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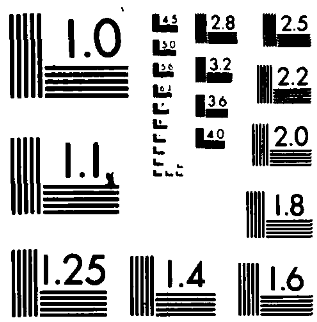

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Interim Report
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LUMPED ELEMENT AND LEAKY-WAVE ANTENNAS FOR MILLIMETER WAVES

Polytechnic Institute of New York

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This contract is concerned with certain types of antennas for millimeter waves that cannot be successfully scaled from their microwave frequency counterparts. Among these antennas, we chose first to explore novel antennas of the leaky-wave type, largely because they form a natural class of antennas for millimeter waves.

Leaky-wave antennas for the millimeter wave range face two main problems.

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The first relates to the small wavelengths involved, which require small waveguide dimensions and pose fabrication difficulties. The second problem is higher metal loss. We are overcoming the first of these problems by considering leaky-wave structures with longitudinally-continuous apertures, and the second by basing the antennas on low-loss waveguides.

With these essential features in mind, our program involves two parallel approaches to the same basic problem: novel leaky-wave antennas suitable for millimeter wavelengths. The parallel approaches employ, first of all, two different basic low-loss waveguides, and, second, two different mechanisms to produce leakage. As a result, two new antenna types have emerged.

The first type of antenna is based on the groove guide, and the second on the nonradiative dielectric guide, which is a variant of H guide. The first mechanism, employed with the groove guide, is based on the introduction of asymmetry, and produces horizontal polarization. The second mechanism, used with the nonradiative dielectric waveguide, involves a foreshortening of the outer waveguide walls on one side, and produces vertical polarization.

The investigations so far have turned out to be very productive. First of all, it should be recognized that our work represents the first contribution to antennas based on these two low-loss waveguides. Next, we developed an accurate analysis of each of the antennas, and we obtained expressions for the performance behavior which are in closed form, thus permitting a relatively easy design procedure. Finally, we obtained numerical results for typical performance characteristics and for their dependence on frequency and on various geometrical parameters.

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INTERIM TECHNICAL REPORT

on Contract No. F19628-81-K-0044

"LUMPED-ELEMENT AND LEAKY-WAVE ANTENNAS FOR MILLIMETER WAVES"

SUMMARY

Antennas for millimeter waves fall into two broad categories: those that can be successfully scaled from their microwave frequency counterparts, and those which cannot. In the first category, one would place reflectors, lenses and horns. The smaller size in fact enhances their attractiveness, since higher directivity can be achieved with smaller size. The second category includes such antennas as slot arrays, leaky-wave antennas, and phased arrays. This contract, for which this Interim Technical Report covers the first 15 months of activity, is concerned with antennas in the second category.

Of the various possible directions we could pursue, we chose first to explore novel antennas of the leaky-wave type. This choice was dictated in part by our past experience with such antennas and in part because leaky-wave antennas form a natural class of antennas for millimeter waves, in view of the small size of waveguides in the millimeter wavelength range. In addition, such antennas can be used as elements in a phased array in which the array is comprised of leaky-wave line sources all parallel to each other and fed from one end, with phase shifts between them to produce scanning in the cross plane.

Leaky-wave antennas for the millimeter wave range face two main problems. The first relates to the small wavelengths involved, which require small waveguide dimensions and pose fabrication difficulties. The second problem is higher metal loss; for antennas which are many wavelengths long, the leakage (which results in radiation) may compete with the intrinsic waveguide loss, and the antenna design can be adversely affected. We are overcoming the first of these problems by considering leaky-wave structures with longitudinally-continuous apertures, and the second by basing the antennas on low-loss waveguides.

With these essential features in mind, our program involved two parallel approaches to the same basic problem: novel leaky-wave antennas suitable for millimeter wavelengths. The parallel approaches employ, first of all, two different basic low-loss waveguides, and, second, two different mechanisms to produce leakage. As a result, two new antenna types have emerged.

The first type of antenna is based on the groove guide, and the second on the nonradiative dielectric guide, which is a variant of H guide. The first mechanism, employed with the groove guide, is based on the introduction of asymmetry, and produces horizontal polarization. The second mechanism, used with the nonradiative dielectric waveguide, involves a foreshortening of the outer waveguide walls on one side, and produces vertical polarization.

The investigations so far have turned out to be very productive. First of all, it should be recognized that our work represents the first contribution to antennas based on these two low-loss waveguides. The first stage of our work therefore involves a measure of invention. Next, we developed an accurate analysis of each of the antennas, and we obtained expressions for the performance behavior which are in closed form, thus permitting a relatively easy design procedure. Finally, we obtained numerical results for typical performance characteristics and for their dependence on frequency and on various geometrical parameters.

Elaborations on the general remarks made above, and some further background material, are contained in Section A, "Introduction," of the Interim Technical Report. Sections B and C of the report describe the two new leaky-wave antennas mentioned above, and present their principles of operation, the transverse equivalent networks for their cross sections, and typical antenna performance characteristics and parametric dependences.

INTERIM TECHNICAL REPORT

on Contract No. F19628-81-K-0044

"LUMPED-ELEMENT AND LEAKY-WAVE ANTENNAS FOR MILLIMETER WAVES"

A. INTRODUCTION

This Interim Technical Report covers the investigations conducted on this contract during the period July 1, 1981 through September 30, 1982. As the contract title implies, the objective in the investigations is the development of novel antennas for the millimeter wavelength range. The word "development" is intended here to include the invention of new or improved antenna structures, theoretical analyses of the performance of such structures, and calculations to determine the feasibility of the antennas and the dependence of the performance properties on the frequency and on various geometric parameters.

Millimeter wave antennas present particular challenges because of two main problems. The first problem relates to the small wavelengths involved, requiring antennas of smaller size. For certain types of antennas this feature is a boon, but for others it presents a greater difficulty of fabrication. The second problem is higher metal loss. For components which are about a wavelength long, the higher loss does not produce much of a problem, so that useful millimeter wave integrated circuitry can be designed up to 100 GHz or so using such relatively lossy guides as microstrip or finline. For antennas which employ traveling waves, on the other hand, the antenna lengths may be typically 20 to 100 wavelengths long, and the waveguide loss may compete with the leakage, or radiation, loss, thereby disturbing or upsetting the antenna design.

Millimeter wave antennas fall into two broad categories: those which can be successfully scaled from their microwave frequency counterparts, and those which cannot. In the first category, one would place reflectors, lenses, and horns. The smaller size in fact enhances their attractiveness, since higher directivity can be achieved with smaller size. The second category includes leaky-wave antennas, slot arrays and phased arrays, where the smaller size and higher loss cause problems. This contract is concerned with the second category, of course.

Since direct scaling from known microwave designs is not suitable for antennas in the second category, it is necessary to seek novel structures or modifications of known structures as the basis for new antennas. During this past year, we have explored novel leaky-wave antennas suitable for millimeter wavelengths. These antennas have two principal features. First, they involve continuous apertures, making the antennas relatively simple to construct. Second, they are based on low-loss waveguides. The two waveguides involved in the investigations were originally designed specifically to possess low attenuation at millimeter wavelengths; in the antennas based on them, the leakage loss (which produces the radiation) therefore dominates over the intrinsic (metal and/or dielectric) loss. An important motivation for concentrating on leaky-wave antennas is that they form a natural class of antennas for millimeter waves in view of the small size of waveguiding structures at millimeter wavelengths.

With these essential features in mind, we investigated two parallel approaches to the same basic problem. The investigations so far have turned out to be very productive, with two new antenna types emerging from them. The first type of antenna is based on the groove guide and produces horizontal polarization. The second type employs nonradiative dielectric guide, which is a variant of H guide, and yields vertical polarization. Furthermore, the mechanism of radiation in each of the two leaky-wave antennas is different. In the first type, an extra strip is inserted longitudinally in asymmetrical fashion so that the incident symmetric mode excitation couples to a transverse mode of antisymmetric form that then leaks power away. In the second type of antenna, the outer walls on one side are foreshortened so that the reactive transverse decay of the mode fields is incomplete, and power leakage results. Each mechanism could in fact be applied to the other type of waveguide; that is why we have said we worked on two new antenna types, rather than on two antennas.

For each case, we have developed the appropriate transverse equivalent network, and we have derived accurate, yet closed-form, expressions for each constituent of the networks. As a result, the dispersion relation for the propagation properties (α and β) for each antenna is also obtained in closed form. Calculations were then made which show that the antennas are feasible, and they also indicate how the propagation properties depend on the frequency and on various geometric parameters. From this information, optimum designs for each antenna type can be deduced.

In Section B we summarize the horizontally-polarized leaky-wave antenna that is based on the groove guide. The basic properties of the groove guide are first reviewed, and then the operating principle of the new antenna is described. The transverse equivalent network is presented, and from it the propagation characteristics are determined via the transverse resonance procedure. Typical antenna performance characteristics are given, together with parametric dependences and a procedure for design optimization.

The second new leaky-wave antenna is discussed in Section C. That antenna is vertically polarized and is based on the nonradiative dielectric guide. The advantages of the nonradiative dielectric guide and its relation to H guide are reviewed first, and the principle of operation of the new antenna based on it is described next. The transverse equivalent network is then discussed, and typical numerical results are presented for antenna performance and for certain geometric parametric dependences.

The author of this Interim Technical Report is the Principal Investigator of this program. General technical assistance has been provided by Professor S.T. Peng, and detailed contributions have been made by Dr. P. Lampariello, now an Associate Professor at the University of Rome, Italy, and previously a NATO Postdoctoral Fellow who spent a year with us at the Polytechnic Institute of New York, and by Mr. Alberto Sanchez, a Ph.D. student who will be receiving his doctorate in June 1983. The contributions of Dr. Lampariello and Mr. Sanchez were made on the antennas discussed in Sections B and C, respectively. It is expected that the analyses in Section B will form the basis for Mr. Sanchez' doctoral dissertation. Technical reports containing detailed theoretical derivations and additional numerical data will be issued later for each of these new antennas.

A talk on the basic principles of the antenna described in Section B was presented at the International IEEE/AP-S Symposium on Antennas and Propagation, held May 24-28, 1982, at Albuquerque, New Mexico. The title and authors of the talk were "A Novel Leaky-Wave Antenna for Millimeter Waves Based on the Groove Guide," by P. Lampariello and A.A. Oliner. The talk was well received by the audience. Further theoretical material and some design information were presented at the European Microwave Conference, held September 13-17, 1982, at Helsinki, Finland. The title and authors of that talk were "Theory and Design Considerations for a New Millimeter-Wave Leaky Groove Guide Antenna," by A.A. Oliner and P. Lampariello.

B. NOVEL LEAKY-WAVE ANTENNA BASED ON THE GROOVE GUIDE

1. Introduction

Groove guide is one of several waveguiding structures proposed for millimeter wave use about 20 years ago in order to overcome the higher attenuation occurring at these higher frequencies. Although these new low-loss waveguides were introduced many years ago, they were not pursued beyond some initial basic studies because they were not yet needed. Now, however, millimeter waves are again becoming important, and attention is again being paid to new types of waveguide. Among these are dielectric strip waveguides of different types, H guide in several forms, and groove guide.

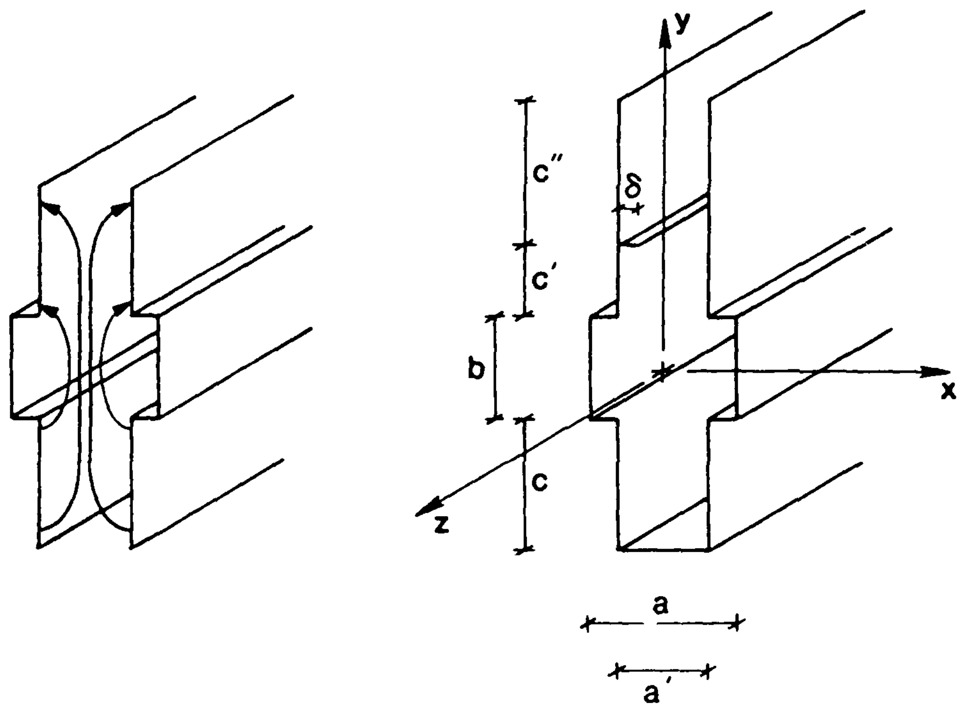
The present investigation involves a novel type of leaky-wave antenna which is based on the groove guide. Although lossy wave-guides may be acceptable for components only a wavelength or so long, they are not suitable for leaky-wave antennas, which may typically be $20\lambda_o$ to $100\lambda_o$ in length, where λ_o is the free-space wavelength. For these antennas, therefore, it is necessary to employ a low-loss waveguide, and groove guide satisfies that requirement. The antenna involves a simple longitudinally continuous structure. As a result, it should be easy and cheap to fabricate, and can probably be made by a simple extrusion process. In view of the small size of waveguiding structures at millimeter wavelengths, leaky-wave antennas form a natural class of antennas for these waveguides.

The antenna has been analyzed in an almost rigorous manner, and a closed-form expression has been derived for the dispersion relation for its complex propagation constant. From numerical calculations, we find that excellent control can be effected over the leakage constant α, so that radiation patterns can be designed in a systematic way.

2. The Basic Groove Waveguide

The cross section of the groove guide is shown in Fig. 1(a), together with an indication of the electric field lines present. One should note that the structure resembles that of rectangular waveguide with most of its top and bottom walls removed. Since the attenuation associated with those walls increases as the frequency is increased, whereas the attenuation due to the presence of the side walls (with the electric field parallel to the walls) decreases with increasing frequency, the overall attenuation of groove guide at higher frequencies is much less than that for rectangular waveguide. The reduced attenuation loss will therefore interfere negligibly with the leakage loss of the novel antenna to be described.

The greater width in the middle region was shown by T. Nakahara [1,2], the inventor of groove guide, to serve as the mechanism that confines the field in the vertical direction, much as the dielectric central region does in H guide. The field thus decays exponentially away from the central region in the narrower regions above and



(a) (b)

Fig. 1(a) Cross section of symmetrical, nonradiating groove waveguide. The ends can either be left open, as shown, or be closed off.

Fig. 1(b) Cross section of the novel leaky-wave antenna, where leakage is produced by the introduction of an asymmetric continuous metal strip.

below. If the narrower regions are sufficiently long, it does not matter if they remain open or are closed off at the ends.

Work on the groove guide progressed in Japan [2,3] and in the United States [4-6] until the middle 1960's, but then stopped until it was revived and developed further by D.J. Harris and his colleagues [7,8] in Wales. To our knowledge, the present paper represents the first contribution to antennas based on the groove guide.

3. The Operating Principle of the New Leaky-Wave Antenna

The new leaky-wave antenna is shown in Fig. 1(b). The basic difference between the structures in Figs. 1(a) and 1(b) is that in Fig. 1(b) a continuous metal strip of narrow width has been added to the guide in asymmetrical fashion. Without that strip, the field of the basic mode of the symmetrical groove guide is evanescent vertically, so that the field has decayed to negligible values as it reaches the open upper end. The function of the asymmetrically-placed metal strip is to produce some amount of net horizontal electric field, which in turn sets up a mode akin to a TEM mode between parallel plates. The field of that mode propagates all the way to the top of the waveguide, where it leaks away. It is now necessary to close up the bottom of the waveguide, as seen in Fig. 1(b), to prevent radiation from the bottom, and (non-electrically) to hold the structure together. Of course, the upper walls could end as shown in Fig. 1(b) or they could attach to a ground plane.

We now have available a leaky-wave line-source antenna of simple construction. The value of the propagation wavenumber β of the leaky wave is governed primarily by the properties of the original unperturbed groove guide, and the value of the attenuation constant α is controlled by the width and location of the perturbing strip.

4. Transverse Resonance Analysis of the New Antenna

The basic structure of the new leaky-wave antenna is given in Fig. 1(b). As discussed above, it is the added continuous strip of width δ that introduces asymmetry into the basic groove guide and creates the leakage. The strip therefore gives rise to an additional transverse mode and couples that mode to the original transverse mode which by itself would be purely bound.

The transverse equivalent network for the cross section of the structure shown in Fig. 1(b) must therefore be based on these two transverse modes, which propagate in the y direction and are coupled together by the narrow asymmetrical strip. These coupled transverse modes combine to produce a net TE longitudinal mode (in the z direction) with a complex propagation constant, $\beta - j\alpha$.

In view of the uniformity of the structure along z, the appropriate transverse modes are the $i = 0$ and $i = 1$ H-type (or LSE) modes with respect to the z direction. The complete equivalent network based on these transverse modes is given in Fig. 2. In the network, which has been placed on its side for clarity, the $i = 1$

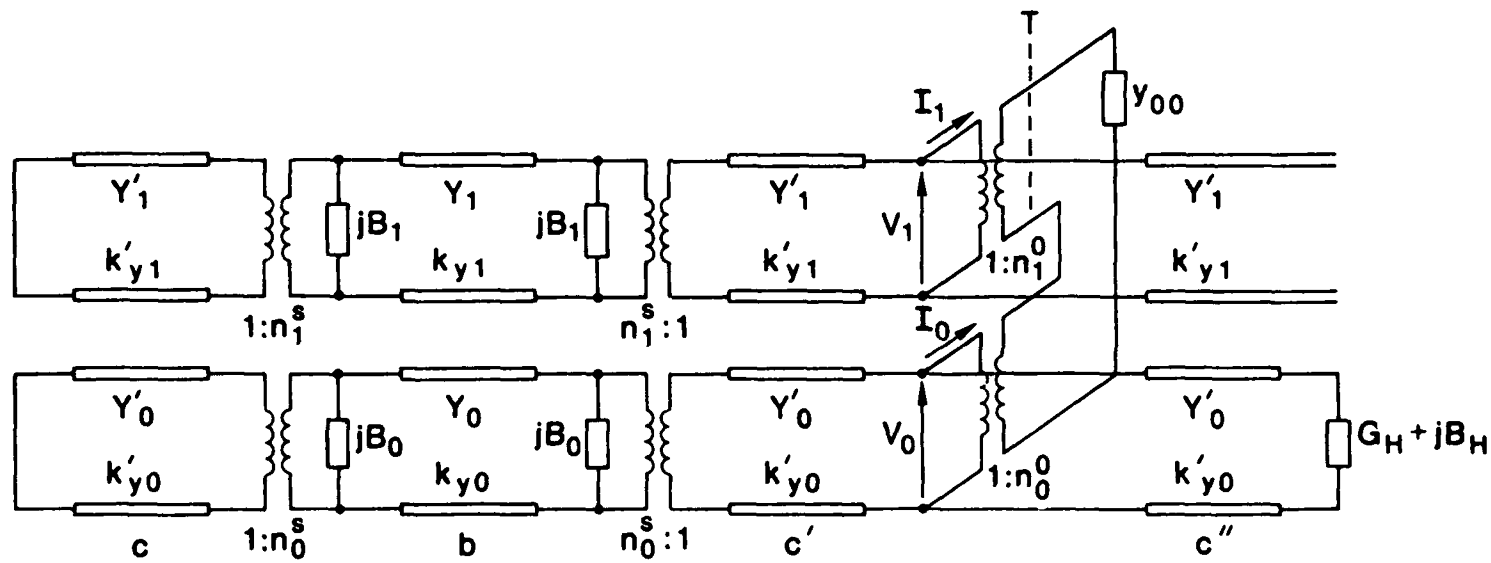


Fig. 2 Transverse equivalent network for the structure whose cross section is shown in Fig. 1(b). (For clarity, the network is placed horizontally rather than vertically.)

transmission lines represent the original mode with a half-sine-wave variation in the x direction in Fig. 1(b), and the i=0 transmission lines represent the new mode which has no variation with x. In the central region, corresponding to the unprimed parameters, both the i=1 and i=0 transmission lines are above cutoff; in the outer (primed) regions, however, the i=1 transmission lines are below cutoff but the i=0 ones are above cutoff, leading to standing waves in sections c, c' and c'', and to radiation via G_H.

Although the fields in the i=1 transmission line of length c' are evanescent, c' is sufficiently short that the added strip located at c' can convert some of the i=1 mode power into the i=0 mode. The amount of power converted per unit length clearly depends on the length c' and the width δ of the strip. Particular note should be made of the simple form of the network at c' which couples the two transmission lines. That form and the expressions for the elements in that network were derived using small obstacle theory in a multimode context; it was necessary to extend the formulations available in the literature because one of the constituent transmission lines (i=1) is below cutoff.

The expressions for the various constituents of this network and the final expression for the β and α, together with their derivations, will be presented in a future Technical Report. It should be mentioned, however, that the theoretical expressions for the individual constituents, as well as for β and α, are in closed form.

5. A Typical Set of Numerical Results

As with any leaky-wave antenna, one can, by suitably changing the dimensions and the frequency, obtain a variety of scan angles and leakage constants. Let us choose as a typical case a'/a = 0.70, b/a = 0.80, c/a = 1.215, c'/a = 0.145, c"/a = 1.50, $\delta/a = 0.21$, and $\lambda_0/a = 1.20$. For this particular set of dimensions, we find $\beta/k_0 = 0.749$ and $\alpha/k_0 = 6.24 \times 10^{-3}$. This value of leakage constant α yields a leakage rate of about 0.34dB per wavelength, resulting in an antenna about $30\lambda_0$ long if, as is customary, 90% of the power is to be radiated, with the remaining 10% dumped into a load. The resulting beam width of the radiation is approximately 2.9°, and the beam radiates at an angle of about 49° to the normal. At a frequency of 50 GHz, for example, dimension a would be 0.50 cm and the antenna would be 18 cm long.

The values of α and β can be changed by altering some of the dimensions, and the principal considerations involved are discussed next.

6. Design Considerations

In order to systematically design radiation patterns, one must be able to taper the antenna aperture amplitude distribution while maintaining the phase linear along the aperture length, i.e., one must be able to vary α while keeping β the same. Fortunately, several parameters can be varied that will change α while affecting β hardly at all; the best ones are δ and c, if c is long enough.

Since the $i = 0$ transverse mode is above cutoff in both the central and outer regions of the guide cross section, however, a standing wave effect is present in the $i = 0$ transmission line. As a result, a short circuit can occur in that transmission line at the position of the coupling strip of width δ, and the value of α then becomes zero. Hence, we must choose the dimensions to avoid that condition, and in fact to optimize the value of α.

In the design, one first chooses the width a and adjusts a' and b to achieve the desired value of β/k_0, which is determined essentially by the $i = 1$ transverse mode. That value of β/k_0 immediately specifies the angle of the radiated beam. It is then recognized that the value of α can be increased if the coupling strip width δ is increased, or if the distance c' between the step junction and the coupling strip is decreased, since the coupling strip is excited by the $i = 1$ transverse mode, which is evanescent away from the step junction in the outer regions. After those dimensions are chosen, the length c must be determined such that the standing wave effect mentioned above optimizes the value of α. If c is sufficiently long, it will affect only the $i = 0$ transmission line and influence β negligibly. The length c" also affects α strongly and β weakly, and it also must be optimized because another mild standing wave exists between the coupling strip and the radiating open end.

We have obtained numerical values in graphical form of the variation of α and β with each of these dimensional parameters, so that design optimization can proceed in systematic fashion. However, we present here, in Figs. 3(a) and 3(b), respectively, only a curve of α/k_0 as a function of c' (Fig. 3(a)), and the value of c + c' (Fig. 3(b)) that must be selected so as to achieve the optimized value of α given in Fig. 3(a). In effect, therefore, Fig. 3(b) indicates the value of c required once α (via c') is specified. It is interesting to note that c + c' is almost constant for optimization.

It is important to realize that the dimensions for optimization are independent of frequency, since the transverse wavenumbers are all frequency independent. Of course, when the frequency is altered the values of β and α will change, but the dimensional optimization is undisturbed. In fact, for the dimensions discussed above, the radiated beam can be scanned with frequency from about 15° to nearly 60° before the next mode begins to propagate.

The new leaky-wave antenna suitable for millimeter waves, for which the transverse resonance analysis and design considerations are presented here, is therefore capable of straightforward understanding and systematic design. It is also sufficiently flexible with respect to the dimensional parameters which can be varied that a reasonably wide range of pointing angles and beam widths can be achieved with it.

We have described here a new type of leaky-wave antenna suitable for millimeter waves. It is based on the groove guide, which is a low-loss waveguide, so that the waveguide attenuation will interfere negligibly with the leakage process. The structure is simple and

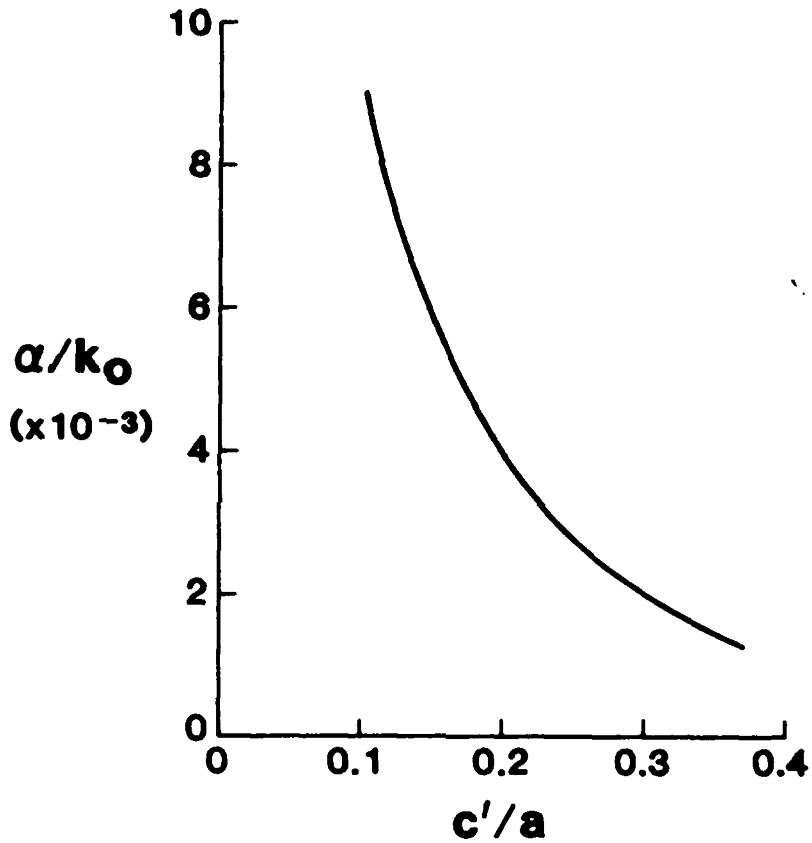


Fig. 3(a) Leakage constant α/k_0 of the leaky-wave antenna shown in Fig. 1(b) as a function of the distance c'/a of the perturbing strip from the step junction.

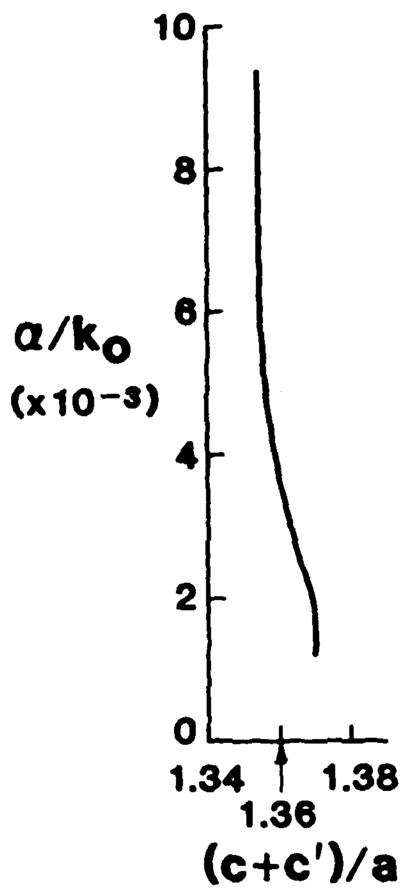


Fig. 3(b) Optimum value of leakage constant α/k_0 as a function of (c + c')/a required for optimization.

longitudinally continuous, rendering it attractive for fabrication at the small wavelengths in the millimeter wave range.

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C. NOVEL LEAKY-WAVE ANTENNA BASED ON NONRADIATIVE DIELECTRIC WAVEGUIDE

1. Introduction

Two papers appeared recently [1,2] which proposed a new type of waveguide for millimeter waves, and showed that various components based on it can be readily designed and fabricated. By a seemingly trivial modification, the authors, T. Yoneyama and S. Nishida, transformed the old well-known H guide, which had languished for the past decade and appeared to have no future, into a potentially practical waveguide with attractive features. The old H guide stressed its potential for low-loss long runs of waveguide by making the spacing between the metal plates large, certainly greater than half a wavelength; as a result, the waveguide had lower loss, but any discontinuities or bends in it would produce leakage of power away from the guide. Yoneyama and Nishida observed simply that when the spacing is reduced to less than half a wavelength all the bends and discontinuities become purely reactive; they therefore call their guide "nonradiative dielectric waveguide." As a result of this modification, many components can be constructed easily, and in an integrated circuit fashion, and these authors proceeded to demonstrate how to fabricate some of them, such as feeds, terminations, ring resonators and filters.

These papers [1,2] treat only reactive circuit components, and no mention is made of how this type of waveguide can be used in conjunction with antennas. The present investigation serves two functions. First, it shows that a leaky-wave antenna can be readily fabricated with "nonradiative dielectric waveguide," and, in fact, that it can be directly connected to the above-mentioned circuits in integrated circuit fashion, if desired. Second, it presents a very accurate theory for the leakage and phase constants of the antenna. A key feature of this theory involves an almost-rigorous transverse equivalent network, which requires two coupled transmission lines. Some subtle features are involved in the derivation of the elements of this equivalent network, including the best choice of constituent transverse modes, an analytic continuation into the below cutoff domain, and mode coupling at an air-dielectric interface. In the discussion below, we present the structure of the antenna, the principle of operation, an outline of the almost-rigorous theory, and a typical numerical example for antenna performance.

The form of the antenna is also responsive to problems facing line-source antennas at millimeter wavelengths; that is, it is simple to fabricate since it is composed of a single continuous open slit, and it is fed by a relatively low-loss waveguide so that the leakage constant of the antenna dominates over the attenuation constant of the waveguide. The antenna is also simple to design because it is possible to vary the leakage constant without measurably affecting the phase constant, and because our theory yields closed-form expressions for the leakage and phase constants.

2. Principle of Operation of the Leaky-Wave Antenna

The new waveguide, shown in Fig. 4, looks like the old H guide except that the spacing between plates is less than half a wavelength to assure the nonradiative feature. In the vertical (y) direction, the field is of standing wave form in the dielectric region and is exponentially decaying in the air regions above and below. The guided wave propagates in the z direction. The leaky-wave antenna based on this waveguide is shown in Fig. 5. In Fig. 5(a) we see that the antenna is created simply by decreasing the distance d between the dielectric strip and the top of the metal plates. When distance d is small, the fields have not yet decayed to negligible values at the upper open end, and therefore some power leaks away. The upper open end forms the antenna aperture, and the aperture amplitude distribution is tapered by varying the distance d as a function of the longitudinal variable z. The polarization of the antenna is seen to be vertical in view of the electric field orientation in the waveguide.

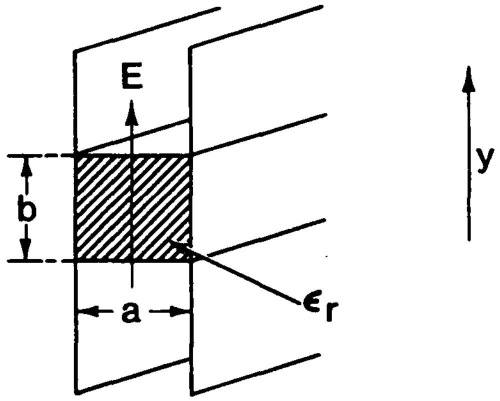
The antenna is seen to be very simple in structure. A side view of the antenna, shown in Fig. 5(b), indicates that the taper in the antenna amplitude distribution is achieved easily by positioning the dielectric strip waveguide with respect to the upper open end, and also that the feeding strip can be readily connected to some other part of the millimeter wave circuit and therefore serve as the output from it.

3. Almost-Rigorous Transverse Equivalent Network

The antenna is analyzed as a leaky waveguide which possesses a complex propagation constant β-jα, where β is the phase constant and α is the attenuation or leakage constant. We thus establish a transverse equivalent network for the cross section of the antenna, and from the resonance of this network we obtain the dispersion relation for the β and α values. An almost-rigorous equivalent network is presented in Fig. 6, where it is seen that two coupled transmission lines are required in the representation. The reason for two lines is that the waveguide modes are hybrid, and possess all six field components in the presence of the radiating open end.

If we employ the usual TE and TM modes in these transmission lines which represent the constituent transverse modes, the lines will remain uncoupled at the air-dielectric interface but will be coupled together at the radiating open end. On the other hand, the open end is uniform longitudinally, and this geometrical arrangement suggests the use of E_z-type and H_z-type modes (alternatively called LSM and LSE modes, respectively, with respect to the xy plane). Transmission lines representing such modes will not couple at the radiating open end, but do become coupled at the air-dielectric interface. These two valid but alternative representations were considered, and we chose the second of these as the simpler approach for our antenna.

The transverse equivalent network in Fig. 6 thus corresponds to the E_z-type and H_z-type transverse modes mentioned above. The



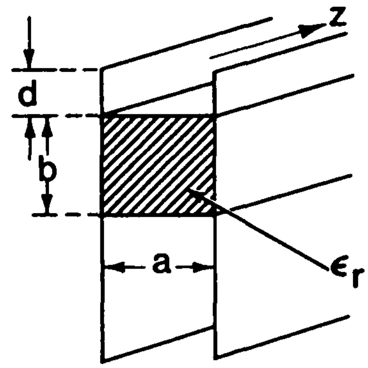


Fig. 4 Cross section view of nonradiative dielectric waveguide, where $a < \lambda_0/2$.

Fig. 5(a) Cross section view of leaky-wave antenna, where leakage is controlled by distance d.

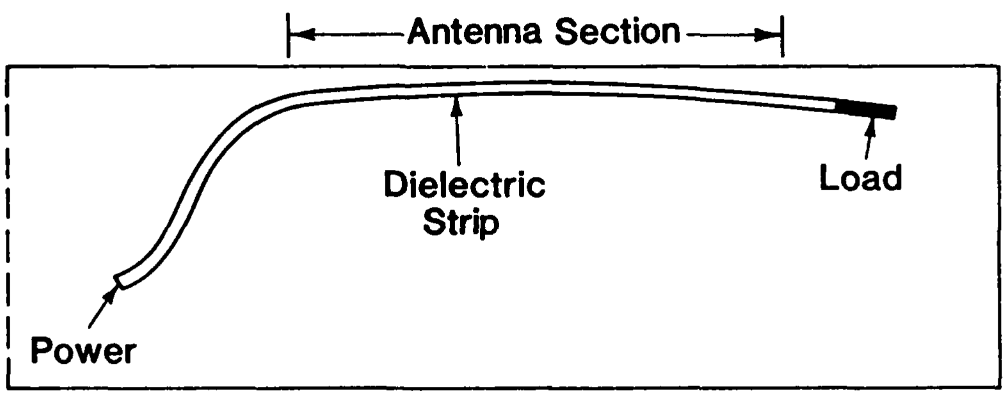


Fig. 5(b) Side view of antenna, where the antenna aperture distribution can be tapered by altering the position of the dielectric strip, and the strip can be connected to the rest of the millimeter-wave integrated circuit.

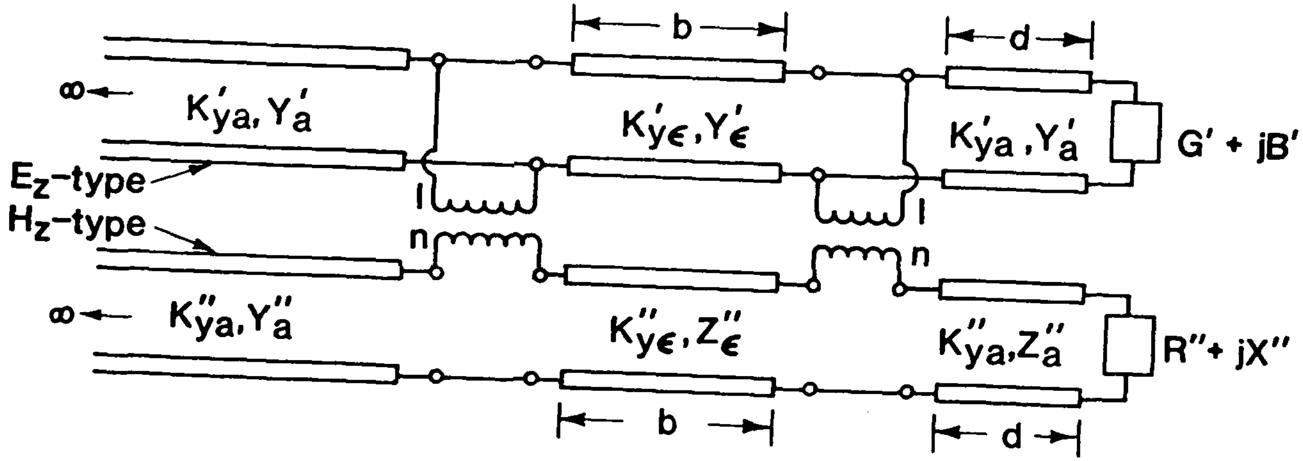


Fig. 6 Almost-rigorous transverse equivalent network for the antenna shown in Fig. 5(a). The network is placed on its side for clarity.

coupling network at the air-dielectric interface was obtained from an adaptation of a network presented earlier by Clarricoats and Oliner [3] for cylindrical air-dielectric interfaces, and suitably transformed for planar interfaces.

The principal new feature in the transverse equivalent network in Fig. 6 relates to the terminal admittances representing the E_z-type and H_z-type modes incident on the radiating open end. Those admittances were not available in the literature but were derived by analytic continuation of expressions for reflection coefficient given by L.A. Weinstein [4]. Those reflection coefficients applied to normal incidence of ordinary parallel plate modes; modifications were made to account for a longitudinal wavenumber variation (corresponding to oblique incidence) and then for modes below cutoff, the latter step producing results which appear totally different since the phases and the amplitudes of the reflection coefficients then become exchanged.

The terminal admittances in Fig. 6 assume that all the higher modes in the transmission lines decay exponentially to infinity. In principle, they "see" the air-dielectric interface distance d away. In practice, that distance is large; for example, for the first higher mode in a specific case the field at the air-dielectric interface was about 30 dB lower than its value at the radiating open end. Because of this feature, however, we have referred to this analysis as <u>almost</u> rigorous.

4. *Typical Numerical Results*

The dispersion relation for α and β of the leaky-wave antenna that was found from a resonance of the transverse equivalent network in Fig. 6 contains elements all of which are in <u>closed form</u>, thus permitting easy calculation. We have examined the various parametric dependences of α and β on the dimensions a, b and d, and on the dielectric constant ε, in order to clarify design information. Here we present only a single typical case, corresponding to certain geometrical parameters given in reference 1. The behavior of β and α are shown in Figs. 7 and 8 for this case as a function of distance d (see Fig. 5(a)). For distance $d > 2$ mm, one sees from Fig. 7 that the value of β remains essentially unchanged, as desired. It is seen in Fig. 8 that α increases as d is shortened, as expected since the field decays exponentially away from the dielectric region. Thus, the value of α that one can achieve spans a very large range.

Leaky-wave antennas are usually designed so that 90% of the incident power is radiated, and the remaining 10% is dumped into a load. Following this criterion, if one selects $d = 2.0$ mm for this geometry, the length of the antenna will be 50 cm, and the beam will radiate at an angle of about 35° from the normal, with vertical electric field polarization, and with a beam width of approximately 1.1°. A larger value of d will result in a narrower beam whose value can be calculated from the curve for α in Fig. 8.

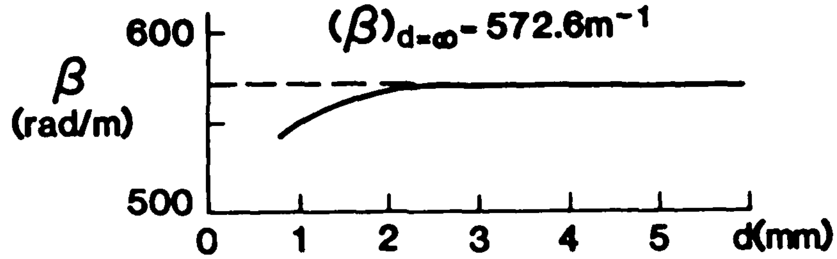


Fig. 7 Phase constant β in radio.:s/meter of the leaky-wave antenna in Fig. 5(a) as a function of d in mm, showing that β is independent of d beyond some minimum value of d.

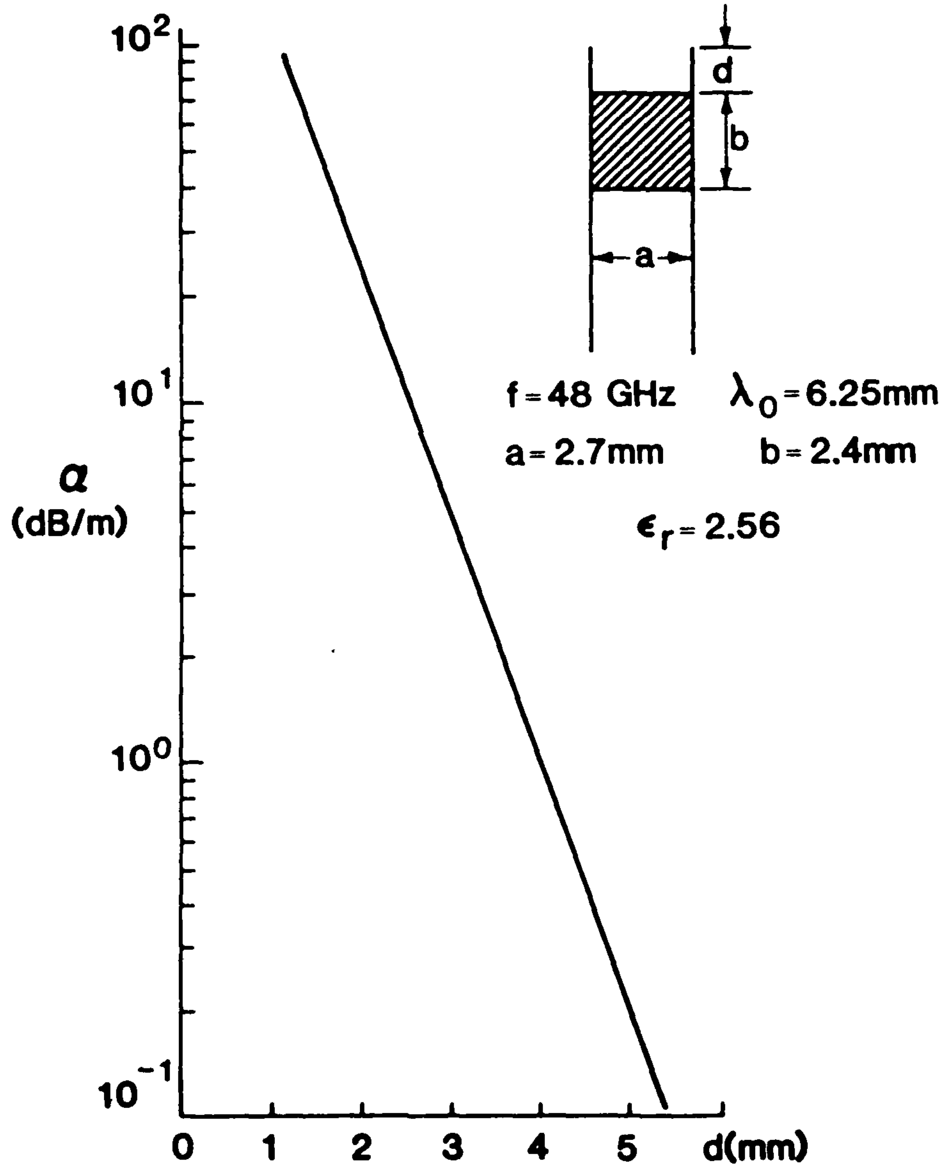


Fig. 8 Leakage constant α in dB/meter of the leaky-wave antenna in Fig. 5(a) as a function of the distance d in mm between the dielectric strip and the radiating open end.

5. References

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