

LEAKY-WAVE ANTENNAS

Leaky-wave antennas (LWAs) constitute a type of radiators whose behavior can be described by an electromagnetic wave (*leaky wave*) that propagates in guiding structures that do not completely confine the field, thus allowing a continuous loss of power to the external environment (*leakage*).

According to IEEE Standard 145-1983, a leaky-wave antenna is “an antenna that couples power in small increments per unit length either continuously or discretely, from a traveling wave structure to free space.”

Distinctive Features And Applications

LWAs (1,2,3) belong to the class of traveling-wave line antennas, for which the illumination is produced by a wave that propagates along a guiding structure (4). Compared with the wavelength, a LWA is long in the propagation direction z , while its cross section is usually of the order of the wavelength [see the reference examples of Fig. 1(a) and 1(b)].

LWAs radiate along their lengths, and in general their relevant behavior can be derived by considering a linear aperture in which the illumination of the current distribution, according to the equivalence principle, is directly linked to the tangential electromagnetic field. Usually LWAs are excited from one input of the open guiding structure with a traveling wave, which propagates mainly in one longitudinal direction (e.g., $+z$) and is attenuated due to the power leakage towards the exterior region, thus leaving a negligible field at the termination of the guide. In a harmonic regime [with an $\exp(j\omega t)$ time dependence], this wave is characterized by a complex propagation constant of the type $k_z = \beta_z - j\alpha_z$ (5,6,7,8,9,10), where β_z is the *phase constant* and α_z is the *attenuation constant* of the leaky wave (when only power loss due to radiation is taken into account, α_z is also called the *leakage constant*).

Usually the radiation pattern of a single LWA has a typical fan shape: in the elevation (or zenith) plane a narrow beam is achievable with a pointing direction that varies with frequency, whilst in the cross (or azimuth) plane the beam is usually wider as a result of the smaller transverse aperture. Depending on the desired application, a suitable longitudinal variation of the aperture distribution, usually reached by modulating geometrical parameters (*tapering*), allows good control of the radiation pattern (sidelobe behavior, etc.). In some cases, in order to obtain beam shaping or physical matching with curved surfaces of the mounting, LWAs can be designed with certain amounts of curvature along their lengths.

The scanning properties in the elevation plane (pointing angle variable with frequency) are related to the type of waveguide employed, which can be of either *uniform* [Fig. 1(a)] or *periodic* [Fig. 1(b)] type (1,2,3,4). LWAs derived from waveguides that are longitudinally uniform (i.e., the structure maintains continuously the same transverse geometry) typically allow angular scanning over one quadrant, from around broadside towards one endfire (the *forward* one, which is concordant with the wave propagation direction). LWAs derived from waveguides that are longitudinally periodic (i.e., the structure is periodically loaded with proper discontinuities, at intervals that are usually short with respect to the wavelength) allow wider angular scanning, both in the

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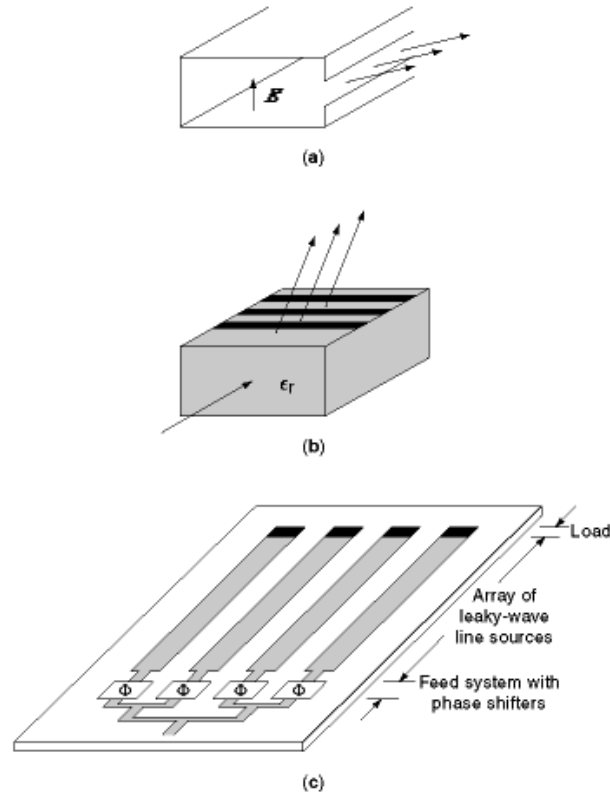


Fig. 1. Basic structures of LWAs: (a) uniform LWAs: geometry representing a partially open metallic waveguide; (b) periodic LWAs: geometry representing a strip-loaded dielectric-rod waveguide; (c) topology of LWA arrays.

forward and in the backward quadrant. However, for various reasons, there are limitations on such scanning ranges for both types of structures (as shown in a subsequent section).

When a pencil beam is to be used for two-dimensional (2-D) scanning, both in elevation and cross planes (zenith and azimuth), a phased array of juxtaposed LWAs may be employed, thus enlarging the equivalent aperture transversely (11,12) [see the reference example of Fig. 1(c)]. LWA arrays are therefore constituted by a linear configuration of sources (i.e., 1-D elements), instead of the planar ones of standard arrays (i.e., 2-D elements). For LWA arrays pointed-beam scanning is achievable by varying both the frequency for the elevation plane and the phase shift for the cross plane.

Since LWAs are derived from partially open waveguides, they present a number of distinctive features as radiators: large power-handling capability, particularly for structures utilizing closed metallic waveguides; reduction of bulk, due to the usually small profiles in the cross sections; capability of designing a wide variety of aperture distributions and consequent flexibility for the beam shaping; possible use as wide-band radiators, allowing large angular scanning by varying the frequency (instead of using mechanical or other electronic means); achievement of very narrow beams with good polarization purity; simplicity of feeding and economy for 2-D scannable pencil-beam arrays (multiple linear phase shifters instead of one planar one); etc.

LWAs are mainly used in the microwave and millimeter-wave region, though investigations have been performed also for both lower- and higher-frequency applications. The first studies on LWAs were presented during the forties, basically for aerospace applications (radar, etc.); since then, a very wide range of solutions

for LWAs has been proposed in response to changing requirements and constraints. The applicability of this type of antennas has also been widened, including various problems of traffic control, remote sensing, wireless communications, and so forth (13,14).

Operation Principles

Existence and excitation of leaky waves in open guides. A leaky wave has a complex longitudinal wave-number k_z that can be derived by solving, as a function of the physical parameters (frequency and geometry of an open waveguiding structure), the characteristic equation (or dispersion relation), which is of the general type

$$D(\mathbf{k}_z, \mathbf{k}_0) = 0 \quad (1)$$

where $k_0 = \omega(\mu_0 \epsilon_0)^{\frac{1}{2}}$ is the vacuum wave-number. [The eigensolutions of Eq. (1) can alternatively be viewed as the pole singularities of the spectral Green's function of the structure, since the expression $D(k_z, k_0)$ is generally present in its denominator (5,6,7,8,9,10).]

As is well known, for lossless closed waveguides the dispersion relation in Eq. (1) generally presents an infinite discrete set of eigensolutions giving the *guided modes* (*proper modes*) which individually satisfy all the relevant boundary conditions. Any field excited by a source in a closed guide can be expanded in terms of the complete set of the infinite discrete eigensolutions of Eq. (1). In conventional guides, the longitudinal wave numbers k_z are either real [propagating waves above their cutoff, with $k_z = \beta_z < k = k_0(\epsilon_r)^{\frac{1}{2}}$; for air-filled structures, one has $\beta_z < k_0$] or imaginary (attenuating waves below their cutoff, with $k_z = -j\alpha_z$). (We recall that in reciprocal structures such eigensolutions exist in pairs: $k_z = \pm k_z$, describing waves traveling in opposite $\pm z$ directions.)

In lossless open waveguides (e.g., dielectric guides), instead, only a finite number of propagating modes can exist as eigensolutions of Eq. (1) satisfying all the boundary conditions (particularly, the radiation condition): these are the so-called bound *surface waves* (each one exists only above its cutoff, with $k_z^2 > k_0^2$, or $k_z = \beta_z > k_0$). In addition to this, for a complete representation of the field, which is no longer confined in a closed section, a *continuous spectrum* of modes must be introduced: it describes the radiated field as an integral over a set of plane waves having a continuous range of wave numbers (e.g., such that $-\infty < k_z^2 < k_0^2$, or $0 \leq k_z = \beta_z \leq k_0$ and $-j\infty < k_z = -j\alpha_z < j0$) (5,6,7,8,9,10). Any field excited by a source in an open guide can therefore be expanded in a *spectral representation*, that is, in terms of a finite set of proper modes and an integral contribution of the continuous spectrum. (Again, in reciprocal structures the solutions exist in pairs: $\pm k_z$.)

On the other side, it is seen that the characteristic equation in Eq. (1) for open guides presents additional discrete solutions that are *nonspectral* in that they correspond to fields that violate the radiation condition (they attenuate along the propagation direction but increase exponentially in a transverse direction away from the structure) and are not included in the spectral representation of the field. These roots are also called *improper*, since they are located on the improper sheet of the Riemann surfaces for k_z (5,6,7,8,9,10).

In many practical circumstances, for describing the radiative effects of the open structures in the presence of a source, the evaluation of the field through the spectral representation (i.e., including the integral contributions of the continuous spectrum) can be very difficult and cumbersome. It is found that the field can generally be evaluated in an alternative and rapidly convergent way, through the so-called *steepest descent* or *saddle point* representation (5,6,7,8,9,10): by properly modifying the integration path of the continuous spectrum involved in the spectral representation, the relevant integral evaluation can be simplified by introducing contributions of improper eigensolutions. The advantage of such a steepest-descent representation is that, for guiding structures designed to operate as LWAs, the radiation field can be evaluated accurately in

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a much simpler fashion by considering just the residual contribution due to the presence of one complex and generally improper mode, that is, the leaky wave, which can therefore be viewed as a simple recasting of the continuous spectrum. In fact, it is seen that in practical cases the remaining part of the continuous spectrum in the steepest-descent representation (the so-called *space wave*) can be made to give negligible contributions to the description of the LWA's radiation (5,6,7,8,9,10).

The existence of a leaky mode, which describes a wave propagating with a certain amount of attenuation through the aperture of a traveling-wave structure, is a necessary condition to ensure its influence on the illumination function. Furthermore, the leaky wave should be *dominant*, in the sense that its excitation has to be strong and therefore its amplitude should be large in comparison with those of other possible guided modes and of the space wave. [A deep discussion of the physical nature of the complex waves and its influence on the evaluation of the field in open structures cannot be given within the limits of this article, but many detailed studies of it can be found in the literature (1,2,3,4,5,6,7,8,9,10).]

From another point of view it can be seen that, when properly excited by a source at a finite section, a leaky wave, even though improper, assumes its physical validity within an angular sector close to the equivalent aperture of the open guiding structure, and the corresponding field distribution is able to furnish a fundamental contribution to the evaluation of the near field (5,6,7,8,9,10). Since the far field is expressed as a simple Fourier transform of the field at the aperture, a leaky wave can furnish a highly convergent and efficient evaluation of the radiation of LWAs, as an extremely advantageous alternative to a continuous-spectrum evaluation.

In an open lossless structure the leaky-wave solutions that are of the type $k_z = \beta_z - j\alpha_z$ describe power flowing away from the structure. Actually, in usual reciprocal structures these roots of the dispersion equation in Eq. (1) appear in pairs of the type $k_z = \pm k_z^*$. This means that, in general, both direct and reverse waves exist, propagating in the $+z$ and $-z$ directions (i.e., the $k_z = \beta_z - j\alpha_z$ and $k_z = -\beta_z + j\alpha_z$ solutions); as mentioned, in standard applications the source is chosen to excite just one of the two opposite traveling waves. In addition, complex conjugate solutions ($k_z = \beta_z + j\alpha_z$ and $k_z = -\beta_z - j\alpha_z$) also occur for describing leakage phenomena related to power entering the guiding structure from the external region, because the field increases along the propagation direction; again, in standard applications the source is placed inside the guiding structure and leakage occurs only through one wave, which carries out power. It should be also mentioned that, in some cases (e.g., the nonreciprocal structures, as discussed in a subsequent section), complex waves of the type $k_z = \beta_z - j\alpha_z$ and its conjugate k_z^* may exist, which describe effects of power leakage as well and also possess a spectral, or proper, nature.

Basic characterization of leaky-wave antennas. LWAs present the advantage of a rather simple characterization of their basic properties, with consequent straightforward approaches for their analysis and synthesis. As mentioned, their characterization is reduced to the evaluation of a dominant complex eigensolution $k_z = \beta_z - j\alpha_z$ that can be supported and strongly excited in a specific open structure.

The characteristic dispersion of the real and imaginary parts of the longitudinal wave number of a leaky wave is presented in Fig. 2 for two different types of structures; specifically, the normalized parameters β_z/k_0 and α_z/k_0 are plotted against frequency f . The radiation region of LWA structures lies largely inside the frequency range where the wave becomes fast ($\beta_z/k_0 < 1$) and power can therefore leak out from the guiding structure towards the outside air region in the typical form of a TEM-like mode: in fact, $\beta_z/k_0 < 1$ is in general the so-called *condition for leakage* of a complex wave that can radiate into an external air region.

The valid frequency range for LWA applications is actually where, as the frequency decreases, β_z/k_0 diminishes monotonically from unity towards rather low values; in this region, to have an efficient directive beam, α_z/k_0 should assume rather small values (e.g., typically α_z/k_0 can be of the order from about 10^{-1} to 10^{-3}). As frequency decreases further, a sudden rise of α_z/k_0 is generally found, which signifies the predominance of reactive phenomena over radiative ones, while β_z/k_0 may present a flat zone with approximately constant low values before showing a further steep rise as the frequency goes to zero; in these ranges, radiative effects can no longer be represented by the leaky wave, and the structures usually cannot work well as radiators (2,7,8,12).

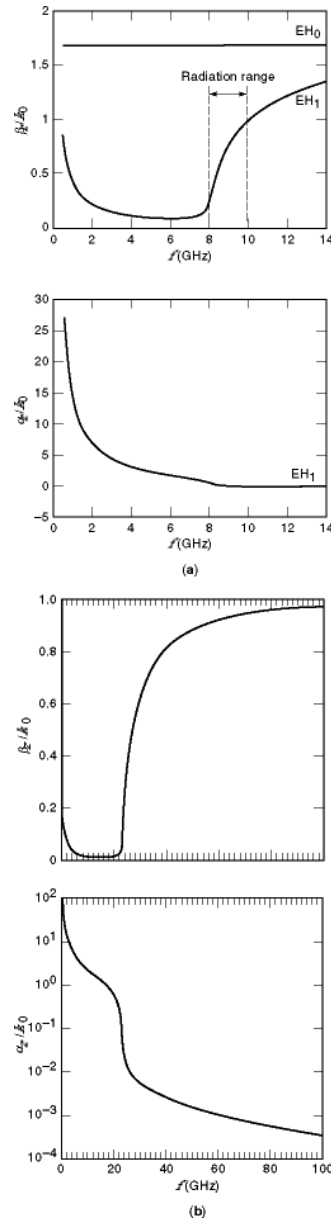


Fig. 2. Typical dispersion behavior of the leaky-mode complex wave number (normalized phase constant β_z/k_0 and leakage constant α_z/k_0 versus frequency f): (a) for an open planar waveguide (microstrip); (b) for a partially closed metallic waveguide (slit ridge).

The case of Fig. 2(a) is representative in particular of leakage in unperturbed intrinsically open waveguiding structures (e.g., dielectric and printed lines). In this case, the leaky waves are complex roots of the same characteristic equation $D(k_z, k_0) = 0$ that furnishes the guided (or bound) modes of the structure. Each leaky mode typically appears as a mathematical continuation of a related guided mode; at higher frequencies the

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mode is generally slow and bound (real and proper), while at lower frequencies it becomes fast (complex and improper) and can radiate ($\beta_z/k_0 < 1$ and $\alpha_z \neq 0$).

It is worth noting here that in open planar structures a different type of leakage can occur as well, which is associated with *surface waves* (TE- or TM-like modes) propagating in the substrates (12), instead of the standard space wave (TEM-like mode) that carries power out into the air. While the latter is able to describe useful far-field radiation in LWA applications, the former usually describes power that leaks out transversely in a layered structure and accounts for loss and interference effects in the planar circuits (see also a subsequent section for comments on this phenomenon).

The case of Fig. 2(b) is representative of leakage in closed metallic waveguides (in this case, filled with dielectric) that are perturbed with a suitable aperture to allow a certain amount of power loss to the environment. In this case the leaky waves are the complex roots of a characteristic equation that appears as a small perturbation of that one for the closed waveguide, in such a way that the leakage mechanism also is properly characterized, having similar phase properties and the additional presence of an attenuation (leakage) constant (see next section). In fact, from Fig. 2(b) it is seen that the behavior of β_z/k_0 resembles that of the closed structure until the cutoff region is approached, where reactive effects become predominant. Also, for an open metal guide that is air-filled, the wave is always fast at any frequency (the condition for leakage is always satisfied), while for an open metal guide that is partly filled with a dielectric the wave is fast at lower frequencies and becomes slow at higher frequencies, where it can no longer radiate ($\beta_z/k_0 > 1$), even in the presence of nonzero α_z .

Evaluation of the leaky-wave phase and leakage constants. The evaluation of the complex eigen-solutions for nonclosed waveguides depends on the physical parameters involved (frequency and geometry) and is generally achievable with numerical methods. Among them, the *transverse resonance technique (TRT)* (15,16) is one of the most efficient approaches for either rigorous or approximate (according to the antenna topology) evaluations. It first requires the introduction of a suitable equivalent transmission-line network, which describes the transverse geometry of the structure. Then, a numerically solvable transcendental equation in terms of transverse eigenvalues k_t and of physical parameters is usually achievable by imposing a resonance condition for the equivalent circuit. The complex eigenvalue k_z is derived from the additional link to the longitudinal problem given by a separation condition for the eigenvalues (e.g., in air, $k_0^2 = \omega^2 \mu_0 \epsilon_0 = k_t^2 + k_z^2$). Where the separation condition holds rigorously also for the variables in the transverse plane (e.g., $k_t^2 = k_x^2 + k_y^2$), the TRT in general gives the exact characteristic equation for the geometry. Even if the problem is not rigorously separable in the transverse plane, an equivalent characteristic equation can be achieved by the TRT, which often gives solutions with good accuracy for many practical purposes. To this aim, the network elements that give the electromagnetic description of the various parts of the transverse geometry (such as radiation impedance, step discontinuities, T junctions, etc.) have to be derived in convenient forms, which are found to be simple and usually accurate (3,4,12,17,18).

When separation of variables does not strictly hold, other numerical methods can be employed to accurately determine the complex eigensolutions for open waveguides. The most appropriate choice depends on several factors related to the computational features of the methods, the geometry of the open structures, etc. (15,16). Among the various possible approaches, integral-equation techniques can work particularly well. In particular, spectral-domain approaches appear well suited for the derivation of the eigensolutions in structures of the printed type (15). Different formulations based on surface integral equations (the boundary-element method, etc.) (16) can also furnish satisfactory numerical results in terms of efficiency, versatility, and accuracy for the analysis of quite general classes of arbitrarily shaped open waveguides, allowing the rigorous determination of the longitudinal wave number for complex modes as well (19,20).

Interpretation of the behavior of a leaky-wave antenna. As described, LWAs are described by a fast wave that propagates through an equivalent aperture, losing power towards free space, with a leakage amount that is usually rather limited to allow a sufficiently directive beam. The simplest LWA geometry for this purpose is that of a closed metallic waveguide in which a suitably small aperture is introduced longitudinally

in order to achieve a continuous power loss along its length, as shown in Fig. 3(a) for a rectangular guide with a slit cut in a side wall. This structure, besides having historical importance as the first proposed LWA in 1940 (1,2,3,4), can be taken as a reference structure for explaining the basic behavior of LWAs in terms of a waveguide description.

For such a structure, a leaky wave can be considered as excited by a standard incident mode for the closed rectangular waveguide, that is, the dominant TE_{10} , which travels in the $+z$ direction with a known phase constant β_{0z} for a fixed choice of the physical parameters (geometry and frequency). For a sufficiently small geometry perturbation due to the slit, the phase constant is changed just slightly to a value represented by β_z , and a low leakage rate α_z then occurs, which, as mentioned, accounts for the longitudinal attenuation due to the field that is no longer confined and flows also in the outside region. The propagating field inside the waveguide and in the proximity of its aperture is therefore described by the complex longitudinal wave number $k_z = \beta_z - j\alpha_z$, whose value depends on the physical parameters [the qualitative behavior is like that shown in Fig. 2(b), and a quantitative description is given in this final part of this subsection].

In this case the leakage is assumed along $+z$ ($\beta_z > 0$ and $\alpha_z > 0$), and on supposing that the vertical field variations are almost negligible ($k_y \approx 0$), it is easily seen, from the general separation condition for waveguides ($k_0^2 = \omega^2 \mu_0 \epsilon_0 = k_t^2 + k_z^2 \approx k_x^2 + k_z^2$), that the horizontal wave-number is also complex:

$$\begin{aligned} \mathbf{k}_z &= \beta_z - j\alpha_z & \text{with } \beta_z > 0, \quad \alpha_z > 0 \\ \mathbf{k}_x &= \beta_x - j\alpha_x & \text{with } \beta_x > 0, \quad \alpha_x < 0 \end{aligned} \quad (2)$$

since one has $\beta_x \alpha_x = -\beta_z \alpha_z$. Therefore a plane wave of inhomogeneous type exists, having a complex propagation vector \mathbf{k} of the type

$$\begin{aligned} \mathbf{k} &= \boldsymbol{\beta} - j\boldsymbol{\alpha} \\ \boldsymbol{\beta} &= \beta_x \mathbf{x}_0 + \beta_z \mathbf{z}_0 \\ \boldsymbol{\alpha} &= \alpha_x \mathbf{x}_0 + \alpha_z \mathbf{z}_0 \end{aligned} \quad (3)$$

where the phase vector $\boldsymbol{\beta}$ is directed at an angle that describes the emission of power from the guide, and the attenuation (leakage) vector $\boldsymbol{\alpha}$ is perpendicular to $\boldsymbol{\beta}$, and represents attenuation along z and amplification along x . Consequently, the field has a spatial dependence of the type

$$\exp[-j(\beta_x x + \beta_z z)] \exp(|\alpha_x| x - \alpha_z z) \quad (4)$$

Therefore, this plane wave travels at an angle $\theta = \sin^{-1} (\beta_z/|\boldsymbol{\beta}|)$ with respect to broadside, carrying out power, and its amplitude increases transversely as expected in a leaky wave. It should be noted that the direction angle θ of the leaky wave is usually expressed under the approximate form $\theta \approx \sin^{-1} (\beta_z/k_0)$, directly derivable from the previous relation, since in general the leakage constant is numerically negligible with respect to the phase constant. The nature of the propagation vector is sketched in Fig. 3(b), while the distribution of equiphase and equiamplitude surfaces with respect to the decreasing power flow along the guide is represented in Fig. 3(c). It should be recalled that, even though the leaky wave has an improper nature, the field generated from a source located at a finite distance along z still satisfies the radiation condition, since the field increases transversely only in a limited sector given by angles less than the θ value describing the direction of power leakage (5,6,7,8,9).

The leakage mechanism and the relationship for the beam peak direction as a function of frequency can be interpreted in a very simple way, also referring to the description of the propagation of the dominant mode

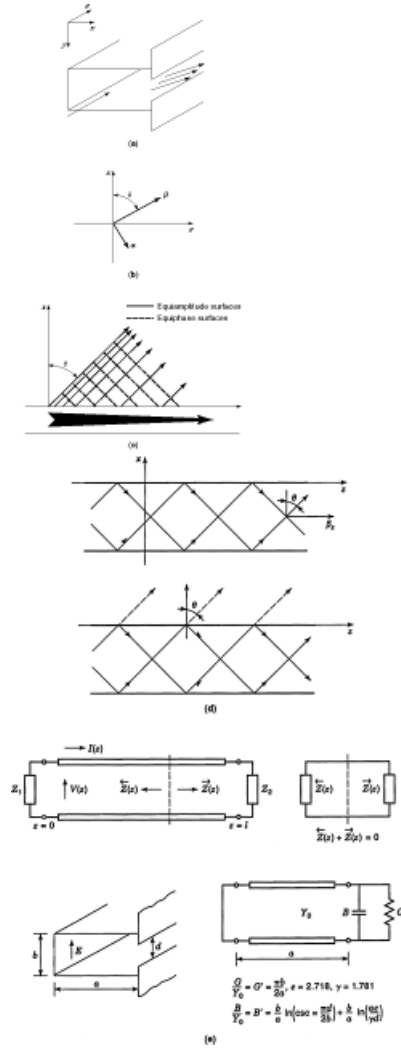


Fig. 3. LWA achieved with a side-wall slit in a rectangular waveguide: (a) geometry of the structure; (b) nature of the propagation vector of the inhomogeneous plane leaky wave (phase and attenuation vectors); (c) equiphaso and equiamplitude planes of the leaky wave with the appropriate leakage along the guide; (d) interpretation of leakage in terms of superposition of homogeneous plane waves at an angle with respect to the longitudinal direction (closed and partially open structures); (e) equivalent transverse-resonance network, resonance conditions, and network parameters for the numerical evaluation of the leaky-wave complex wave numbers as a function of the physical parameters involved.

of our structure in terms of superposition of two uniform plane waves incident at an angle on the lateral walls of the guide, as represented in Fig. 3(d). With the introduction of a small aperture in one wall, at each reflection a certain amount of power (related to the aperture dimension and to the other parameters involved through α_z) leaves the guide at an angle $\theta \approx \sin^{-1}(\beta_z/k_0)$. The pointing angle is therefore near broadside for frequencies close to the cutoff of the closed guide and tends towards endfire as frequency increases.

A quantitative description of this LWA is easily achieved with a simple analysis of the complex eigenvalue, derivable through a modification of the dominant mode by employing a TRT (3,4,21). To this end, one requires

a characterization of the slit aperture in the side wall as a circuit element in the equivalent transmission line. For the evaluation of such discontinuities a great deal of work has been done in the past decades, mainly through variational methods (4,12,15,16,17,21). The description of the radiative and reactive effects of the slit in the side wall of the rectangular guide can be represented by a lumped element (e.g., an admittance $Y_R = G_R + jB_R$) as a function of geometry and frequency. The transverse network and the relationships that allow the derivation of the characteristic equation having complex eigensolutions are briefly reported in Fig. 3(e). The relevant solution in the complex plane for the perturbed dominant mode describes the leaky-wave behavior.

Design Techniques

Basic radiation features. The basic design principles of LWAs are generally derivable from the knowledge of the desired beam width and of the pointing direction. In LWAs these quantities can be linked in a straightforward way to the complex longitudinal wave-number.

The direction θ_M of the beam maximum, in fact, is mainly related to the phase constant for the chosen frequency. It has been seen that the value of the normalized phase constant β_z/k_0 predicts with a good approximation the direction of the maximum radiation θ_M according to the simple relationship

$$\sin \theta_M \approx \beta_z/k_0 \quad (5)$$

Since β_z has dispersive behavior, as is typical of waveguiding structures, scanning of the beam is achieved by changing the frequency: typically, as the frequency is increased from the cutoff, the pointing angle varies from around broadside ($\theta_M = 0^\circ$), towards forward endfire ($\theta_M = 90^\circ$). (Comments on the limitations of the scanning capability of LWAs will be presented in the next subsection.)

As regards the beam width, we recall that the leakage constant α_z expresses the rate of power loss along the line due to the radiation, thus influencing primarily the effective dimension of the equivalent aperture for the line source. In fact, the more α_z increases, the more the actual illumination length decreases (and the less the beam width is focused).

A basic relation between the leakage constant and the antenna length L derives from the specification of the radiation efficiency η , expressible in LWAs as $\eta = [P(0) - P(L)]/P(0)$, where $P(0)$ is the input power delivered to the structure and $P(L)$ is the output power left at the termination. The relation between efficiency, leakage rate, and length is generally dependent on the desired radiation pattern and therefore on the aperture distribution: referring to a uniform-section LWA, where α_z is independent of z , one has $\eta = 1 - \exp(-2\alpha_z L)$. It should also be noted that, for narrow-beam applications, very high efficiency should require an extreme prolongation of the line source; in practice, in LWAs it is typical to radiate around 90% or at most 95% of the input power, and the remaining power at the termination is absorbed by a matched load to avoid a back lobe of radiation due to the reflected wave. (Other considerations related to the efficiency and the illumination will be discussed in a subsequent subsection.)

Once the efficiency is chosen, a fixed relation therefore exists between the length in wavelengths (L/λ_0) and the normalized leakage constant α_z/k_0 . For a uniform-section LWA, an inverse proportionality between L and α_z is found:

$$\frac{L}{\lambda_0} \approx \frac{c}{\alpha_z/k_0} \quad (6)$$

$$c = \frac{1}{4\pi} \ln \left(\frac{1}{1 - \eta} \right)$$

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where c is related to the desired efficiency (e.g., for 90% efficiency $c = 0.185$). For a nonuniform section, since α_z depends on z , the relation between efficiency, length, and leakage rate depends on the chosen illumination and is more complicated.

In order to achieve narrow beams in the elevation angle, the effective longitudinal aperture has to be sufficiently wide (usually several wavelengths), and this implies a rather low leakage rate. The half-power (-3 dB) beam width $\Delta\theta$ is directly related to the antenna length given in free-space wavelengths (L/λ_0) through an approximate relationship, which takes into account also the contribution of the scan angle (3):

$$\Delta\theta \approx \frac{a}{(L/\lambda_0) \cos \theta_M} \quad (\text{rad}) \quad (7)$$

where the proportionality factor a is dependent on the aperture distribution: it has the smallest value for a constant aperture distribution ($a \approx 0.88$) and increases for tapered distributions (typically being more than unity) (3). From the previous expression, it is seen that, since $\cos \theta_M \approx k_t/k_0$, the beam width is also expressible as $\Delta\theta \approx 2\pi/(k_t L)$. This means that the beam width is, as a first approximation, practically constant when the beam is scanned away from broadside by varying the frequency for air-filled LWAs (where k_t is independent of frequency), but it changes for dielectric-filled LWAs (where k_t depends on frequency).

The effective aperture is reduced for a fixed antenna length as the beam approaches endfire (where the previous expression becomes inaccurate), and $\Delta\theta$ tends in practice to increase. It can be seen that for an ideal semiinfinite uniform structure (i.e. an antenna aperture from $z = 0$ to $z = L \rightarrow \infty$), the beam width is determined by the leakage rate only, since in this case it can be found that $\Delta\theta \approx 2\alpha_z/k_t$. Moreover, in this situation the radiation pattern depends only on β_z and α_z and does not present sidelobes:

$$R(\theta) \approx \frac{\cos^2 \theta}{(\alpha_z/k_0)^2 + (\beta_z/k_0 - \sin \theta)^2} \quad (8)$$

For finite antenna lengths, sidelobes are produced and the expression for $R(\theta)$ is more involved. In general the specifications on the sidelobe level are related to the choice of the aperture distribution, whose Fourier transform allows the derivation of the radiation pattern (see subsequent section on this subject).

Uniform and periodic leaky-wave antennas: scanning properties. It is seen that the beams for LWAs based on partially open air-filled metallic waveguides scan, in theory, an angular region from around broadside ($\beta_z/k_0 \approx 0$) towards one endfire ($\beta_z/k_0 \approx 1$).

In practice, around broadside the structure works near the cutoff region of the closed waveguide, where reactive effects due to mismatching are increasingly important. The leaky-wave values for β_z/k_0 cannot then be extremely low, and at the same time α_z/k_0 tends to increase too much, adversely affecting the possibility of focusing radiation at broadside.

As regards the behavior at endfire it is seen that, since β_z/k_0 tends to unity asymptotically as the frequency increases, in the unimodal range (where these structures are usually employed) the beam cannot closely approximate endfire radiation in an air-filled LWA. A way of improving the angular scanning is to fill these structures with dielectric materials. Thus, since in this case the normalized phase constant approaches the square root of the relative permittivity as the frequency is increased ($\beta_z/k_0 \rightarrow \epsilon_r^{1/2}$), the value $\beta_z/k_0 = 1$ can actually be approached in a much more restricted frequency range. It should however be noted that for such dielectric-filled structures the beam width may change strongly as a function of frequency and therefore as the pointing angle varies [see comments on Eq. (7)].

Moreover, it should be noted that in many leaky structures (such as dielectric and printed ones), as the frequency is increased, the leaky-mode solution changes into a guided-mode solution through a complicated *transition region* (2,22,23,24). In this frequency range, also called the *spectral gap*, the contribution of the

leaky wave to the field tends progressively to decrease, and generally the structure does not work well as a LWA. The representation of the electromagnetic field in this situation becomes more involved (the leaky-wave contribution is in general no longer strongly representative of the aperture field, and the space wave assumes increasing importance), and additional analyses are required, whose discussion is beyond the limits of this work.

As mentioned, while the uniform LWAs usually radiate only in the forward quadrant, within the limits specified above, the LWAs derived from periodically modulated slow-wave guides can radiate all the way to backward endfire in the lower frequency range.

The design principles for periodic LWAs are for the most part similar to those for uniform LWAs (1,2,3,4). The main difference lies in the characterization of the fast wave, which is now associated with a Floquet spatial harmonic of the periodic guide (1,2,3,4,10,24). One can see that if a uniform guide is considered whose operating mode is slow ($\beta_z/k_0 > 1$; e.g., a dielectric waveguide), and a longitudinally periodic discontinuity is properly added (e.g., an array of metal strips or notches, etc., placed at suitable distances p), such periodicity furnishes a field expressible as an infinite number of space harmonics ($\beta_{zn} p = \beta_{z0} p + 2n\pi$), where β_{z0} is the phase constant of the fundamental harmonic, which is slightly different from the original value β_z of the unperturbed guide. With proper choices of the physical parameters, it is in general possible to make only one harmonic fast (typically, the $n = -1$ one), so that it can radiate as a leaky wave (with an additional attenuation constant α_z).

In this case, the phase constant of this fast harmonic can assume both positive and negative values ($-1 < \beta_z/k_0 < 1$), as a function of the parameters involved: in particular, as the frequency is increased, the beam inclines from backward endfire towards the broadside. In general, however, periodic LWAs have difficulties in working well in the broadside region, since in general for periodic structures there exists an *open stopband* (24) where the attenuation constant rapidly increases, resulting in a widening beam width with mismatching effects.

As the frequency is further increased after attaining broadside, the beam is then scanned also in the forward quadrant. In periodic LWAs, depending on the choice of the design parameters, additional limitations on the forward scanning behavior may exist when a second harmonic starts to radiate before the first harmonic reaches its endfire, thus limiting the single-beam scanning range (2,3,24).

Leaky-wave arrays for pencil-beam radiation. If an increase of directivity in the cross plane is desired, a simple improvement in LWAs based on long radiating slots can be achieved by a physical enlargement of the transverse aperture (e.g., with a flared transition to enlarge the effective cross aperture). As said before, a more efficient way to increase directivity in the cross plane is to use a number of radiators placed side by side at suitable lateral distances, thus constituting a linear array: it is then possible to achieve radiation with a focused pencil beam. In addition, if properly phased, these arrays of LWAs allow 2-D scanning of the beam: in the elevation plane, as is typical for LWAs, the scanning is achievable by varying the frequency, while in the cross plane the scanning is achievable with phase shifters that vary the phase differences among the single line sources. As noted, in LWAs only a unidimensional set of phase shifters is therefore necessary, yielding structural simplicity and economic advantage in comparison with the usual radiators requiring a two-dimensional set of shifters for the scanning. Additional desirable features of such arrays are in general the absence of grating lobes and blind spots and the achievement of good polarization properties.

For the analysis of such LW arrays, an efficient method is that based on the *unit-cell* approach (11,12). In this way, it is possible to derive the behavior of the whole structure by referring to a single radiator, taking into account the effects on it due to the presence of all the others. In the equivalent network this is achievable by changing only the description of the radiation termination for a periodic array environment (infinite number of linear elements); in particular, an *active admittance* can be calculated, which describes the external radiating region as a function of the geometry and of the scan angle. More sophisticated techniques also allow accurate analyses of arrays by taking into account the mutual couplings for a finite number of elements (11).

Procedures for pattern shaping. Most of the basic considerations concerning the beam direction and the beam width have been described in connection with a general line source, whose characteristics are

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supposed to be longitudinally constant (uniform section, so that β_z and α_z are independent of z). However, among the basic requirements on the radiation pattern, in addition to the specification for the maximum of the beam direction and for its half-power width, the sidelobe behavior also has great importance. More generally, it is desired to examine the properties of the source in comparison with a desired radiation pattern. Since LWAs can be viewed as aperture antennas with a current distribution having a certain illumination $A(z)$, it is possible to obtain the far field through a standard relationship:

$$E(\theta) = G(\theta) \int_0^L |A(z')| e^{j \text{Arg}[A(z')]} e^{jkz' \sin \theta} dz' \quad (9)$$

The radiation pattern for E is expressed in terms of a Fourier transform of the line-source complex current distribution on the aperture multiplied by the pattern of the element current G (e.g., a magnetic dipole).

It is easily seen that if the LWA's geometry is kept longitudinally constant, the amplitude distribution has always an exponential decay of the type $\exp(-\alpha_z z)$. As is known, this behavior furnishes a quite poor radiation pattern for the sidelobes, which are rather high (around -13 dB). It follows that, in conjunction with the choice of a fixed illumination function $A(z)$ giving a desired sidelobe behavior (cosine squared, cosine, triangular, Taylor, etc.), the leakage rate has to be modulated along the main direction z of the line source; in practice this is achievable by properly modifying the cross section of the structure along z , a procedure usually known as *tapering*. Considering that, for a smoothly tapered antenna, the power radiated per unit length from the antenna aperture is simply related to the aperture distribution [viz., $-dP(z)/dz = 2\alpha_z(z)P(z) = c|A(z)|^2$], it is possible to obtain a useful analytical expression for $\alpha_z(z)$ as a function of the amplitude $A(z)$, the line-source length L , and the efficiency η (3,4,25):

$$\alpha_z(z) = \frac{1}{2} \frac{|A(z)|^2}{\frac{1}{\eta} \int_0^L |A(z')|^2 dz' - \int_0^z |A(z')|^2 dz'} \quad (10)$$

From Eq. (10) it is also seen that if high efficiency (close to unity) is desired, α_z has to be increased to extremely high values near the terminal section (as mentioned, in common practice efficiency does not exceed 90% to 95%).

In general, in the tapering procedure the longitudinal modification of the geometry should be made in an appropriate way in order to affect only the leakage constant, keeping the phase constant the same (in pencil-beam applications, β_z should not depend on z , in order to have the correct pointing angle for each elementary current contribution on the aperture).

The pattern-shaping procedure requires therefore the knowledge of the phase and leakage constants as functions of the geometrical and physical parameters of the chosen structure, and this is achievable, as was said, by finding the suitable complex eigensolution with numerical methods. Since the pattern shaping requires a proper α_z distribution with β_z constant, the procedure is greatly simplified if it is possible to find geometrical parameters through which the leakage and phase constants are varied as independently as possible. This possibility is related to the topology of the waveguiding structure.

An example of tapering is sketched in Fig. 4 for a leaky structure, the so-called *stepped* LWA [Fig. 4(a)], recently proposed for high-performance applications with well-controlled radiation patterns (26). On the basis of a preliminary analysis of the effects of the geometry on α_z and β_z , it is possible to find the appropriate longitudinal variation of parameters to obtain the desired α_z distribution with a fixed β_z . In Fig. 4(b) the detailed behavior of the modulation in the height of the lateral steps is shown as a function of z for a desired illumination (cosine type). A first specification of the imbalance of the steps, with their mean value kept

constant (dashed profile), modifies appropriately the longitudinal distribution of the leakage constant, leaving the phase constant almost unchanged. A second change is advisable to compensate the phase nonlinearity, which can have rather disturbing effects on the radiation patterns; in this topology it is possible to vary the steps' mean value slightly, with the previously fixed imbalance, to obtain the final valid profile (solid curves). The corresponding radiation patterns are then illustrated in Fig. 4(c) and 4(d), for the single-part and the double-part tapering procedures: Fig. 4(c) is a rather distorted pattern related to the nonoptimized tapering (dashed profile), while Fig. 4(d) is a correct cosine-type pattern related to the optimized tapering (solid profile). The tapering procedure can be performed numerically in an easy way from a TRT network representation of the structure. The typical scanning behavior of these kinds of antennas is finally illustrated in Fig. 4(e) for a beam pointed by varying the frequency.

It is seen that, for the control of the aperture distribution, the longitudinal variation of the cross section occurs in a continuous and quite smooth fashion, so that it can be assumed that for each z it is possible to calculate the local value of k_z as if the structures were infinitely long. Therefore, the first step in the design procedure requires the evaluation of the β_z and α_z values as a function of the physical parameters of a specific structure, in particular the dimensions and the frequency. After this basic analysis, which gives the phase and leakage constants for a specified structure, the general synthesis procedure starts from the desired radiation characteristics. Thus, from the angle of the beam maximum one finds the value of β_z/k_0 at a desired operation frequency; this value has to be kept longitudinally constant. From the beam width, it is also fixed the relative length of the antenna. From the efficiency and the sidelobe specifications, the aperture illumination $A(z)$ is chosen, and then it is possible to calculate the leakage distribution $\alpha_z(z)$ from Eq. (10). Once the longitudinal phase and leakage constants are determined, with the help of the analysis technique the required LWA geometry is completely achievable.

Overview Of Specific Structures

Here we give a brief overview of the main LWA configurations with their basic behavioral features. More detailed information can be obtained from the references presented for the various topologies.

Partially open metallic waveguides.

Slitted-side-wall rectangular-guide, channel-guide, holey and slotted, and circular-guide LWAs. The first-proposed LWA exploits the leakage due to the perturbed dominant mode in a laterally cut rectangular guide [Fig. 5(a)]. The resulting magnetic current is longitudinal, corresponding to the vertical electric field on the aperture. A thorough analysis (4,22) has led to simple analytical expressions for the characterization of the equivalent network, giving the complex wave number k_z [see, e.g., Fig. 3(e)]. Taper is achievable by suitably varying the width of the slit. Possible modifications of this basic geometry have been proposed; in particular, it is possible to use a square section supporting a higher mode or to completely open the side wall (also filling the structure with a dielectric), as investigated in the so-called channel-guide antenna (22) [Fig. 5(b)].

One of the main drawbacks of all these configurations having a side cut is related to the leakage constants, which in general cannot be reduced below a certain limit. Spurious solutions due to channel-guide (27) and slot-type (28) modes are also found to adversely affect the radiation performance.

Instead of long slits, the introduction of small holes (29) or slots (30) spaced at distances less than the guide wavelength gives the possibility of reducing the leakage [as in the holey guide shown in Fig. 5(c)]. The structure can be viewed as quasiuniform, and the described design principles are still valid. Holes and slots can suitably be placed on the guide top wall as well, even in complicated configurations (transverse slots, series of closely spaced planar holes, etc.) (1,2,3,4). These structures may present some difficulties in the control of radiation patterns and in practical manufacture.

The main principles of LWAs based on partially open metal waveguides can be applied to many other structures. Studies have been performed by several authors, for instance, on slitted circular waveguides [Fig.

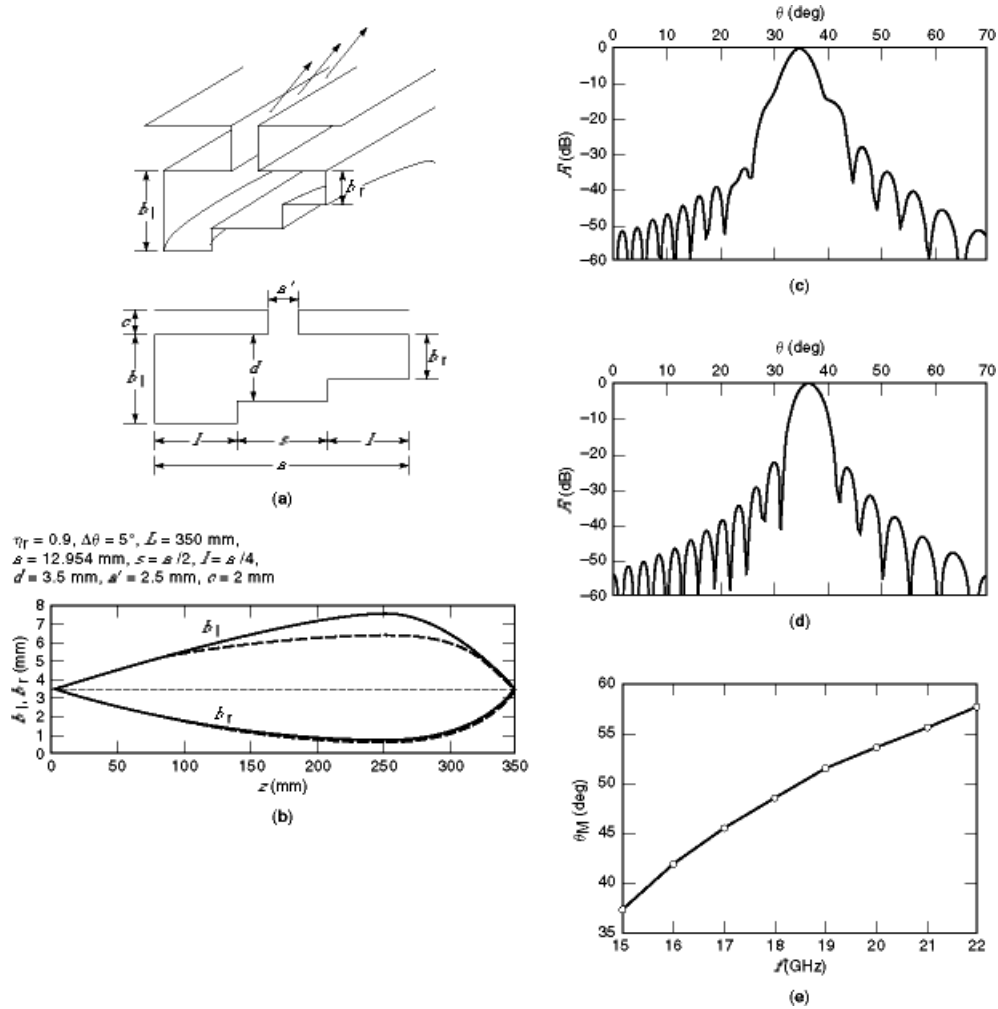


Fig. 4. Example of the tapering procedure for a LWA to achieve a required aperture distribution for pattern shaping: (a) Reference structure of a stepped rectangular-guide LWA, relevant parameters, and equivalent network. (b) Longitudinal modulation of the lateral steps (b_1, b_r , versus z) for a cosine illumination function for a microwave application. The leakage mainly depends on the imbalance $\Delta b = (b_1 - b_r)/(b_1 + b_r)$ of the steps, while the phase mainly depends on their mean height $b_m = (b_1 + b_r)/2$. The dashed curves of b_1, b_r versus z are obtained with a single-part tapering procedure, that is, only varying Δb with constant b_m (thus, variations on the phase constant are introduced). The solid curves are due to a double-part tapering procedure, where phase errors are compensated by suitably varying b_m : this is the correct profile for achieving a radiation pattern with a cosine distribution [see part (c)]. (c) Distorted normalized radiation pattern R (dB) according to the dashed curves. (d) Correct radiation pattern according to the solid curves for cosine illumination of the stepped LWA. (e) Typical scanning properties for the pointed beam as a function of the frequency (stepped LWA).

5(d)] (31). In this case, the leakage is derivable from the perturbed dominant TE_{11} or other higher modes. Again, practical limits may be encountered on the control of the leakage amount and on finding suitable parameters for effective tapering.

Inductive-grid and asymmetrical trough-guide LWAs. The inductive-grid LWA [Fig. 6(a)] consists of a parallel-plate guide operating in its first higher mode (TE_1), with a cover made of closely spaced transverse

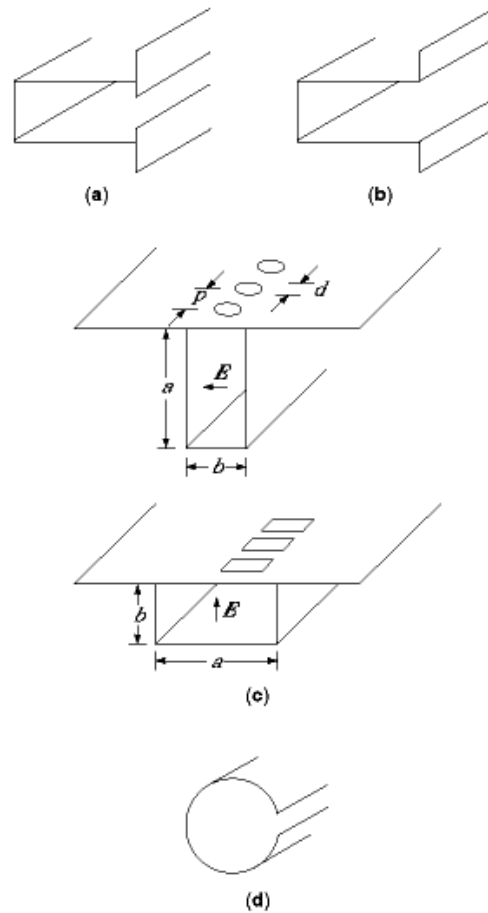


Fig. 5. (a) Slitted-side-wall rectangular-guide LWA; (b) channel-guide LWA; (c) holey- and slotted-side-wall LWAs; (d) slitted circular-guide LWA.

metal strips similar to an array (32). This geometry allows for sidelobe control by varying the strip width to control the leakage, and the side-plate height to adjust the phase. Though such a structure can work well, delicate manufacturing problems can occur that make the geometry not very practical.

Another possibility based on a metallic guide, with wider apertures, is given by the trough waveguide [(Fig. 6(b)] (33), which basically consists of a bisected strip-line structure operating in the first higher mode, which becomes leaky when a suitable geometrical asymmetry (as a metal insert) is introduced with respect to the central horizontal plane. It has been found that the structure offers flexible performance, though the leakage properties can again be difficult to control by tapering.

Top-wall slitted and stub-loaded rectangular-guide and groove-guide LWAs. Reduced leakage is achievable by slitting the top wall of the rectangular guide, decreasing the current modification due to the cut [Fig. 7(a)]. By shifting the cut with respect to the central vertical plane, it is possible to modify the leakage rate; investigations have also been performed with tapered meander profiles for sidelobe control (34). It is found that the needed alterations of the phase constant for a tapered profile strongly affect the accuracy of the radiation pattern, which can be severely distorted. Furthermore, this geometry does not easily allow for compensation of phase errors with an additional independent geometrical parameter. Moreover, the introduction

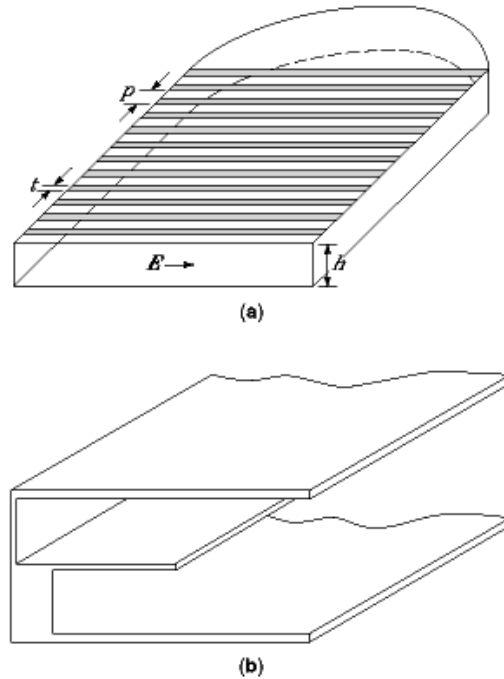


Fig. 6. (a) Inductive-grid LWA; (b) asymmetrical trough-guide LWA.

of a simple cut in the top wall of the guide can compromise the polarization purity, due to the effects of higher-order modes at the aperture.

A way of improving the polarization purity in the basic geometry of a top-wall slitted rectangular guide is to use an aperture parallel-plate stub, able to reduce the contribution of the higher modes at the aperture, which are below cutoff, while the dominant leaky wave travels unattenuated as a TEM-like mode at an angle (35,36,37) [Fig. 7(b)]. Wide metal flanges, simulating an open half space on the upper aperture, can increase the directivity of this type of LWA. Attention has to be paid to possible channel-guide effects for large values of the stub height. The topology might allow a printed-type version of this type of LWA, by filling the guiding structure with a dielectric medium (3,12). It is also worth noting that the geometry under investigation can be viewed equivalently as an asymmetrical horizontally bisected groove guide. Instead of shifting the stub with respect to the central vertical plane, another possibility with such geometry is to create an asymmetry through a small metallic insert [Fig. 7(c)]. Theoretical and experimental investigations have demonstrated the utility of these structures, though the limits described above are still present when tapering techniques are required for pattern shaping.

Slitted asymmetrical ridge and stepped rectangular-guide LWAs. The dominant mode of ridge waveguides can be made leaky with a symmetrical stub-loaded aperture if some asymmetry in the height of the lateral arms is produced [Fig. 8(a)]. The characteristics of this topology show that the average value of the heights (*mean height*) of the lateral arms of the ridge acts mainly on the phase constant, while the difference between the arms' heights (*imbalance*) acts mainly on the leakage constant (38). A tapering procedure that first adjusts the leakage constant to set the imbalance and then compensates the phase constant through slight changes in the mean height should be very simple and effective for pattern shaping.

The recently proposed geometry of the stepped LWA (26,39,40) [Figs. 4(a) and 8(b)] maintains the basic advantages of the ridge structures with additional general desirable features (increased geometrical flexibility,

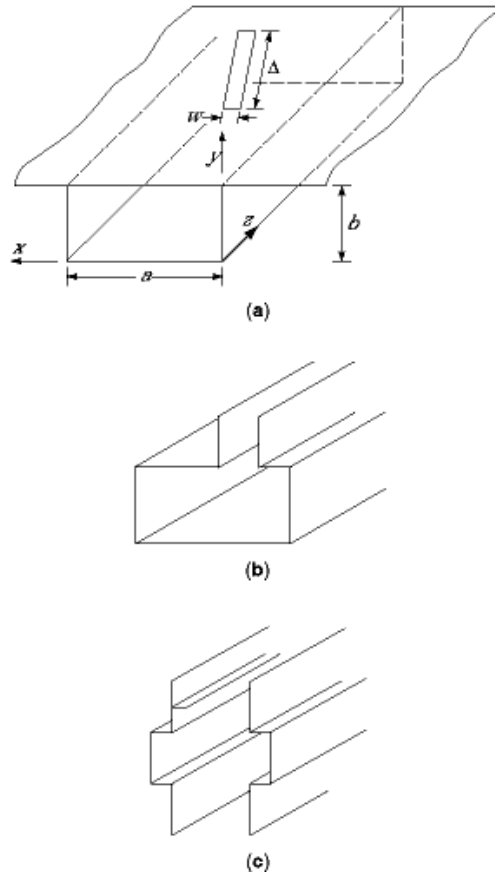


Fig. 7. (a) Top-wall-slitted rectangular-guide LWA; (b) stub-loaded rectangular-guide LWA; (c) strip-loaded groove-guide LWA.

compactness, low profiles for aerospace applications, etc.). The structure has been investigated theoretically as concerns the possibility of suitably adjusting the lateral steps for good independent control of phase and leakage. Simple design procedures show the actual capability of synthesizing arbitrary illumination functions with greatly reduced sidelobes. It has been found that a two-part tapering procedure (first varying the imbalance longitudinally and then compensating with slight modifications of the mean height) is generally sufficient for appropriate sidelobe control. (An example of modulation by variation of the lateral steps has been presented in Fig. 4.) Practical aspects have also been examined, including the effects of ohmic losses (25) and of radomes for environmental protection (41). Experimental analyses have been performed, too, on both nontapered and tapered prototypes (cosine illumination, etc.), for both microwaves and millimeter waves. Measured characteristics show very good agreement with theory and excellent radiation performance (precise pattern shaping, high efficiency and power handling, good polarization purity, etc.) (39,40). Many practical advantages make this structure one of the most desirable candidates among LWAs based on metal guides.

Printed and dielectric waveguides.

Printed lines: microstrip LWAs. The possibility of using LWAs also in printed circuitry (12) has received in recent decades an interest that is probably destined to increase in the near future due to the wide use of planar technology for light, compact, and low-cost microwave integrated circuits (MICs). Among the various

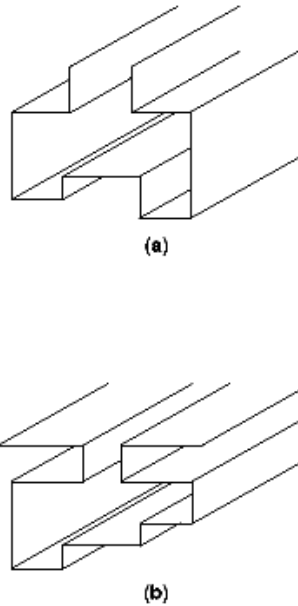


Fig. 8. (a) Slitted asymmetrical ridge LWA; (b) stepped rectangular-guide LWA.

printed waveguides that can act as leaky-wave radiators (coplanar guides, slot and strip lines, etc.) (12,42), we particularly mention structures derivable from lengths of microstrip. Many different configurations can be employed with microstrips acting as traveling-wave radiators. A first class is based on modulating the dominant mode of the structure with periodic loadings, such as resonant patches or slots [Fig. 9(a)], and also by varying the line shape periodically with different meander contours [Fig. 9(b)] (43). Different solutions have been tested, but the theory of this topic seems to deserve further study.

A different configuration involves the use of uniform structures acting on higher-order modes that can become leaky for certain values of the parameters involved [Fig. 9(c)]. The analysis of the complex propagation characteristics of the microstrip line shows in fact that, in addition to the dominant quasi-TEM mode, the higher-order modes generally become leaky in suitable frequency ranges (12,42) [see Fig. 2(a)]. In particular, it is seen that the first higher mode EH_1 can be excited with a proper odd-type source (the midplane of symmetry is a perfect electric conductor) and, as the frequency is raised, it starts to leak power. In general, for the planar structures, leakage can occur in two forms: the surface-wave leakage (power that is carried away through the TE and/or TM surface modes of the layered structure), and the *space-wave* leakage (power that is carried away through the TEM mode of free space). It is found that, for suitable choices of the parameters with an appropriate excitation, the EH_1 mode can represent rather accurately the radiation of the microstrip in a certain frequency range (12) [see, e.g., Fig. 2(a)]. The coupling between the feeding and the radiating line must be well evaluated, and simplified equivalent networks can be convenient for this purpose (45).

Radiation performance of printed-circuit LWAs (as concerns power handling, polarization, efficiency, pattern shaping, etc.) is often less versatile and satisfactory than that of LWAs derived from metal guides (12). From a practical point of view, difficulties are found particularly in adjusting the phase and leakage constants independently through the physical parameters. Recent investigations involve simple possibilities of tapering, also with microstrip topologies, utilizing other higher-order modes (46). Uniform-type microstrip LWAs have also been investigated in array configurations for 2-D pencil-beam scanning (12,46,47).

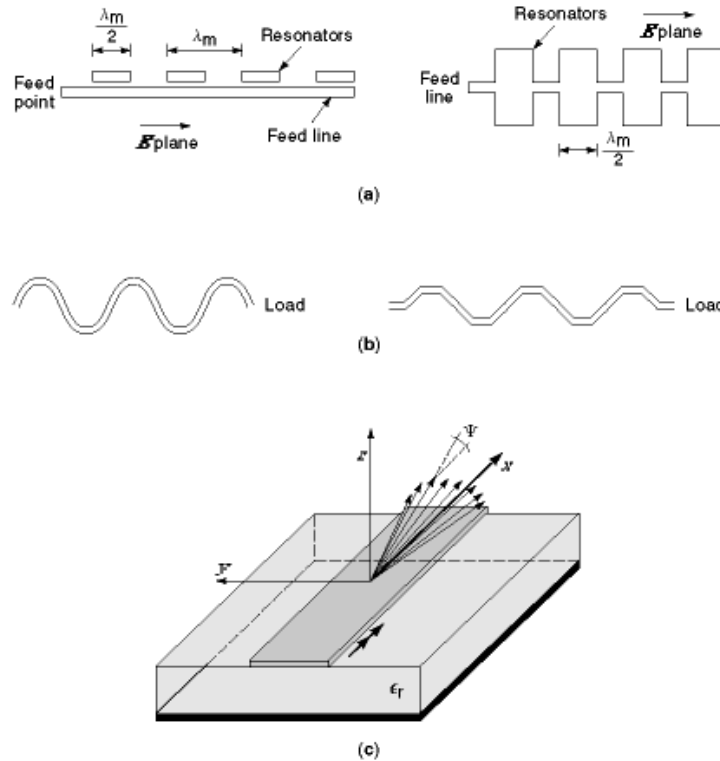


Fig. 9. (a) Periodically loaded microstrip LWAs. (b) Periodic meander microstrip LWAs. (c) Uniform higher-mode microstrip LWA: space-wave radiation can be associated, e.g., with the strip current distribution of the EH_1 mode, which is leaky in a suitable frequency range [see Fig. 2(a)].

Nonradiative dielectric guide LWAs. The nonradiative dielectric (*NRD*) waveguide is a recently proposed guiding structure for millimeter-wave applications (48) [Fig. 10(a)]. It is a hybrid metal–dielectric guide having the same shape as the H guide proposed for microwave applications: it consists of a dielectric rod inserted between metal plates placed at a distance apart that is less than the free-space wavelength. In this way, any discontinuity that preserves the central horizontal-plane symmetry gives only reactive contributions, reducing interference and radiation effects in integrated circuits. A number of passive and active components have been realized with this topology (49,50), and integrated antennas have also been proposed (51,52,53,54). Usually, *NRD* LWAs should employ some asymmetry in the basic geometry in order to make the operating modes leaky. A first possible choice (51) [Fig. 10(b)] is to shorten the plates so that the bound operating mode (LSM_{01}) (23,48,49,50) presents a nonnegligible amplitude contribution at the equivalent aperture and can give rise to an outgoing leaky wave in the fast-wave range. Another possible choice (12,52) [Fig. 10(c)] is to insert some geometrical asymmetry with respect to the central plane (typically an air gap between dielectric and metal), so that a field having a net electric component perpendicular to the plates can be excited, and power can leak out in the form of a TEM-like mode traveling at an angle in the parallel-plate region towards the outside. Various analyses and design procedures have been developed for these configurations (51,52,53,54) in conjunction with measurements on prototypes, both in single and in array configurations (12,53,54).

Dielectric-rod, image, insular, inset-guide, etc. LWAs. As was said, in basic dielectric guides a periodic loading is required in order to isolate a suitable fast-wave space harmonic from the intrinsically slow-wave structure. The reference structures can be various types of dielectric waveguides, such as circular or rectangular

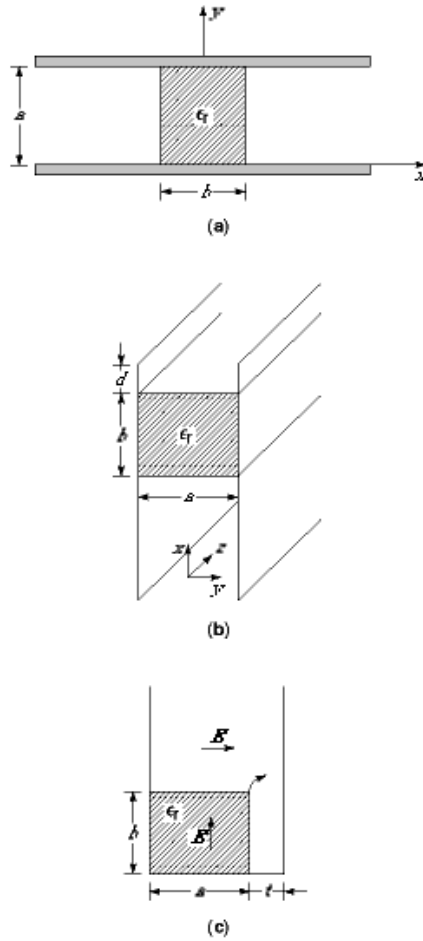


Fig. 10. (a) Nonradiative dielectric (NRD) waveguide; (b) shortened NRD LWA; (c) asymmetrical NRD LWA.

dielectric-rod [Fig. 11(a)] (55), image (56), insular, and inset guides (57), [Fig. 11(b)]. The most usual periodic perturbation is represented by a grating of grooves (58) or metal strips (55,59), usually placed in or on the top surface of the guide [Fig. 11(c)]; also lateral metal patches can be used in hybrid forms (dielectric–microstrip) [Fig. 11(d)] (60). When sidelobe control is required, the taper is realized on the periodic perturbation (e.g., with grooves or strips slightly changing their dimensions longitudinally). Various studies have been made to characterize the theoretical performance of these radiators (61); also, practical aspects have been analyzed, such as the proper feeding elements in order to avoid spurious radiation and the reduction of the beam width in the cross plane with flared horns (57) [Fig. 11(e)]. All these topologies are good candidates, particularly for high-frequency applications (millimeter and submillimeter waves), where the use of dielectric instead of metal for guidance can reduce the loss effects.

Layered dielectric-guide LWAs. It has been observed that LWAs based on single dielectric layers [Fig. 12(a)], with a ground plane on one side, usually present quite high leakage values, with consequent weak capability of focusing radiation. A significant improvement is achievable by using additional dielectric layers [Fig. 12(b)]; in particular, interesting analyses have been performed on substrate–superstrate layered

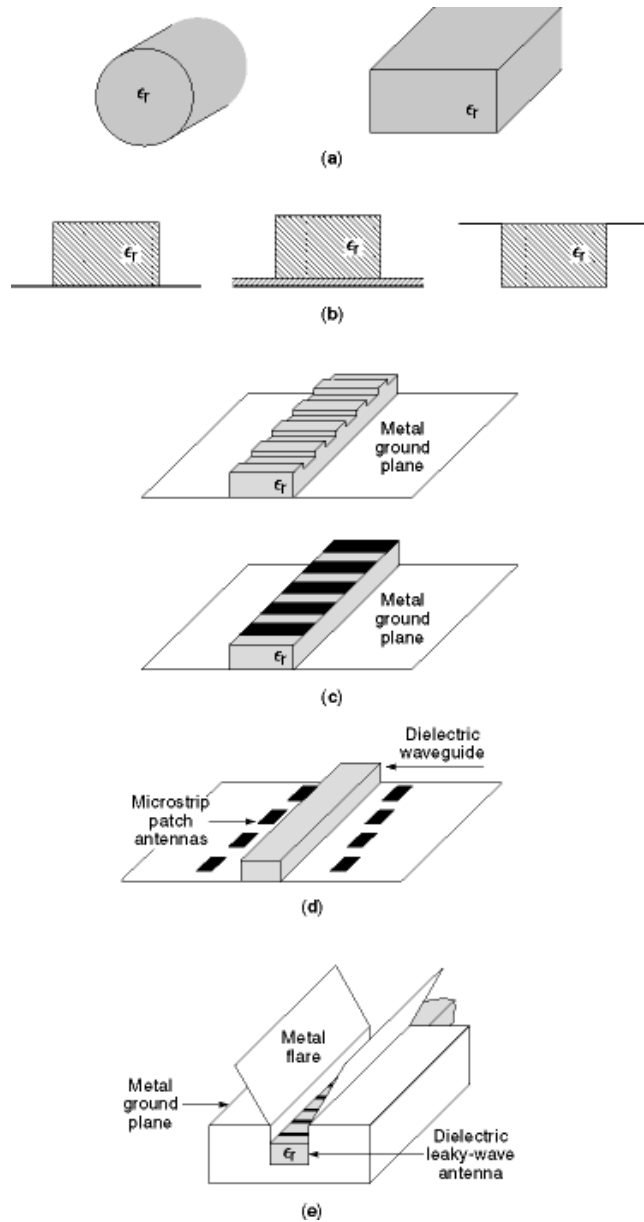


Fig. 11. (a) Circular and rectangular dielectric rods; (b) image, insular, and inset dielectric waveguides; (c) periodically loaded dielectric LWAs; (d) hybrid dielectric microstrip (insular guide with patches) LWA; (e) dielectric LWA with a flared horn to reduce the cross-plane beam width.

structures (62,63,64). By properly dimensioning the heights and the dielectric constants (usually the substrate has lower permittivity than the superstrate), it is possible to excite with a simple element (dipole or slot) a leaky wave giving a conical (due to the symmetries of the topology), highly directive beam (62,63). Recently, this basic substrate–superstrate topology has been arranged to allow for a very focused pencil beam with a limited

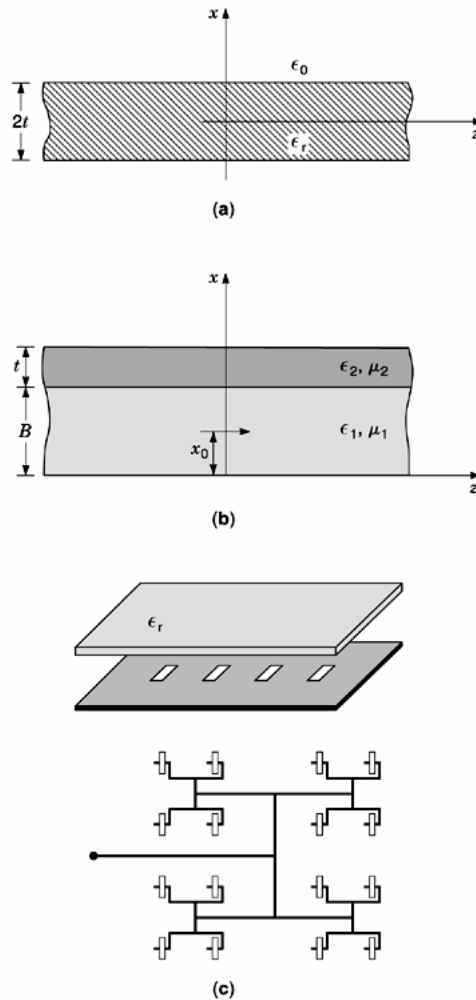


Fig. 12. (a) Dielectric-slab waveguide. (b) Layered-dielectric LWA based on a substrate superstrate structure with a dipole excitation. (c) High-gain LW arrays of widely spaced elements in a substrate superstrate structure: linear and planar configurations (for the latter case, a top view is shown for a microstrip feeding network of widely spaced slot elements on the ground plane of the substrate superstrate structure).

number of radiating elements in the form of a widely spaced array, exploiting an interaction between leaky and Floquet modes [Fig. 12(c)] (65). The advantages of such configurations are in the possibility of achieving, through very simple design procedures, good radiative performance (high directivity, absence of grating lobes, etc.) with an array of a few spaced 1-D or 2-D elements, thus reducing the cost of the beamforming network and suitably exploiting the greater interspace available (dual-polarization applications, etc.).

Nonreciprocal structures: gyrotropic LWAs. In general the use of complex media can give additional potentialities to LWAs. In particular, the possibility of achieving a unique widely scannable directional beam with a symmetrical source, in addition to other advantageous features, has recently been investigated for basic nonreciprocal structures employing gyrotropic media (66,67). A reference structure is considered, represented by a transversely magnetized grounded ferrite slab with a simple current line source placed symmetrically

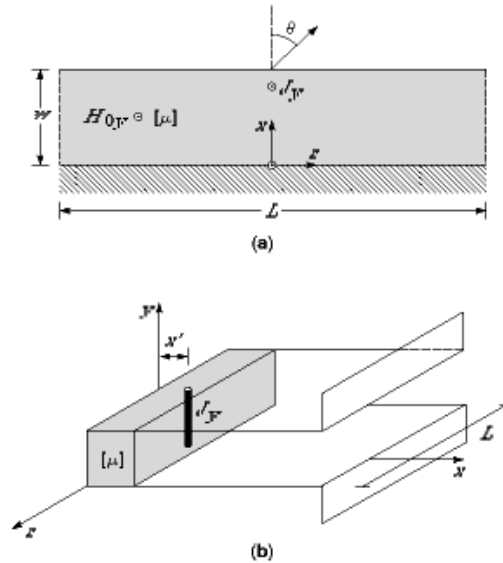


Fig. 13. (a) Nonreciprocal gyrotropic waveguide based on a transversely magnetized grounded ferrite slab with a line current source; (b) bisected parallel-plate ferrite-loaded LWA.

inside the layer and in the direction of the bias field [Fig. 13(a)]. In practice, realizations of this topology can be obtained with a bisected parallel-plate structure [Fig. 13(b)]. It has been found that further improvements of the radiation performance are achievable with multilayered gyrotropic configurations.

In these nonreciprocal structures the analysis is still possible by means of a suitable extension of the TRT (68). By varying the frequency or the bias field, even in a uniform structure, it is possible to have only one pointed beam that scans continuously from one endfire to the other, passing through broadside. It has been demonstrated that this unusual behavior is linked to two branches of a dominant “anomalous” mode of the nonreciprocal waveguide (66): one branch is a complex improper solution (a standard leaky mode, responsible for forward radiation); the other one is a complex proper solution, responsible for backward radiation.

Practical Considerations And Measurements

Feed, losses, manufacture, etc. Feeding LWAs is usually quite simple. In particular, for LWAs consisting of metal guides, the feed is represented by a continuous transition from the closed structure supporting a suitable guided mode to the related open one supporting the perturbed (leaky) mode (1,2,3,4). Tapered transitions from the closed to the open structures can be realized to reduce the discontinuity effects and the possible excitation of spurious modes that could arise from abrupt transitions. At the output termination, the introduction of a matched load further decreases the contribution of the remaining power that, if reflected, would give rise to a back lobe, in a direction symmetrical to the main beam with respect to the broadside (40).

The use of dielectric structures can present special difficulties in feeding, in particular in planar configurations. Attention has to be paid to avoiding the excitation of additional guided and leaky modes, and also to obtaining good excitation of the desired leaky wave. Neglect of these aspects can lead to deterioration of the efficiency and of the radiation performance. For planar guides, such as microstrip or layered dielectrics, local coupling elements (such as slots or dipoles) are usually employed to excite the leaky mode from an input line

towards the radiating line. Proper locations of matched loads or terminations again have to be arranged in order to reduce the amount of power not properly radiated.

Ohmic losses usually do not greatly affect the radiative performance (efficiency, etc.) of LWAs, since the attenuation due to the leakage of radiated power is generally more important than the attenuation due to dissipated power in the nonideal guiding structure (25). However, as the frequency increases, power loss can be excessive, particularly for LWAs based on closed metal guides. Therefore, for millimeter-wave applications the choice of open guides with dielectrics and limited use of metal is often advisable.

The general simplicity of LWA structures makes their manufacture usually easy to accomplish, though various construction problems can arise, depending on the chosen topology and the frequency range. Simple structures are particularly desirable at millimeter wavelengths, due to the reduced dimensions. On the other hand, too simplified shapes often cannot allow good control of the radiation performance. In particular, a delicate aspect concerns the usually small longitudinal modifications of the geometry related to tapering for sidelobe control. In this case, accurate analyses on the fabrication imprecisions and tolerances have a particular importance in order to not overwhelm the required geometrical variations for tapering, thus degrading the improvements of the pattern shaping (40).

Measurement techniques. The radiation properties of LWAs can be tested experimentally through different types of measurements, most of them applicable to aperture antennas (1,2,3,4,40,69,70). Some basic parameters, such as efficiency, mismatching effects, etc., can be measured directly through the transmission and/or reflection scattering parameters with a network analyzer. Radiation patterns and directivity properties as a function of the observation angles (θ and ϕ in the zenith and azimuth planes, respectively) can be measured for various values of the frequency, with different techniques, at the aperture, in the radiating near field (Fresnel region), and in the far field (Fraunhofer region) (40).

Measurements at the aperture are quite easy to perform, in particular for LWAs incorporating partially open metal guides. The basic parameters to be determined in LWAs, from which a complete knowledge of the radiative characteristics is achieved, are the phase and the leakage constants. A measurement of the field in close proximity to the aperture can be achieved with a small pickup element (e.g., an electric dipole probe placed parallel to the aperture electric field). The amplitude and phase of the signal received by the probe are thus measurable through a network analyzer, with possible compensations related to the mutual coupling between the current distribution at the aperture and the current probe element (69). With numerical processing of the data, the distributions of the leakage and phase constants are easily calculated. Far-field patterns are also immediately calculable from these aperture measurements (40).

Alternative measurements can be performed directly on the radiation pattern in standard fashions. If for instance an anechoic chamber is available whose dimensions do not allow immediate evaluations in the far-field region ($r > 2D^2/\lambda$), measurements for achieving the radiation pattern are also possible by calculating the LWA's performance at intermediate distances typical of the Fresnel region (radiating near field). The LWA's field can be measured through another reference antenna (e.g., a calibrated horn), and rotating supports are useful in order to facilitate the measurements as a function of the observation angles and frequency. From these measurements at intermediate distance, by exploiting the equivalence principle, it is possible to easily reconstruct the far-field radiation pattern. When either the dimensions of the anechoic chamber are sufficiently wide or a controlled free-space region is available for simulating a far-field (Fraunhofer) region, measurements of the radiation patterns are immediately achievable, again with a reference antenna and movable structures. Experiments on all the types of measurements, recently performed for a class of LWAs (40), show good agreement among the various results.

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