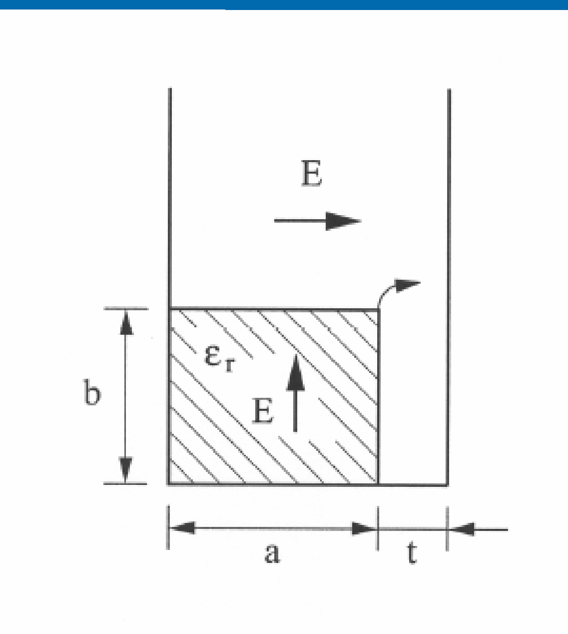
[Studies by Honey, Zucker, etc.]

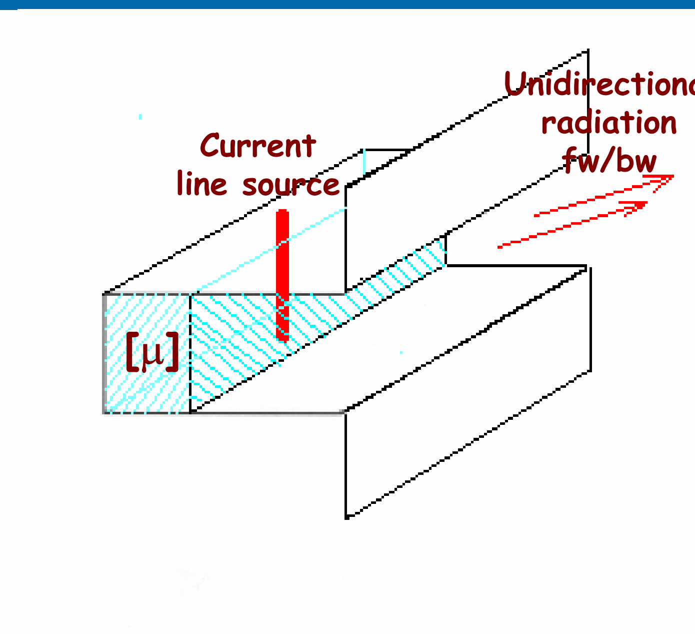
Examples (II)

LWAs based on metallic/dielectric waveguides









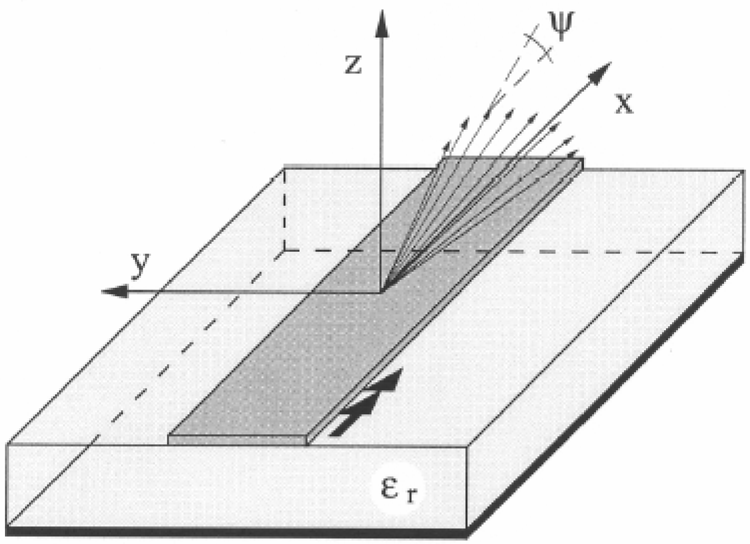
***Foreshortened* and *asymmetrical* nonradiative dielectric (NRD) LWAs**

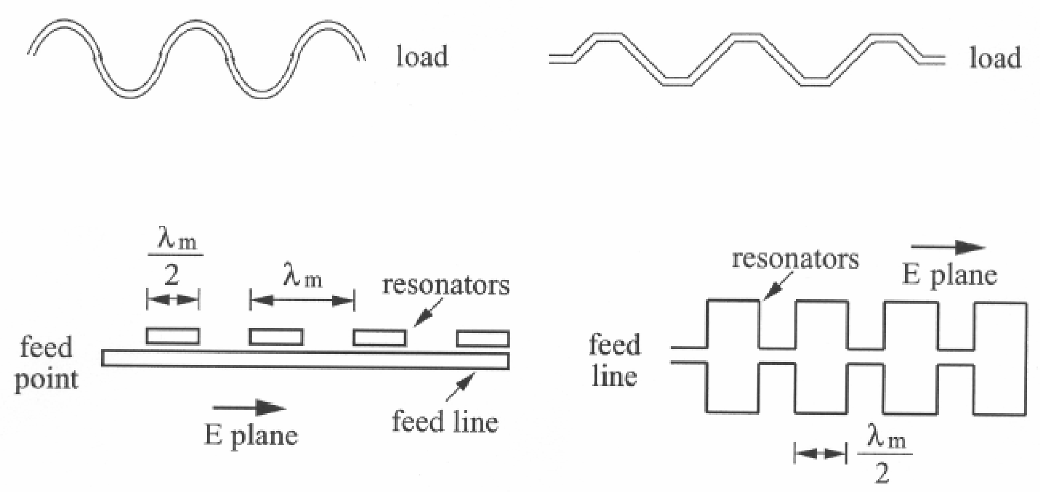
***Nonreciprocal* ferrite NRD LWA**

[Studies by Yoneyama, Peng, Oliner, Rome Group, etc.]

Examples (III)

LWAs based on printed lines





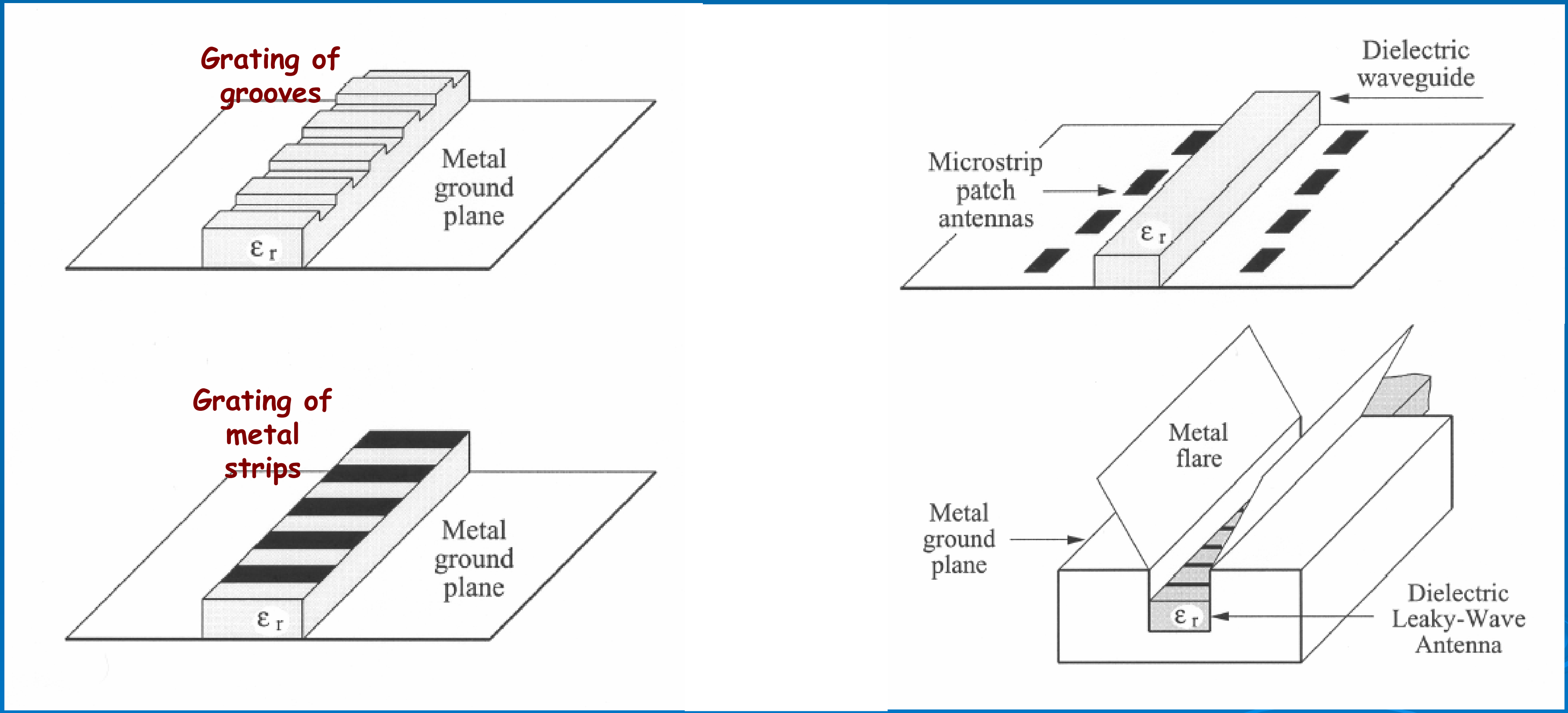
Uniform
higher-order mode microstrip LWA

Two pairs of *periodical-meander* and *periodically-loaded* microstrip LWAs

[Studies by Menzel, James, Hall, Tzuang, Ito, Rome Group, etc.]

Examples (IV)

LWAs based on dielectric guides



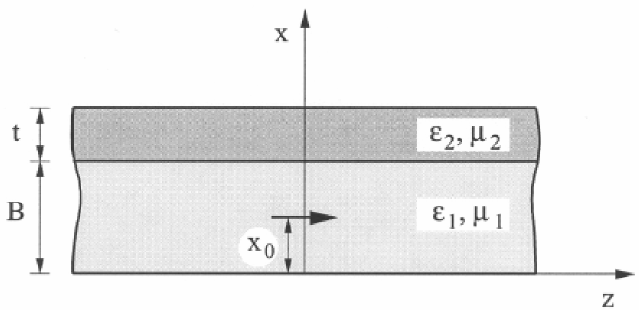
Pair of *periodically-loaded* image-guide LWAs

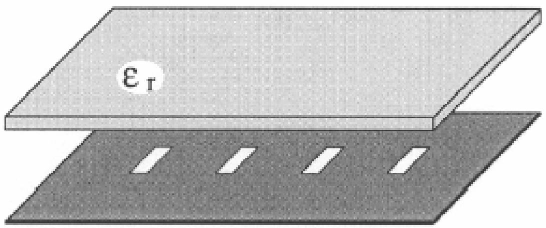
Patch-loaded and *flared-horn* dielectric-rod LWAs

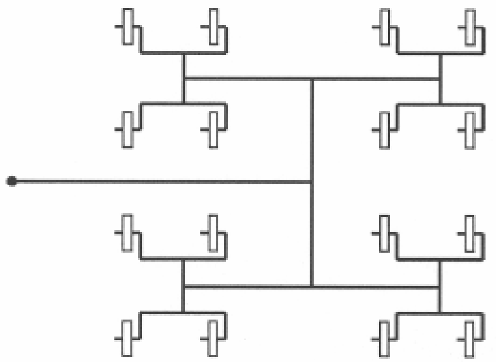
[Studies by Peng, Schwering, Horn, James, Kobayashi, Mittra, etc.]

Examples (V)

LWAs based on planar layered guides







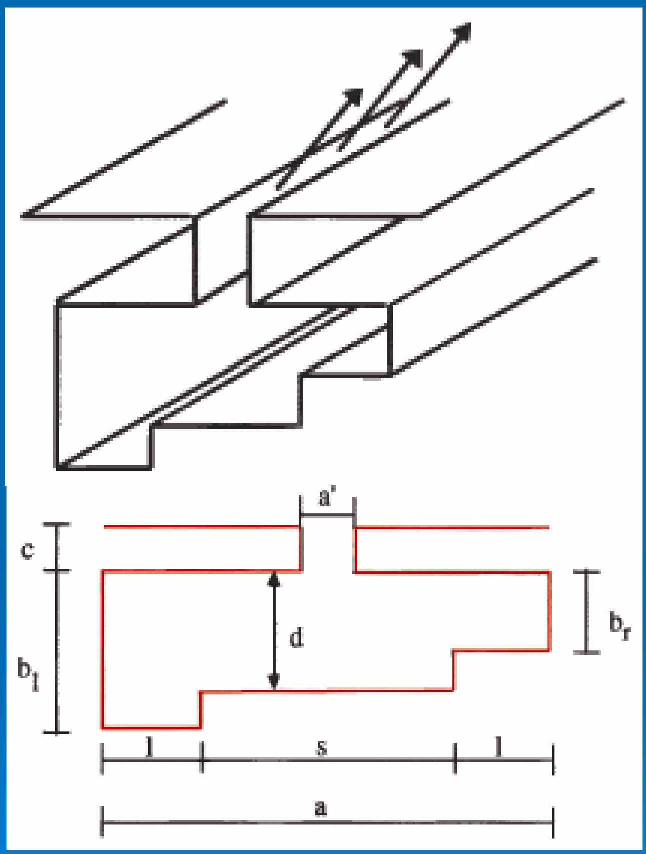
Substrate/superstrate *dipole-excited* LWA

Substrate/superstrate *slot-excited widely-spaced linear* and *planar* LW array

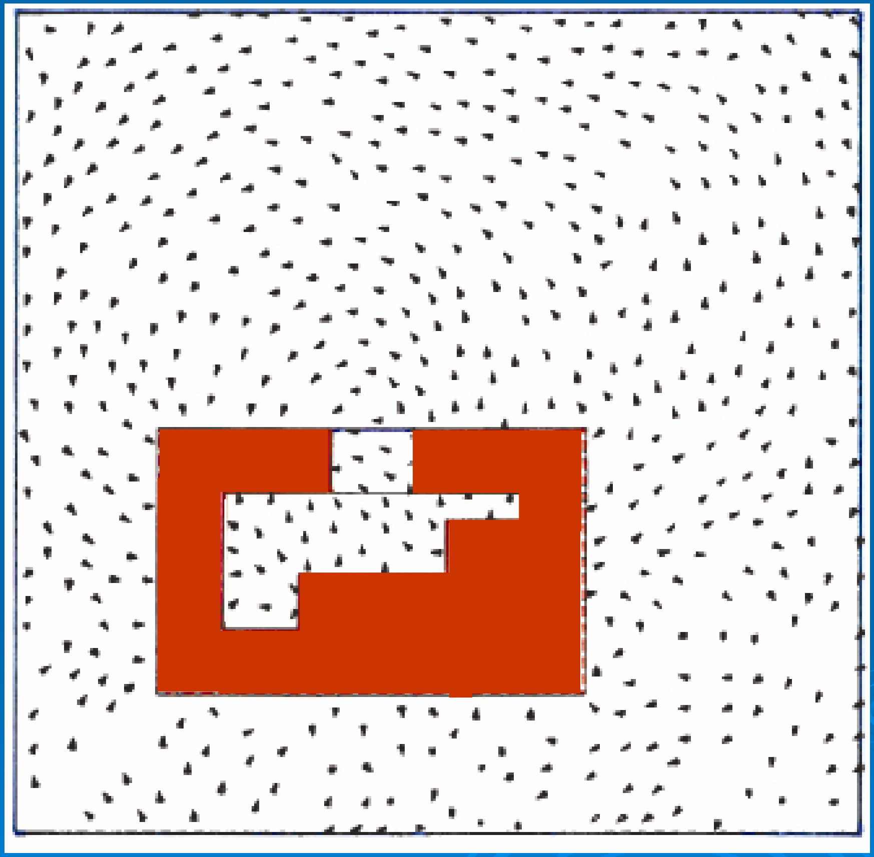
[Studies by Alexopoulos, Jackson, Oliner, Siena and Rome Groups, etc.]

Stepped LWA (S-LWA)

Rectangular guide with two lateral steps and a central slit (Rome Group 1995 patent)



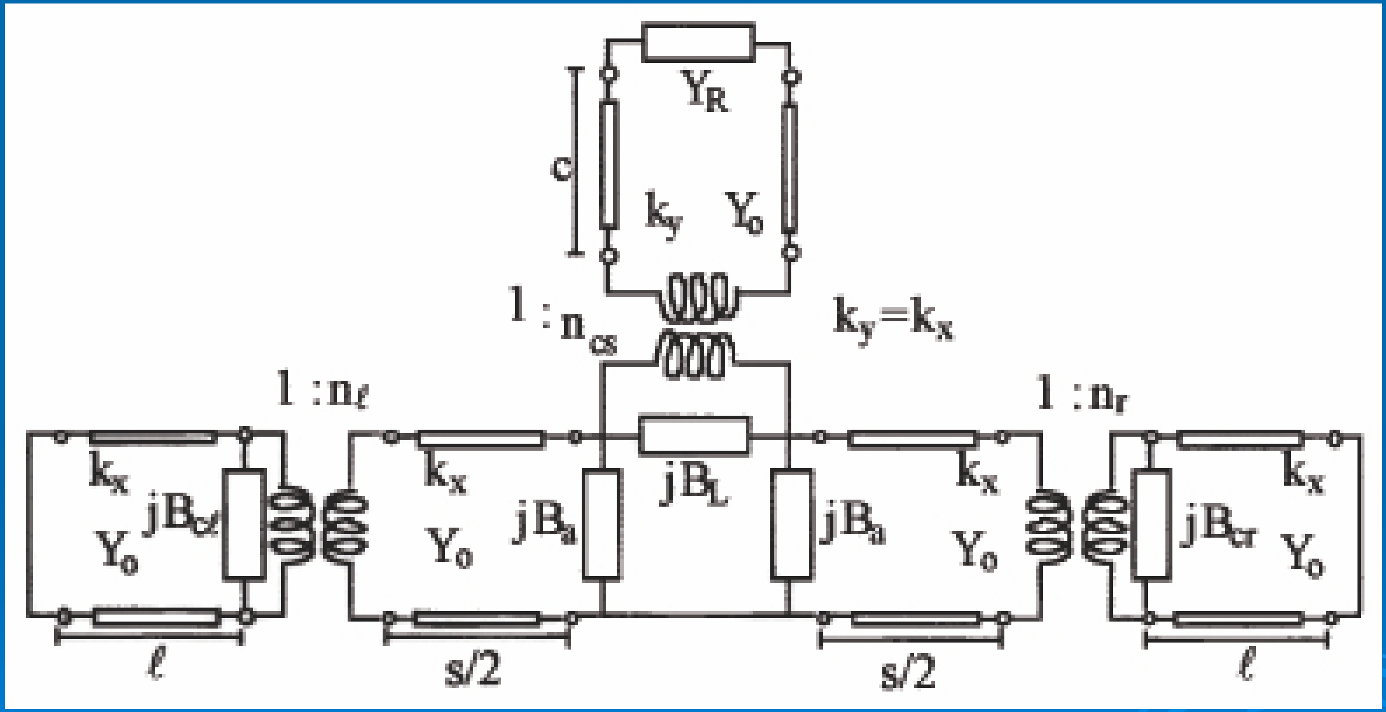
3D view & transverse geometry with relevant parameters



Computed (FEM) arrow plot for the electric-field distribution in the cross plane

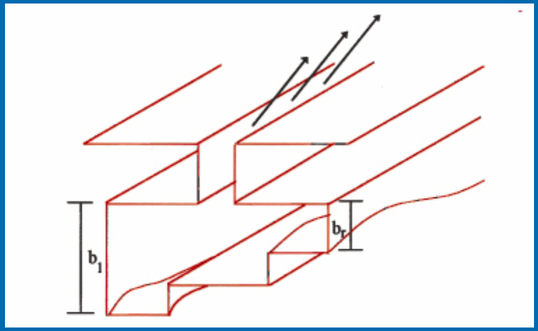
S-LWA equivalent network

Circuit with transmission lines and lumped elements for a Transverse-Resonance-Technique (TRT) solution of k_z



… Computation of LW complex wavenumber $k_z = \beta_z - j\,\alpha_z$ as a function of geometry and frequency

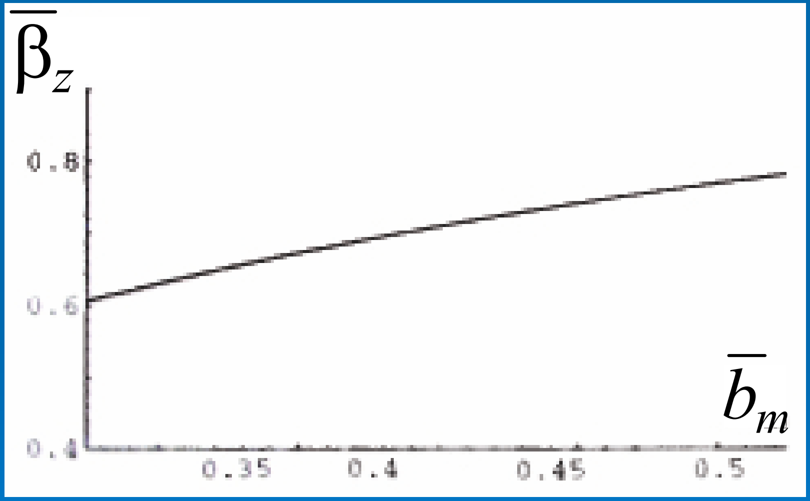
Influence of arms' lengths



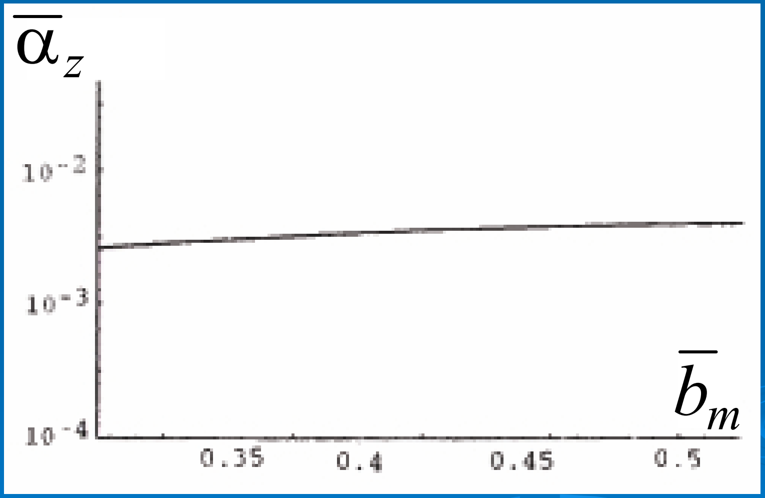
TAPERING:
Geometrical parameters
for almost independent control
of phase and leakage rates:

I. Arms' mean length $\overline{b}_m$

$$\overline{b}_m = \frac{b_l + b_r}{2a}$$



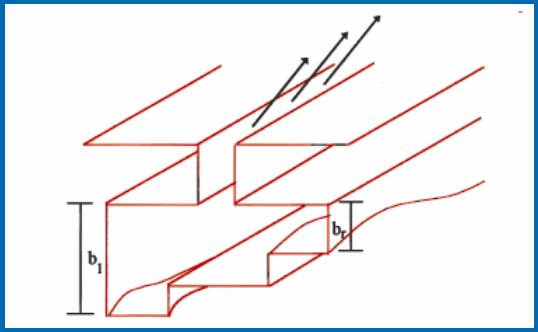
Normalized phase constant vs. the arms' mean length



Normalized leakage constant vs. the arms' mean length

Main action of $\overline{b}_m$ on phase rate

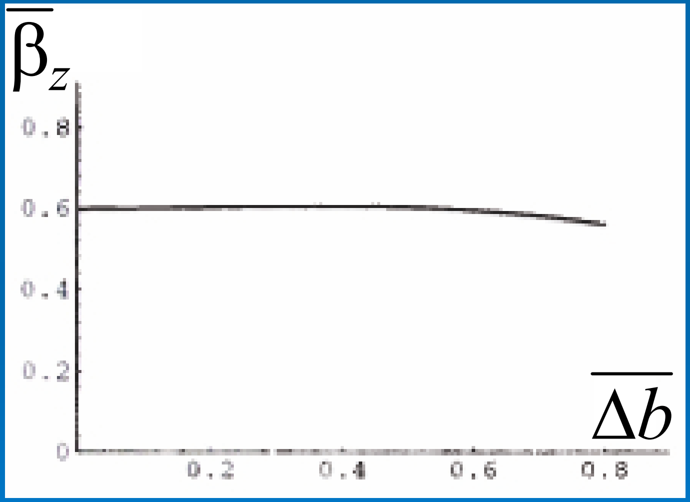
Influence of arms' unbalance



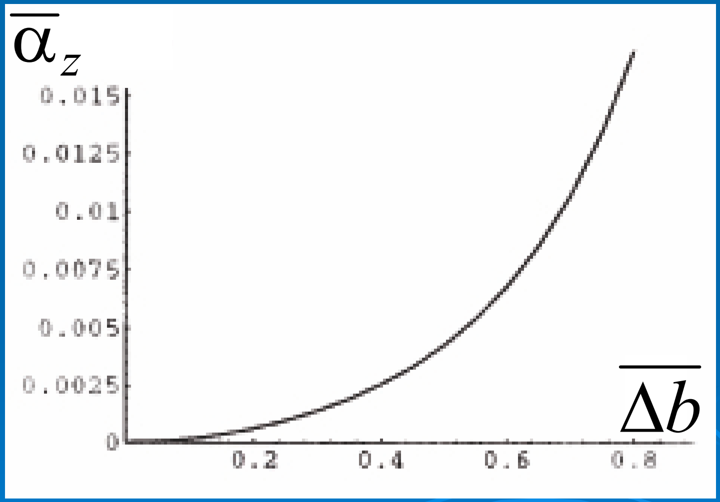
TAPERING:
Geometrical parameters for almost independent control of phase and leakage rates:

II. Arms' unbalance $\overline{\Delta b}$

$$\overline{\Delta b} = \frac{b_l - b_r}{b_l + b_r}$$



Normalized phase constant vs. the arms' unbalance



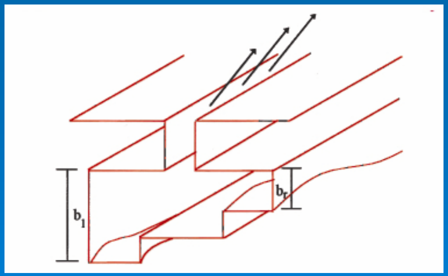
Normalized leakage constant vs. the arms' unbalance

Main action of $\overline{\Delta b}$ on leakage rate

Tapering for pattern control

- Choice of the illumination function on the aperture
- Determination of the leakage distribution for a desired efficiency
- Choice of the general geometrical and physical parameters (frequency and scan ranges, etc.)
- Numerical determination of the relevant longitudinal modulation of the geometrical parameters

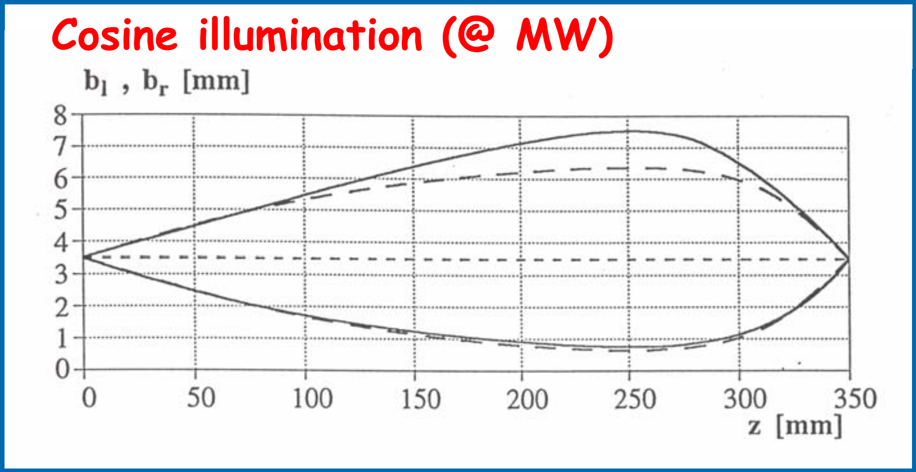
Ad-hoc software based on TRT for S-LWA analysis and design



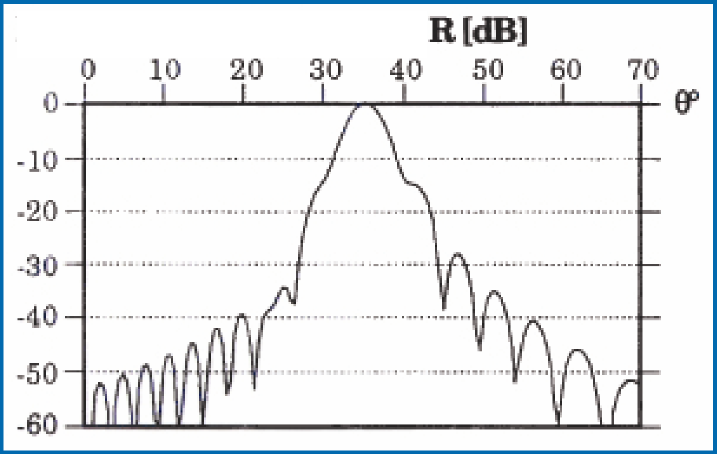
S-LWA 'iterative' design procedure:
Computation of arms' unbalance by keeping fixed their mean value; Adjustment of the mean value by keeping fixed the already-determined unbalance; and so forth if necessary …

S-LWA 'direct' design procedure:
Numerical determination of the lengths of lateral arms for any fixed phase- and leakage-constant distribution
(solution of TRT equation in implicit form)

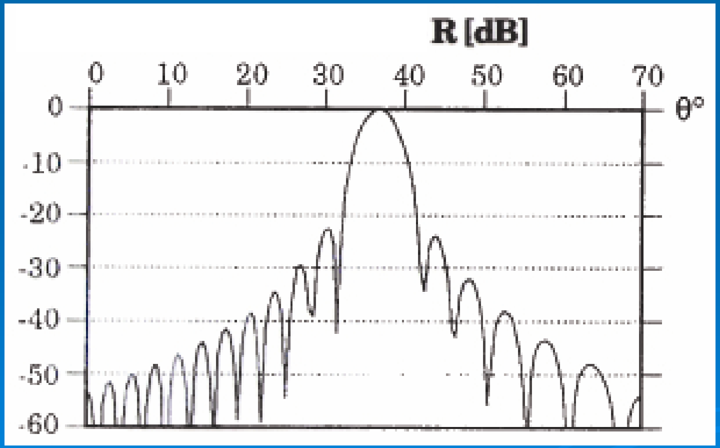
S-LWA advanced patterns



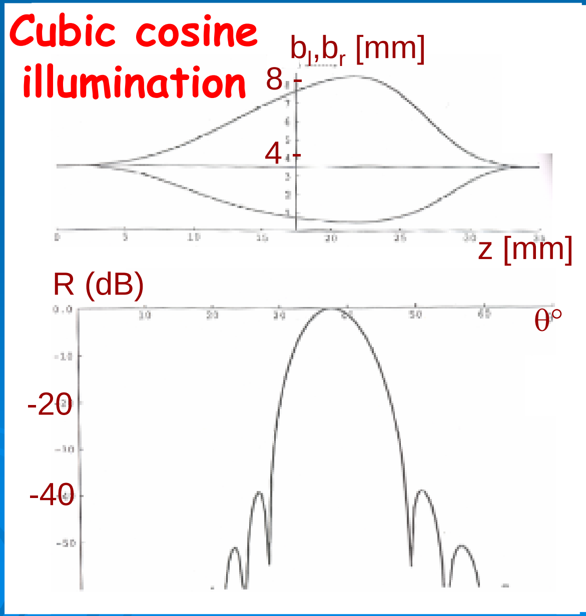
Cosine tapering: 'improved' *z*-distribution of the lateral-arm heights b_l, b_r



'Distorted' cosine radiation pattern after a first tapering procedure with *constant* b_m



'Expected' cosine radiation pattern with the 'improved' tapering



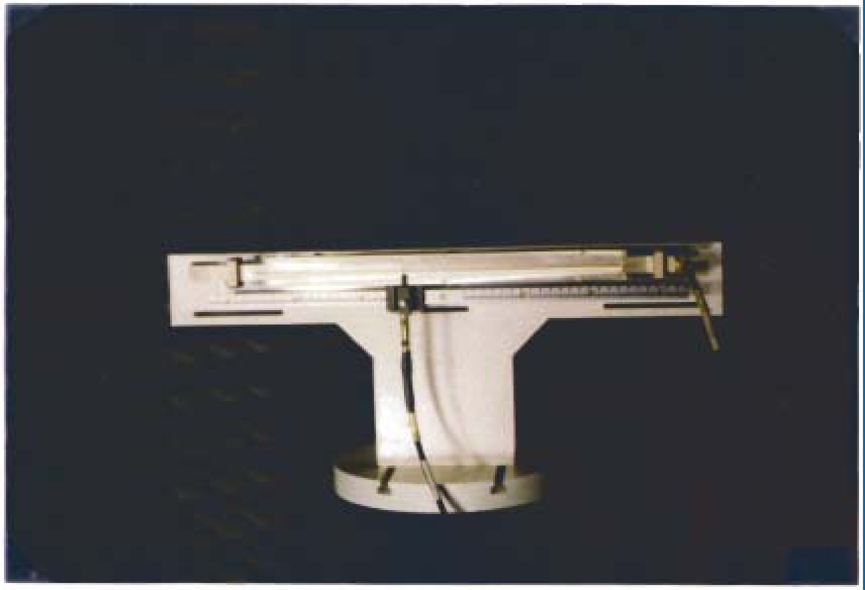
Arms' tapering for *cubic cosine* and relevant radiation pattern

Experimental analysis

Realization

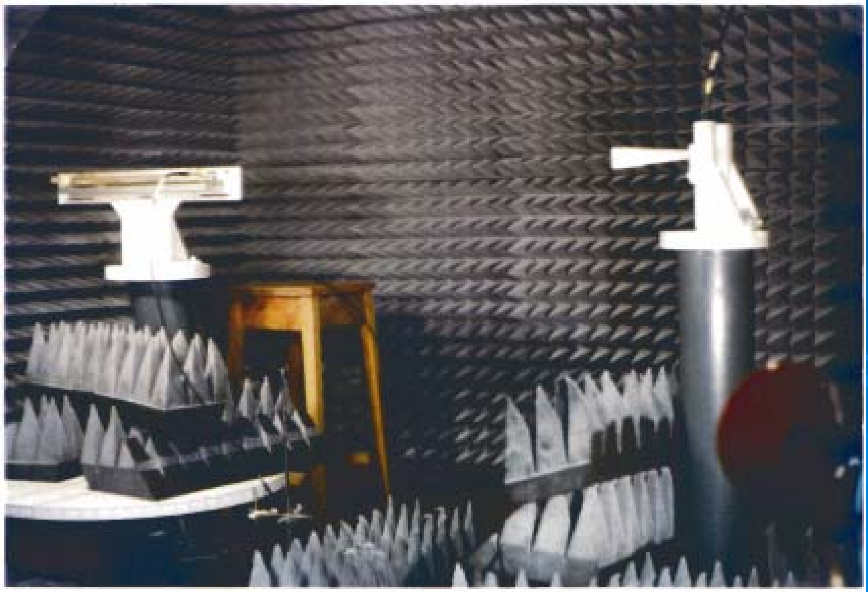
(in conjunction with Alenia Spa)

- S-LWAs with standard and advanced illuminations (cos, cos^3…)
- Design, manufacture, and test of various prototypes for microwaves and mm waves (Ku & Ka bands)



Measurements

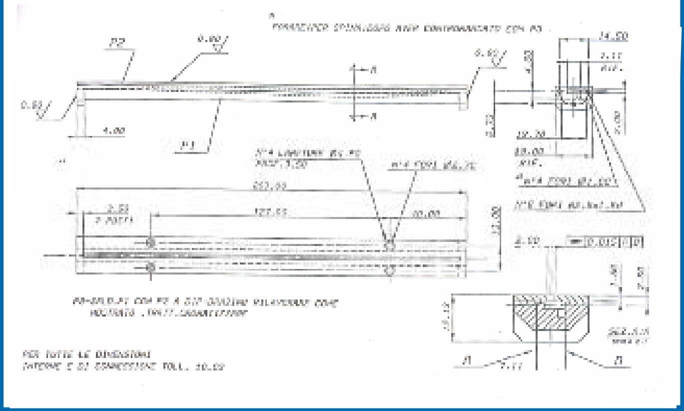
- Aperture region (near-field probing)
- Fresnel region (intermediate-field construction)
- Fraunhofer region (far-field free-space evaluation)

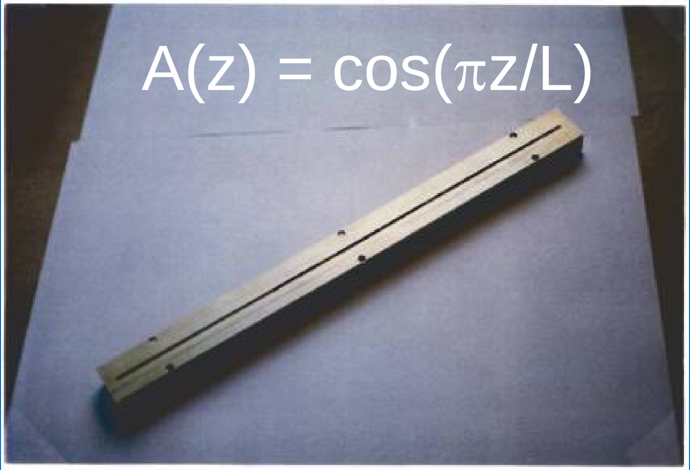


S-LWA manufacture

Realization aspects:

- Fabrication of the metallic profiles with numerically-controlled machines
- Tolerances (<30 μm) give rise to 'random' errors, that influence in particular the phase distribution, strongly responsible of possible distortion of the radiation pattern
- Check for possible 'systematic' errors in fabrication (e.g., aperture disalignment, etc.), which can affect also the amplitude distribution
- Care for smooth transitions in the feed (between closed and open structure) to reduce spurious effects of discontinuities (particularly for nontapered geometries)



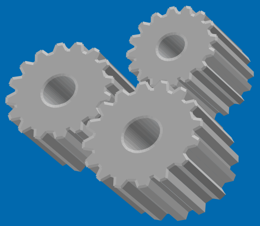


A stepped LWA prototype

The 'non-ideal' factors in the manufacturing process influence the 'ideal' behavior of phase and leakage distributions, and hence can sensitively modify the radiation patterns, in particular for high performance (e.g., rise and unbalancing of sidelobes, spurious beams, etc.)

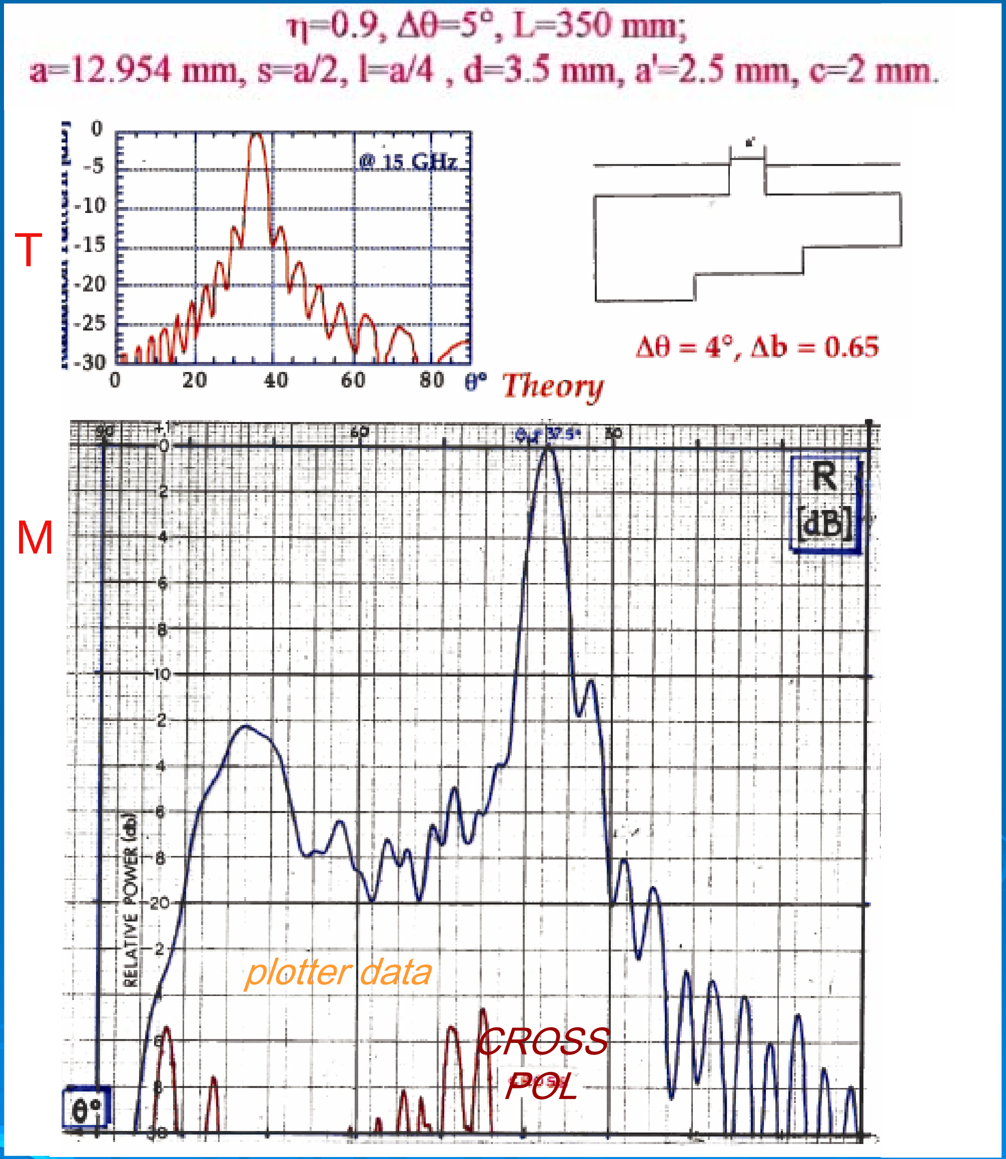
A nontapered X-band S-LWA

“T”: data from *Theory*



“M”: data from *Measurements*

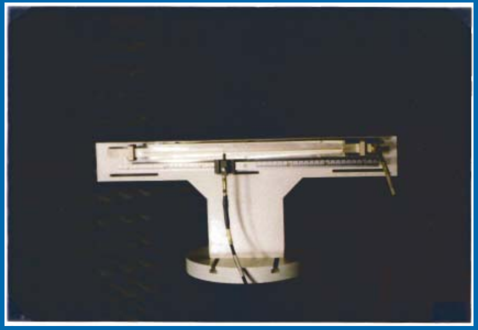
Prototype of nontapered S-LWA for microwaves @ 15-22 GHz (Ku band)



- *Correct prediction of beam direction and width*
- *Spurious radiation related to realization errors*
- *Low cross-pol levels*

Test of tapered prototypes

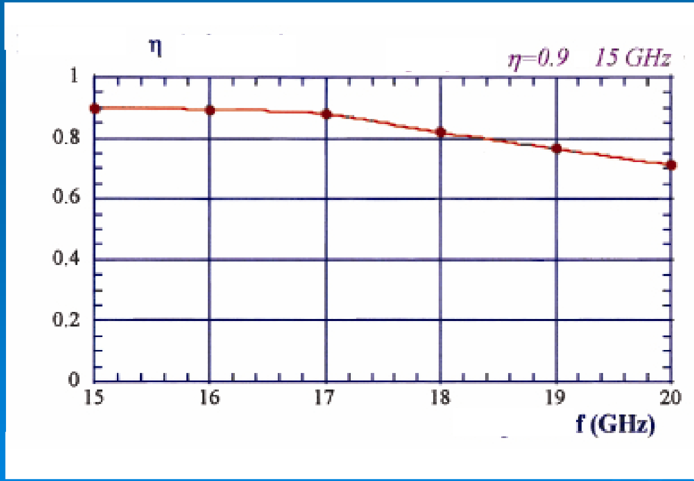
Prototype of S-LWA for Ku band with a *cosine* illumination



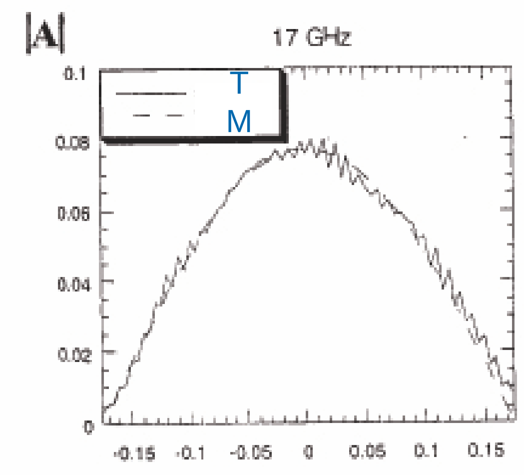
Near-field tests with a dipole probe

Measurements of Scattering parameters

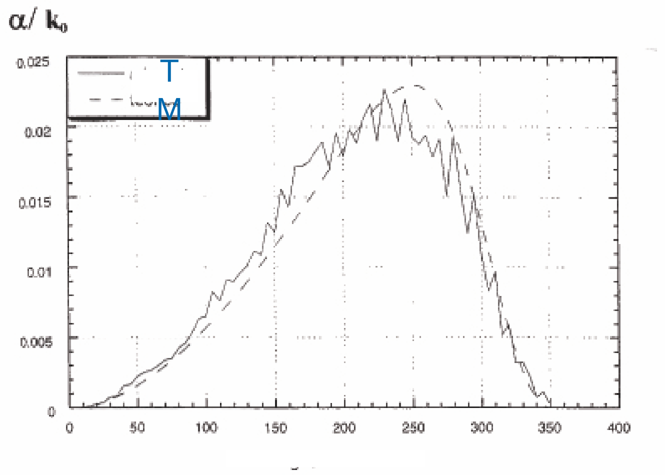
- Radiation efficiency
- Amplitude & phase on the aperture
- Leakage and phase-constant distributions
- Far-field Fourier-transform reconstruction



Efficiency η vs. f



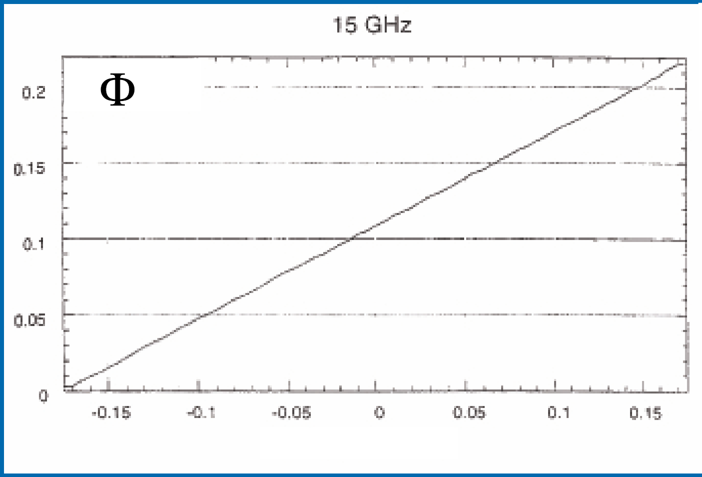
Amplitude A vs. z



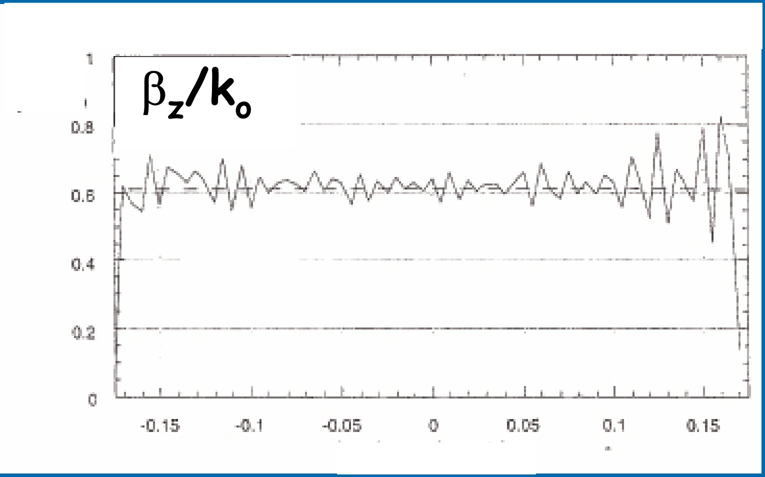
Leakage rate α_z/k_o vs. z

Distribution on the aperture

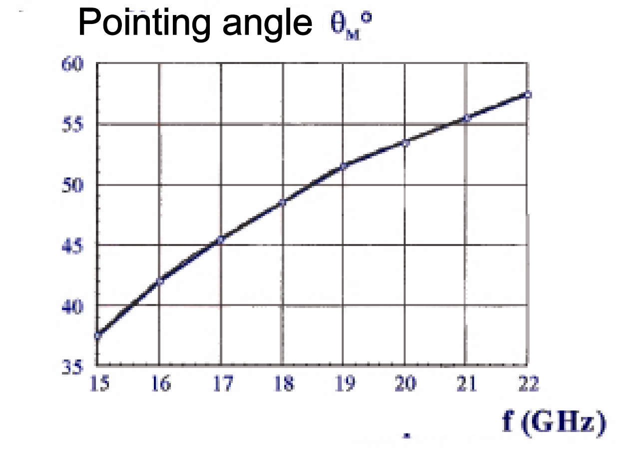
...Measurements of the phase (and related quantities) on the aperture



Phase distribution Φ vs. z



Phase constant β_z/k_o vs. z



f (GHz)	β_z/k_o *M*	β_z/k_o *T*	Pointing angle °
15	0.61600	0.61074	38.025
16	0.67142	0.67217	42.177
17	0.71848	0.71721	45.929
18	0.75208	0.75289	48.771
19	0.78032	0.78181	51.290
20	0.80890	0.80452	53.989
21	0.83093	0.82465	56.194
22	0.84666	0.84170	57.850

Data on pointing angle θ_M°, β_z/k_o, and comparisons *M/T*

Fresnel-zone measurements

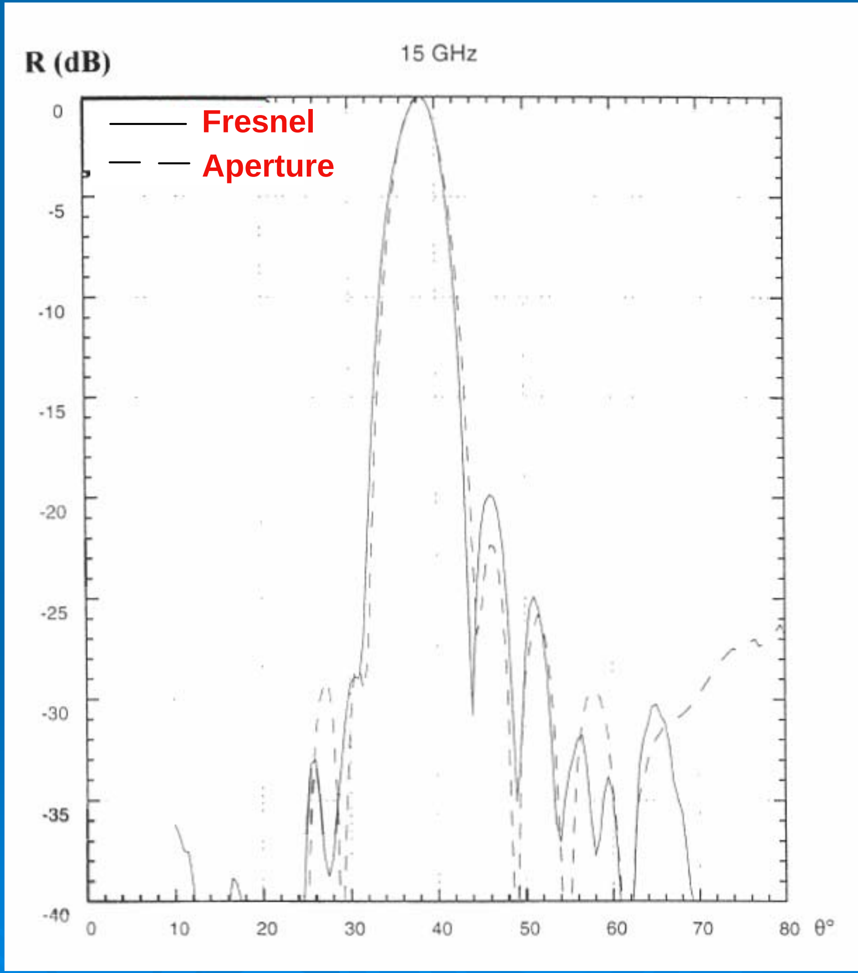
…Prototype of S-LWA for Ku band with a *cosine* illumination

Tx/Rx setup (LWA/horn) in anechoic chamber

Measurements of Scattering parameters

- Intermediate-field evaluation
- Far-field reconstruction by equivalence

- *Correct prediction of radiation features*
- *Some distortion effects on side-lobes (phase errors)*



Radiation patterns R (dB) vs. θ from near-field and intermediate-field data

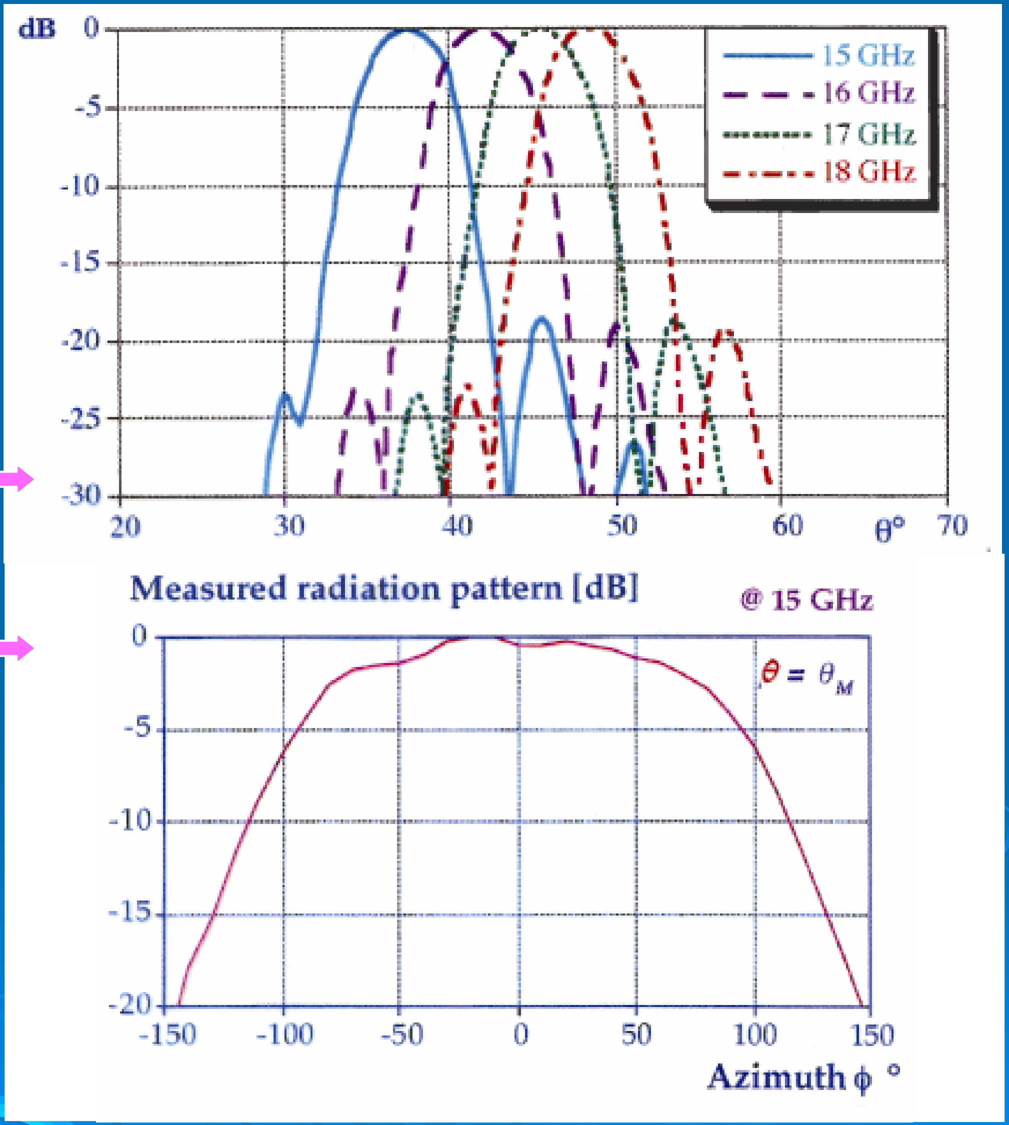
Far-field measurements

Free-space environment

...cosine

Radiation pattern in elevation:
R (dB) vs. θ *(pencil beam scanning by f)*

Radiation pattern in azimuth:
R (dB) vs. ϕ *(fan beam)*



Also S-LWA prototypes with further reduced sidelobes (e.g., *cubic cosine*) have been designed and tested with excellent results

S-LWAs at mm-waves

Ka band prototype

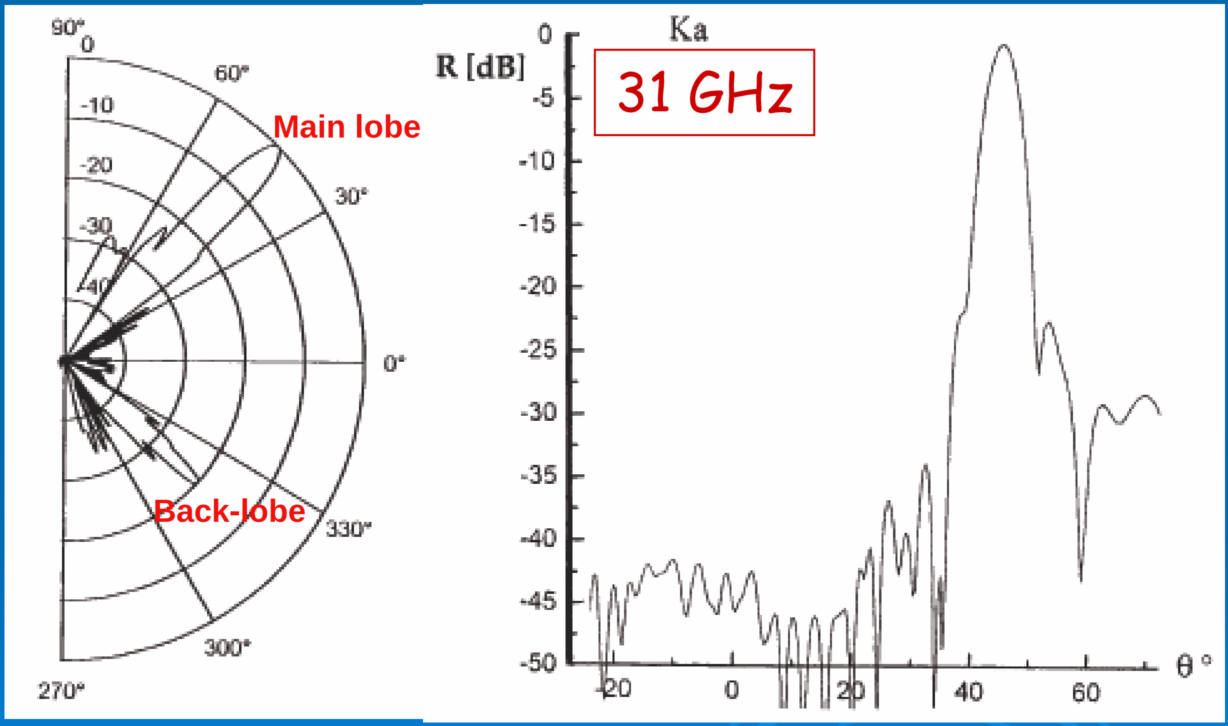
η=0.9, $\Delta\theta$=5°, L=200 mm;
a=7.11 mm, s=a/2, l=a/4 , d=2 mm, a'=2 mm, c=1.6 mm.
Range 27-35 GHz

Cos illumination

Measurements:

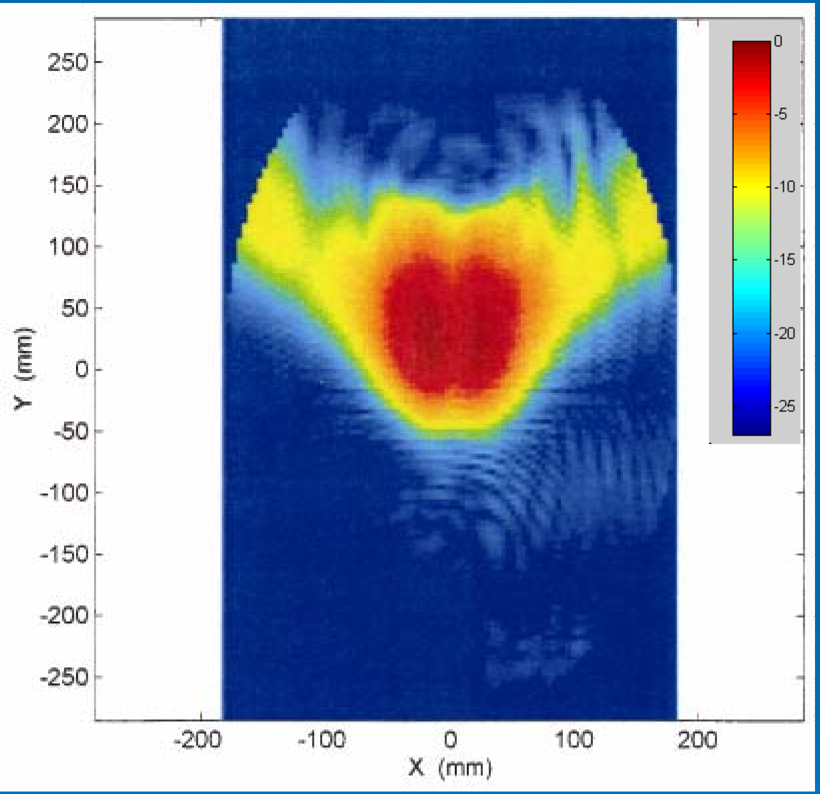
The basic data are obtained with a near-field technique (aperture amplitude) from which the radiation pattern is derived …

- *Correct prediction of radiation for main beam and side-lobes even with reduced dimensions*
- *Presence of a back-lobe (non-ideal matched load)*

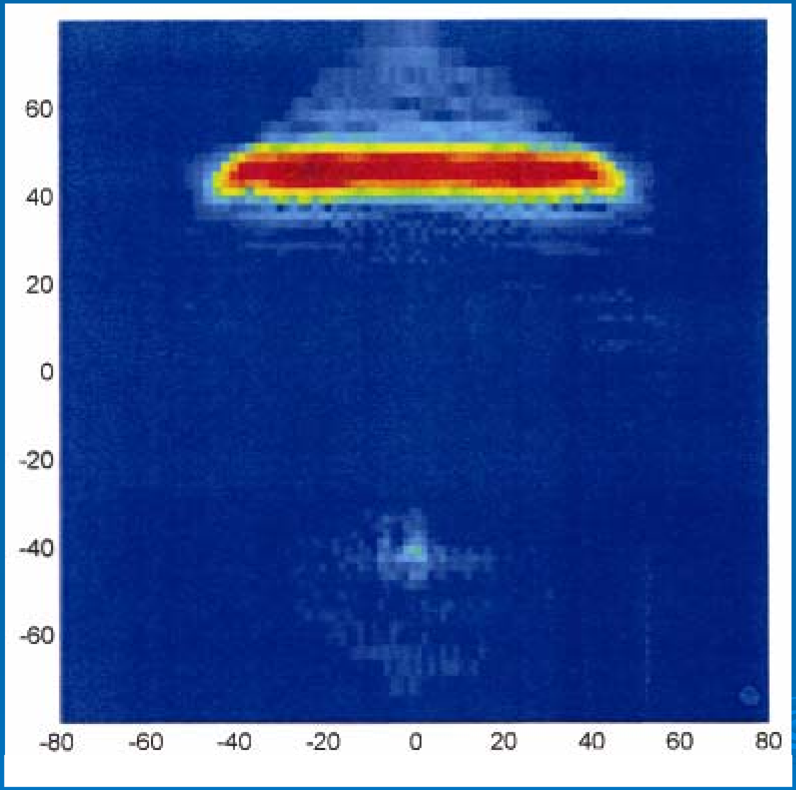


Measured radiation patterns R (dB) vs. θ in polar & linear forms

Measured near and far field



Near Field

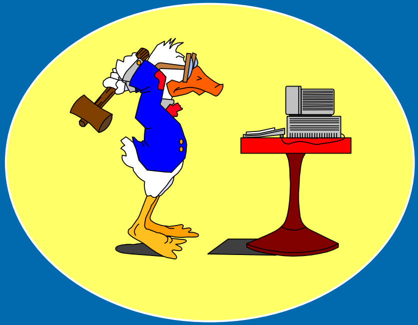


Far Field

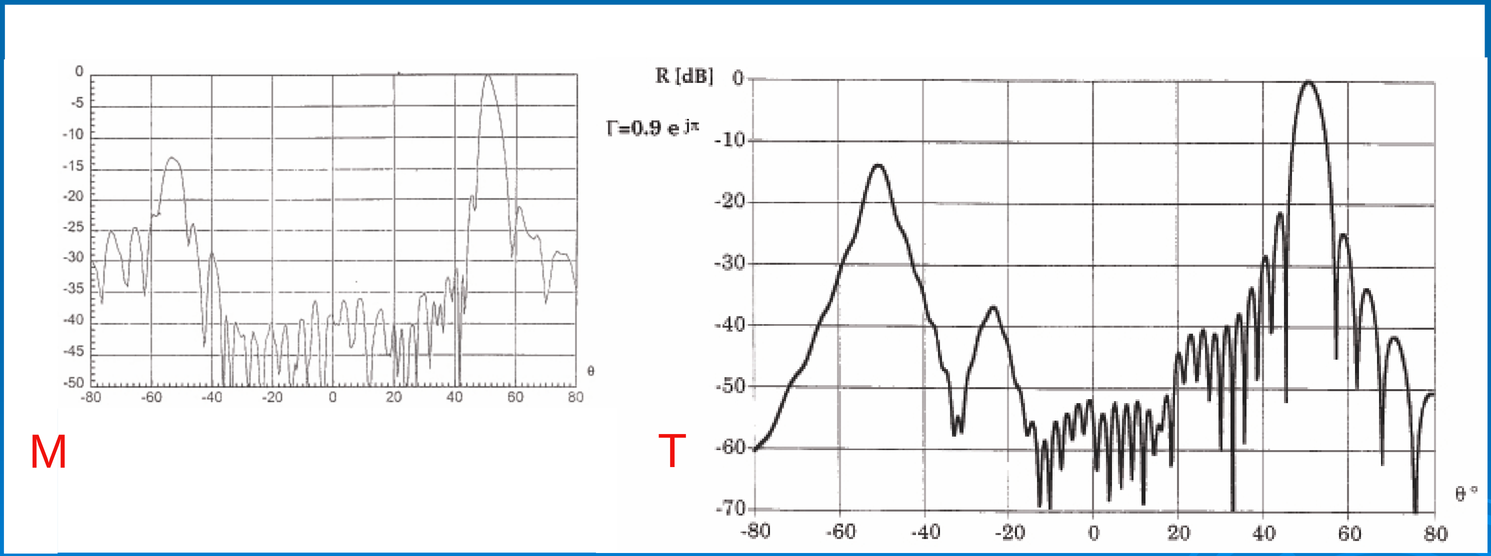
Typical LWA radiation features:
2D colour plot of the measured field amplitude
(mm cos S-LWA)

Validation of S-LWA design

The theoretical techniques for analysis (based on TRT) and for design (tapering procedures) result completely validated and satisfactory for S-LWA performance.

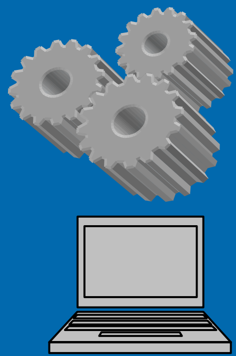


Agreement with measurements is in general excellent up to mm-wave range and even for advanced narrow-beam patterns with reduced sidelobes (20-30 dB)



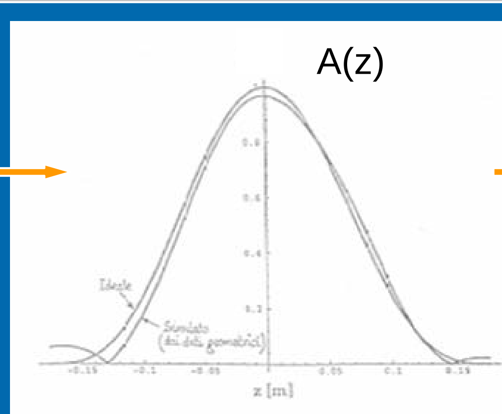
Measured/Theoretical comparisons of **R(dB)** vs. θ for a mm-wave cosine S-LWA with the effect of a short-circuit termination

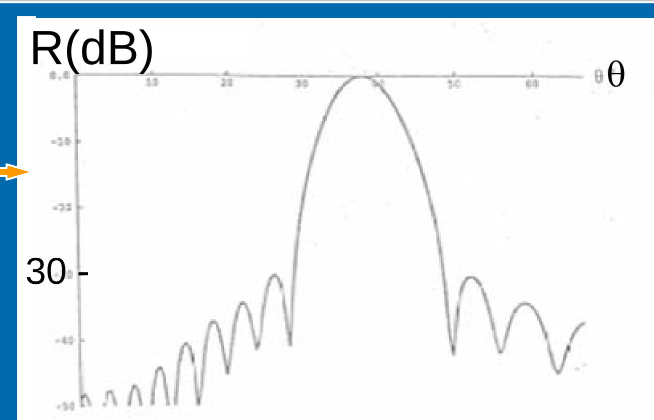
Test on error effects



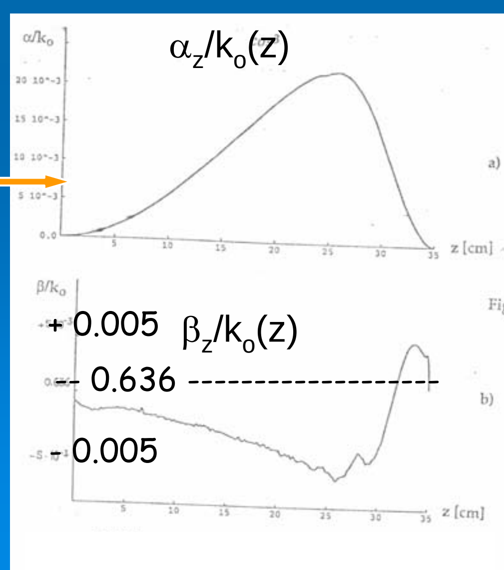
The knowledge of the actual geometrical data for the prototypes allows us to analyze also theoretically the effects of manufacturing errors

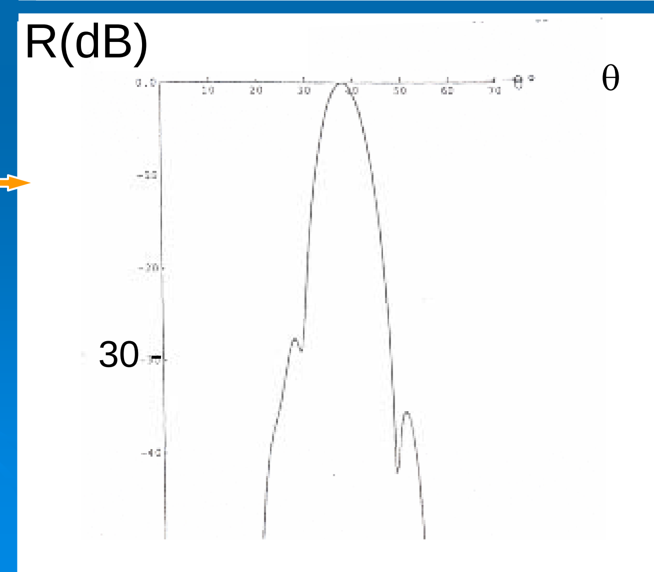
Systematic errors:
Side-lobe rising due to uncorrect realization of the radiating slot (disalignment …)



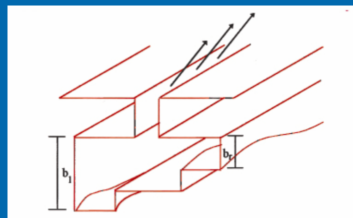


Random errors:
Side-lobe unbalancing due to tolerance variations in the realization of the tapering



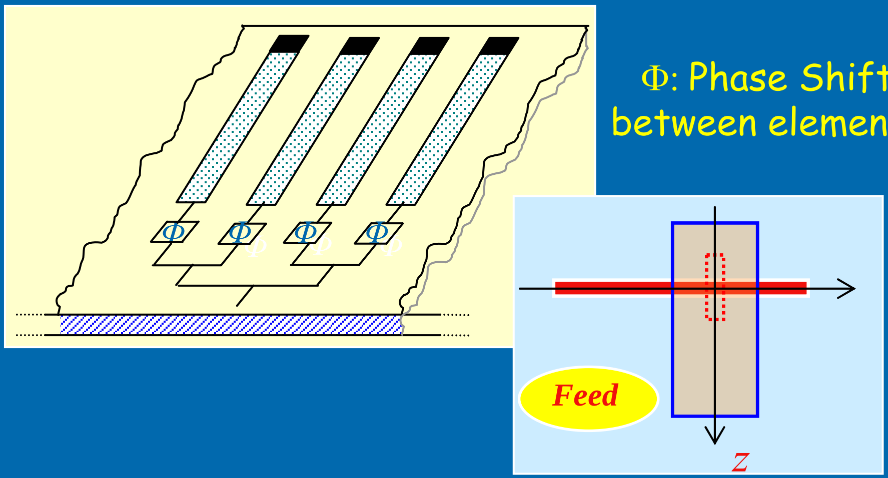


Features of stepped LWA

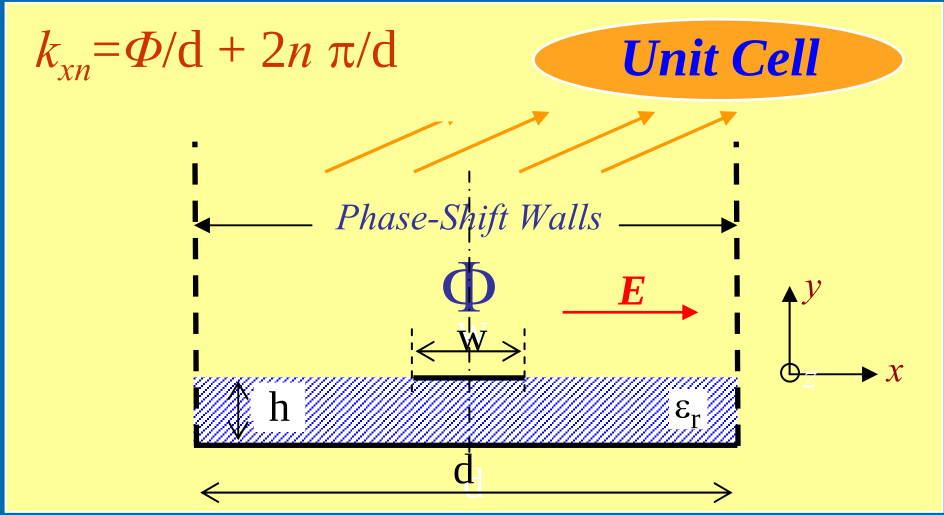


- Excellent antenna performance (easy integration and matching with feeders, high efficiency and power handling, low cross-pol and spurious effects)
- Basic radiation features (beam width and pointing, frequency scan, etc.) accurately predicted by theory
- Simple and efficient synthesis techniques of aperture distribution for advanced radiation patterns (narrow beams with reduced sidelobes) through almost independent control of phase and leakage constants
- Limited influence of manufacturing tolerance, random errors, and ohmic losses up to the millimeter-wave range
- Such non-ideal aspects can be checked also theoretically

Microstrip linear LW arrays



Φ: Phase Shift between elements

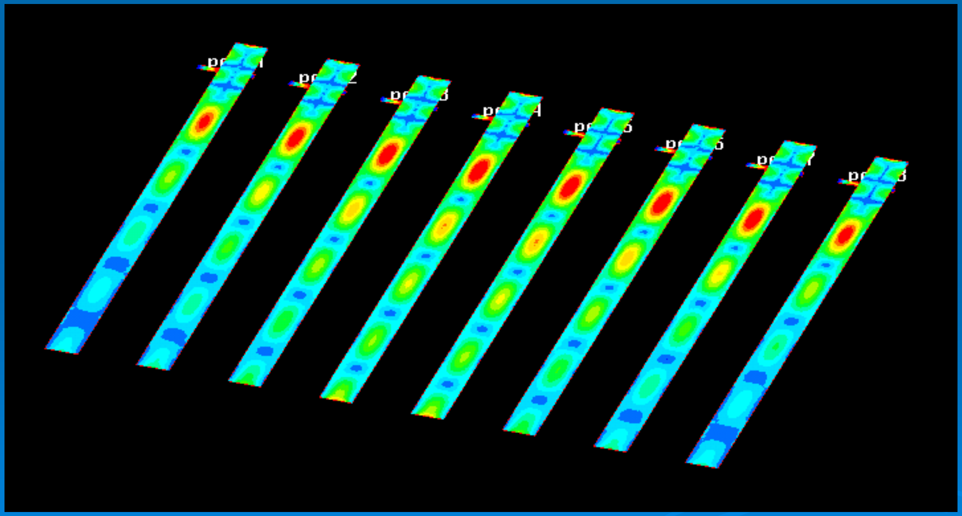


Infinite array: one spatial (transverse) period

Main method of analysis in the Unit Cell: Spectral Domain Approach

Determination of the complex wavenumbers as a function of the physical parameters

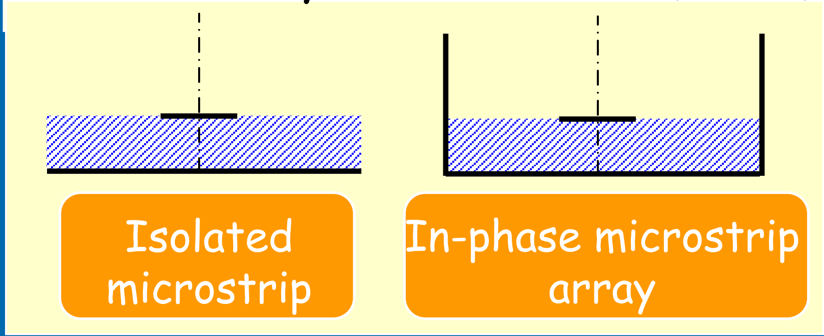
Computation of the LW strip currents, from which the radiation features of the LW array are achieved…

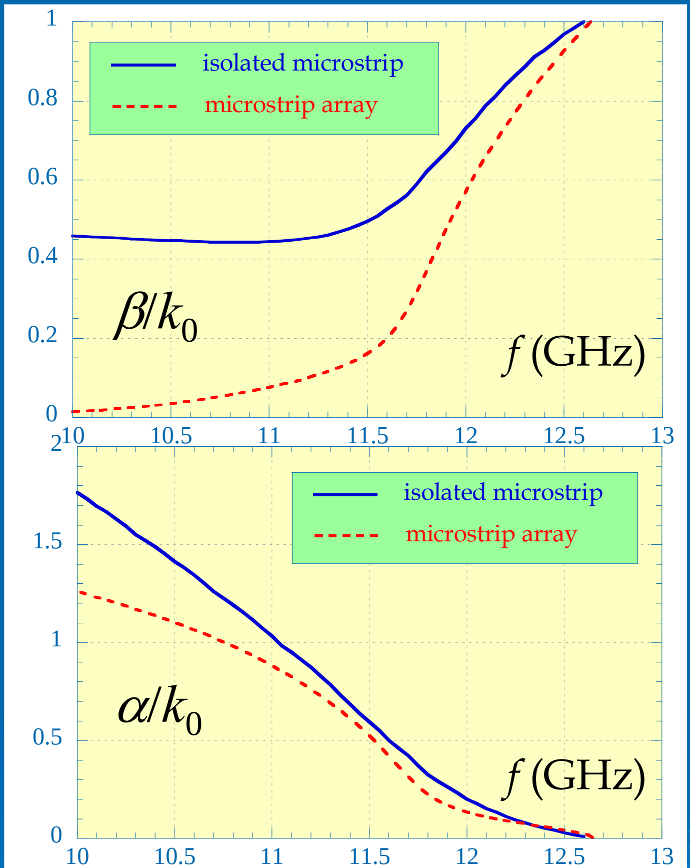


Magnitude of currents on a finite array without phase shift

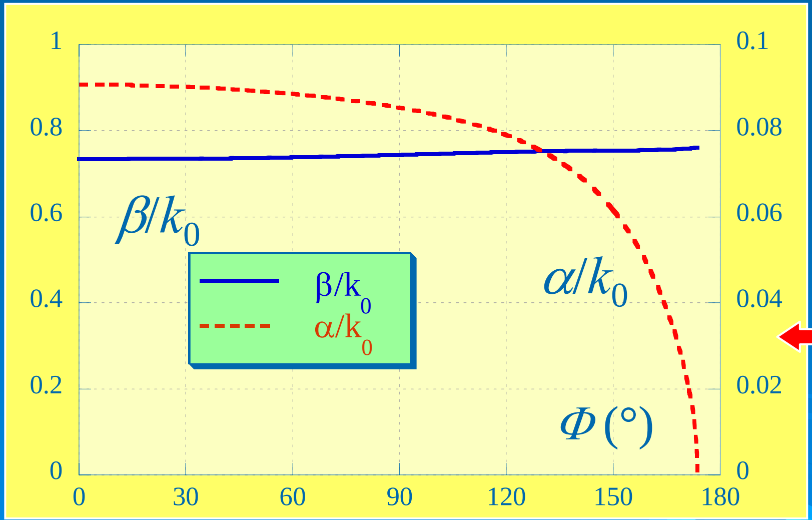
Properties of LW harmonics

Coupling effects
in the array environment ($\Phi=0°$)

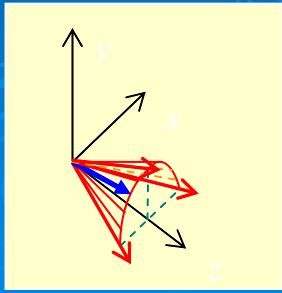




ε_r = 10.2, h = 0.635 mm, w = 3.3 mm, d = 18 mm



Action on phase and leakage of Phase Shift Φ



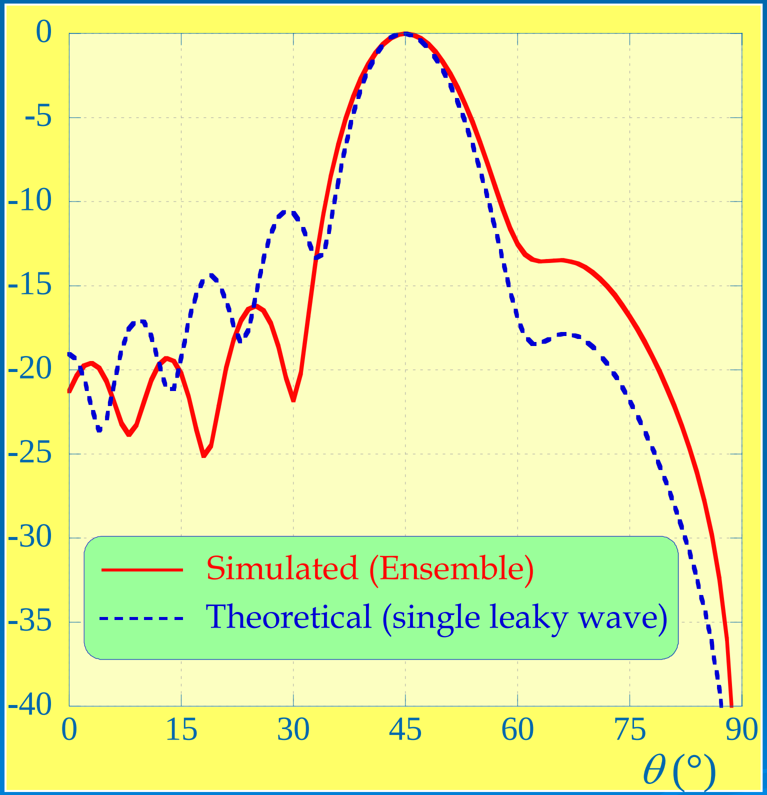
f =12.2 GHz; d/λ_0 = 0.73

LW-array pencil beams

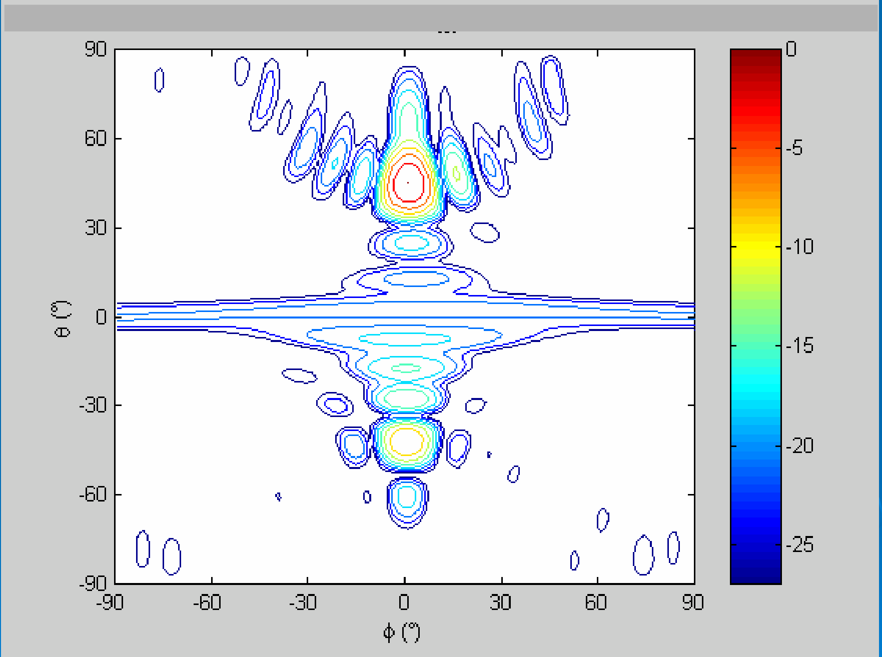
Radiation features: comparisons between the LW unit-cell approach and a full-wave MoM of a CAD for a finite number of elements

$\Phi = 0°$ (in-phase feed)

$$\theta_m = \sin^{-1}\sqrt{(\beta_z/k_o)^2 + (k_{xn}/k_o)^2}$$
$$\varphi_m = \tan^{-1}(k_{xn}/\beta_z)$$



Radiation pattern of E vs. θ ($\phi=\phi_M$)



Radiation contour of $|E|_{tot}$ at 3 dB level

θ_{max} (LW) = 45.7 ° $\Delta\theta_{3dB}$ (LW) = 11.6 °
θ_{max} (CAD) = 45 ° $\Delta\theta_{3dB}$ (CAD) = 13 °

2D scanning features

$\Phi = 40°$

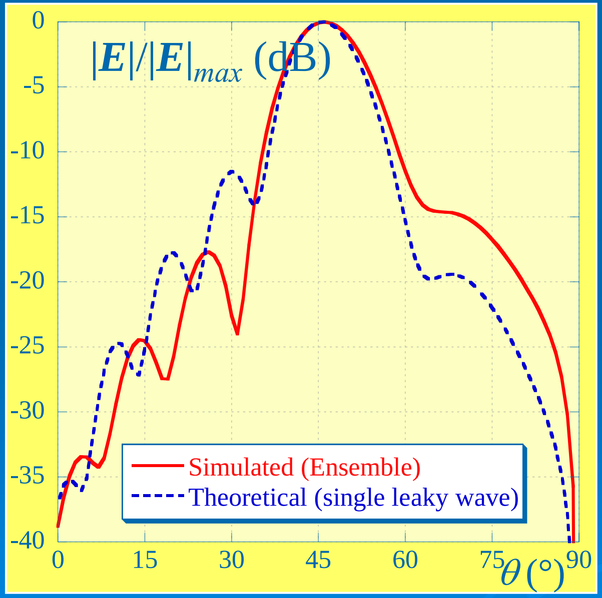
Pointing angles:

φ_{max} (LW) = 8.8 °

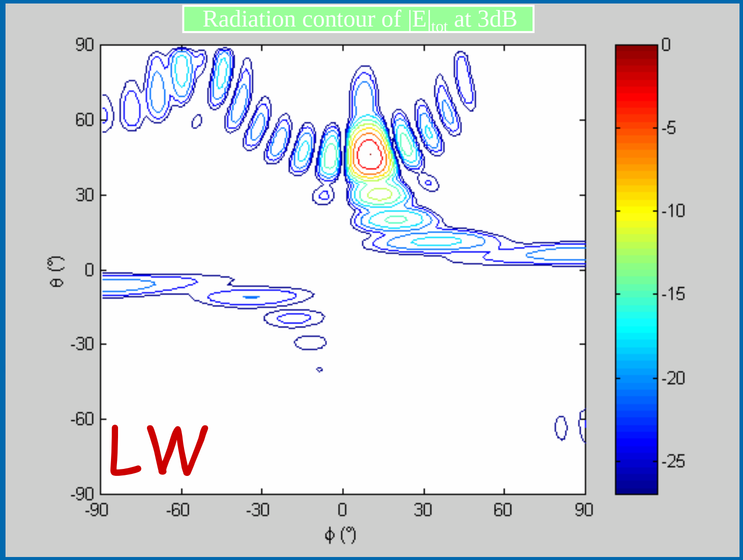
φ_{max} (CAD) = 9 °

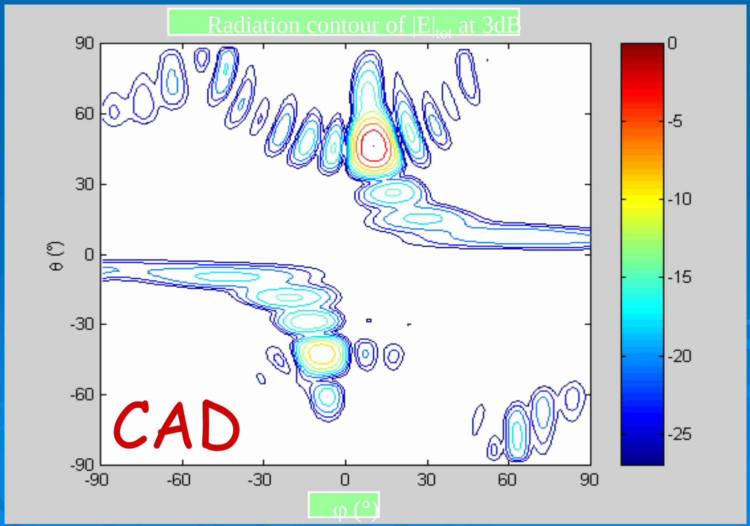
θ_{max} (LW) = 46.6 °

θ_{max} (CAD) = 46 °



Radiation pattern of E vs. θ ($\phi=\phi_M$)

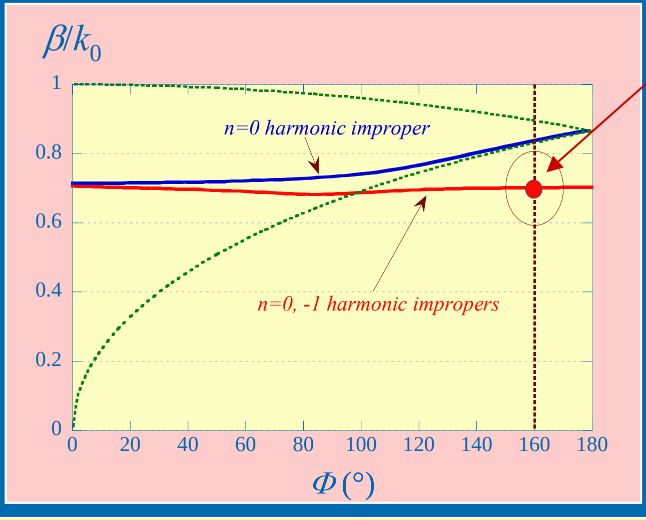




Comparisons of radiation contours of $|E|_{tot}$

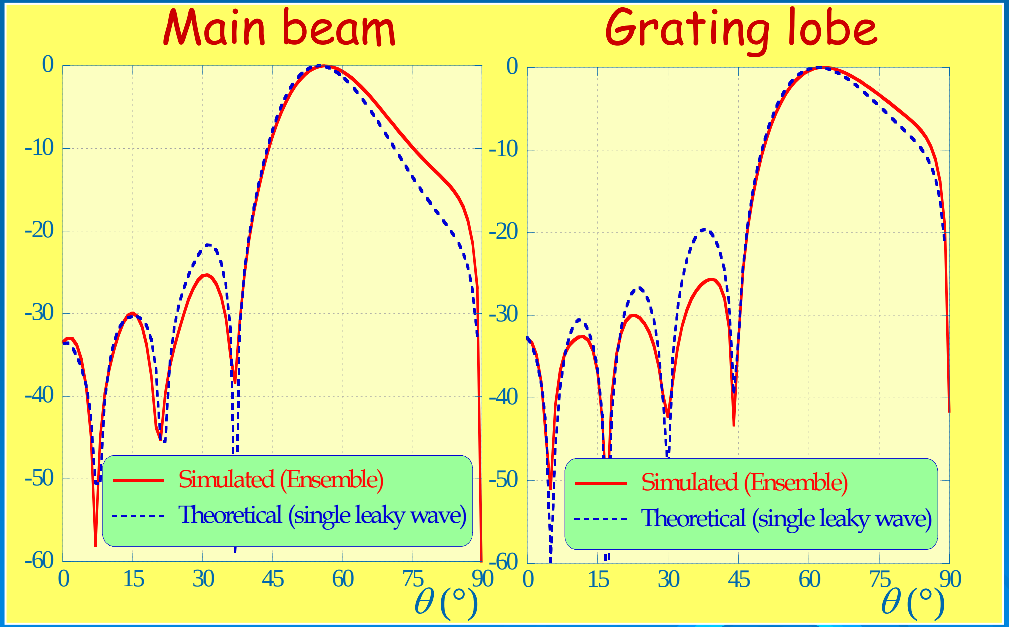
Scanning and grating lobes

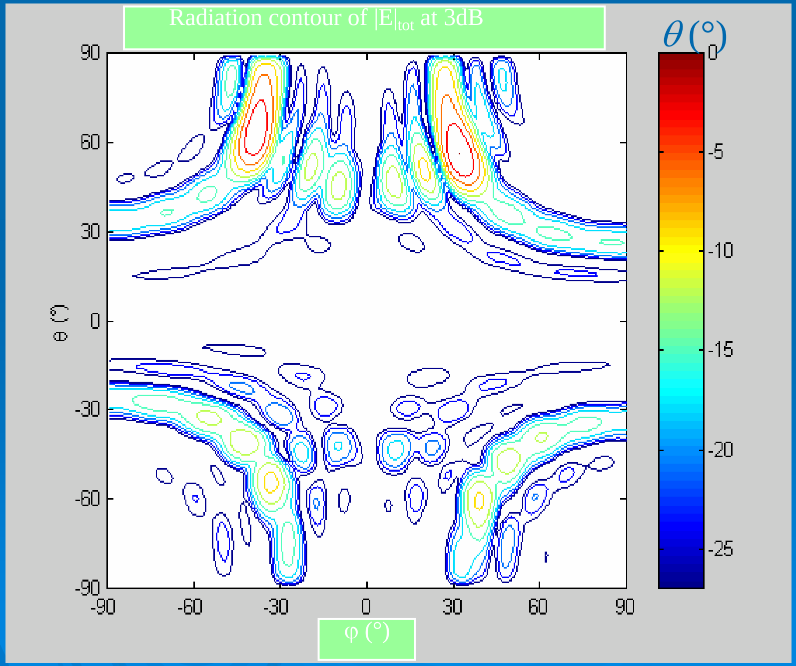
Φ = 160°



An additional mode with other improper harmonics can be found, capable to describe a grating lobe…

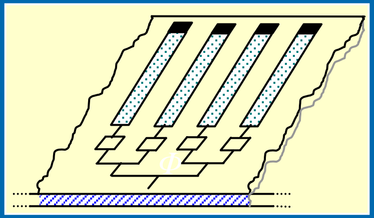
Pointing Angles:	Main Beam	Grating lobe
φ_{max} (LW)	32.3 °	-38.4 °
φ_{max} (CAD)	32 °	-38 °
θ_{max} (LW)	56.2 °	63.6 °
θ_{max} (CAD)	56 °	63 °

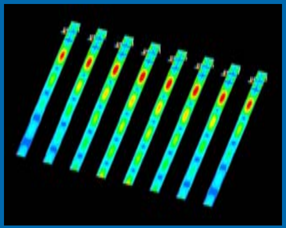




Radiation contour of $|E|_{tot}$

Features of LW printed array





By properly dimensioning the structure (choice of frequency, strip width and length, substrate, number of elements), a pencil beam is achievable with a nearly-conical scanning as a function of phase shift.

As phase shift increases, leakage rate usually tends to decrease (affecting the beam width), even though blind spots are not actually encountered, and grating lobes can be present for wide element spacings.

Compared to heavier full-wave (CAD) methods, the LW 'modal' analysis based on the computation of complex wavenumbers is satisfactory and can efficiently account for peculiar behaviors (e.g., the end-of-scanning transition between leaky and surface wave, the additional leaky mode that accounts for grating lobes, etc.).

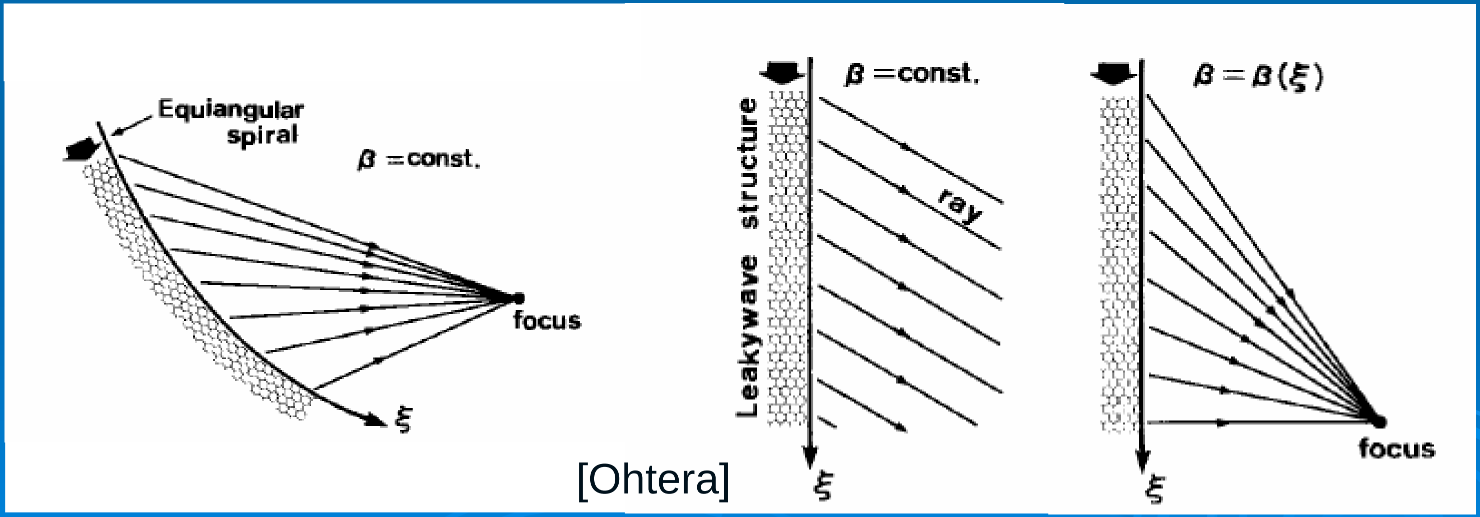
Wide-beam LWAs

Possibility to focus/diverge radiation in a fixed (wide) angular range

Two LWA topologies: *Curved*/Straight

'Curved': the guiding structure has a fixed cross section (then a fixed phase constant and pointing direction) but longitudinally is suitably curved to cover a fixed sector …

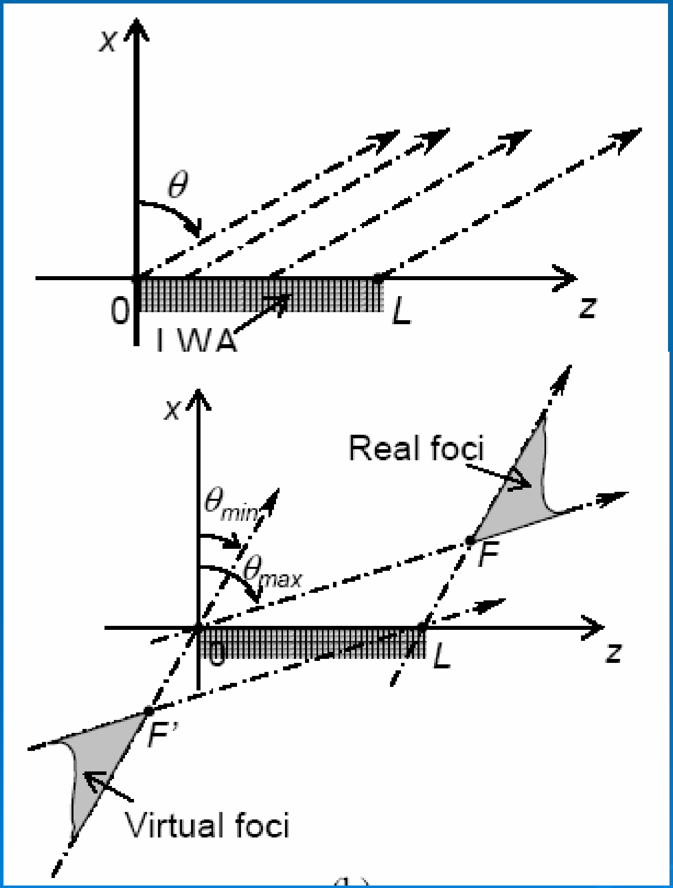
'Straight': the guiding structure is rectilinear but longitudinally the cross section is suitably modulated to vary the phase constant and cover a fixed sector …



Focusing radiation in an angular sector: ray-optics approximations

LWA-design for wide beams

Wide-beam with straight LWAs: focusing and diverging radiation



Formulas for synthesis:

$$\sin\theta(z) = -\frac{d\psi}{dz}$$

$$\beta(z) = k_0 \sin\theta(z)$$

$$\beta(z) = k_0 \frac{z - z_{F'}}{\sqrt{x_{F'}^2 + (z - z_{F'})^2}}$$

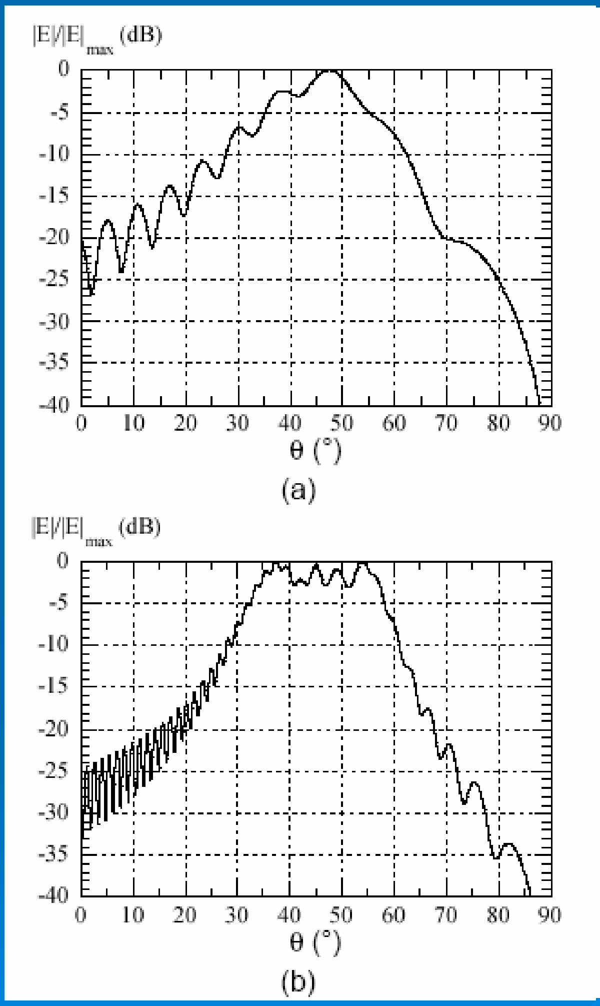
$$|A(z)|^2 = \frac{C}{\sqrt{x_{F'}^2 + (z - z_{F'})^2}}$$

$$\alpha(z) = \frac{1}{2\sqrt{1 + \left(\frac{z - z_{F'}}{x_{F'}}\right)^2}} \left[\left(\frac{1}{\eta} - 1\right)\sinh^{-1}\left(\frac{z_{F'}}{x_{F'}}\right) + \right.$$
$$\left. + \frac{1}{\eta}\sinh^{-1}\left(\frac{L - z_{F'}}{x_{F'}}\right) - \sinh^{-1}\left(\frac{z - z_{F'}}{x_{F'}}\right)\right]^{-1}$$

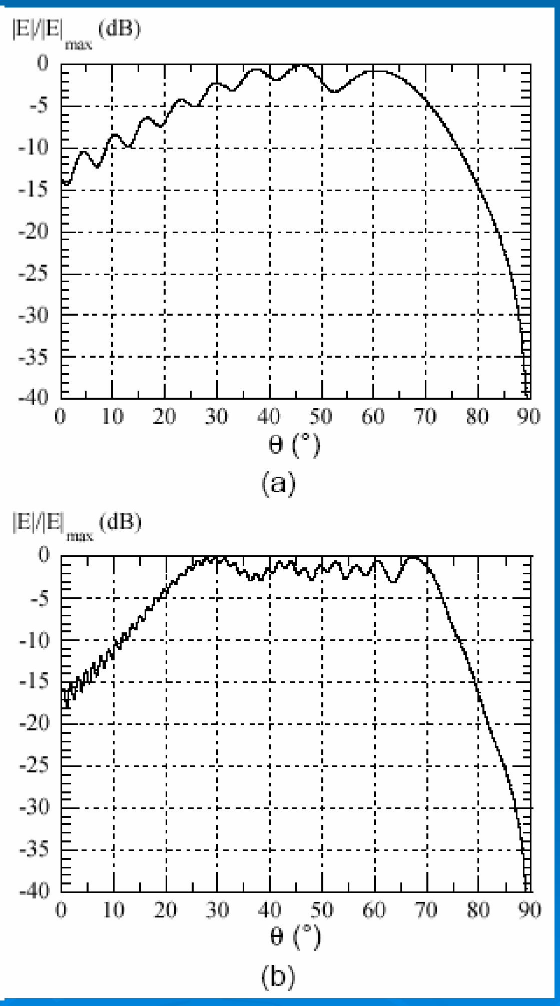
Radiation in an angular sector from real or virtual foci

Patterns with straight LWAs

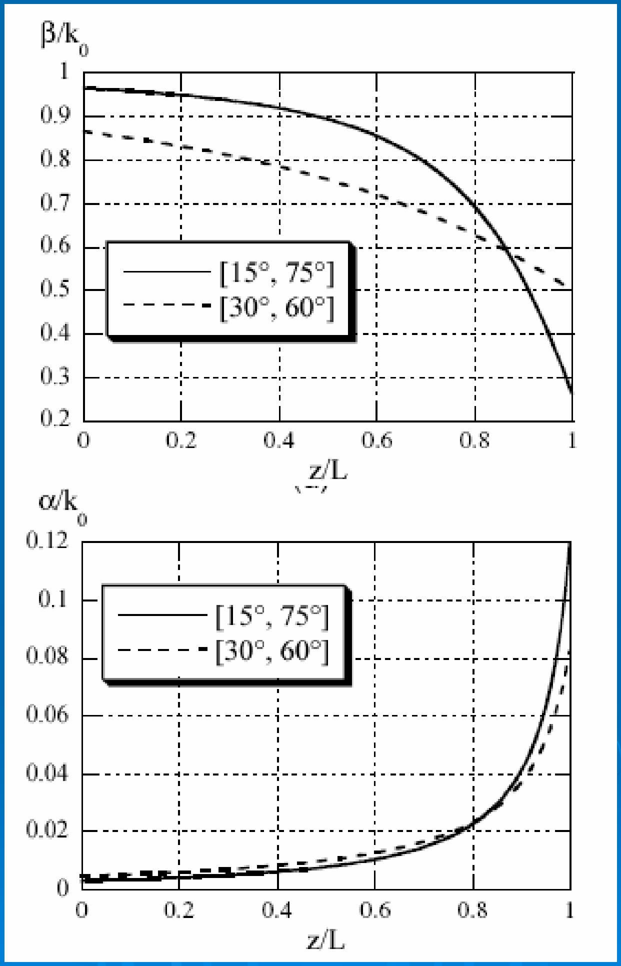
Shaped wide-beam radiation patterns for different sectors and LWA lengths



30°-60°: a) 10 λ_o, b) 40 λ_o



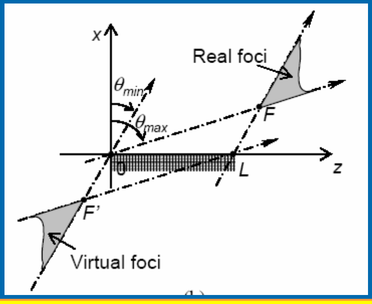
15°-75°: a) 10 λ_o, b) 40 λ_o



Longitudinal tapering for both leakage and phase rates

Range (and rate) of variation of both α and β can be significant …

Features of wide-beam LWA



In addition to curved structures, interesting solutions of LWAs for shaped wide beams are possible with simple straight-line geometries having both leakage and also phase rate that vary longitudinally.

The design procedures are quite easy to implement and give good results particularly for long structures compared to wavelength.

For wide angular coverage, severe practical constraints are related to very large variation of the ranges of phase and leakage constants: the choice of suitable topologies with a strong and almost independent geometrical control of such parameters is advisable.

LWA's specific references

[1] C. Di Nallo, F. Frezza, A. Galli, G. Gerosa, and P. Lampariello, "Stepped leaky-wave antennas for microwave and millimeter-wave applications," *Ann. Télécommun.*, 52, pp. 202-208, 1997.

[2] P. Baccarelli, P. Burghignoli, F. Frezza, A. Galli, and P. Lampariello, "Novel modal properties and relevant scanning behaviors of phased arrays of microstrip leaky-wave antennas," *IEEE Trans. Antennas Propagat.*, 51, pp. 3228-3238, 2003.

[3] P. Burghignoli, F. Frezza, A. Galli, and G. Schettini, "Synthesis of broad-beam patterns through leaky-wave antennas with rectilinear geometry," *Antennas Wireless Propagat. Lett.*, 2, pp. 136-139, 2003.

[4] C. Di Nallo, F. Frezza, A. Galli, and P. Lampariello, "Analysis of the propagation and leakage effects for various classes of traveling-wave sources in the presence of covering dielectric layers," *1997 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 605-608, June 1997.

[5] C. Di Nallo, F. Frezza, A. Galli, and P. Lampariello, "Rigorous evaluation of ohmic-loss effects for accurate design of traveling-wave antennas," *J. Electromagn. Waves Appl.*, 12, pp. 39-58, 1998.

[6] P. Baccarelli, C. Di Nallo, F. Frezza, A. Galli, and P. Lampariello, "Attractive features of leaky-wave antennas based on ferrite-loaded open waveguides," *1997 IEEE AP-S Int. Symp. Dig.*, pp. 1442-1445, July 1997.

[7] L. Borselli, C. Di Nallo, A. Galli, and S. Maci, "Arrays with widely-spaced high-gain planar elements," *1998 IEEE AP-S Int. Symp. Dig.*, pp. 1142-1145, June 1998.

Thanks to my colleagues for their conscious or unconscious support…

That's all, folks!