GUIDANCE AND LEAKAGE PROPERTIES OF OFFSET GROOVE GUIDE

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ABSTRACT

A new leaky-wave structure, the offset groove guide, is analyzed accurately by two completely different methods: a novel tee-junction equivalent network approach and a numerical mode-matching procedure. The new structure is discussed first, and it is then shown that the numerical values for the propagation characteristics obtained by each method agree very well with each other. When the offset metal walls are finite in height, an unexpected additional set of leaky modes is present that can couple to the expected offset-groove-guide leaky mode and produce quite complicated but interesting modal behavior. This behavior is discussed as a function of offset and wall height.

1. Introduction

Groove guide is one of several low-loss waveguiding structures proposed about 20 years ago for use at millimeter wavelengths. The cross section of the original groove guide is shown in Fig. 1(a), together with an indication of the electric field lines of the lowest mode. The greater width in the central region serves as the mechanism that confines the field. The field thus decays exponentially away from the central region in the narrower regions above and below it, causing the mode to be purely bound. The introduction of any asymmetry, however, converts some of the power in that bound mode into radiation so that the net resulting mode becomes leaky.

An example of that asymmetry is indicated in the offset groove guide shown in Fig. 1(b). When the offset is small, as may occur when the groove guide is supposed to be symmetrical but is not carefully made, the bound dominant mode becomes only slightly leaky. On the other hand, when the offset is deliberately made large, large leakage rates are found to be present. The leakage rate can therefore be controlled over a large range of values simply by adjusting the amount of offset. It was recognized by us that this effect could be used to produce a simple new leaky-wave antenna [1] for which the beam width can be easily adjusted. Actually, in that application the structure in Fig. 1(b) is bisected horizontally with a metal wall; the structure then resembles a rectangular waveguide with an offset open stub on its top wall.

An inspection of the electric field lines in Fig. 1(b) shows that the asymmetry produces a net horizontal electric field in the narrower regions above and below the central region; such electric field lines are not present in the symmetrical guide in Fig. 1(a). The net horizontal electric field lines correspond to TEM waves that propagate at an angle in the parallel plate narrower regions and therefore leak power away from the central region. This leakage of power then causes the propagation constant in the offset groove guide to be complex, as $k_z = \beta - j\alpha$, if z is the longitudinal direction, perpendicular to the page.

The behavior of the phase constant α and the leakage constant β as a function of the geometric parameters was computed in two totally different ways, and then compared. The two methods are:

(a) By using a transverse equivalent network that is based on a new E-plane tee network with elements for which we have derived closed-form expressions. The dispersion relation is therefore simple and is also in closed form.

(b) By using an accurate mode-matching procedure in which the convergence was checked each time.

As is seen below, the results obtained using these two completely different methods agree very well with each other.

2. The Two Methods of Calculation

As indicated above, the offset groove guide shown in Fig. 1(b) has been analyzed accurately by two entirely different methods. These two methods are now described briefly, with the greater attention paid to the one involving a new tee network, which is discussed first.

(a) Transverse Equivalent Network Employing a New E-Plane Tee Network

The cross section of the structure being analyzed is shown as the upper portion of Fig. 2; it is seen to be the same as the one in Fig. 1(b) after the latter is bisected horizontally with a metal wall, an action that does not change the field distribution. The height of the stub arm is assumed at first to be infinite. The structure is then viewed as an E-plane tee junction with main guide arms of unequal length. The transverse equivalent network that characterizes this E-plane tee junction structure is shown in the lower portion of Fig. 2.

Two features are novel here. The first is the approach itself, viewing the offset groove guide in terms of a tee junction. The second new feature is that we have derived closed-form expressions for the elements B_a , B_L and n_c of the network. The dispersion relation is obtained from a resonance of this network; since all the constituent elements are in closed form, the dispersion relation is also.

(b) Accurate Mode-Matching Procedure

The mode matching is performed in the vertical direction in the structure shown in the upper portion of Fig. 2. In the upper waveguide, of narrower width, only the TEM mode is above cutoff; in the lower guide, three modes are above cutoff, the TEM mode and the first TE and TM higher modes. The mode-matching procedure is set up rigorously, and then, for most points, 100 TE and TM modes are included in the numerical computations. Convergence in the mean-square sense is employed.

3. Comparison of Results

Calculations were made for various sets of dimensions and some of those calculations are shown in Figs. 3 and 4. Plots are presented for the variations of β/k_o and α/k_o (normalized phase constant and normalized leakage constant) as a function of offset and as a function of frequency. In all cases, the results are computed using both of the methods discussed above.

The first point to be noted is that in all cases the agreement between the values computed the two entirely different ways is very good indeed. That agreement holds over wide ranges of relative offset (d/a) and frequency (f), indicating that both methods yield accurate results and implying that the simple, closed-form expressions for the elements of the tee network are reliable.

The next point to observe is that the leakage rate (α/k_o) spans a very large range of values as d/a is varied, and does so in a smooth monotonic fashion. In addition, the β/k_o value remains rather constant as d/a is changed. For the antenna application, this performance is very gratifying, since it indicates that the beam width can be adjusted over a large range of values by varying d/a, and that the angular location of the beam remains relatively unaffected.

4. Modifications Due to the Finite Height of the Offset Walls

The numerical values presented in Figs. 3 and 4 correspond to offset walls of infinite height (or length in the vertical direction). In practice, however, those walls must be finite, of height c. It turns out that, unless special precautions are taken, the effect of finiteness is to produce sets of new complex waves that greatly complicate the propagation characteristics. It is true that most of the basic performance features are determined from the study of the infinite-wall-height case. In most cases, furthermore, one would expect that a finite-height pair of walls, rather than ones of infinite height, should produce only minor modifications in performance. In the offset groove guide, however, the finiteness introduces an unexpected completely new effect that can change the performance substantially.

It was mentioned above that the asymmetry produces a TEM mode that leaks power away an an angle. When the offset walls are of finite height c, this power then reaches the upper open end; some power is reflected to form a mild standing wave in the region of length c, and the rest of the power is radiated. Under those conditions, the effect of finite c would be to introduce only a modest perturbation in the performance characteristics. Let us call this perturbed leaky mode the "offset-groove-guide leaky mode," and let us recognize that for this mode most of the power resides in the wider region (of width a and height b), with some small portion of the power leaking away per unit length along z in the region of height c.

The complication that arises is due to the fact that another set of leaky modes can exist in the offset groove guide, but only when c is finite. These additional leaky modes, which can exist independently of the offset-groove-guide leaky mode, are a modification of the so-called "channel-guide leaky modes" that were studied some 30 years ago. The power in those modes exists primarily in the region of height c, and their fields are TEM-like, with the electric fields normal to the metal parallel-plate walls.

When the values of both β and α of a channel-guide leaky mode are equal to those for the offset-groove-guide leaky mode, those modes will couple; as a result, the propagation behavior can become quite complicated. Ordinarily, the leakage constants α for the channel-guide leaky modes are very high. Thus, if the α for the offset-groove-guide leaky mode is low, corresponding to small offsets from symmetry, no coupling effects will occur. For larger offsets, and therefore larger values of α, coupling will indeed occur, as we shall see next. (Such coupling effects due to the presence of the channel-guide leaky modes were also found in nonradiative dielectric (NRD) guide with an air gap and with finite walls [2], but the effects observed here are more pronounced.)

5. Quantitative Examples of the Coupling Behavior

The coupling behavior due to the finite height of the offset walls was analyzed using the two methods described above. In each case, the discontinuity corresponding to the radiating open end was taken directly from the Waveguide Handbook [3], and the transverse equivalent networks were modified accordingly. The propagation characteristics computed the two different ways again agreed well with each other.

Quantitative results for three specific structures are presented in Fig. 5. The parameter values are: $a/\lambda_o = 0.8$, $a'/\lambda_o = 0.4$, and $b/\lambda_o = 0.4$; the three cases differ in the values of the offset, d/λ_o. For each case, the normalized phase constant β/k_o and the normalized leakage constant α/k_o are plotted as a function of c/λ_o, where c is the height of the metal parallel-plate walls. If the frequency is taken to be 50 GHz, then a = 4.8 mm and b = 2.4 mm, corresponding to standard rectangular waveguide in that frequency range. The values of d then become 1.0 mm, 0.8 mm and 0.5 mm, with the larger values of d representing smaller offsets.

In Fig. 5, for the case on the left, corresponding to the smallest offset value, the nearly horizontal line for β/k_o represents the offset-groove-guide leaky mode, which is seen to change very little as c/λ_o varies. The curves indicated by 1 through 4 mean those for the channel-guide leaky mode, which are seen to change significantly as c/λ_o varies because they resemble a rectangular waveguide mode. With respect to the leakage constant behavior, the offset-groove-guide leaky mode exhibits lower values of α/k_o than do the channel-guide leaky modes, and its behavior is approximately oscillatory as c/λ_o changes. The points indicated by A correspond to one another; at this value of c/λ_o the phase constants coincide but a large difference exists between the leakage constants. As a result, these two leaky modes do not couple, but each mode propagates while maintaining its own characteristic complex wave nature.

At point B, on the other hand, the complex propagation constants (i.e., both β and α) of each of the two leaky modes are almost coincident. They then couple to each other for this value of c/λ_o. The coupling behavior in the β/k_o curve results in typical directional coupling response, where one complex mode changes over into the other as one moves away from the coupling point. In the α/k_o curve, the two separate curves approach each other until they touch, and then the modes also interchange with each other. This type of interchange along curve 4 is indicated by the dotted points.

In the other cases in Fig. 5, the offset (and therefore the asymmetry) is greater, and such coupling behavior occurs at lower values of c/λ_o. The amount of the coupling also increases, so that the propagation characteristics become quite complicated.

6. References

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2. H. Shigesawa, M. Tsuji and A. A. Oliner, "Effects of Air Gap and Finite Metal Plate Width on NRD Guide," Digest 1986 IEEE International Microwave Symposium, pp. 119-122, Baltimore, MD, June 2-4, 1986.

3. N. Marcuvitz, Waveguide Handbook, Vol. 10, MIT Radiation Laboratory Series, McGraw-Hill Book Co., New York, 1951, pp. 179-183.

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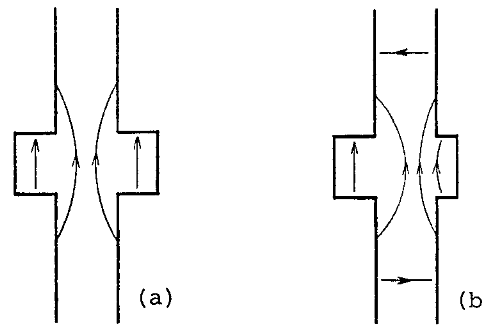


Fig. 1 Cross section and typical electric field lines for: (a) lowest mode in symmetrical groove guide, and (b) lowest mode (which now becomes leaky) in offset groove guide.

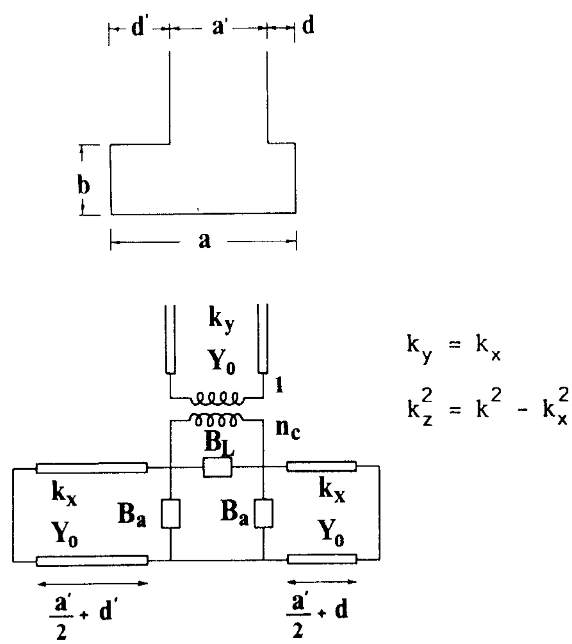
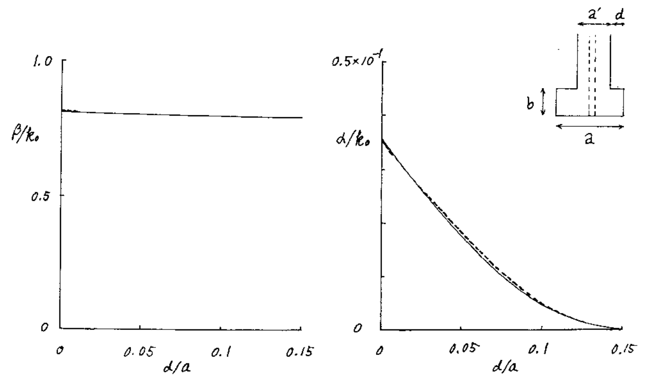


Fig. 2 Cross section and transverse equivalent network for the horizontally bisected offset groove guide.



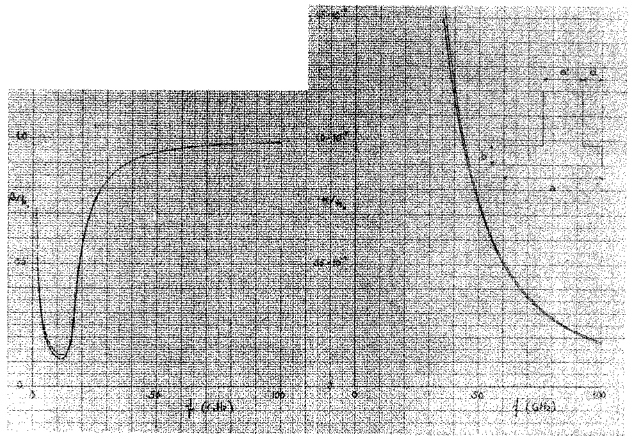


Fig. 3 Normalized phase constant β/k_0 and normalized leakage constant α/k_0 as a function of relative offset d/a for the offset groove guide. The parameters are: a = 1.00 cm, a' = 0.700 cm, b = 0.300 cm, f = 28.0 GHz. The solid lines correspond to the mode-matching results, and the dashed lines to the tee-network solution.

Fig. 4 Normalized phase constant β/k_0 and normalized leakage constant α/k_0 as a function of frequency for the offset groove guide. The parameters are: a = 1.00 cm, a' = 0.400 cm, b = 0.200 cm, d = 0.200 cm. The lower line in both plots corresponds to the mode-matching results, the upper line in each to the tee-network solution.

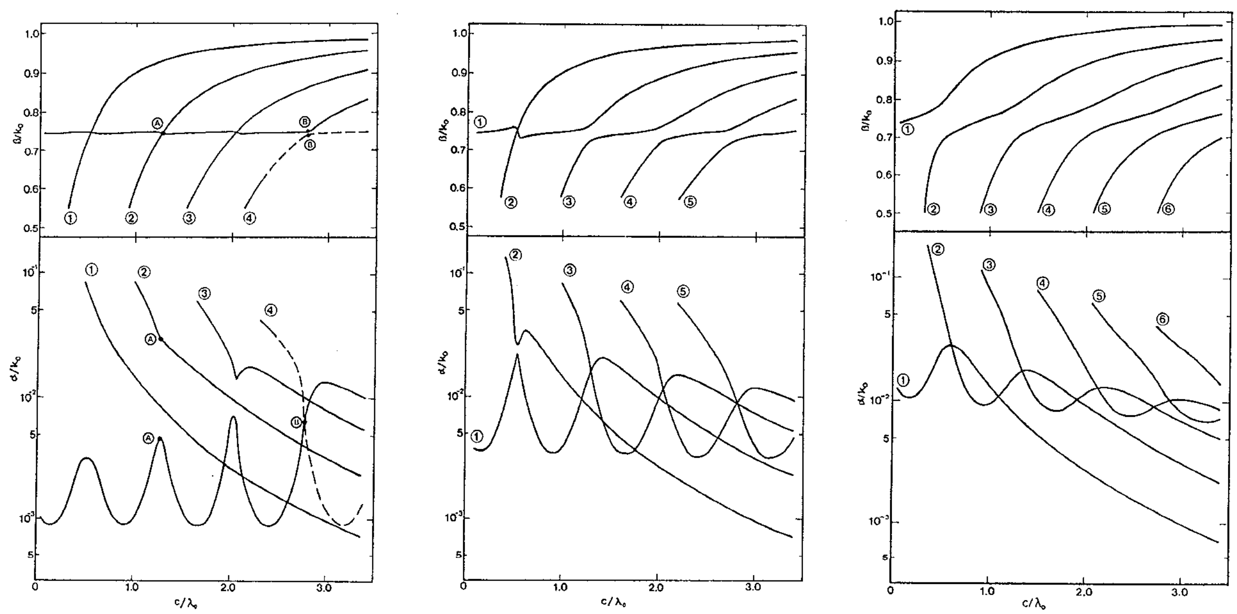


Fig. 5 Behavior of normalized phase constant β/k_0 and normalized leakage constant α/k_0 as a function of normalized height c/λ_0 of the finite-height offset walls. The parameters are $a/\lambda_0 = 0.8$, $a'/\lambda_0 = 0.4$, $b/\lambda_0 = 0.4$. From left to right, the normalized offsets d/λ_0 are 0.167, 0.133 and 0.083, corresponding to d = 1.0 mm, 0.8 mm and 0.5 mm, respectively, when f = 50 GHz. The amount of offset increases in the cases from left to right. As seen, stronger coupling effects occur for larger values of offset and c/λ_0.