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LEAKY WAVE RADIATION FROM A PERIODICALLY
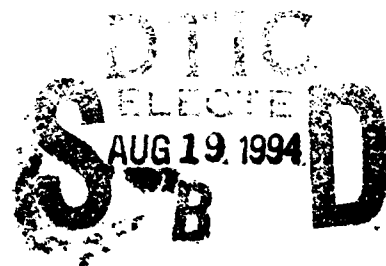
SLOTTED WAVEGUIDE

by

Jean-Paul Renault

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Distribution

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ACKNOWLEDGMENT

ABSTRACT

A rectangular waveguide with transverse slots located periodically in the broad wall is analysed by the transverse resonance procedure. The slots are replaced by equivalent conductances and susceptances; these are used in the resonance equation to obtain leaky and surface wave solutions.

The theoretical solutions for the complex axial propagation constant are found, and these results are verified experimentally. The transverse resonance method of solution is shown to present advantages over previously derived results.

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I. INTRODUCTION

Leaky waves in many cases of practical interest are excited in lossless wave-guides in which are cut either uniform or periodic apertures. These waves, which have a complex propagation constant, propagate along the leaky structure with a veloc-ity greater than that of light and are continuously attenuated, indicating the leakage of energy they undergo as they travel. The theoretical discussion of leaky wave struc-tures using only field considerations would, therefore, generally be extremely arduous, including particularly the solution of a discontinuity problem. But leaky waves are solutions of the source-free field equations, so their propagation constants can be cal-culated rigorously by means of a transverse resonance procedure. This procedure includes two steps: first it is necessary to find a transverse network representation, and then a resonance equation has to be solved. The first step consists mostly of evaluating the discontinuities. Generally, however, this does not need to be carried out since the results are already available in the literature. The next step consists of the solution of a network problem. The resonance equation is a complex transcendental equation which requires the use either of a computing machine or of numerical methods. However, when the solution can be regarded as a perturbation of the propagation con-stant of the closed waveguide, a perturbation technique may be used which leads to solutions in closed form where the functional behavior is immediately evident.

The theory of this network approach has already been discussed [1] and the evaluation of discontinuities has been carried out in many cases of practical interest[2]. In this report a transverse resonance procedure will be applied to a transversely-slotted rectangular waveguide as illustrated in Figure 1.
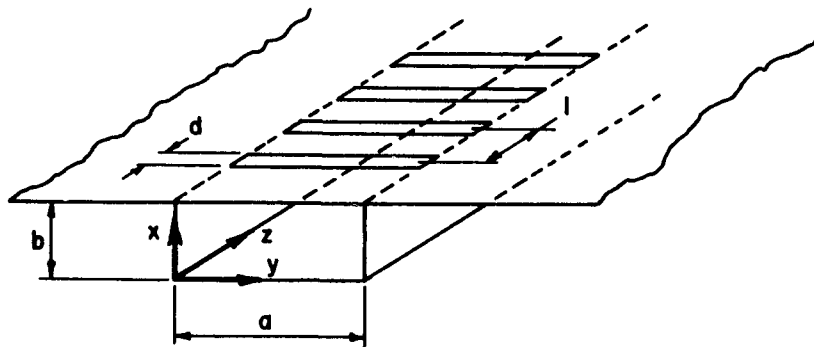
Figure 1.   Transversely-slotted waveguide

(1) L. O. Goldstone and A. A. Oliner, "Leaky-wave Antennas I: Rectangular Wave-guides, " Research Report R-606-57, PIB 534 M. R. I. ; August 57

(2) N. Marcuvitz, " Waveguide Handbook", Rad. Lab. Series, Vol. 10, McGraw-Hill Book Co., New York, 1951

The structure consists of an array of closely-spaced transverse slots which extend completely across the broad face of a rectangular waveguide. The waveguide is assumed to be infinite, and its slotted face is inserted in an infinite conducting plane. This structure is well known and has already been studied by R. F. Hyneman[3]. However, it will be discussed here from a completely different point of view. Whereas Hyneman started from the general field equations and used iterative techniques with computing machines to get numerical results, in the following analysis a simple perturbation technique will be used to obtain simple closed form expressions for the guide wavelength and attenuation constant.

Experimental measurements have also been made of the attenuation constant and guide wavelength, and these measured results are compared with the theoretical expressions. It is found that very good agreement is obtained with the presently-derived theory, but that the calculations of Hyneman differ considerably from the measured values. Furthermore, Hyneman indicates that a surface wave is present on this structure, but the present theory finds no evidence of the presence of such a wave. These points are considered in detail below.

(3) R. F. Hyneman, " Closely-Spaced Transverse Slots in Rectangular Waveguide" IRE Transactions on Antennas and Propagation, Nb 4, pp. 335-342, October 1959.

II. ANALYSIS OF THE STRUCTURE

A few restrictions have to be made in order to simplify the analysis of the problem. First, if the propagation constant of the leaky wave is to be regarded as a perturbation on the closed waveguide propagation constants, the slots have to be small, i. e., the ratio of length to width a/d must be sufficiently great, the ratio of width to free space wavelength d/λ sufficiently small, and the spacing of the slots must be large compared to their width. Under these conditions the only appreciable component of the tangential electric field in the apertures is the z component and the characteristics of the wave traveling on the structure are only slightly different from those of the unperturbed case and are thus susceptible to analysis by perturbation methods.

Then, if this structure is to exhibit a leaky-wave behavior, the leakage of energy has to be uniform. In other words, the structure has to be regarded as radiating continuously and not as a discrete array of apertures. This will be the case if the slots spacing is very small with respect to the free-space wavelength $(l < \lambda)$.

(a) Network Representation

A slotted guide where only one leaky wave propagates can, when viewed transversely, be represented by a single length of transmission line short-circuited at one end and terminated at the other end in an appropriate lumped network representing the discontinuity.

It has already been mentioned that the only appreciable component of the tangential electric field is the z component, so that the mode propagating in the slotted waveguide can be regarded as a perturbation on a TE mode propagating in the y direction (H type mode (i)); besides, "a" and "b" can be chosen such that only the fundamental H type modes are never coupled on such structures[1], so that at the discontinuity the only modes which are excited are H-type modes of all orders, the lowest one being the only one to propagate. Therefore, the waveguide viewed transversely can be represented by a single piece of transmission line of length b, short circuited at one end and terminated in the appropriate lumped network which will be determined later. In fact, this single transmission line picture is valid only if b is large enough so that none of the decaying modes can reach the back wall and be reflected with an appreciable amplitude.

$$E_z = E_0 \sin \frac{\pi y}{a} \exp(-jk_z z) \qquad (1.1)$$

The z dependence is the usual $\exp(-jk_z z)$ dependence and the y dependence is assumed to be very similar to $\sin \pi y/a$, the y dependence in the closed waveguide.

E_z between the slots, at $x = b$ is equal to zero. Due to the periodicity of this structure an expansion of E_z in a Fourier series can be carried out which yields the following expression

$$E_z = \sum_{n=-\infty}^{+\infty} a_n \sin \frac{\pi y}{a} \exp -jk_z z \, \exp -j \, (2n_\pi z / \ell) \qquad (1.2)$$

If κ is the transverse wave number, corresponding to each n there will be a κ_n such as

$$\kappa_n = k^2 - (\pi/a)^2 - (k_z + \frac{2n\pi}{\ell})^2 \quad , \qquad (1.3)$$

where k_z is replaced by $k_z + \frac{2n\pi}{\ell}$, according to Eq. (1.2). But k_z does not differ very much from k_{z0} for which

$$k^2 = \frac{\pi^2}{a^2} + k_{z_0}^2 \quad , \qquad (1.4)$$

and ℓ is much smaller than λ, $k = 2\pi/\lambda$ is much smaller than $2\pi/\ell$). Therefore, except for $n = 0$, which corresponds to the lowest leaky mode, κ_n is approximately equivalent to $-j(2\pi n/\ell)$ and the corresponding modes decay rapidly away from the plane $x = b$. Even for $n = 1$ this will be true since ℓ and b are of the same order at $x = -b$ and the fields are too highly attenuated to be appreciably reflected, thus justifying the single transmission line picture. The preceding discussion shows that the electromagnetic energy is partly stored in the neighborhood of the discontinuities, which corresponds to the decaying modes, and partly radiated away.

In the lumped network the radiated energy is represented by a conductance G and the stored energy by a suspectance jB as illustrated in Fig. 2.
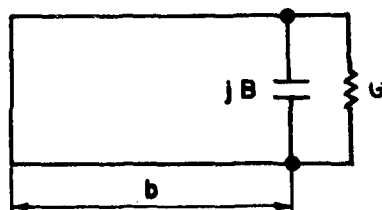
Fig. 2: Transverse equivalent network.

1. Determination of G

The conductance G could be found by computing the power radiated far from the antenna. But the lowest H-type mode (n = 0 in (1.3)), being the only one which is propagating, is the only mode which contributes to the power radiated in the far zone. Therefore, in the determination of G we can disregard all the space harmonics, and, in so far as G is concerned, the tangential electric field in the aperture can be taken as

$$E_z = E_0 \sin \frac{\pi y}{a} \ \exp -jk_z z \tag{1.5}$$
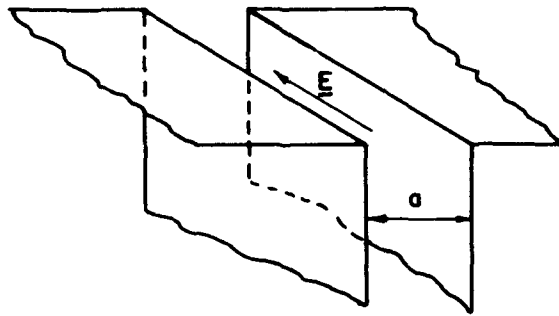
Fig. 3: Parallel plate waveguide
radiating into half-space

This corresponds to the situation represented in Fig. 3: G is the admittance equivalent to a parallel plate waveguide radiating into half space with the electric field parallel to the guide walls. The conductance G is given by [4]

$$\frac{G}{Y_0} \approx 0.285 \ \frac{2\pi}{\kappa a} \tag{1.6}$$

where Y_0 is the characteristic admittance of the parallel plate waveguide and the κ the transverse wavenumber given by

$$\kappa^2 = k^2 - k_z^2 - (\pi / z)^2 \tag{1.7}$$

(1.6) can be rewritten

$$\frac{G}{Y_0} = \frac{G_0}{\kappa} \ 1.6 \quad \text{where} \quad G_0 = 0.285 \ \frac{2\pi}{a} \tag{1.8}$$

and G_0 does not depend on κ .

(4) N. Marcuvitz, " Waveguide Handbook", Rad. Lab. Series, Vol. 10, McGraw-Hill Book Co., New York, 1951, p. 191 Eq. 2b.

2. Determination of B

The attenuated modes, although not contributing to the power radiated, contribute to the stored energy which is represented in the network by the susceptance jB. The fields corresponding to these modes have appreciable values only in a fairly limited region which does not extend far from the slots. It is therefore possible to consider that the field distribution depends mostly on the geometry of the slots and very little on the surrounding region. Accordingly, it does not make much difference if we replace the structure represented in Fig. 4.a, (which is the actual structure studied here) by the structure of Fig. 4.b.

(a)   (b)
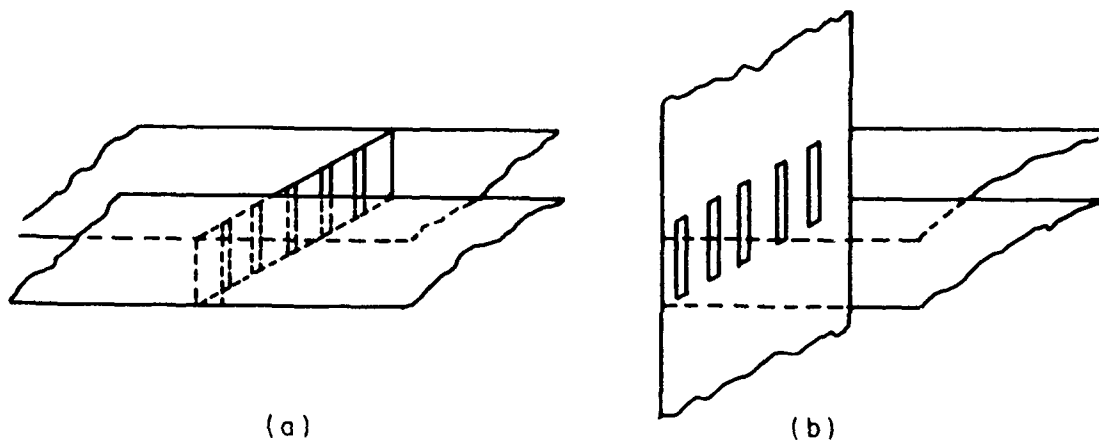
Figure 4: Equivalent Radiating Structures

Clearly this is not completely rigorous since the field distributions corresponding to the decaying modes in the structures illustrated above are likely to differ slightly. However, the results derived from this approximation yield results in excellent agreement with experimental data.

Furthermore the parallel plate waveguide with an array of transverse slots cut in a plane perpendicular to its walls as illustrated in Fig. 4.b has for an image an array of infinite slots cut in an infinite conducting plane. The susceptance of such a discontinuity with tangential magnetic field parallel to the edges of the slots is found to be[5]

$$\frac{B}{Y_0} \approx \frac{2 \kappa l}{\pi} \, l \, n \, csc \, \frac{\pi d}{2 l} \tag{1.9}$$

which can be rewritten

$$\frac{B}{Y_0} = B_0 \kappa \tag{1.9a}$$

(5) N. Marcuvitz, "Waveguide Handbook", Rad. Lab. Series, Vol. 10, McGraw-Hill Book Co., New York, 1951, p. 280 Eq. 1a.

where $B_0 = \frac{2\ell}{\pi} \ell n \; csc \left(\pi \, d/2\ell \right)$, (which does not depend on κ).

(b) Transverse resonance

The second part in this problem is to determine κ from the network representation by means of a resonance procedure. The resonance equation can be written in the following manner

$$\overset{\leftrightarrow}{Y}(\kappa) = \overset{\leftarrow}{Y}(\kappa) + \vec{Y}(\kappa) = 0 \tag{2.10}$$

where $\overset{\leftarrow}{Y}(\kappa)$ is (see Fig. 2) the admittance of the short-circuited piece of transmission line i. e. $-j \, Y_0 \, \cot \kappa \, b$ and $\vec{Y}(\kappa)$ the net admittance of the lumped network representing the discontinuities i. e. $G + jB$. Therefore (2.10) becomes

$$-j \, Y_0 \cot \kappa b + jB + G = 0 \tag{2.11}$$

or

$$-j \cot \kappa \, b + jB_0 \, \kappa + \frac{G_0}{\kappa} = 0 \tag{2.12}$$

thus,

$$\cot \kappa \, b = B_0 \, \kappa \; -j \, \frac{G_0}{\kappa} \; , \tag{2.13}$$

and dividing both sides by κb, we see that

$$\frac{\cot \kappa b}{\kappa b} = \frac{B_0}{b} \; -j \, \frac{G_0}{\kappa^2 b} \tag{2.14}$$

Let $xb = u$, Eq. 2.14 becomes

$$\frac{\cot ub}{u} = \frac{B_0}{b} \; -j \, \frac{G_0 \, b}{u^2} \tag{2.15}$$

This resonance equation should identical to the equation obtained by Hyneman[6] in which he started from the field equations. But whereas the left-hand sides are identical, the right-hand side is here in a simple compact form as opposed to Hyneman's which uses a product of complicated series and integrals. However, once these integrals and series are evaluated the results should be the same, since in the Waveguide Handbook the discontinuities were evaluated from the field equations. One of the principal advantages of the approach used here is that it does not carry out these complicated computations and uses results already available.

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(6) See Ref. no. (3) Eq. 14 p. 337.

1. Leaky-wave solutions

It is clear from Eq. 2.14 that the solution for K has to be complex, corresponding to a leaky-wave solution. Since the slots are small (Sec. Ia) the solution K of 2.14 can be regarded as a perturbation on the dominant H_{10} mode in a completely closed waveguide for which there is no x dependence, and therefore $K = 0$. Thus, it is expected that the resonant value of K and accordingly of u will be small. So, in order to find the value of K for the lowest leaky-wave on the structure, the left hand side of Equation (2.15) can be expanded in powers of u = Kb, keeping only the first two terms and neglecting terms of higher order.

$$\cot u = \frac{\cos u}{\sin u} \approx \frac{1 - \frac{u^2}{2}}{u - \frac{u^3}{6}} \approx \frac{1}{u} \left(1 - \frac{u^2}{2} + \frac{u^2}{6}\right) = \frac{1}{u} - \frac{u}{3}$$

so [7]

$$\frac{\cot u}{u} \approx \frac{1}{u^2} - \frac{1}{3} \tag{2.16}$$

Substituting in (2.15), we get

$$\frac{1}{u^2} - \frac{1}{3} = \frac{B_0}{b} - j \frac{G_0 b}{u^2} \tag{2.17}$$

or

$$1 - \frac{u^2}{3} = \frac{B_0}{b} u^2 - j G_0 b \tag{2.18}$$

Using $K = u/b$

$$K^2 = \frac{1}{b^2} \frac{1 + j G_0 b}{\frac{B_0}{b} + \frac{1}{3}} \tag{2.20}$$

So K can be calculated, taking the square root of K^2 with positive real and imaginary part which indicates the leaky-wave behavior. From K, k_z can be found as

$$k_z = \beta - j\alpha = \sqrt{k^2 - \left(\frac{\pi}{a}\right)^2 - K^2} \tag{2.21}$$

where α is the attenuation constant per unit length and β the phase shift per unit

[7] The first term neglected in the expansion of $(\cot u / u)$ is $(-u^2/45)$. Since in most cases of interest $|u|$ turns out to be close to 1 this approximation is generally better than 5% accurate.

length (in the z-direction). Dividing both sides of (2.21) by $k = 2\pi/\lambda$ yields

$$\frac{\lambda}{\lambda_g} - j\frac{\alpha\lambda}{2\pi} = \sqrt{1 - (\lambda/2a)^2 - (\kappa\lambda/2\pi)^2} \qquad (2.22)$$

λ_g is the guide wavelength $\lambda_g = 2\pi/\beta$. Therefore

$$\frac{\lambda}{\lambda_g} = \text{Re} \sqrt{1 - (\lambda/2a)^2 - (\kappa\lambda/2\pi)^2} \qquad (2.23)$$

and

$$\alpha\lambda = -2\pi \text{ Im} \sqrt{1 - (\lambda/2a)^2 - (\kappa\lambda/2\pi)^2} \qquad (2.24)$$

In cases considered here where $|\kappa|$ is small, a more explicit functional dependence can be obtained by means of a perturbation method. Let k_{z0} be the longitudinal wavenumber for the closed waveguide

$$k_{z0} = \sqrt{k^2 - (\pi/a)^2} , \qquad (2.25)$$

and (2.21) can be rewritten

$$k_z = \beta - j\alpha = \sqrt{k_{z0}^2 - \kappa^2} \qquad (2.26)$$

$$\frac{k_z}{k_{z0}} = \sqrt{1 - (\kappa/k_{z0})^2} \qquad (2.27)$$

which can be expanded in a power series of κ^2/k_{z0}^2 which is, neglecting t ms of higher order than κ^2/k_{z0}^2

$$\frac{k_z}{k_{z0}} \sim 1 - \frac{\kappa^2}{2k_{z0}^2} \qquad (2.28)$$

Hence

$$k_z \approx k_{z0} - \frac{\kappa^2}{2k_{z0}} \qquad (2.28a)$$

Substituting for κ^2 the value given by Eq. (2.20)

$$k_z \approx k_{z0} - \frac{1}{2b^2 k_{z0}} \frac{1 + jG_0 b}{\frac{B_0}{b} + \frac{1}{3}} \qquad (2.29)$$

from which α is evaluated as

$$\alpha = \frac{1}{2 b k_{z0}} \quad \frac{G_0}{\dfrac{B_0}{b} + \dfrac{1}{3}} \quad ; \tag{2.30}$$

then

$$\alpha \lambda = \frac{\lambda}{2 b k_{z0}} \quad \frac{G_0}{\dfrac{B_0}{b} + \dfrac{1}{3}} \tag{2.31}$$

or

$$\alpha \lambda = \frac{\lambda \, \lambda_{g0}}{4 \pi b} \quad \frac{G_0}{\dfrac{B_0}{b} + \dfrac{1}{3}} \tag{2.31a}$$

where λ_{g0} is the closed guide wavelength. Similarly for β,

$$\beta = k_{z0} - \frac{1}{2 b^2 k_{z0}} \quad \frac{1}{\dfrac{1}{3} + \dfrac{B_0}{b}} \tag{2.32}$$

or

$$\frac{\lambda}{\lambda_g} = \frac{\lambda}{\lambda_{g0}} - \frac{\lambda \, \lambda_{g0}}{8 \pi^2 b^2} \quad \frac{1}{\dfrac{1}{3} + \dfrac{B_0}{b}} \quad . \tag{2.32a}$$

2. **Surface wave solution**

It is clear that Equation (2.14)

$$\frac{\cot \kappa b}{\kappa b} = \frac{B_0}{b} - j \frac{G_0}{\kappa^2 b} \tag{2.14}$$

does not admit any real or purely imaginary solution for κ. Therefore, in so far as the network representation derived in Sec. IIa is valid, there cannot be at the same time a leaky-wave and a surface wave supported by the structure considered here. This is in contradiction with what Hyneman[8] seemed to have observed.

Moreover if a surface wave was to be excited alone there would be no power radiated at infinity and the term in G of Eq. 2.14 would vanish. Eq. (2.14) would reduce to

$$\frac{\cot \kappa b}{\kappa b} = \frac{B_0}{b} \tag{2.33}$$

(8) See Reference no. (3) Sec. D., pp. 339, 340.
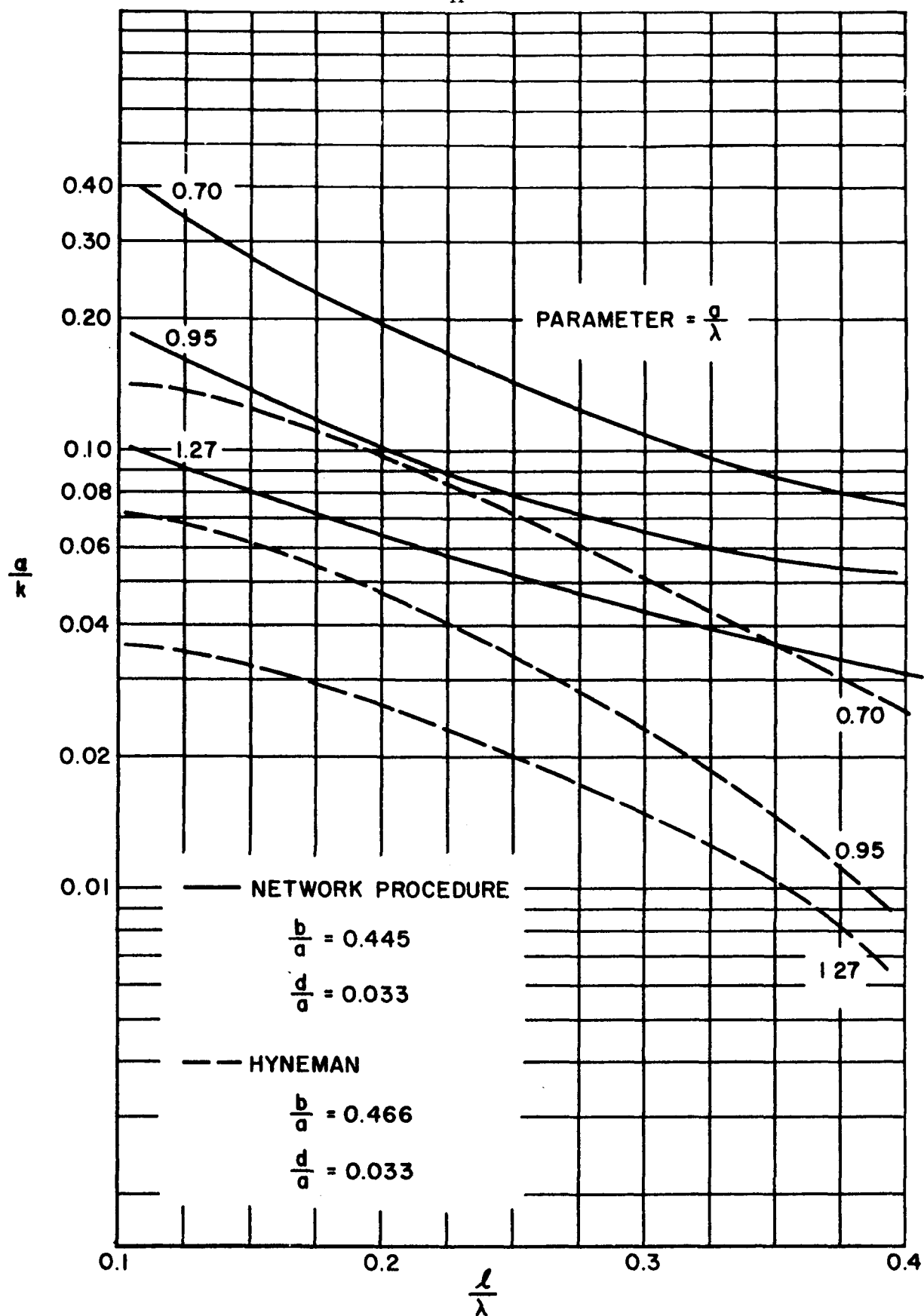
Fig.5. THEORETICAL ATTENUATION vs.
SLOT SPACING IN WAVELENGTHS

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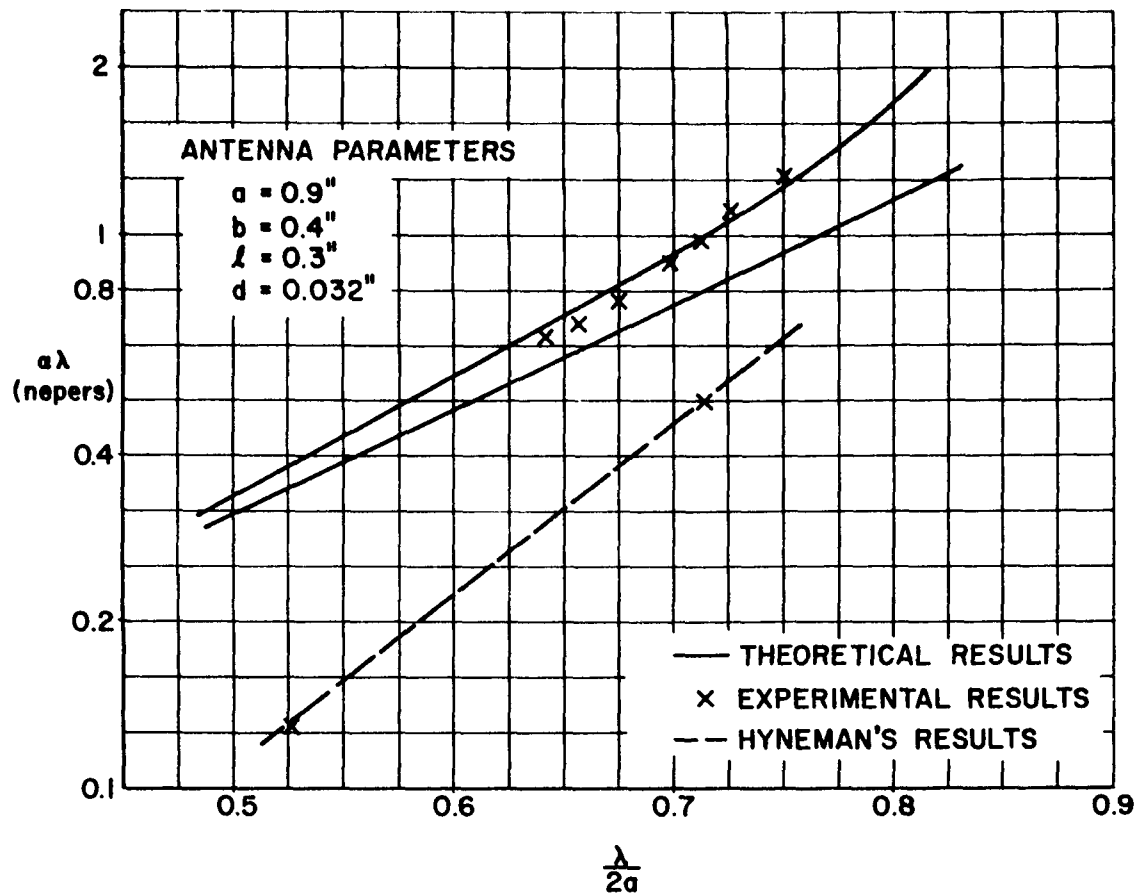
Fig. 6. ATTENUATION vs. WAVELENGTH
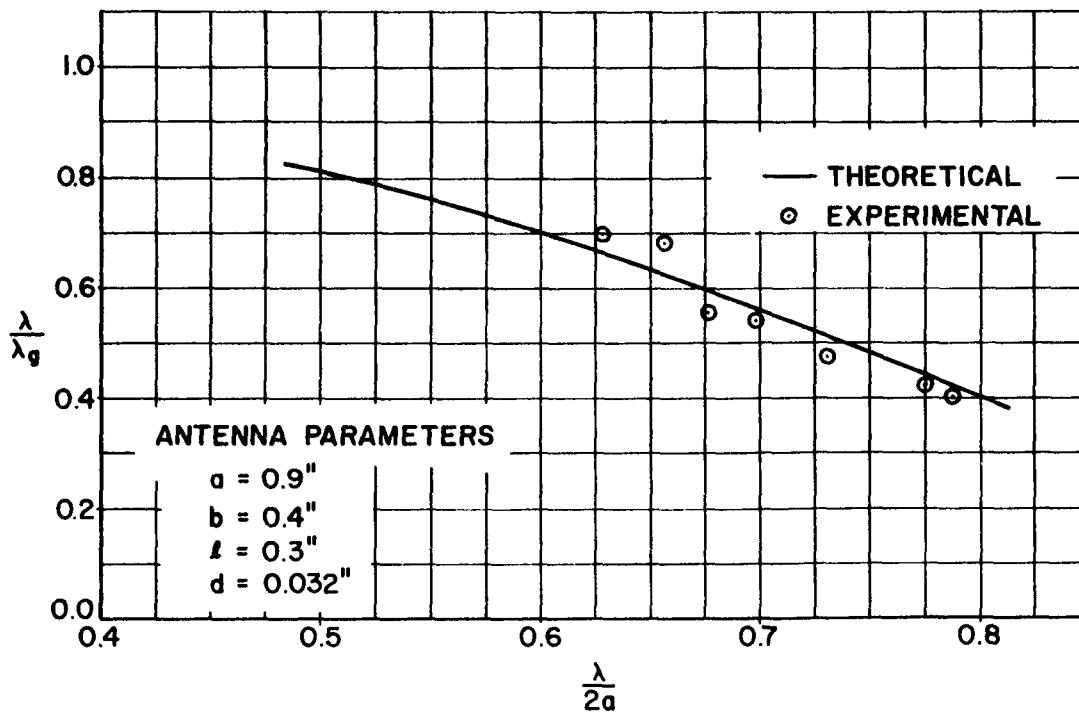
Fig. 7. $\frac{\lambda}{\lambda g}$ vs. WAVELENGTH

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III. RESULTS

a. Theoretical Results

From the expression (2.24) the normalized attenuation constant $\alpha/k = \alpha\lambda/2\pi$ was computed. The results are plotted on Fig. 5 for several values of α/λ, versus the spacing of the slots l/λ. On the same figure are compared the results obtained by Hyneman for a waveguide only slightly different: the obviously disagree.

On Fig. 6 the plots of attenuation constants $\alpha\lambda$ versus $\lambda/2a$ are found first as computed from Eq. (2.24) and then from the perturbational expression as in (2.31) (2.31). The discrepancy between these two curves, though increasing with the wavelength, is always relatively small. In fact, whereas neglecting $u^2/45$ in the expansion of $\cot u/u$ is an excellent approximation since $|u|$ is found to be close to 1, it is not such a good approximation to neglect terms of the order $\kappa^4/(8k_{z0}^3)$ in the expansion of k_z in (2.27) because for $b = 0.4''$, $|\kappa| = |u|/b$ is equivalent to $|\kappa| \approx 2.5$.

In any case, the perturbation expression is a far better approximation than Hyneman's results[8] which are plotted on the same figure and show clearly the functional dependence of the leaky-wave characteristics.

Finally on Figure 7 $\lambda/(\lambda_g)$ versus $\lambda/2a$ is plotted as given by Eq. (2.23).

b. Experimental Results

An antenna of the type described in the introduction of this report was constructed as illustrated in Fig. 8.
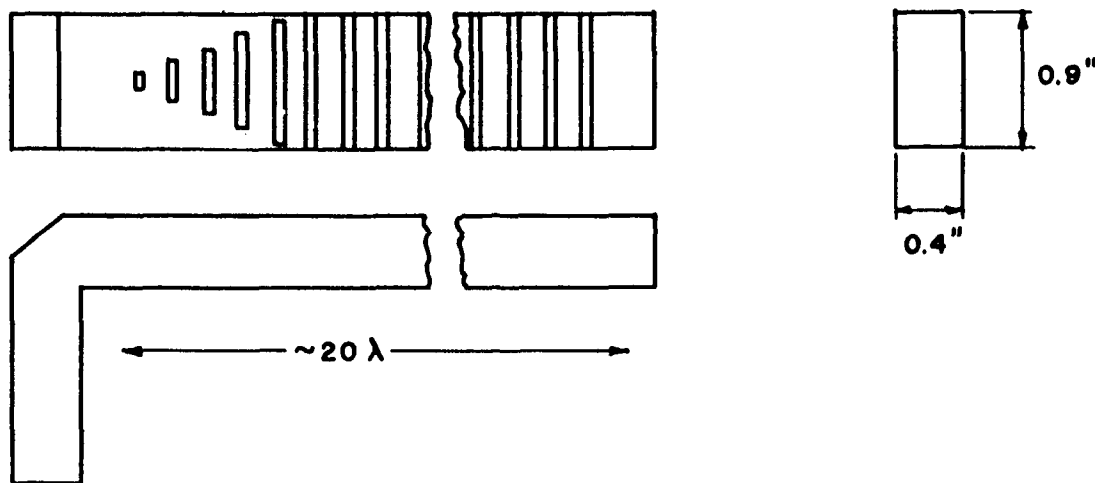
Fig. 8 Antenna constructed for the measurements.

(8) There were only two points available in Hyneman's report (Ref. (3)) to plot the curve of Fig. 6.

In order to avoid reflections at the open end of the guide, the length of the antenna was taken to be around 20 wavelengths so that no wave reach the end with an appreciable amplitude. In addition, it was found necessary to increase progressively the length of the slots, because if they all extended completely across the broad face, the discontinuity in the neighborhood of the first ones could be important enough to excite a strong space-wave which would almost conceal completely the leaky wave.

The waveguide was inserted in a large aluminum ground plane 8' X 8' and radiated into a microwave darkroom approximately 10' X 10' X 10' the walls of which were covered with an absorbing material. The probe consists of a length of flexible miniature coaxial cable which is supported by a polyfoam structure and is covered by absorbing material to minimize as much as possible the distortion of the field. The probe carriage is motor driven and its travel is controlled by limit switches and a reversing switch.

1. Attenuation measurements.

The probe is oriented perpendicularly to the slotted face of the antenna. The signal available from the probe is fed to a recorder through a DC amplifier (Fig. 9). As the probe travels along the antenna at a uniform speed, the recorder plots the amplitude distribution of the leaky wave. These data are plotted on semi-log graph paper, the slope of the straight line which best fits a particular set of data is used to compute the attenuation constant. The results so obtained are shown on Fig. 6.

2. Phase measurements.

The phase measurements are taken with the configuration slightly modified. A null method is used to compare the phases of the aperture field and of a reference signal. The magnitude and phase of this reference are adjusted by means of a calibrated attenuator and a slotted section. Comparison of the phases is accomplished by a hybrid tee junction. A block diagram of the set up used here is shown in Fig. 10. The experimental values of the guide wavelength are plotted on Fig. 7.
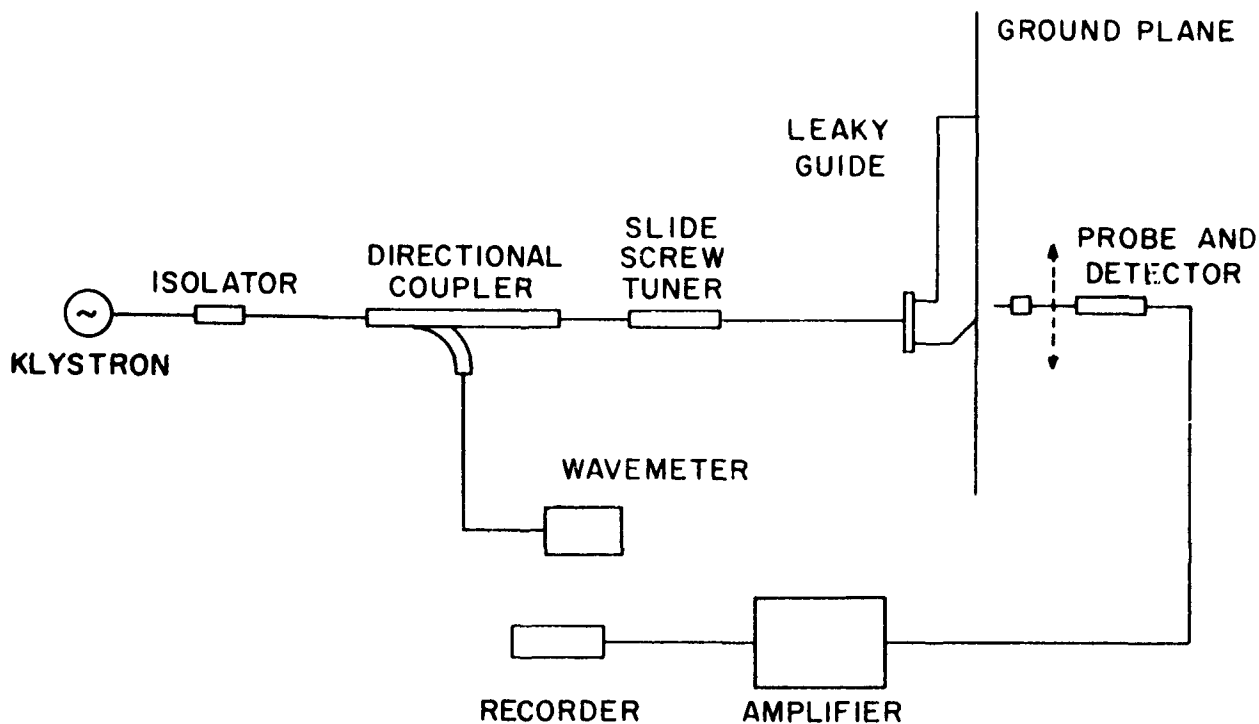
Fig. 9 Block diagram of equipment for attenuation measurement.
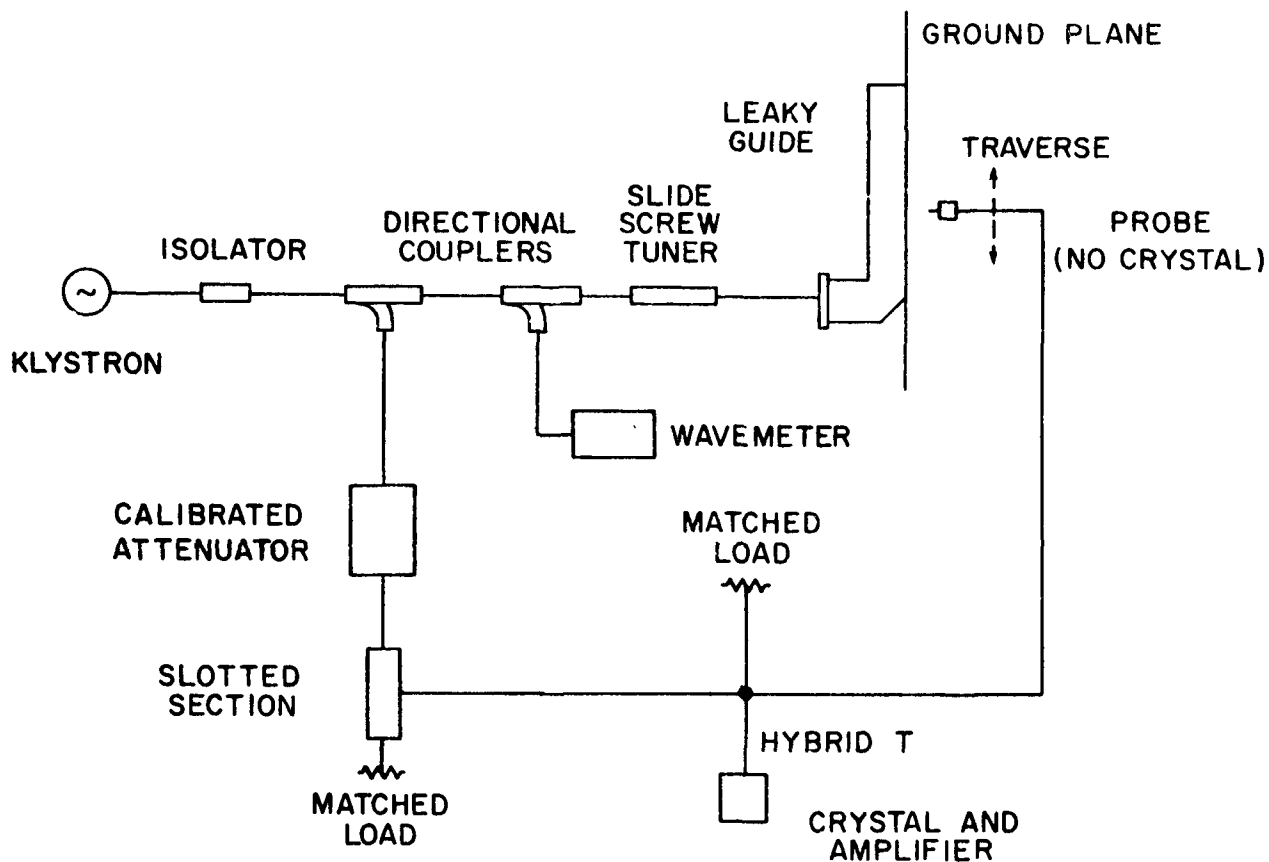
Fig. 10 Block diagram of equipment for guide wavelength measurement.

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IV. CONCLUSIONS

The experimental results obtained for the attenuation constant and the guide wavelength agree very satisfactorily with the theoretical values (see Fig. 6 and 7). This fact shows that those approximations which were made in Section II a were perfectly justified.

The validity of the network representation used here seems therefore to be fully guaranteed, and the results derived therefrom are in far better agreement with measured values than any results previously derived by other methods.

Furthermore, it becomes very doubtful that this structure could excite a surface wave together with a leaky wave, as indicated by Hyneman.

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