ANTENNAS VCE Virtual Center of Excellence

ACE – Antenna Center of Excellence

The European School of Antennas

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

Roma, 24-26/2/2005

LEAKY-WAVE ANTENNAS: FUNDAMENTALS

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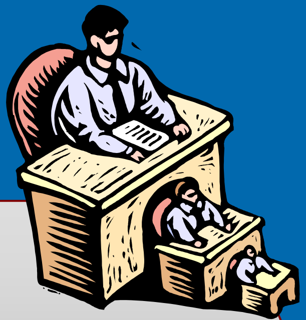
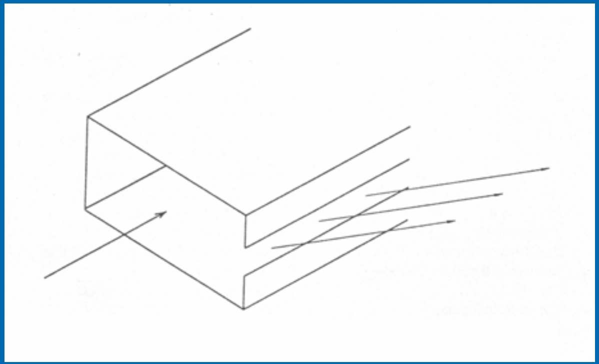
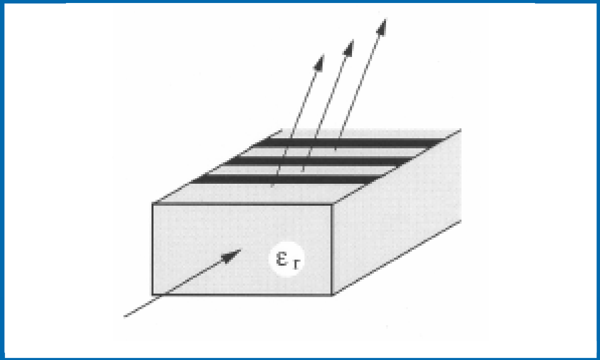


Definition

LWA

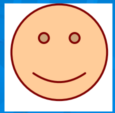
- **Leaky Wave Antenna** (IEEE Standard 145-1993)
  "an antenna that couples power in small increments per unit length, either continuously or discretely, from a traveling wave structure to free space"





- **leak** (Oxford Dictionary)
  "accidentally lose or admit contents, especially liquid or gas, through a hole or crack"

*... **leaky** (adjective), **leakage** (noun) ...*

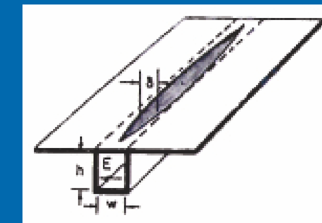


"For some it's leaky, for others it's lucky!"

Brief history and trends

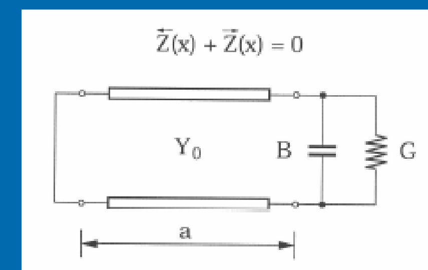
- **40's:** ***First LWA solutions***

- Hansen: "Radiating electromagnetic waveguide," U.S. Patent no. 2,402,622, 1940



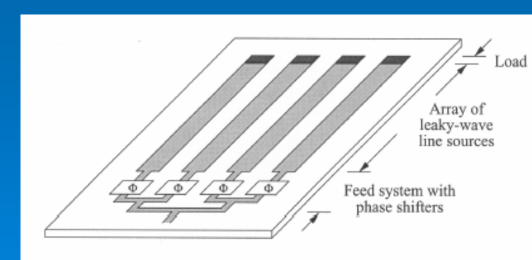
- **From 50's to 70's:** ***Big efforts for basic studies on LWs and LWAs***

- Investigations on the role of LWs in radiation (Tamir, Oliner, Felsen, Hessel, Clarricoats, Ishimaru, etc.)
- LWAs and LW arrays based on metallic guides (Oliner, Elliot, Collin, Zucker, Walter, etc.)
- LWA representations with equivalent networks (Marcuvitz, Felsen, Oliner, etc.)



- **From 80's up to now:** ***New LW effects and LWA structures***

- LWAs based on dielectric, planar, and printed configurations (Oliner, Jackson, Peng, Praha Group, Rome Group, etc.)
- LWAs for beam-shaping applications (Ohtera, Rome Group, etc.)
- Computer-oriented leakage analysis (Jackson, Kyoto Group, Rome Group, etc.)
- New structures and desired/undesired leakage effects (Oliner, Jackson, Ito, Mesa, Rome Group, etc.)



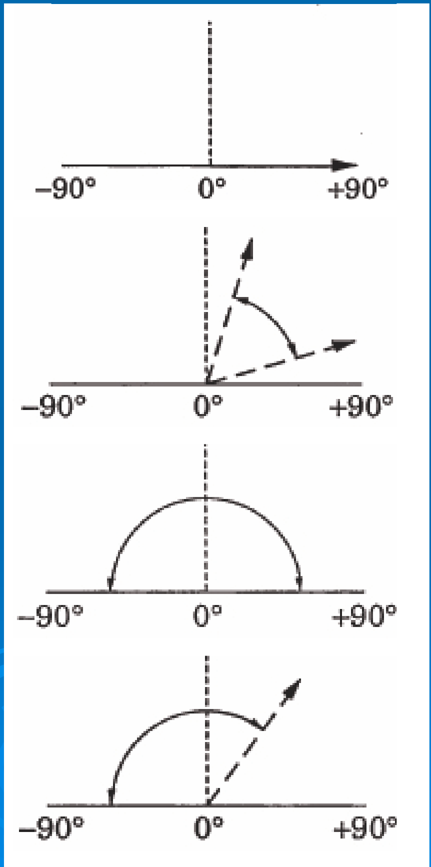
Traveling-wave antennas

" TRAVELING-WAVE ANTENNAS " (TWAs)

Rhombic … Log-periodic … Surface-Wave … Leaky-Wave Antennas

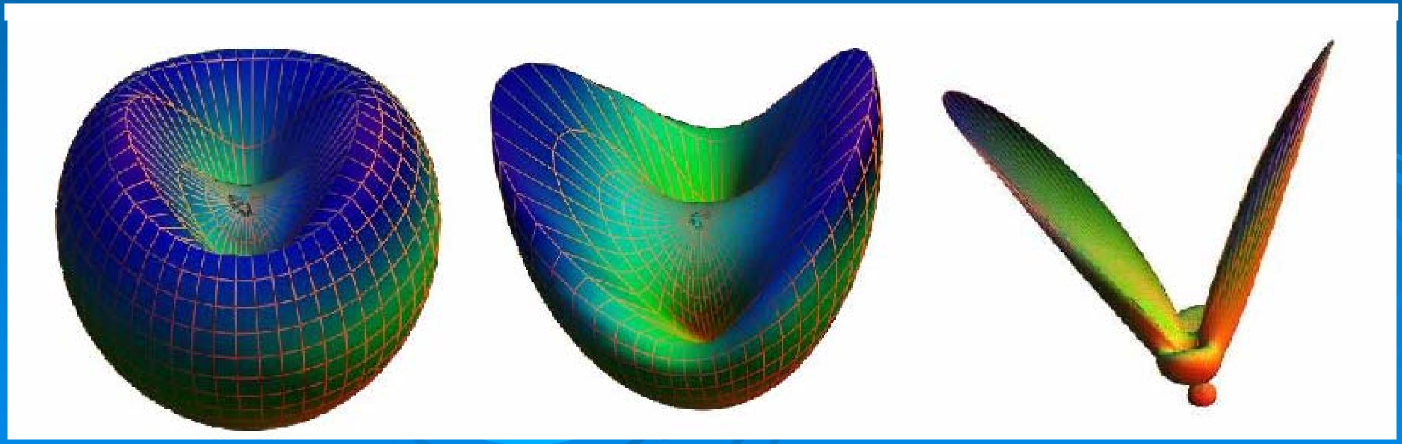
Different solutions for beam directions and scanning

- **Surface-wave antennas**
  endfire direction
- **Uniform LWAs**
  forward ('fw') quadrant
- **Periodic LWAs & periodically-loaded slow-wave arrays**
  forward and backward ('bw') quadrant
- **Inverted-element arrays**
  backward and partly forward quadrant



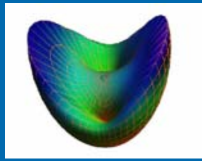
LWA classifications

- based on beam scan:
  - Forward, forward/backward, 1D-2D scanning …
- based on beam shape:
  - fan beam, pencil beam, conical beam, wide beam …
- based on topology and geometry:
  - - unidimensional (uniform/periodic), bidimensional (1D array, 2D array),
    - tapered/nontapered, straight/curved geometry …
- based on waveguiding structures:
  - - metallic, hybrid, dielectric, printed, planar waveguides,
    - basically-closed/basically-open structures,
    - microwave/millimeter-wave guides …

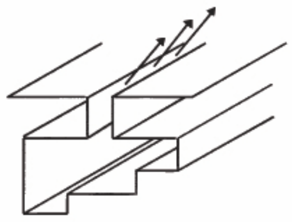


LWA beam features

Narrow beams are usually obtained with LWAs
whose aperture is long compared to the wavelength

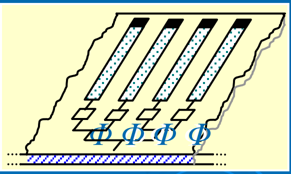


Fan beams

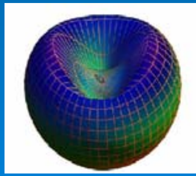


- This is the typical pattern radiated by a single 1D LW source
- The beam is scannable in elevation as a function of the frequency
- The angular sectors of scanning vary according to the LW topologies
- Specific radiation patterns can be achieved by controlling the illumination

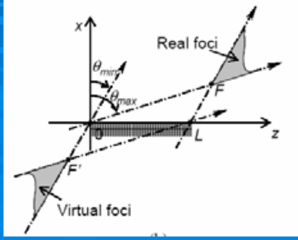
Pencil and conical beams



- Pencil beams can be achieved with a linear (phased) array of LW sources
- The beam is scannable in elevation and also in azimuth with phase shifters
- Conical beams can be achieved with a single-fed 2D layered configuration
- The beam is scannable by frequency until broadside



Wide beams

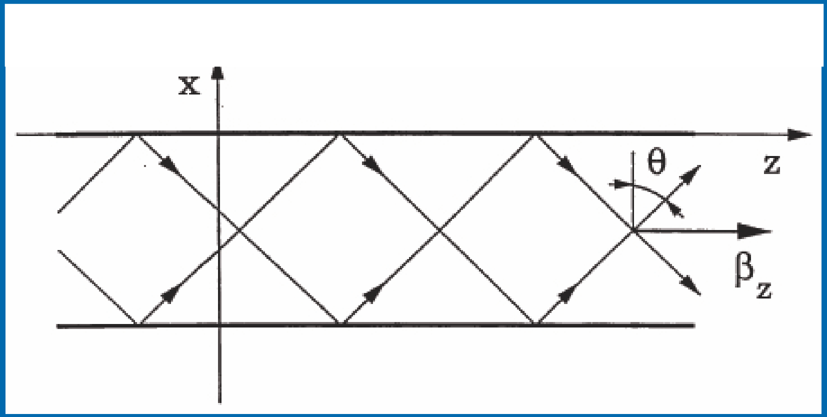


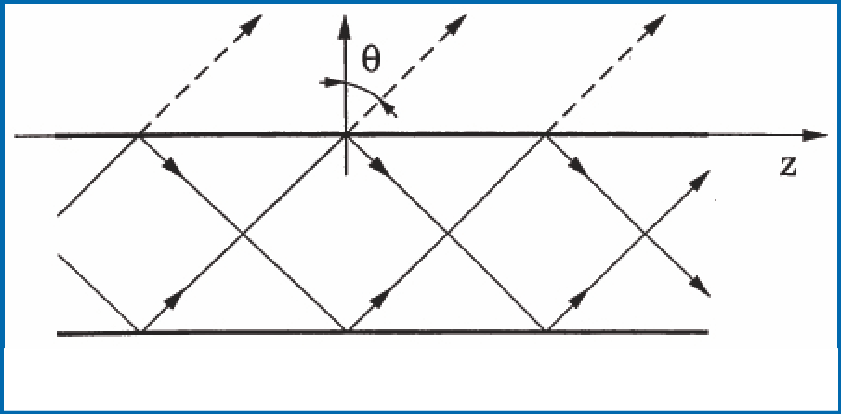
- This pattern can be achieved with curved and also straight LW radiators
- Controlled beam shaping is possible varying LW parameters vs. geometry

Basic leakage phenomenon

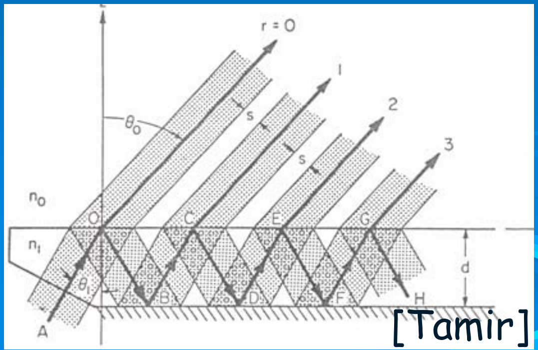
The dominant mode in a close rectangular guide can be viewed as a superposition of a pair of homogeneous plane waves, launched at an angle θ (that varies with frequency) and totally reflected by the metal side walls

A 'small' aperture on a side wall allows part of the field of the plane waves to exit and propagate externally in the θ direction, with a guided power which decreases due to the partial reflection on the side wall





The field on the aperture can be described through a complex wavenumber $k_z = \beta_z - j\,\alpha_z$: the phase constant β_z is a 'slight' modification of the closed-guide propagation constant, and the leakage constant α_z accounts for the loss rate related to the outward radiation …

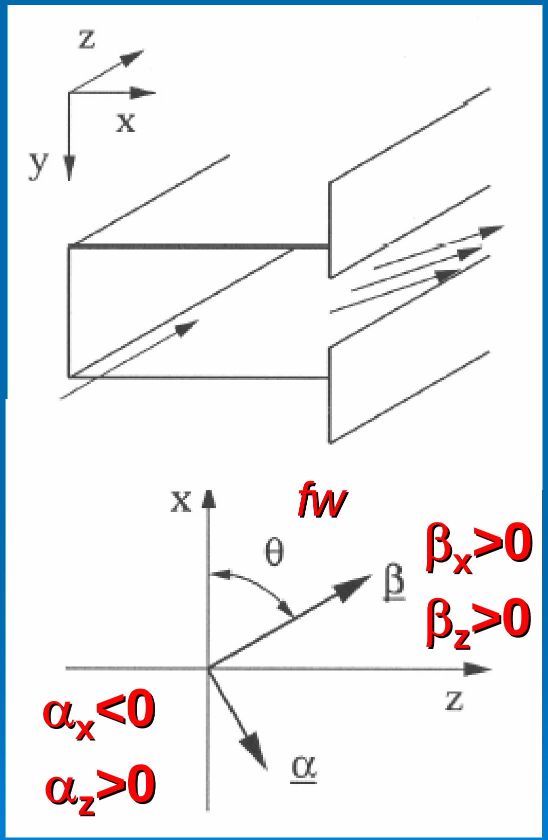


[Tamir]

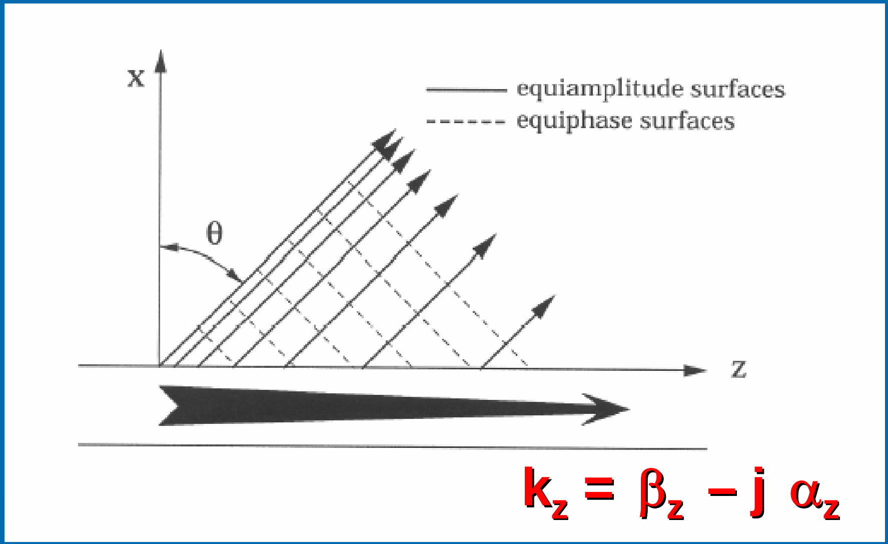
Interpretation in terms of partially reflected and refracted plane waves at an interface also in open dielectric waveguides …

Leaky wave on the aperture

A mode of a closed guide becomes *leaky*
by suitably introducing an aperture in the structure



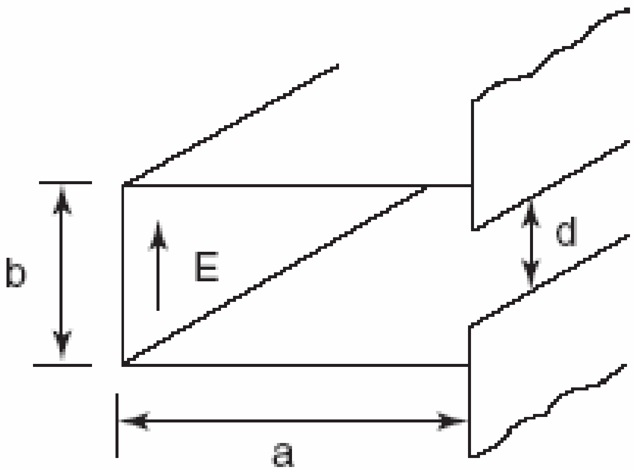
Inhomogeneous *improper* plane wave: the *leaky* mode



The amplitude of the guided traveling wave
decreases along **+z** with an exponential rate given by α_z
due to the leakage through the aperture
at an θ angle related to the phase constant given by β_z

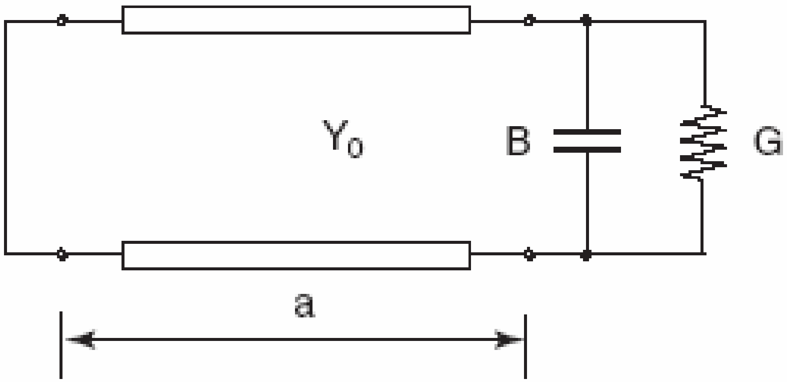
Exercise 1: Derive relationships for *x* and *z* phase and attenuation constants of a non-homogeneous plane wave that is leaky.

LWA equivalent networks



LWA based on a rectangular guide with an aperture on a side wall

$$\overleftarrow{Z}(x) + \overrightarrow{Z}(x) = 0$$



$$\frac{G}{Y_0} = G' = \frac{\pi b}{2a} \qquad e = 2.718,\ \gamma = 1.781$$

$$\frac{B}{Y_0} = B' = \frac{b}{a}\ln\left(\csc\frac{\pi d}{2b}\right) + \frac{b}{a}\ln\left(\frac{a e}{\gamma d}\right)$$

Equivalent network

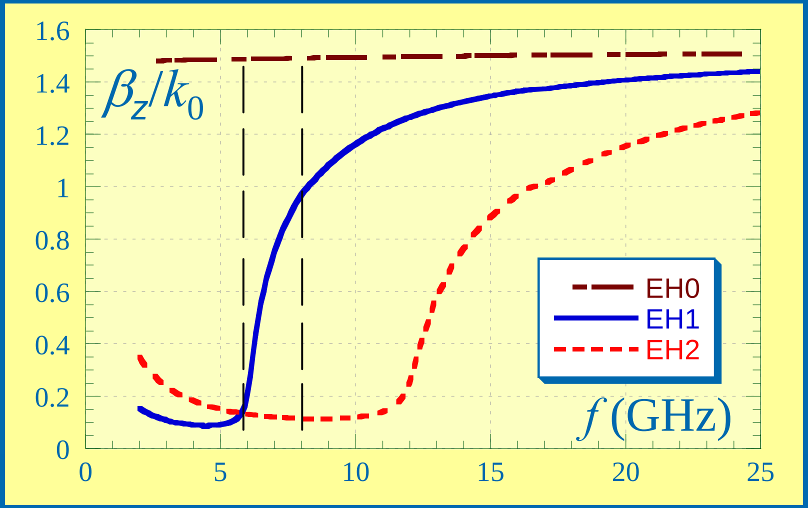
based on transmission lines and lumped circuit elements, which can be described analytically by means of variational methods…

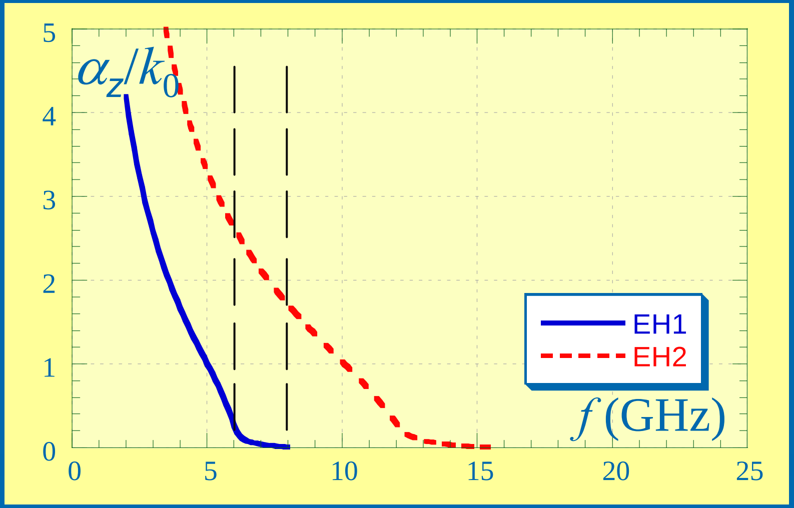
Solution for the complex wavenumber vs. geometry and f with Transverse Resonance Technique

Leaky-mode dispersion plots

Typical modal dispersion plots
& physical leaky ranges

Normalized phase and leakage constants
$\bar{\beta}_z = \beta_z / k_o$, $\bar{\alpha}_z = \alpha_z / k_o$

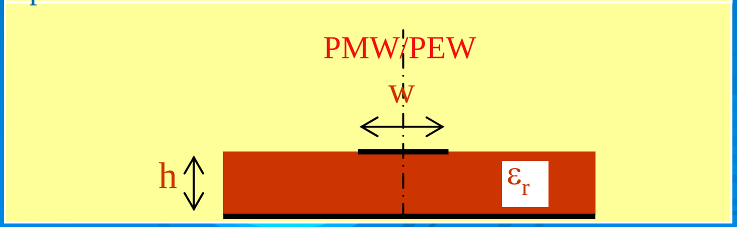




Normalized Phase Constant
β_z/k_o **vs. f**

Normalized Leakage Constant
α_z/k_o **vs. f**

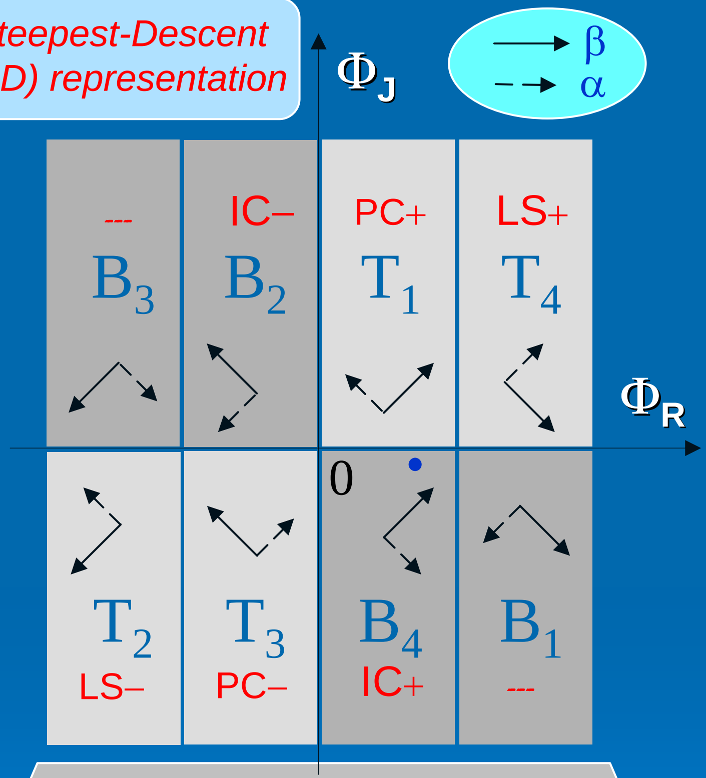
ε_r = 2.32, h = 0.794 mm, w = 15 mm



LW contribution & SD

$k_z = k_o \sin\Phi$ $k_x = k_o \cos\Phi$

Steepest-Descent (SD) representation



L : lossy
I : improper
P : proper
S : surface wave
C : complex wave

+ : forward
– : backward

Riemann sheets:

T = 'Top'
B = 'Bottom'

The *leaky wave* represents a mode with complex propagation constant, which in general is improper (it does not satisfy the radiation boundary condition in the transverse plane) but is capable to furnish a simple and accurate description of the radiation phenomenon in a 'nonspectral' ('steepest-descent' – 'SD') representation, alternative to the canonical 'spectral' integral representation.

Field in open guides expressed by an inverse Fourier Transform in the spectral variable k_z

Representation depending on integration path

Spectral representation:
e.g., discrete finite spectrum of guided modes
+ integral contribution of the 'continuous spectrum'

Nonspectral representation:
e.g., discrete spectrum of proper and improper modes
+ SD contribution of the 'space wave'

LWA working principles

Conditions for leakage:

a) 'Existence' condition:
the antenna geometry can be viewed as an open waveguide capable to support a complex eigenmode (solution of the characteristic equation, i.e., a pole of the relevant Green's function of the structure)

b) *'Excitation' condition:*
the relevant LW field furnishes the dominant contribution on the antenna equivalent aperture

Basic features for leakage useful in LWAs:

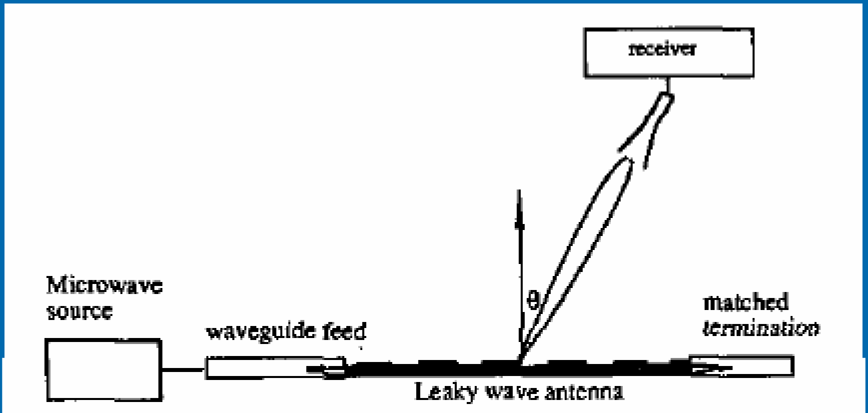
the LW on the equivalent aperture represents an inhomogeneous plane wave, which travels from the guide outwards at an angle in the free space and is *fast*:
the normalized phase constant is a quantity (in modulus) less than unity

$|\overline{\beta}_z|<1$

the LW should have a field whose amplitude gives a *predominant* contribution along the whole equivalent aperture of the guide, which is long in terms of λ:
the normalized leakage constant is a quantity much less than unity

$\overline{\alpha}_z<<1$

Line-source LWA features



[Varadan et al., 1994]

Typical operating conditions in LWAs:

The leakage rate should be fairly low, at least in the input transition region between the feeding guiding structure and the radiating line.

In this way the phase-constant perturbation is relatively little, with a small mismatch to the exciting source.

The equivalent aperture has to be many wavelengths, so that little energy is left at the end.

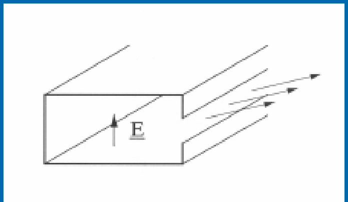
Since the phase velocity is in general a function of frequency, the beam is frequency scannable.

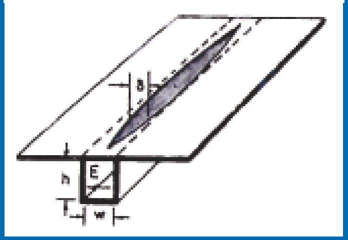
Uniform and periodic LWAs

Uniform LWAs:

The guide (typically a 'fast-wave' structure) is (partly) open and **mantains the same transverse geometry**, even though a continuous longitudinal modulation can occur.

Radiation is described through the *complex wavenumber* of an '**eigenmode**' of the uniform open structure… ***FORWARD radiation.***

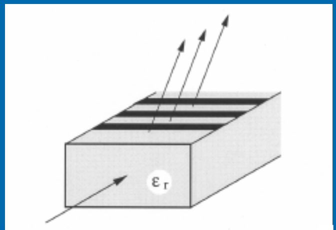


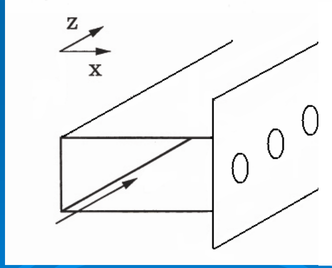


Periodic LWAs:

The guide (often a 'slow-wave' structure) is (partly) open and **presents suitable periodic discontinuities**, which are usually small compared to wavelength.

Radiation is described through the *complex wavenumber* of a '**spatial harmonic**' of the periodic open structure… ***BACKWARD and FORWARD radiation.***

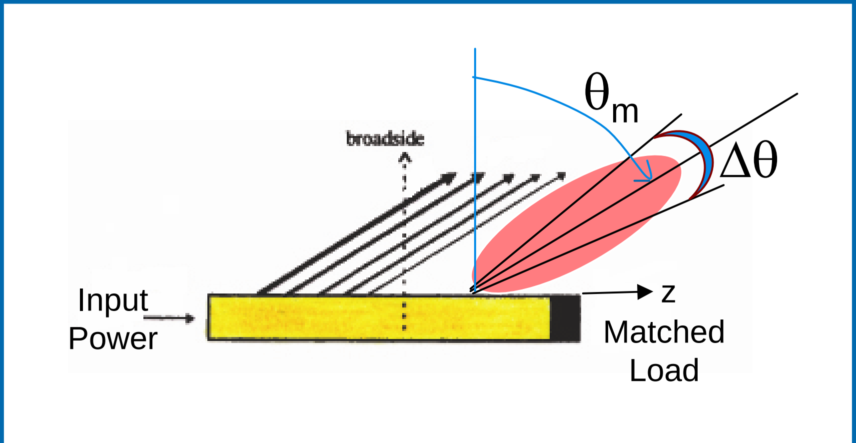




Unconventional LWAs:

Particular radiative features can be obtained by employing guiding structures with **nonconventional media**, such as *ferrites, plasmas, and metamaterials.*

LWA basic parameters



LWA fundamental radiation parameters:

Beam direction (pointing angle θ_m - with respect to broadside) depends on β_z/k_o

Beam width (-3 dB angle range $\Delta\theta$) depends on α_z/k_o,

which fixes the antenna length L for a fixed efficiency η

$$\sin\theta_m \cong \beta_z / k_o \qquad \Delta\theta \cong \frac{1}{L/\lambda_o \cos\theta_m} \qquad L/\lambda_o \cong \frac{0.183}{\alpha_z / k_o}$$

($\approx$Uniform) (η=0.9)

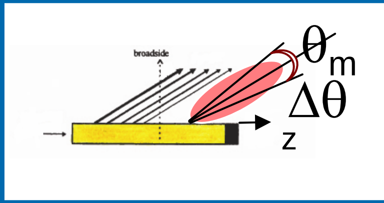
Exercise 2: Justify the approximate relationships for the main beam features in terms of the leaky complex wavenumber and antenna length.

LWA main beam features

Beam direction θ_m: $$\sin\theta_m \cong \beta_z / k_o$$

In metallic LWAs a band of about an octave can be often used:

- @ low frequencies, limitations around cutoff of the guided mode
- @ high frequencies, limitations related to higher-mode excitation …



Beam width $\Delta\theta$: $$\Delta\theta \cong \frac{a}{L/\lambda_o \cos\theta_m}$$

The beam width depends inversely on normalized antenna length ($\tilde{L} = L/\lambda$) projected normally to the beam direction θ_m.

$$\Delta\theta \approx 55° / \tilde{L}$$

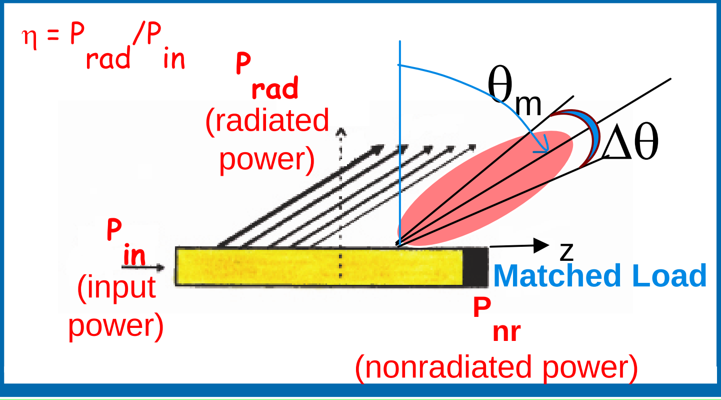
Constant Aperture

$$\Delta\theta \approx 2\pi / (k_t L) = \lambda_c / L$$

The beam width is determined primarily by the antenna length, but it is also influenced by the amplitude distribution (leakage rate):

@ Numerator for $\Delta\theta$:	Constant aperture:	a	→	0.88
	Uniform geometry:	a	→	0.91
	A middle-range value:	a	→	1
	A tapered aperture:	a	→	1.25 …

LWA efficiency



The antenna length is usually chosen to have a desired efficiency η.

Intrinsic limitations in LWA efficiency:

In LWA, usually 90 % or at most 95 % of the power is radiated (and the remaining should be absorbed by a matched load).

Further increasing in efficiency over such limits gives rise to practical problems:

- LWA's length *L* should increase and the dimensions can become impractical;
- The variations of the leakage rate for pattern control should be very sharp and can become difficult to be realized in practice.

$$\frac{P_{nr}}{P_{in}} = \frac{P(z=L)}{P(z=0)} = \frac{P_{in} - P_{rad}}{P_{in}} = $$
$$= 1 - \eta = e^{-2\alpha_z L} = e^{-4\pi(\alpha_z / k_o)(L/\lambda_o)}$$

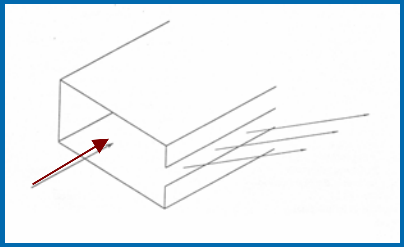
Relationship between $\tilde{L}$ and $\overline{\alpha}_z$ for a fixed η

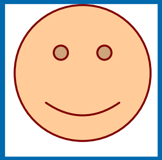
$$L/\lambda_o \cong \frac{0.183}{\alpha_z / k_o}$$

Uniform geometry with η = 0.9

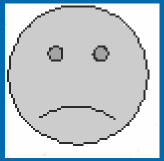
Uniform LWA scan ranges

Air-filled metallic LWAs:



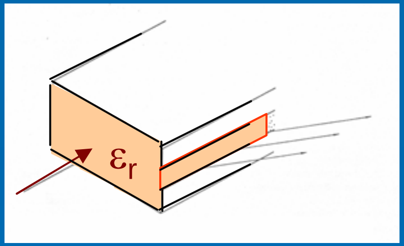


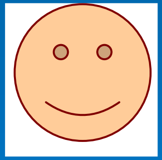
Frequency-independent beam width



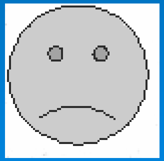
Difficult approach to endfire

Dielectric-filled metallic LWAs:

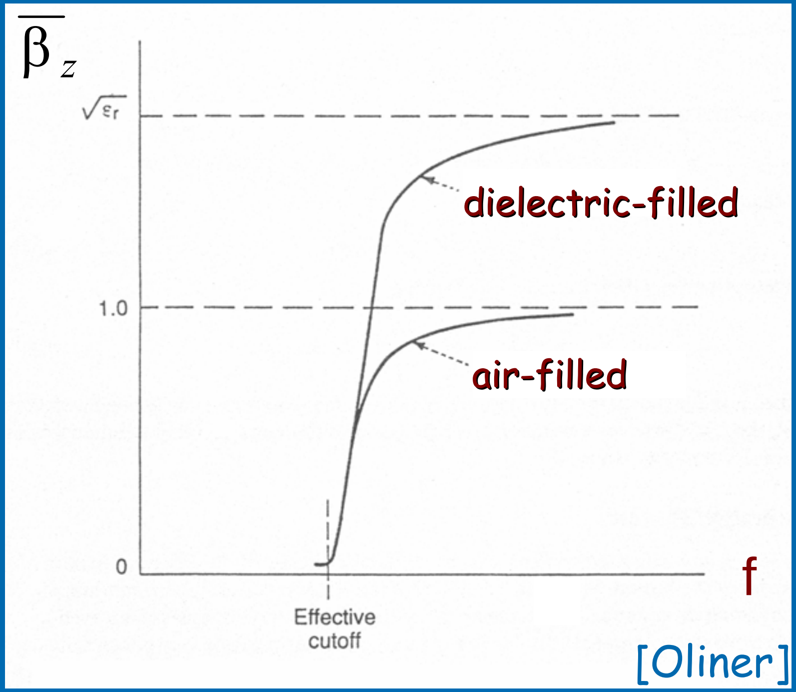




Straightforward scan to endfire



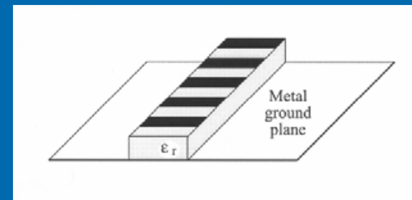
Beam width varying with frequency



Phase-constant dispersion behavior of a leaky mode in air- & dielectric-filled LWAs

Periodic line-source LWAs

Unperturbed dominant mode: e.g., a slow wave in the range of interest



$$\boldsymbol{\psi}(x,y,z) = e^{-jk_{z0}z}\,\boldsymbol{P}(x,y,z)$$

Periodic *z*-perturbation of the structure (spatial period ***d***)

$$\mathrm{P}(x,y,z) = \mathrm{P}(x,y,z+d) = \sum_{n=-\infty}^{+\infty} \mathrm{a}_n(x,y)\,e^{-j\frac{2\pi}{d}nz}$$

Floquet mode expansion (series of ***space harmonics***)

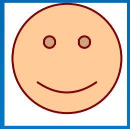
$$\boldsymbol{\psi}(x,y,z) = \sum_{n=-\infty}^{+\infty} \boldsymbol{a}_n(x,y)\,e^{-j\left(k_{z0}+\frac{2\pi}{d}n\right)z} = \sum_{n=-\infty}^{+\infty} \boldsymbol{a}_n(x,y)\,e^{-jk_{zn}z}$$

Wavenumbers of Floquet modes (complex in open structures)

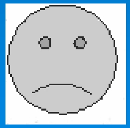
$$k_{zn} = k_{z0} + \frac{2\pi}{d}n = \beta_{z0} - j\alpha_z + \frac{2\pi}{d}n = \beta_{zn} - j\alpha_z$$

Leakage: when a space harmonic becomes *fast*

$$-1 < \beta_{zn}/k_o < +1$$



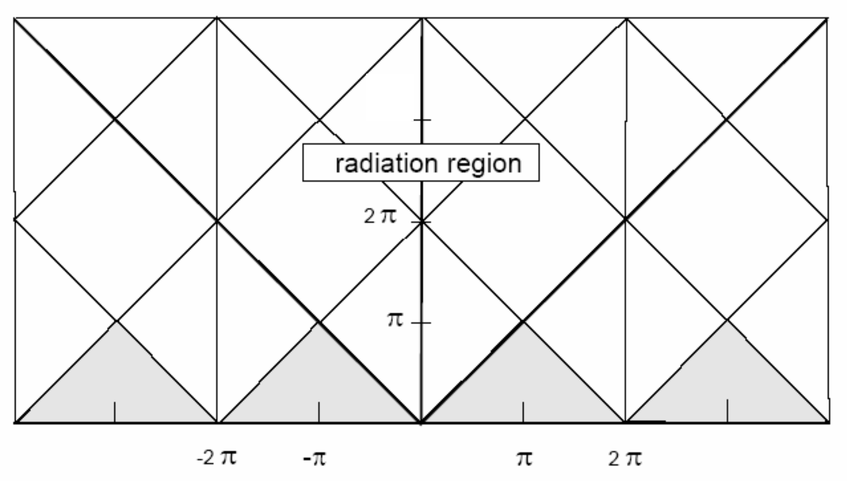
With proper choice of the period and the other parameters involved, just one leaky space harmonic can become leaky (usually for n = -1), thus giving rise to a radiated beam, which can be scanned from backward to forward quadrants as frequency varies.



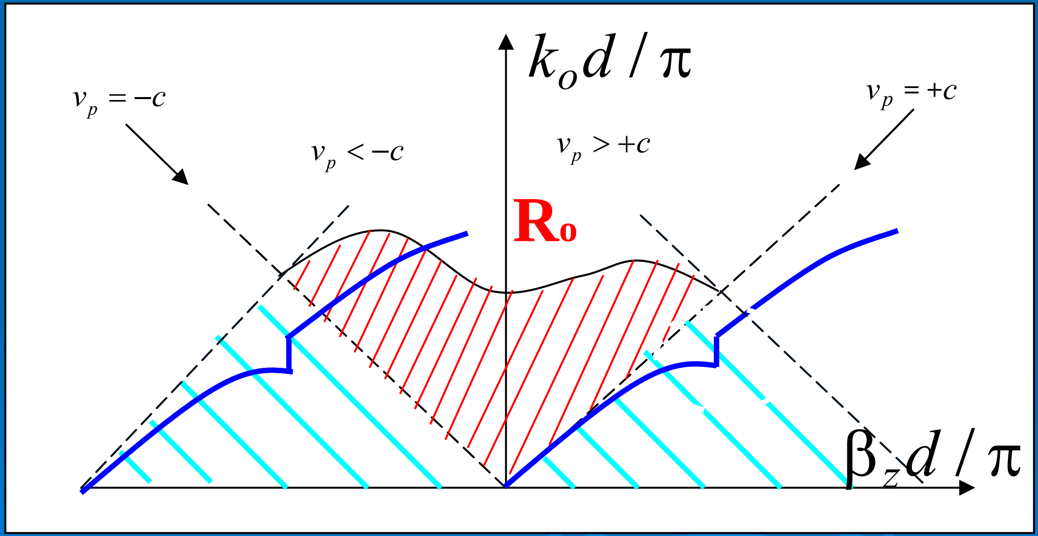
Design problems are typically related to the occurrence of grating lobes, if other harmonics become fast, and to the holding of efficient radiation at broadside, where a 'stopband' behavior is usually present …

Features of periodic LWAs

The main features of periodic structures can conveniently be analyzed by representing the dispersion behavior of the space harmonics in the Brillouin diagram, where different propagation behaviors (forward/backward - guidance/radiation) occur inside triangles in the plane $k_o d/\pi$ vs. $\beta_z d/\pi$.



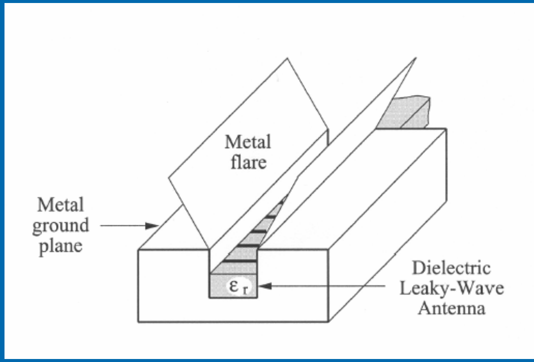
Brillouin diagram



As in the case of uniform structures, for the periodic LWAs the knowledge of the behavior of the complex wavenumber of a leaky harmonic provides fundamental information on the main beam characteristics.

2D LWAs for narrow beams

Two-dimensional (2D) directivity to achieve pencil beams generally requires the equivalent aperture to be also transversely increased with respect to standard line-source LWAs

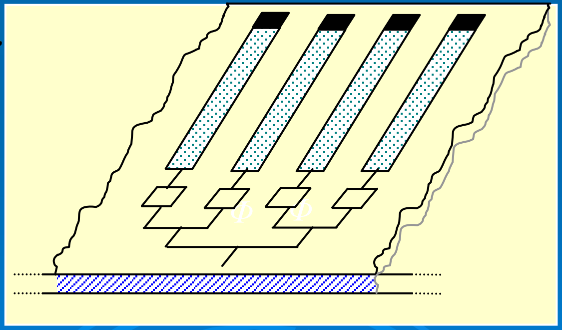


In some LWA types it is possible to introduce flared horns

A more general solution is based on the introduction of a number of lines side by side:

Linear array (1D 'periodicity' in the transverse plane)

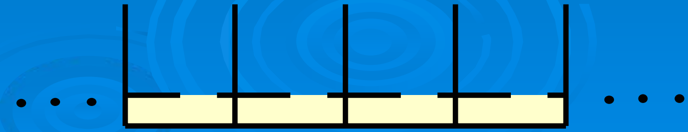
Simplified analysis of the structure considering the array factor…



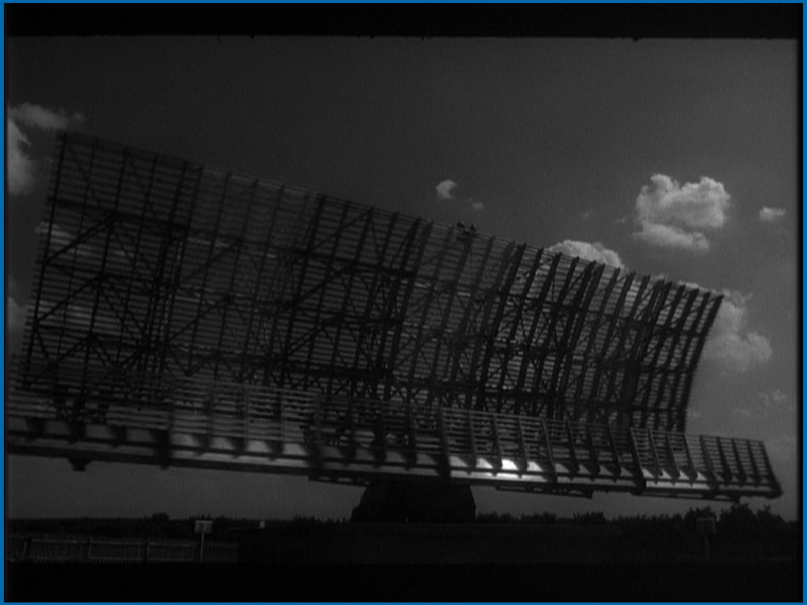
A mutual interaction between adjacent elements occurs…

The coupling can be slight/strong depending on the element pattern (end-to-end/broadside)

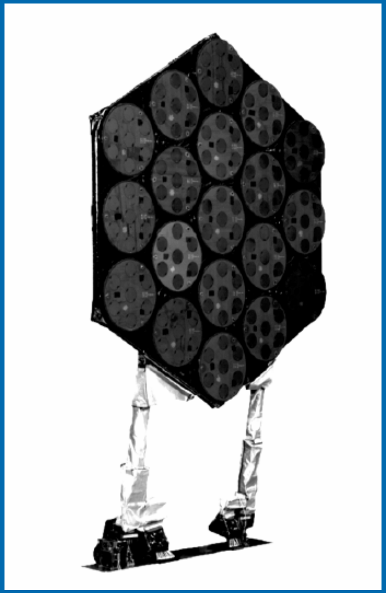
2D pattern control with proper phase and also amplitude distributions in the feed …



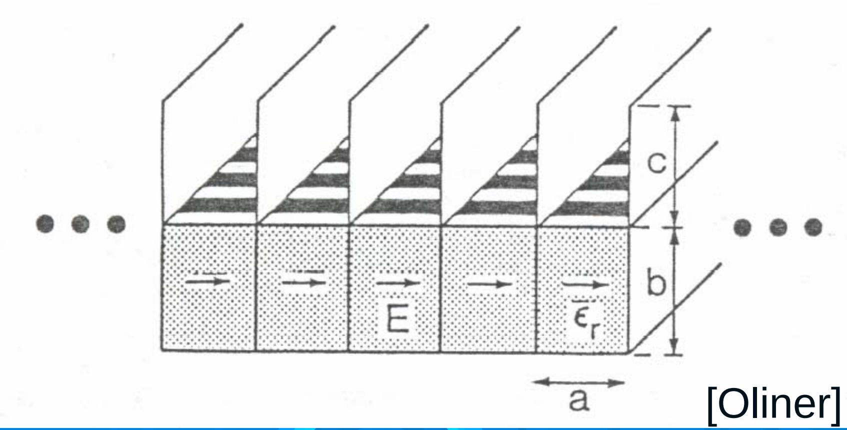
LW arrays for 2D scan

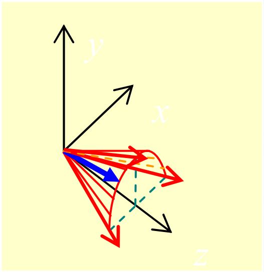


Scan of mechanical type in 2D antenna arrays:
Starting scene of Kubrick's "Dr. Strangelove" (1963) !



Scan of electronic type
in 2D arrays fed by phase shifters

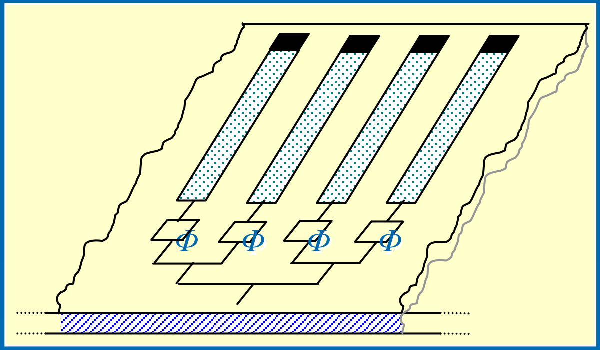


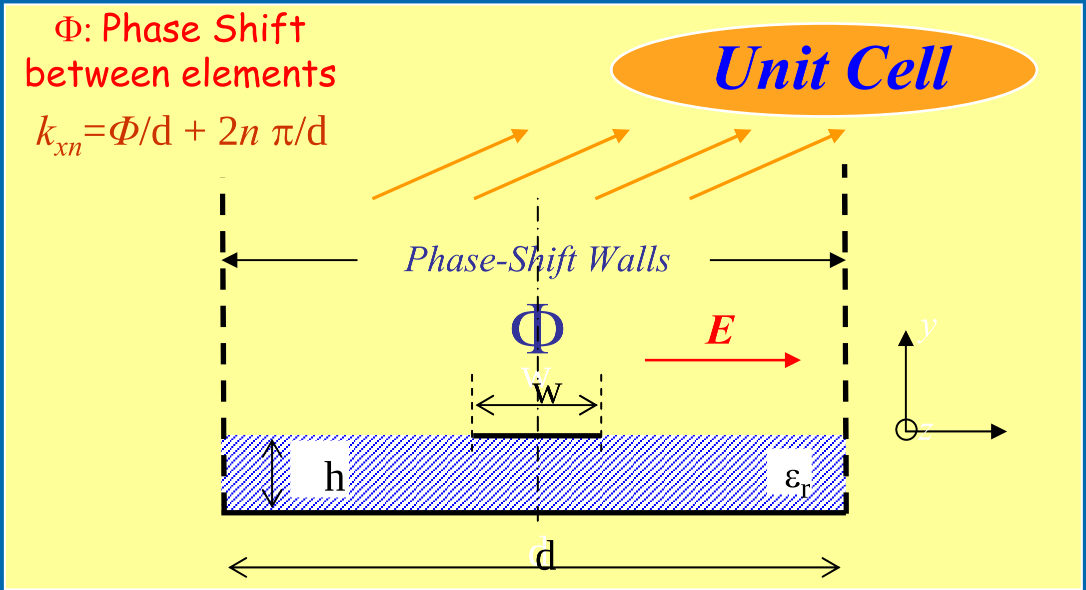


LW linear arrays: scan with frequency & only-1D phase shifters

Unit cell for LW arrays

- Simple analysis method with the unit-cell approach
- Transverse spatial period limited by phase-shift walls
- Wavenumber analysis of the leaky harmonics vs. phase shift Φ and the other parameters





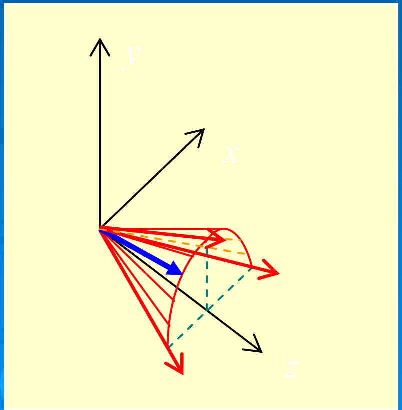
$$\theta_m = \sin^{-1}\sqrt{(\beta_z/k_o)^2 + (k_{xn}/k_o)^2}$$

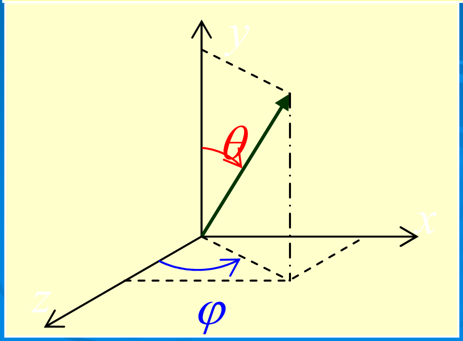
$$\varphi_m = \tan^{-1}(k_{xn}/\beta_z)$$

Frequency variation: action on elevation

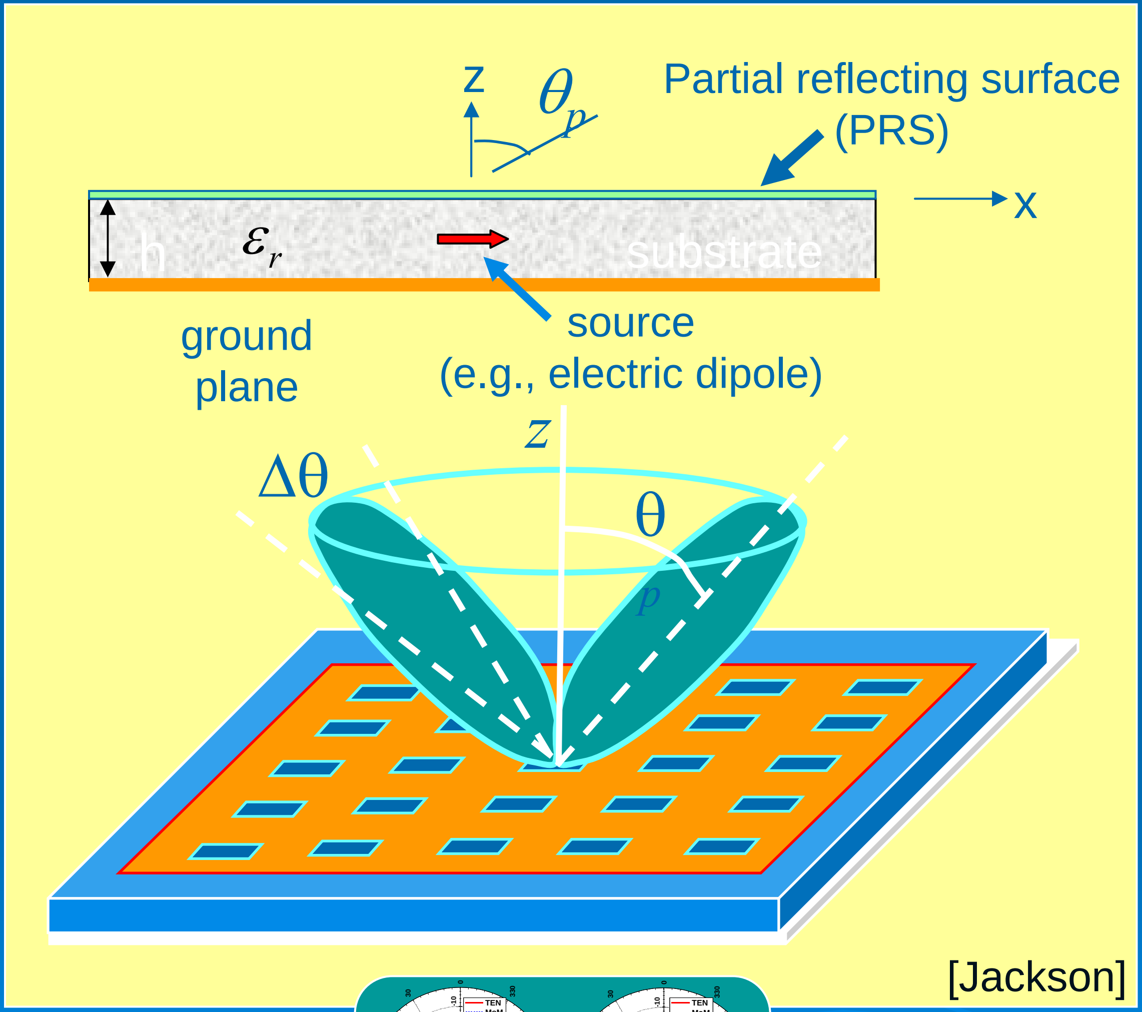
Phase variation: action on cross plane

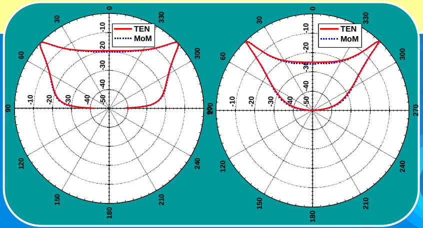
Nearly conical scanning



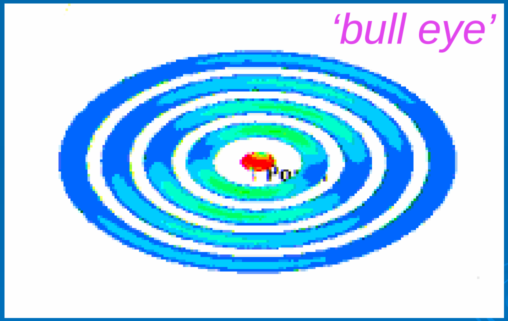


Planar LWAs & conical beams





Planar configurations, excitable with a single feeder, can give rise to conical beams due to radial leakage from a partial reflecting surface, e.g., a high-ε superstrate or a 2D array of slots, patches, etc. of various shapes …



This type of radiation can be explained in terms of leaky propagation of TE and TM modes in the layered structure

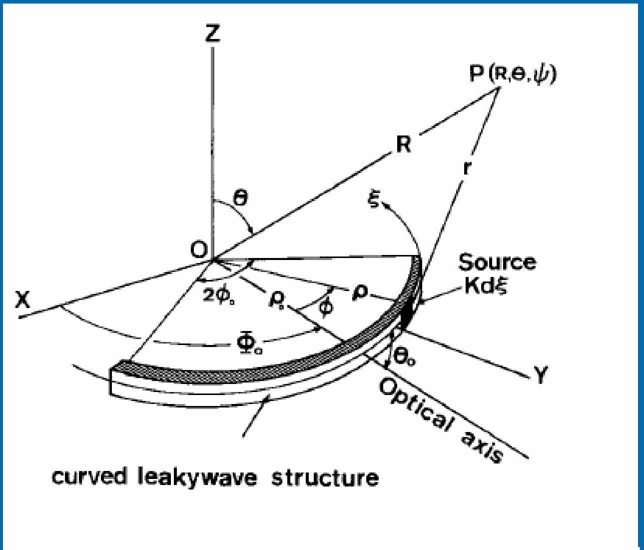
Curved LWAs

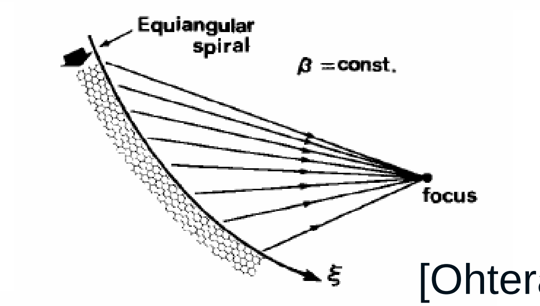
Many topologies of LWAs possess the useful property of possible installation on curved profiles or surfaces

For large radii of curvature *R* (e.g., *R* > 20 λ), the changes (with respect to the straight structure) of phase and leakage rates are negligible …

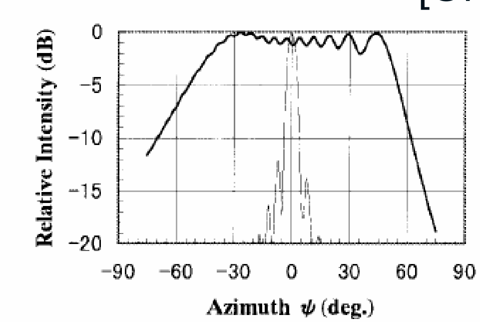
In this case, to obtain a narrow beam the longitudinal distribution of the phase constant has to be suitably modified ('tapering' for phase distribution) without affecting the leakage rate.

Conversely, specific geometry profiles (e.g., spirals, etc.) can provide shaped wide beams (no need of tapering)…



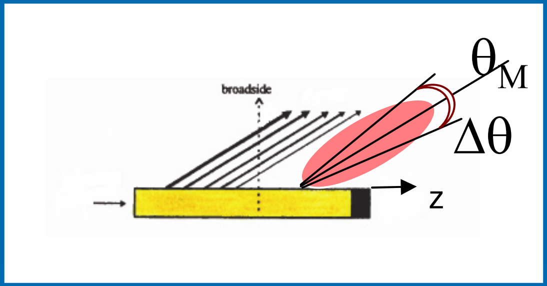


[Ohtera]



Radiation patterns of LWAs

Far-field pattern *E*
as a function of the elevation angle θ and the free-space wavenumber *k*
expressed as a Fourier transform of the complex aperture field *A(z)*
for a line source of lenght *L* with elementary pattern *G*



$$E(k\sin\theta) = G(k\sin\theta)\int_0^L |A(z')| e^{j\angle A(z')} e^{jkz'\sin\theta}\, dz'$$

Fourier-type relationship from the aperture field
(as a function of the longitudinal space variable *z)* to the radiation pattern
(as a function of the transformed variable related to the observation angle θ)

Exercise 3: Justify the general espression of LWA radiation pattern and that one achievable for uniform nontapered aperture.

Synthesis methods

A desired radiation pattern (as concerns side-lobe levels, beam width, etc.) is related to the choice of a suitable distribution on the equivalent aperture ('source' or 'illumination function')

Synthesis problem:

finding a source function which produces a given pattern function

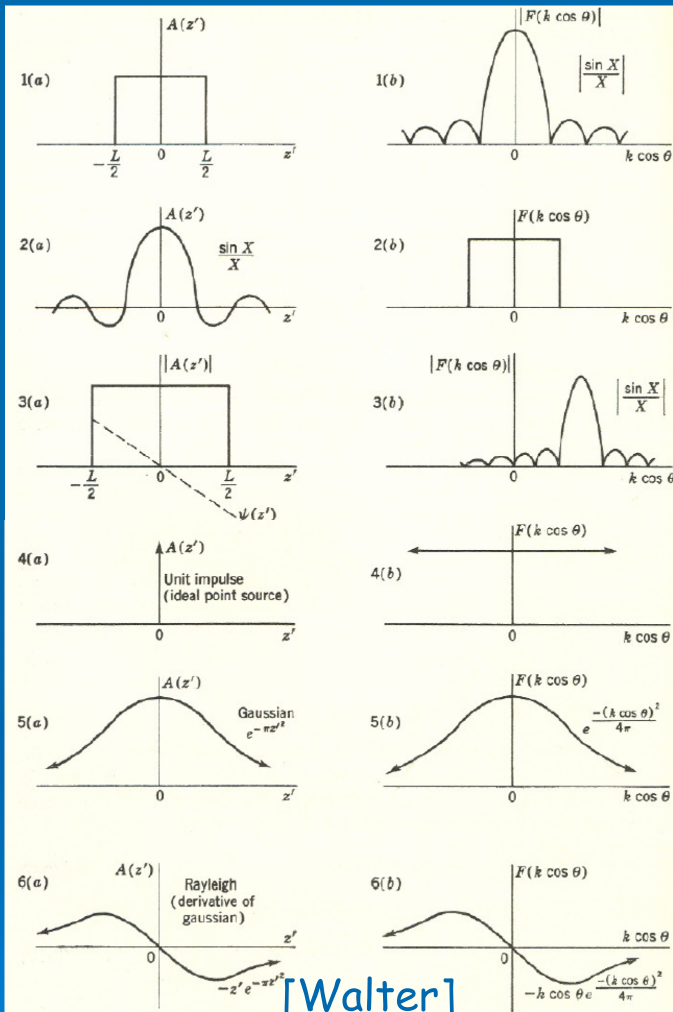
In LWAs, the methods for the proper synthesis of the illumination functions are those ones commonly employed in traveling-wave antennas and, more generally, in aperture antennas …

$$F(k\sin\theta)=\frac{E(k\sin\theta)}{G(k\sin\theta)}=\int_{0}^{L}\left|A(z')\right|\mathrm{e}^{j\angle A(z')}\mathrm{e}^{jkz'\sin\theta}\,\mathrm{d}z'$$

$$A(z')=\frac{1}{2\pi}\int_{-\infty}^{+\infty}F(k\sin\theta)\mathrm{e}^{-jz'k\sin\theta}\,\mathrm{d}(k\sin\theta)$$

For a line source, the synthesis methods allow us to easily relate a desired radiation pattern with A(z), which is a complex function (amplitude and phase) of the longitudinal direction

Illuminations of line sources



Common Fourier Transform pairs

[Jasik]

Line-Source Distributions

TYPE OF DISTRIBUTION $-1 \le x \le 1$	DIRECTIVITY PATTERN $E(u)$		HALF POWER BEAMWIDTH IN DEGREES	ANGULAR DISTANCE TO FIRST ZERO	INTENSITY OF 1st SIDELOBE db BELOW MAX.	GAIN FACTOR
$f(x)=1$	$\ell \frac{\sin u}{u}$		$50.8\frac{\lambda}{\ell}$	$57.3\frac{\lambda}{\ell}$	13.2	1.0
$f(x)=1-(1-\Delta)x^2$	$\ell(1+\mathcal{I})\frac{\sin u}{u}$, $\mathcal{I}=(1-\Delta)\frac{d^2}{du^2}$	$\Delta=$ 1.0	$50.8\frac{\lambda}{\ell}$	$57.3\frac{\lambda}{\ell}$	13.2	1.0
		.8	$52.7\frac{\lambda}{\ell}$	$60.7\frac{\lambda}{\ell}$	15.8	.994
		.5	$55.6\frac{\lambda}{\ell}$	$65.3\frac{\lambda}{\ell}$	17.1	.970
		0	$65.9\frac{\lambda}{\ell}$	$81.9\frac{\lambda}{\ell}$	20.6	.833
$\cos\frac{\pi x}{2}$	$\frac{\pi\ell}{2}\frac{\cos u}{(\frac{\pi}{2})^2-u^2}$		$68.8\frac{\lambda}{\ell}$	$85.9\frac{\lambda}{\ell}$	23	.810
$\cos^2\frac{\pi x}{2}$	$\frac{\ell}{2}\frac{\sin u}{u}\frac{\pi^2}{\pi^2-u^2}$		$83.2\frac{\lambda}{\ell}$	$114.6\frac{\lambda}{\ell}$	32	.667
$f(x)=1-\lvert x\rvert$	$\frac{\ell}{2}\left(\frac{\sin\frac{u}{2}}{\frac{u}{2}}\right)^2$		$73.4\frac{\lambda}{\ell}$	$114.6\frac{\lambda}{\ell}$	26.4	.75

A specified far-field pattern $F(k \sin \theta)$ gives a source distribution, which in general is not restricted in length. **In practice, the use of a finite source length L gives an approximate pattern $F_a(k \sin \theta)$**

Approximation that minimizes the mean squared error for the pattern

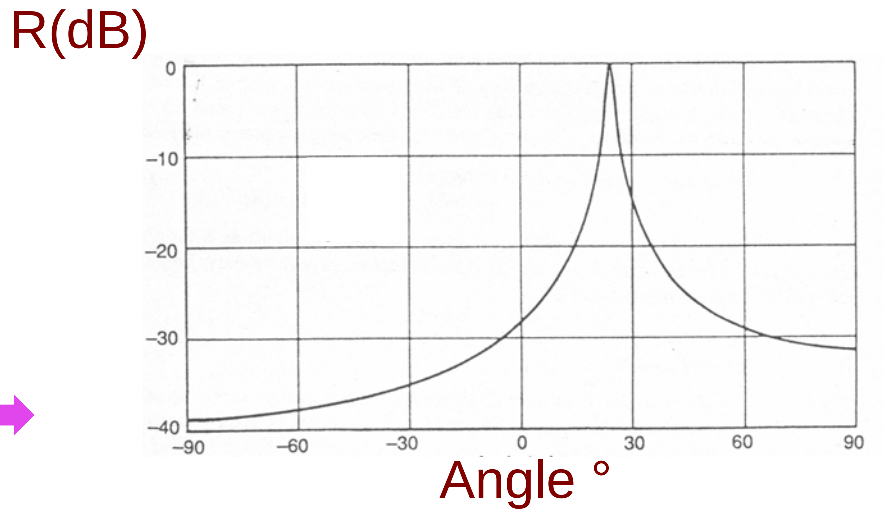
$$F_a(k\sin\theta) = L\int_{-\infty}^{+\infty} F(\xi)\frac{\sin\frac{L(k\sin\theta-\xi)}{2}}{\frac{L(k\sin\theta-\xi)}{2}}d\xi$$

Uniform LWA patterns

Typical radiation patterns of a *nontapered* LWA

Radiation pattern for infinite length

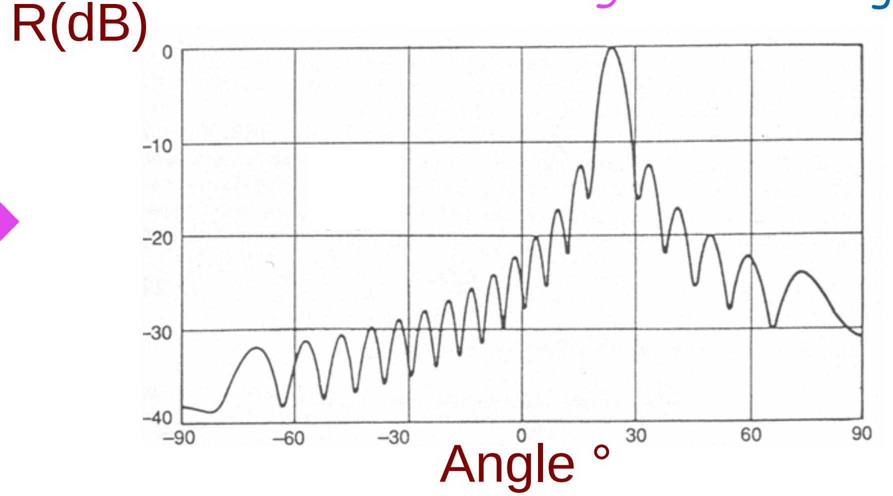
$$R(\theta) = \frac{\cos^2\theta}{\bar{\alpha}_z^2 + (\bar{\beta}_z - \sin\theta)^2}$$



$\phi_{-1} = 24°$
$\alpha\lambda_0 = 0.1$
$L = 150\lambda_0$

Effect of a finite length

[Schwering and Peng]



$\phi_{-1} = 24°$
$\alpha\lambda_0 = 0.1$
$L = 10\,\lambda_0$

For lines that are not extremely long in terms of wavelength, the side-lobes are rather high (typically below -13 dB, as in uniform illumination)

Techniques for side-lobe control …

Design procedure of LWAs

The fundamental step in LWA design is represented by the determination of the *longitudinal distribution of the leakage rate*, once the illumination function is fixed in accordance with the desired radiation pattern and efficiency.

Power variation along z …

$$-\frac{dP(z)}{dz} = p_R + p_L$$

$$\frac{dP(z)}{dz} = -2\alpha_z(z)P(z)$$

$$P(z) = P(0)e^{-2\int_0^z \alpha_z(z')dz'}$$

p_R radiated power per unit length

p_L dissipated power per unit length

Link with illumination …

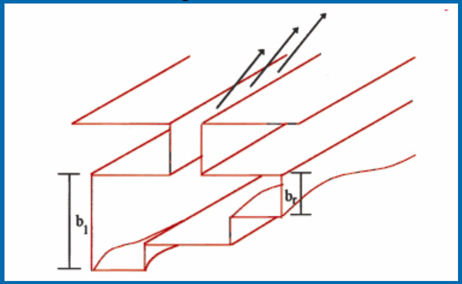
$$p_R(z) = C|A(z)|^2$$

$$\alpha_z(z) = \frac{1}{2}\frac{|A(z)|^2}{\frac{1}{\eta}\int_0^L |A(z')|^2 dz' - \int_0^z |A(z')|^2 dz'}$$

Exercise 4: Verify the relationship between leakage rate $\alpha(z)$ and illumination function $A(z)$ on the aperture

Tapering for pattern shaping

The longitudinal modulation of the leakage rate requires a modification of the radiating structure, by varying the electrical and/or the geometrical characteristics, known as 'tapering' procedure.



Such a procedure also alters the phase constant of the structure: in practice, it is advisable to have topologies for which *the leakage and the phase constants are essentially independent of each other.*

Possible action with some (geometrical) parameter on leakage without affecting phase much and similar action with some other parameter on phase without affecting leakage much …

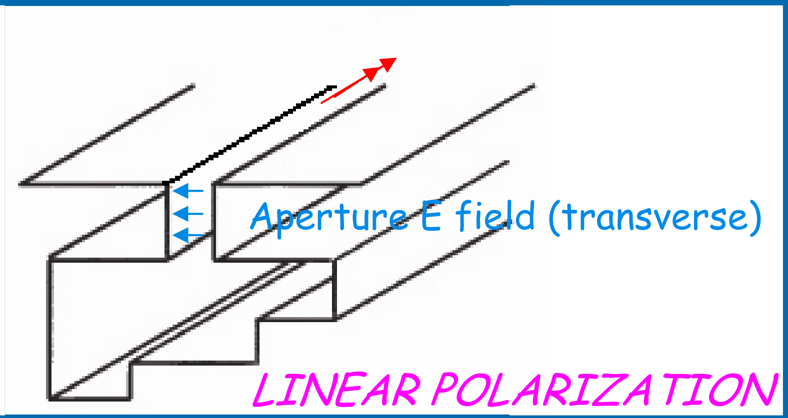
It is assumed that all variations in α and β are *sufficiently gradual* so that the propagation constant at a point is the same as that for an infinitely-long structure of the same cross section of the tapered structure at the considered point.

The ultimate aspect in LWA design is the determination of the proper geometry (in connection with the chosen topology) capable to furnish the appropriate illumination function on the aperture, in turn determined on the basis of the desired radiation pattern.

LWA polarization features

The polarization properties of LWAs can often be desumed by simply analyzing the relevant characteristics of the constitutive equivalent-element pattern responsible for radiation.

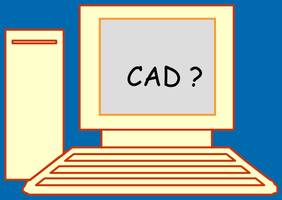
EXAMPLE



The polarization of the 'constitutive element' is usually of dipole type and linear polarizations (vertical/horizontal) can typically be obtained, often with a high purity degree (low cross-polarization levels).

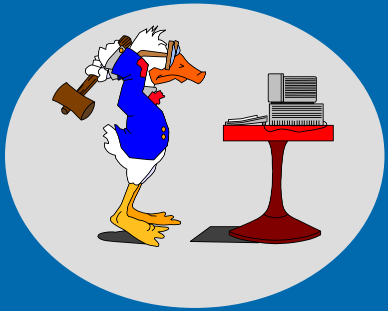
Circularly-polarized radiation is also possible with specific LWAs.

Numerical methods & LWAs



Uptodate commercial CAD packages for electromagnetics (typically based on FEM, FDTD, or MoM techniques) allow direct LWA analysis and synthesis to be performed.

Problems in memory storage and computation times can arise due to the large dimensions of typical LWAs and arrays…



The 'semianalytical' methods, generally based on the solution of waveguiding problems through the evaluation of the complex (leaky) modes, is very efficient, quite accurate, and physically meaningful for LWAs.

Basic features of numerical techniques for LWA analysis

Method	*Versatility*	*Accuracy*	*Pre-proc.*	*CPU*	*RAM*
Transverse Resonance	High	Medium/ Low	Low	Low	Low
Boundary Elements	Medium/ High	High	High	Medium	Medium
Spectral Domain	Medium	High	Medium/ High	Medium	Medium

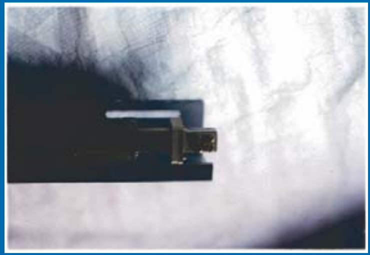
LWAs in practice: feed etc.

FEEDERS

If possible, not too abrupt transitions from unperturbed to leaky structure …

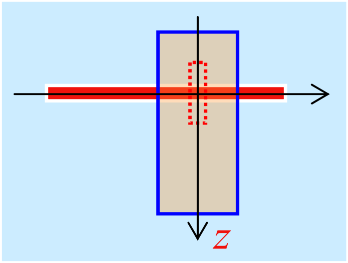
Metallic-type LWAs:

The feeders are usually obtained through direct transition with the closed metallic guide and are very efficient (further reduction of impedance mismatching and spurious effects is achieved with smooth transitions).



Printed-type LWAs:

The feeders (microstrip, slot, probes, etc.) are generally more complicated to design and result less-efficiently coupled with the radiating line, due to spurious effects (direct feed radiation, excitation of surface waves, etc.).



TERMINATIONS

It is advisable to insert a matched load (e.g., resistive cards) at the line end to absorb residual nonradiated power, which could be otherwise reflected giving rise to a disturbing 'backlobe' (cf. patterns with short-circuited loads).

LWA loss effects etc.

RADOMES

Environment protection in different types of LWAs can be achieved by means of covering dielectric layers: this introduction can sensitively affect efficiency, radiation parameters, etc., and has to be properly considered for accurate design.

LOSSES

Usually ohmic losses (mainly in metallic structures) do not adversely affect the LWA performance up to the low mm-wave range: only for very narrow beams the leakage rate could be compared with the attenuation rate due to dissipations.

The use of basically-open and of low-loss dielectric structures is anyway advisable as the upper mm-wave range is approached.

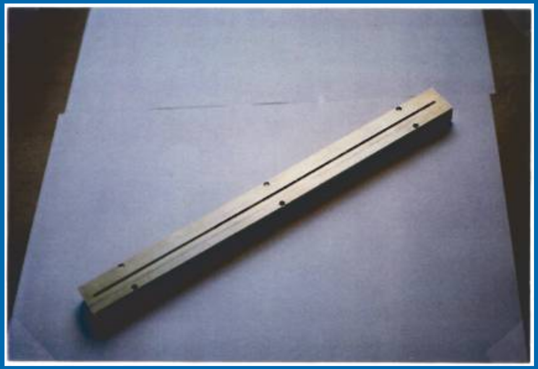
For many LWA topologies, it is possible to obtain an accurate evaluation of the reduction of efficiency and of the modification of the leakage rate related to ohmic losses.

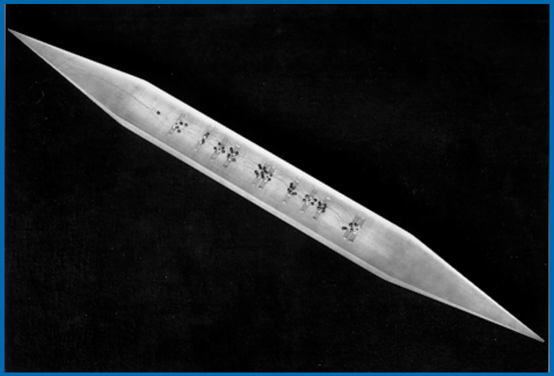
Exercise 5: Find a relationship for the LWA efficiency in terms of both leakage rate and ohmic-loss rate.

LWA manufacturing aspects

Manufacturing *tolerances* can be particularly important in accurate tapering and in higher-frequency (mm-wave) applications.

Numerically-controlled machines for fabrication are advisable.

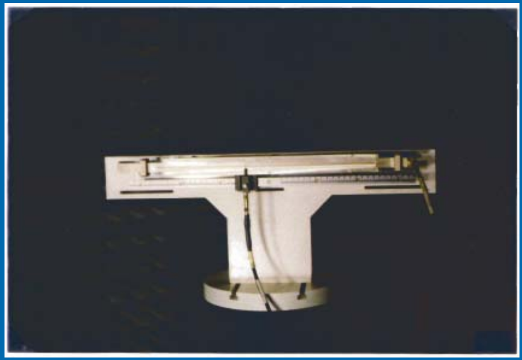




'Systematic' and/or 'random' errors **in the realization process of the desired geometry affect both the leakage and the phase distribution (quadratic and cubic-type errors) …**

The relevant effects can be observed in distortion of the radiation pattern, particularly for design with very reduced sidelobes (e.g., 'spoilt' shape, side-lobe rising and unbalancing, etc.).

LWA measurements & tests



Measurements

Experimental tests make use of the most part of the usual measurement setups and procedures for aperture antennas …

Information on LWA basic parameters (phase and leakage) and derived quantities (efficiency, directivity, radiation pattern) is preferably achievable by means of aperture techniques (near field).

Care has to be paid for the interaction effects with probes.

Basic equipment: network vector analyzer and anechoic chamber

Fresnel (intermediate field) and Fraunhofer (far field) comparisons are also advisable to fully validate the results.

General concluding remarks

In the class of traveling-wave antennas, LWAs can furnish types of radiators with interesting performance (efficiency, power handling, polarization, flexibility for beam shaping and geometrical solutions, etc.).

With a single LWA, fan beams are usually obtained, scannable by frequency in the fw quadrant (uniform LWAs) or in the fw/bw quadrant (periodic LWAs).

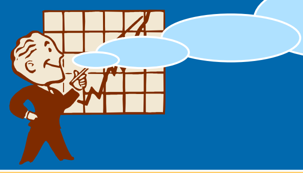
With linear arrays of LWAs, pencil beams can be obtained, scannable by frequency in elevation and by phase shift in azimuth.

Beam shaping for advanced radiation patterns is achievable by means of suitable longitudinal tapering.

Further peculiar beam performance (shaped wide beams, conical radiation, etc.) can also be exploited also in connection with unconventional materials.

LWAs can find application in various wireless links (control and monitor systems, WLAN, etc.) particularly in the microwave and mm-wave ranges.

LWA's basic references



Everything you always wanted
to know about LWAs
but were afraid to ask …

1. C. H. Walter, *Traveling wave antennas*, New York: McGraw-Hill, 1965; Los Altos, CA: Peninsula Publishing, reprint, 1990.
2. A. Hessel, "General characteristics of traveling-wave antennas," Ch. 19 in *Antenna theory*, R. E. Collin and F. J. Zucker (eds.), New York: Mc-Graw-Hill, 1969.
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7. T. Tamir and A. A. Oliner, "Guided complex waves," Parts I and II, *Proc. IEE*, 110: 310-334, 1963.

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