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LEAKY MODES OF SYMMETRICAL GROOVE GUIDE

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Abstract

Both the odd and even higher modes of groove guide, a low-loss waveguide proposed some years ago for millimeter wavelengths and of interest again today, are investigated quantitatively. We verified an early prediction that all the odd higher modes leak, and we find that all even higher modes do also. The leakage is obtained quantitatively by deriving accurate transverse equivalent networks, all of whose elements are in closed form. The implications for new leaky-wave antennas are also indicated.

Introduction

Groove guide is one of a group of waveguiding structures proposed 20 or more years ago for use at millimeter wavelengths. Those waveguides were not pursued beyond some initial basic studies because they were not yet needed, and because adequate sources for millimeter waves were not yet available. Today, such sources are readily available, and the many advantages of millimeter waves are becoming increasingly appreciated.

It was also recognized some years ago that the shorter wavelengths associated with millimeter waves produce problems relating to the small size of components and the high attenuation of the waveguides. New types of waveguide were therefore proposed for which the attenuation per unit length would be substantially lower than that for customary waveguides, and for which, in some cases, the cross section dimensions were greater. Groove guide is one of the waveguides in that category, and attention is again being paid to it in the context of components for it and new leaky-wave antennas which are based on it.

The basic form of open symmetrical groove guide is shown in Fig. 1, together with an indication of the electric field lines present for the lowest mode. One should note that the structure resembles that of rectangular waveguide with most of the top and bottom walls removed. The attenuation associated with those walls increases as the frequency is increased, whereas the attenuation due to the side walls (with the electric field parallel to the walls) decreases with increasing frequency. Therefore, the overall attenuation for groove guide at higher frequencies is very much less than for rectangular waveguide.

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 below. 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 in the 1970's by D. J. Harris and co-workers[7-8] in Wales.

It has been shown in the previous publications that the dominant mode in groove guide is a TE mode in the longitudinal direction whose theoretical propagation characteristics agree reasonably well with measurements. Little is known, however, about the nature of the higher modes. The only reference in the literature relates to the odd higher modes, and it corresponds to a small section in a paper[2] by Nakahara and Kurauchi. By examining the simple relations among various wavenumbers, these authors obtained the very interesting conclusion that the dominant mode is always bound, and that all odd higher modes are leaky. These considerations show whether or not the particular mode is leaky, but they do not indicate the magnitude of the leakage.

Transverse Equivalent Network for First Higher Odd Mode

We have recently verified their original qualitative conclusions for these odd higher modes, and by extension we obtained additional information on the propagating or evanescent nature of various field components. We then derived a transverse equivalent network that takes into account the coupling between the dominant and the first higher odd transverse mode; this network is shown in Fig. 2. From this equivalent network we have obtained quantitative values of the propagation behavior, including the leakage constant.

Let us recognize that we are investigating the case for which the cross section dimensions are large enough to permit both the dominant and the first higher odd longitudinal modes to propagate. Looking in the y direction of Fig. 1, we then see that the guide can be initially excited such that the incident power is basically in the $i = 1$ transverse mode, for which the x dependence is a half sine wave, or in the $i = 3$ transverse mode, for which the x dependence contains three half sine waves. These excitations result in the $n = 1$ and $n = 3$ longitudinal modes, respectively. In either case, we observe that at the step junction an $i = 1$ or $i = 3$ transverse mode will couple to all other transverse modes of the same symmetry; for example, the $i = 3$ mode will couple to all of the $i = 1, 5, 7, \ldots$ transverse modes. In the transverse equivalent network of Fig. 2, the $i = 1$ and $i = 3$ transverse modes are separated out, and separate transmission lines are furnished for each of them. It is necessary to derive expressions for all the parameters of the network in Fig. 2, and we have obtained simple closed-form expressions for all of them. The coupling susceptance between the transmission lines was derived using small obstacle theory in a multimode context.

When the groove guide is excited in dominant mode fashion, the $i = 1$ transmission line is propagating in the central region of width a, but evanescent in the outer narrower regions of width a'. Also, it can be shown that the $i = 3$ transmission line is below cutoff everywhere, so that the dominant longitudinal mode is purely bound. On the other hand, when the groove guide is excited in the first higher odd longitudinal mode, corresponding to the $i = 3$ transverse mode, the $i = 3$ transmission line is propagating in the central region but evanescent in the outer regions. But, the $i = 1$ transmission line can now be shown to be propagating in both the central and the outer regions. The result is that the first higher odd mode is leaky, but

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with the interesting feature that the energy that leaks has the variation in x of the dominant mode, not of the first higher mode.

These coupled transverse modes combine to produce a net TE longitudinal mode (in the z direction) with a complex propagation constant, $\beta - j\alpha$. From the transverse equivalent network of Fig. 2 one can readily derive the dispersion relation in the form of a transcendental relation all of whose constituents are in a simple closed form. The leakage constant α can be found readily from this dispersion relation.

Numerical Results for First Higher Odd Mode

We now present some numerical results for the behavior of the phase constant β and the attenuation constant α of the leaky mode that results when the groove guide is excited in the first higher odd longitudinal mode (the $i = 3$ transverse mode). In Figs. 3(a) and 3(b) we plot the variation of β and α as a function of frequency. We see from Fig. 3(a) that β is almost linear with frequency at the higher frequencies, but shows substantial curvature near cutoff. The variation of α with frequency, in Fig. 3(b), is seen to be almost hyperbolic at the higher frequencies; nearer to cutoff, α is seen to rise substantially.

These variations follow directly from the simple wavenumber relationships. By taking the real part, and noting that the transverse wavenumbers are independent of frequency, we find that β is approximately linearly proportional to the frequency when α is small, which occurs for the higher frequencies. Such behavior is in agreement with that in Fig. 3(a). When we take the imaginary part, we find that the product $\alpha\beta$ should remain independent of frequency. In the frequency range for which β is proportional to frequency, we thus find that α must vary as the reciprocal of the frequency, in agreement with Fig. 3(b).

The variations of β and α with the dimension b, which is the height of the central region, are presented in Figs. 4(a) and 4(b). The behavior of α, in Fig. 4(b), is particularly interesting. We observe that the curve seems to be comprised of a basic envelope which decreases monotonically as b increases, modified by a series of nulls which depress the envelope curve periodically. The basic envelope shape can be understood physically when we recognize that the k_{y3} dependence (of the exciting mode) in the central region varies with b. When b is large, $k_{y3}b$ is large and the variation of the field in the y direction in the central region approximates a half-period sine wave in shape. Thus, the field at the step junctions is substantially lower than the field at the middle of the central region. As a result, the interaction between the $i = 1$ and $i = 3$ modes is substantially reduced, and the value of α becomes much lower. When b is small, $k_{y3}b$ is small, and the field variation in the central region becomes only a fraction of the half-period sine wave, so that the field at the step junctions is nearly the same as that in the middle of the central region. Then, the interaction between the $i = 1$ and $i = 3$ modes is increased, and α increases.

The cause of the nulls in Fig. 4(b) may be understood by reference to the transverse equivalent network in Fig. 2. A standing wave in the vertical direction is present in the $i = 1$ mode in the central region. When the electrical length of that standing wave is a multiple of π, it is seen from Fig. 2 that a short circuit will appear across the terminals in the $i = 1$ transmission line that connect the $i = 1$ line with the exciting $i = 3$ line. No power is then coupled into the $i = 1$ line from the $i = 3$ line, and no leakage occurs for those values of b. Of course, as b approaches zero those terminals are again short-circuited and the leakage vanishes, as seen in Fig. 4(b).

Higher Even Modes

The results described above apply to the spectrum of odd higher modes. We have also examined the spectrum of even higher modes. We find there that qualitatively the same leakage behavior is obtained, but that certain interesting differences appear in the dependence of the leakage constant on the dimensional parameters. For that study we have derived a transverse equivalent network which couples the second mode and the zero-order mode, which is a TEM-like mode, and we find that, if we excite the second mode in the groove guide, it will leak, but the transverse form of the leakage is TEM-like and not of the form of the exciting second mode. In a sense, this leakage behavior is similar to that found for third mode (first higher odd mode) excitation, but the polarization of the electric field of the leakage energy is horizontal here whereas it was vertical there. This behavior is very interesting from the standpoint that it can form the basis for two new types of leaky-wave antenna, with vertical and horizontal polarization, respectively. These antennas would have a continuous aperture and be very simple in form, a feature which would be particularly attractive for millimeter wavelengths.

Some of the above-described material for the odd modes was presented recently at a national conference in Italy.[9] Space does not permit the presentation here of quantitative numerical results for the first even higher mode, but qualitatively they are similar to those for the first odd higher mode, although some interesting differences appear. It is hoped that a more complete version can be presented soon for publication.

Acknowledgment

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References

1. Polytechnic Institute of Brooklyn, Microwave Research Institute, Monthly Performance Summary, Report PIBMRI-875, pp. 17-61, 1961.

2. T. Nakahara and N. Kurauchi, "Transmission Modes in the Grooved Guide," J. Inst. of Electronics and Commun. Engrs. of Japan, Vol. 47, No. 7, pp. 43-51, July 1964. Also in Sumitomo Electric Technical Review, No. 5, pp. 65-71, January 1965.

3. H. Shigesawa and K. Takiyama, "Transmission Characteristics of the Close Grooved Guide," J. Inst. of Electronics and Commun. Engrs. of Japan, Vol. 50, No. 11, pp. 127-135, November 1967. Also in "On the Study of a Close Grooved Guide," Science and Engineering Review of Doshisha University, Japan, Vol. 9, No. 1, pp. 9-40, May 1968.

4. F. J. Tischer, "The Groove Guide, a Low-Loss Waveguide for Millimeter Waves," IEEE Trans. on Microwave Theory Tech., Vol. MTT-11, pp. 291-296, September 1963.

5. J. W. E. Griemsmann, "Groove Guide," Proc. Sympos. on Quasi-Optics, Polytechnic Press of

Polytechnic Institute of Brooklyn, pp. 565-578, 1964.

6. N. Y. Yee and N. F. Audeh, "Wave Propagation in Groove Guides," Proc. National Electronics Conf., Vol. 21, pp. 18-23, 1965.

7. D. J. Harris and K. W. Lee, "Groove Guide as a Low-Loss Transmission System for Short Millimetric Waves," Electron. Lett., Vol. 13, No. 25, pp. 775-776, December 8, 1977. Professor Harris and his colleagues have published many papers on this topic, of which this is one of the first. One of their latest works is given as reference 8.

8. D. J. Harris and S. Mak, "Groove-Guide Microwave Detector for 100 GHz Operation," Electron. Lett., Vol. 17, No. 15, pp. 516-517, July 23, 1981.

9. P. Lampariello and A. A. Oliner, "Bound and Leaky Modes in Symmetrical Open Groove Guide," Atti della 4ª Riunione Nazionale di Elettromagnetismo Applicato, Firenze, Italy, October 4-6, 1982.

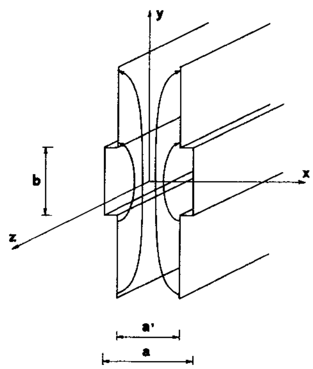

Fig. 1 Cross section of symmetrical, nonradiating groove waveguide. The ends can either be left open, as shown, or be closed off.

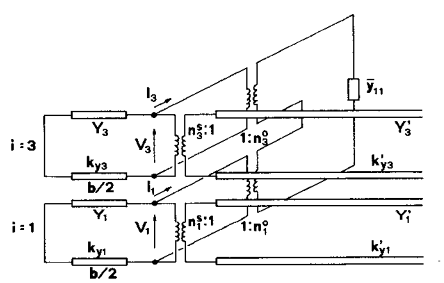

Fig. 2 Transverse equivalent network, bisected in view of symmetry, for the structure whose cross section is shown in Fig. 1 (for clarity, the network is placed horizontally rather than vertically).

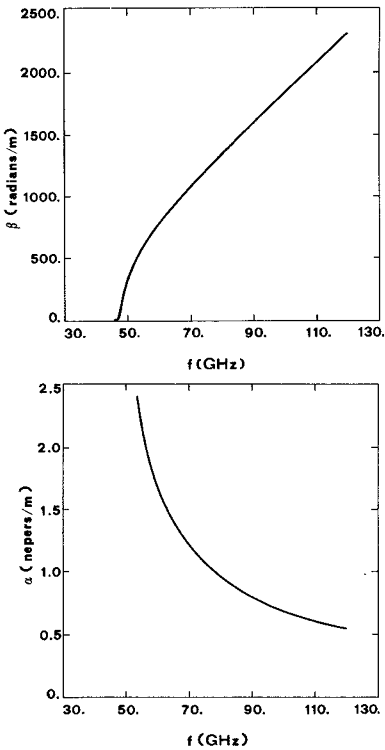

Fig. 3 The variations with frequency of the phase constant β and the leakage (or attenuation) constant α of the leaky mode that results when the groove guide is excited in the first higher longitudinal mode ($a'/a = 0.7$, $b/a = 0.4$).

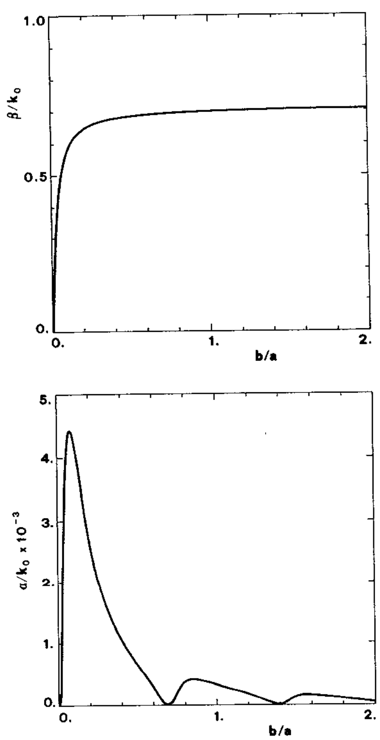

Fig. 4 The variations of the phase constant β and the leakage constant α, both normalized to the free space wavenumber k_o, of the leaky mode as a function of the height b of the central region in the groove guide, normalized to the width a ($f = 64$ GHz, $a'/a = 0.7$).