New Interesting Leakage Behavior on Coplanar Waveguides of Finite and Infinite Widths

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***Abstract*—In previous work we showed that above a critical frequency the dominant mode on coplanar waveguide leaks power in the form of a surface wave on the surrounding substrate, and that this leakage can cause undesirable cross talk and can produce unexpected package effects. Further studies now reveal several new interesting behavioral features, such as unexpected sharp and deep minima (cancellation effects), various dimensional dependences, and how the leakage behavior varies significantly when the guide width changes from finite to infinite.**

I. Introduction

We HAVE shown in previous work [1], [2] that, when the frequency of operation is increased sufficiently, the dominant mode on conventional coplanar waveguide (CPW) becomes leaky instead of remaining purely bound, as had always been believed. This leakage of power occurs in the form of a surface wave on the surrounding substrate that travels away at an angle from the CPW itself. Such power leakage can, of course, result in cross talk with neighboring portions of the circuit, and it can produce unexpected package effects. It may therefore be important from a practical standpoint to understand when such leakage effects can occur and what their characteristics are.

We have recently studied these leakage effects in more detail, and we find several new interesting behavioral features. In this paper, we describe these new features, and we systematize them to indicate when the leakage effects are strong and when not, when interesting unexpected sharp and deep minima (cancellation effects) occur and how they depend on the structural parameters, and how the leakage behavior varies significantly when the CPW width changes from finite to infinite.

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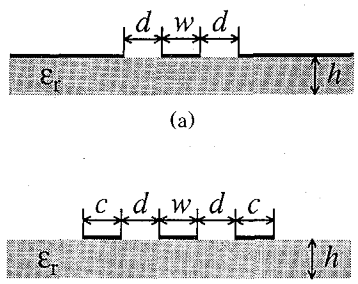

Fig. 1. Cross-section views of conventional coplanar waveguide. (a) When the lateral width is infinite. (b) When it is finite, with outer strips of width c.

II. Background

The surface wave that leaks power is different when the CPW has finite or infinite width. These two structures are shown in Fig. 1 with the dimensional notation to be used. The guides are of the conventional type, not conductor backed, and the difference between them is only that width c is infinite or finite. When c is *infinite*, the structure that surrounds the central guiding region is a dielectric layer of thickness h with a conducting plane on its top surface. The lowest surface wave that this surrounding structure can support is the TM_0 surface wave. When c is *finite*, the surrounding structure is a dielectric layer of the same thickness, but without any conducting plane, and the lowest surface wave it can support is the TE_0 surface wave.

The CPW dominant mode has relatively little dispersion, but the surface waves are strongly dispersive, with low values of β/k_0, the normalized phase constant, at low frequencies and with values approaching the index of refraction of the substrate at very high frequencies. At some frequency the dispersion curves for the CPW mode and the relevant surface wave mode cross each other. We have shown that at frequencies above this crossing the CPW dominant mode is no longer purely bound, but becomes leaky, with the power leaked away at an angle in the form of the lowest surface wave that can be supported

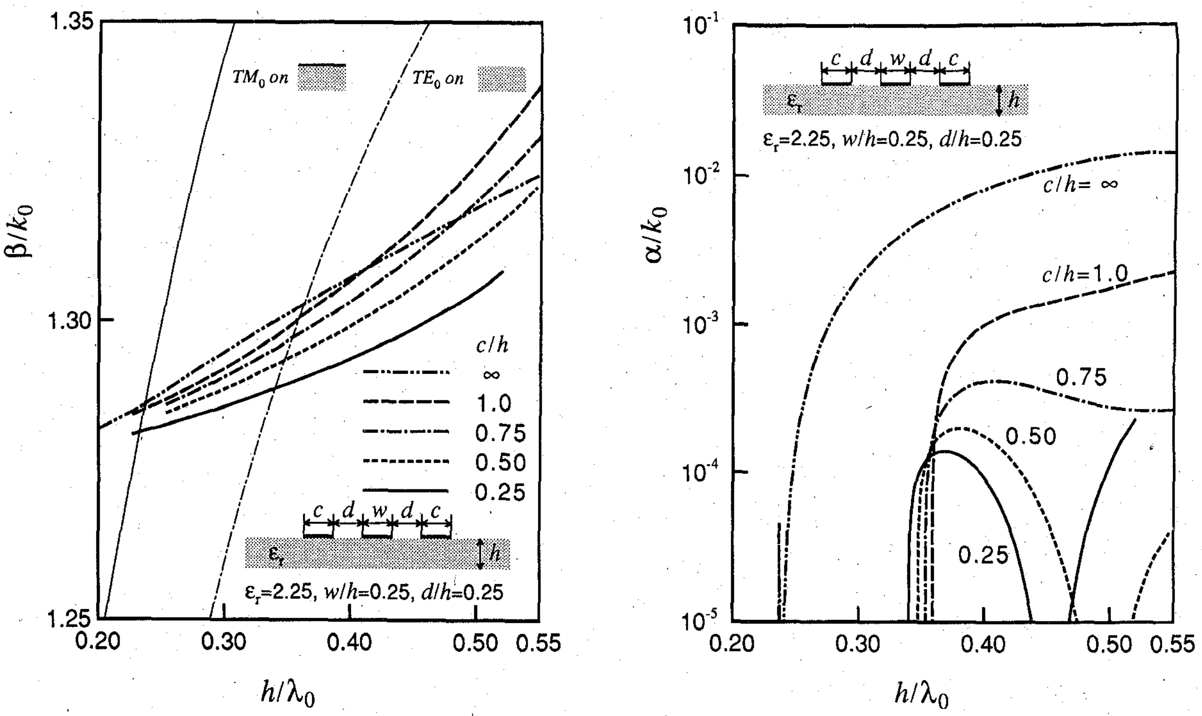

Fig. 2. Behavior of the normalized phase constant β/k_0 and the normalized leakage constant α/k_0 of conventional coplanar waveguide of finite width as a function of frequency (in the normalized form h/λ_0). The outer strip width c is taken as the parameter, and results for the case of infinite width are included for comparison.

by the surrounding structure. At still higher frequencies, crossings occur that involve the higher surface waves, with the result that power is also leaked into those surface waves as well. Concentrating now on only the behavior when leakage begins, we thus note that the power that is leaked occurs in the form of the TE_0 surface wave on an ungrounded dielectric layer when c is finite, and the TM_0 surface wave on a grounded dielectric layer of the same height (or thickness) when c is infinite. We observe not only that the surface waves are different but that the surrounding structures are different as well.

III. The New Leakage Properties

The new leakage studies that we have conducted recently shed important light on three behavioral features:

1) The conditions under which the leakage rate is strong or weak,
2) The significant modifications in leakage behavior that occur when the CPW width changes from finite to infinite, and
3) The presence of unexpected sharp minima (cancellation effects) in the leakage rate.

We first discuss the new leakage behavioral features for CPW's of finite width, and then examine the corresponding features for the case for which the CPW has infinite width. In Section IV, electric field plots are presented which verify some of the behavioral features described in the present section. All of the numerical results herein have been obtained by the spectral domain method.

A. Behavioral Features for CPW's of Finite Width.

Many of these new behavioral features are summarized in Fig. 2, which presents the variations of the phase constant β and the leakage constant α, both normalized to the free-space wavenumber k_0, as a function of h/λ_0, the height (or thickness) of the dielectric substrate relative to the free-space wavelength. The curves are intended primarily to indicate the behavior of coplanar waveguide of *finite* width c, but for comparison the curves for infinite width are also included. The abscissa axis actually represents the variation with frequency, since h was held constant in the calculations.

We should first note that leakage occurs only at frequencies that are greater than the critical frequency at which the β/k_0 curve for the CPW dominant mode for the particular c/h value crosses the relevant surface wave curve. As indicated above, the relevant surface waves are the TE_0 surface wave on an ungrounded dielectric layer when c is finite and the TM_0 surface wave on a grounded dielectric layer when c is infinite. The data in Fig. 2 are seen to be consistent with these conditions.

The first *new* feature evident from Fig. 2 is that the value of leakage rate α/k_0 varies considerably, with the leakage rate soon after the onset of leakage increasing with increasing guide width c. Note that the ordinate scale is logarithmic, so that the α/k_0 for $c/h = 1.0$ is almost 10 times larger than that for $c/h = 0.25$. Furthermore, the leakage rate for infinite width is seen to be almost 10 times larger than that for $c/h = 1.0$, or almost two orders of magnitude larger than that for $c/h = 0.25$.

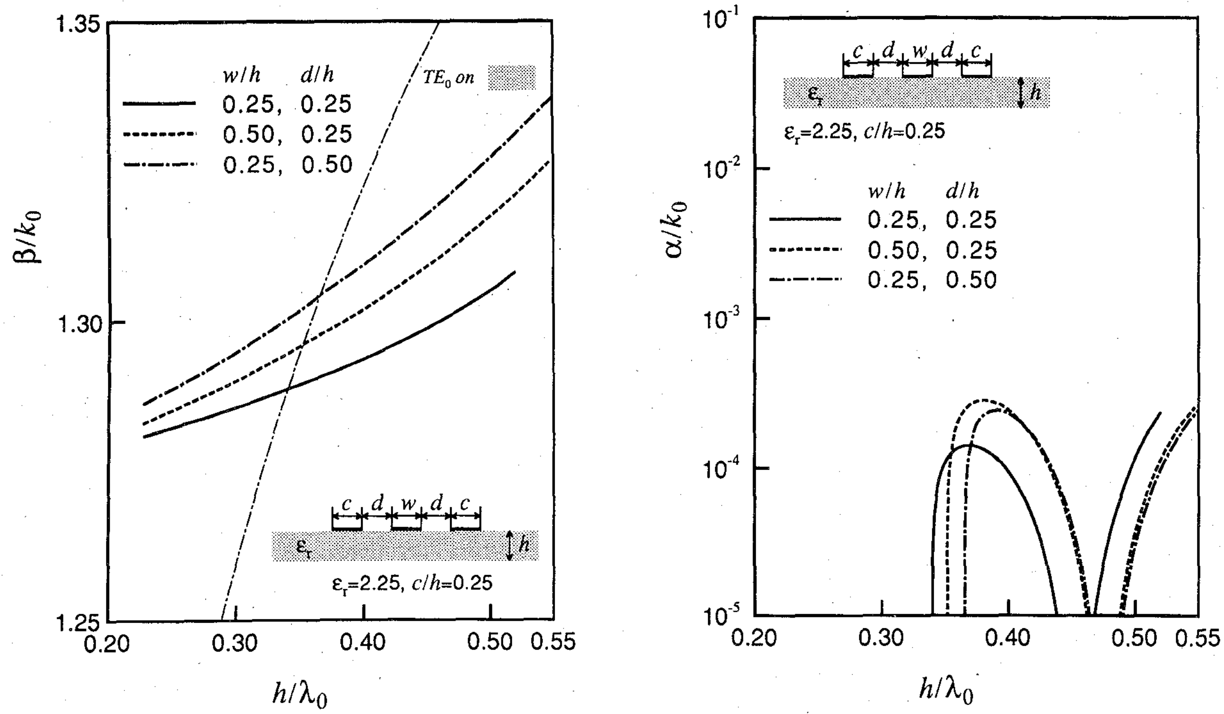

Fig. 3. These curves show the effects on β/k_0 and α/k_0 as a function of normalized frequency of changing the relative center strip width w/h and the relative gap width d/h of CPW of finite width. The relative outer strip width c/h is chosen here to be 0.25 since that width results in a cancellation dip.

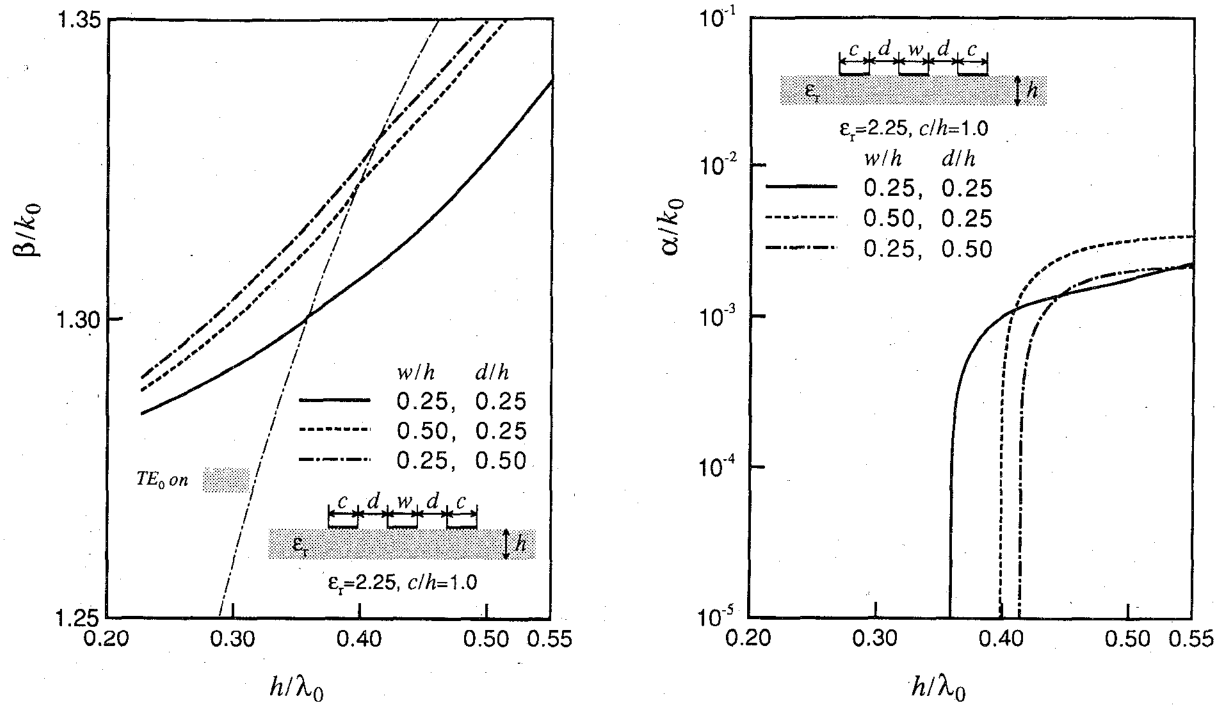

Fig. 4. Same as in Fig. 3 except that c/h is now chosen to be 1.0 so that no cancellation dip is present.

The next evident new feature is the presence of *sharp and deep minima* in the curves for α/k_0 for $c/h = 0.25$ and 0.50. We propose that these sharp drops are due to cancellation or resonance effects caused by the excitation of an additional surface wave at the outer edges of the strips of width c. At the outer edges of the strips there is leakage of power outward in the form of the TE_0 surface wave on an ungrounded dielectric layer, since that is the structure of the surrounding substrate. At the same time, however, those edge discontinuities will also excite inward the TM_0 surface wave under the metallic strip of width c, and therefore under the complete CPW structure of finite width. This TM_0 mode will then propagate at some angle with respect to the guide axis between the two outer

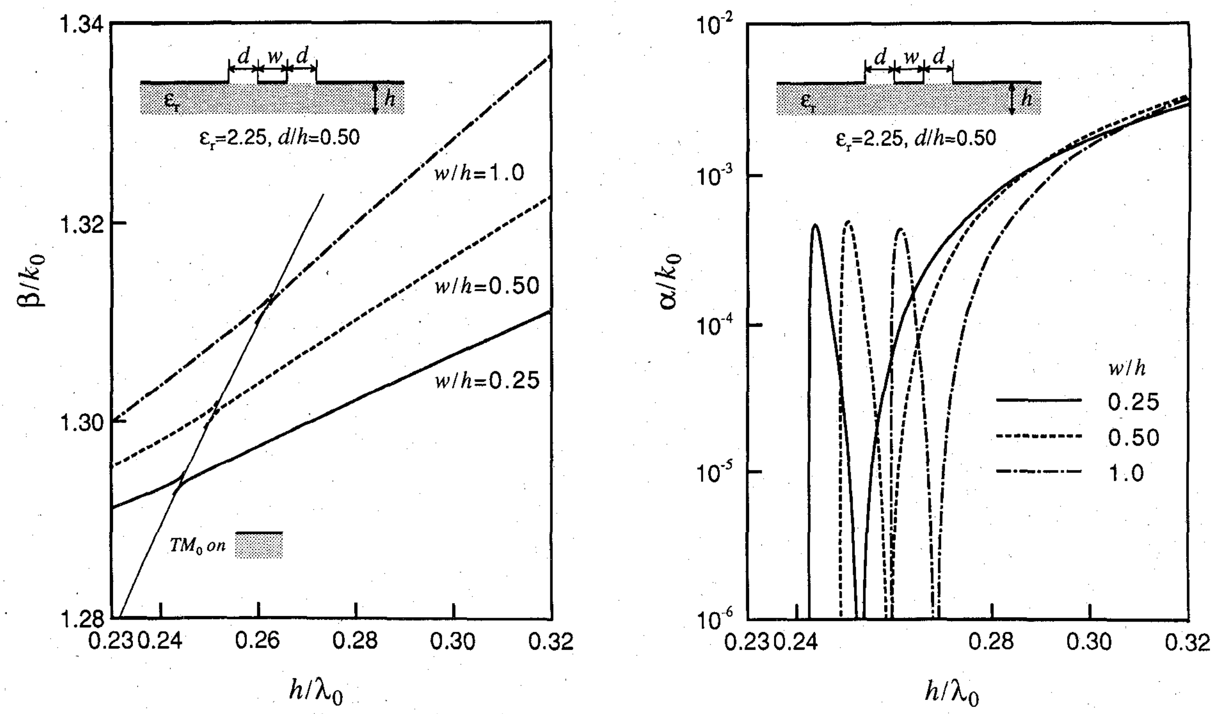

Fig. 5. Behavior of β/k_0 and α/k_0 as a function of normalized frequency for conventional coplanar waveguide of infinite width. The normalized gap width $d/h = 0.50$ for these curves, and the width w of the metal center strip is taken as the parameter. The sharp maximum and the sharp and deep minimum at the onset of leakage form the outstanding feature.

edges and become multiply reflected by them. For certain dimensions and frequencies a resonance can occur which would manifest itself in a cancellation effect and produce a sharp drop in the leakage rate. We have found a rough correlation with the curves in Fig. 2 based on this approach, but we have not been able to demonstrate close numerical agreement because it has been difficult to assess independently the reactive content of the edge discontinuities. A somewhat similar effect was discovered about a decade ago in leakage from dielectric strip waveguides [3]; very good quantitative agreement was found using this viewpoint but the reactive content of the edge discontinuities there was very small and could be neglected.

From Fig. 2 it is clear that changing the relative width c/h of the CPW exerts a very strong influence on the behavior of the leakage constant α/k_0. How important are the other dimensional parameters, the center strip width w/h and the gap width d/h?

The effects on β/k_0 and α/k_0 of changing w/h and d/h are illustrated in Figs. 3 and 4 for two different values of c/h. In Fig. 3, c/h is chosen as 0.25 since that width results in a cancellation dip. An examination of the values of α/k_0 shows that changing either w/h or d/h produces a relatively small change in the leakage values. The frequency corresponding to the onset of leakage is a little different for each of the three cases shown in Fig. 3 because the crossings of the β/k_0 curves with the TE_0 dispersion curve occur at slightly different frequencies. It may also be observed that the sum of w and d seems slightly more important than do the individual values of w or d.

In Fig. 4, c/h is taken as 1.0, for which no cancellation dip was found in Fig. 2. Here again, we note that the onset of leakage varies a bit with changes in w or d, but that no significant differences in behavior are found. Again, the sum of these two parameter values is slightly more important than their individual values. We may conclude from Figs. 2–4 that the behavior of α/k_0 depends very strongly on the value of c/h but rather weakly on the values of w/h or d/h.

B. Behavioral Features for CPW's of Infinite Width

When the outer strip width c of the CPW changes from finite to infinite, certain interesting differences occur in the leakage behavior. One of these differences has already been observed in Fig. 2, where the magnitude of α/k_0 for infinite width is shown to be much larger than one finds for any finite width. Further differences are found from Figs. 5 and 6, below, which are concerned only with CPW of infinite width.

The results in Fig. 5 indicate the effect of varying the width w of the metal center strip. In the β/k_0 plot, we observe the expected crossings with the surface wave curve. Interesting fine structure appears in the transition region in the immediate vicinity of the crossings, but we do not discuss those features here.

We concentrate in Fig. 5 on the α/k_0 behavior, in particular on the narrow sharp minima and associated narrow sharp peaks that occur immediately after the onset of leakage. Note that the abscissa scale is an expanded one. At higher frequencies, as seen in Fig. 2, the value of α/k_0 will exceed 10^{-2}, but in the range of these sharp peaks the values are less than 10^{-3}. By comparison

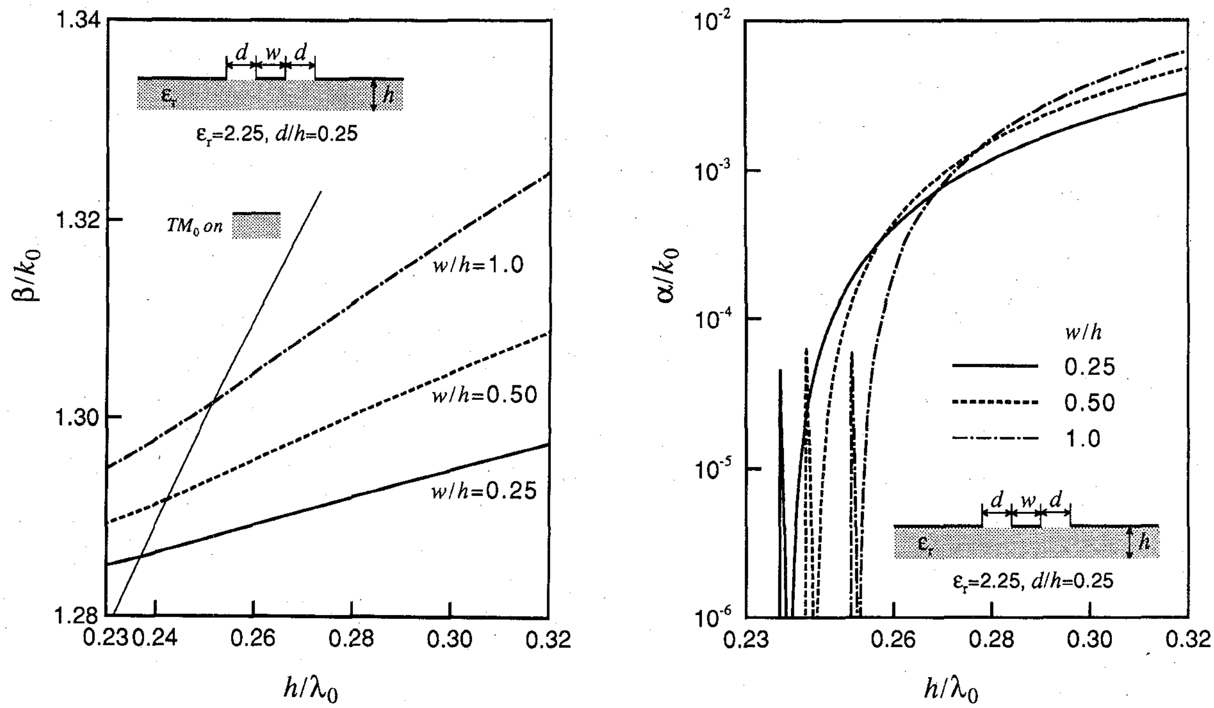

Fig. 6. The same as in Fig. 5 except that $d/h = 0.25$. The sharp maximum and the minimum at the onset of leakage are now much narrower.

with Fig. 2, we see that the *peaks* when c is infinite are *much narrower* than the ones found when c is finite.

Examination of the α/k_0 plot in Fig. 5 shows that when the width w of the central strip is varied the location of the peaks shifts, because the crossing with the surface wave curve occurs at a slightly different frequency. However, the widths and heights of the peaks and the widths of the minima are hardly changed at all.

The results shown in Fig. 5 apply to the case for which the relative gap spacing $d/h = 0.50$. When the gap spacing is reduced to $d/h = 0.25$, the resulting changes in behavior are shown in Fig. 6. We see that the changes are dramatic. The sharp peaks in the α/k_0 plot have now become much narrower, and the magnitudes at the peaks are now a decade smaller. Furthermore, as in Fig. 5, changing w/h only shifts the location of the peaks but affects the other features in only a minimal way. It is therefore clear that with respect to these sharp peaks and minima the central strip width plays a negligible role whereas the value of *gap width* strongly affects the properties of these peaks and minima.

The explanation in terms of a cancellation effect here as the cause of these narrow effects is harder to prove. We can again see that the discontinuity at the end of gap d will excite a TM_0 surface wave on a grounded dielectric layer in the region outside, and a TE_0 surface wave on an ungrounded dielectric layer in the gap region. So far, the explanation is encouraging because the gap region has been found to influence the behavior strongly. However, the curve for that surface wave lies below the CPW dominant mode curve, in contrast to the case for c finite, so that in the transverse direction (across the gap) the surface wave is evanescent instead of propagating. On the other hand, a reactance can be associated with the stored power in the gap so that some cancellation effect is possible, but a quantitative comparison with the data in Figs. 5 and 6 is not easy to make.

IV. Electric Field Plots at Different Frequencies

In an attempt to understand more fully the sharp maxima and minima in the curve of α/k_0, we computed the electric field vector behavior at three different frequencies, corresponding to the following physical situations: before any leakage occurs, at the leakage maximum just after the onset of leakage, and at the cancellation point. We selected the case for which the CPW has infinite width because the cancellation mechanism was difficult to prove quantitatively for that case. The three selected frequencies are indicated in Fig. 7, which corresponds to one of the sets of dimensions in Fig. 6.

The electric field plot corresponding to point ① in Fig. 7, for which there is *no* leakage, is shown in Fig. 8. The full guide cross section is seen in the inset, but only the right half is utilized in the field plot. The solid horizontal lines represent the metal portions of the CPW, and the horizontal dashed line refers to the bottom of the dielectric layer. The field is so strong in the neighborhood of the central region of the guide, however, that the field everywhere else is too small to be seen on this scale. As a result, the field away from the central region, within the box shown outlined on the right side of Fig. 8, is presented in Fig. 9, enlarged by a factor of 25.

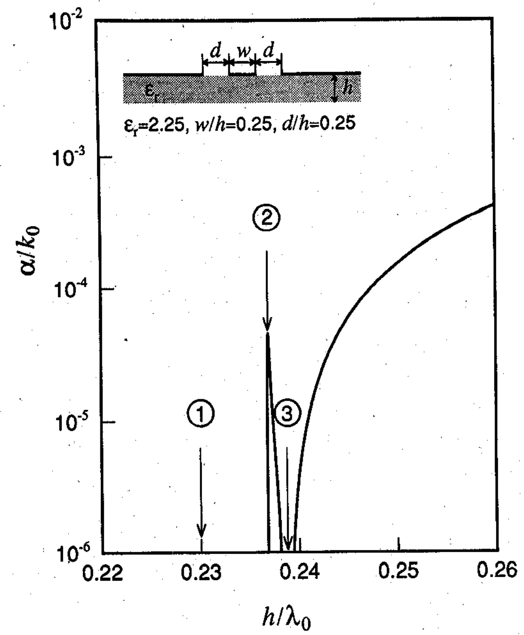

Fig. 7. In this graph of leakage rate versus frequency for CPW of infinite width, the three frequencies denoted by ① to ③ correspond to those chosen for the electric field plots in Figs. 9–11.

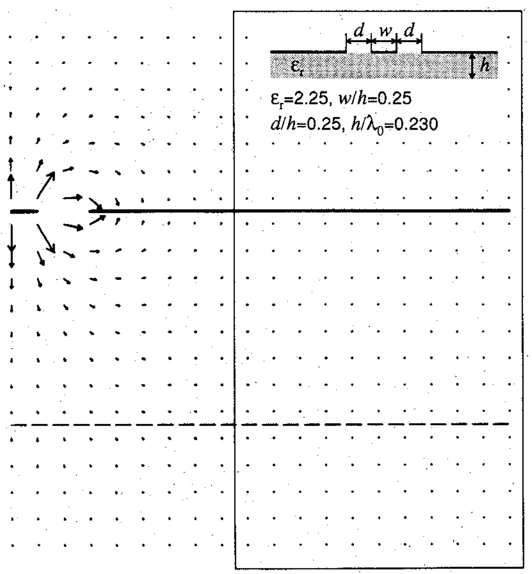

Fig. 8. Electric field plot corresponding to frequency ① in Fig. 7, for which there is no leakage. Only the right half of the CPW is utilized in the field plot; the solid horizontal lines represent the metal strips, and the horizontal dashed line refers to the bottom of the dielectric layer. The field is so strong in the central region of the CPW, however, that the field everywhere else is too small to be seen on this scale. The field within the box shown outlined on the right, away from the central region, is presented in Fig. 9 enlarged by 25 times.

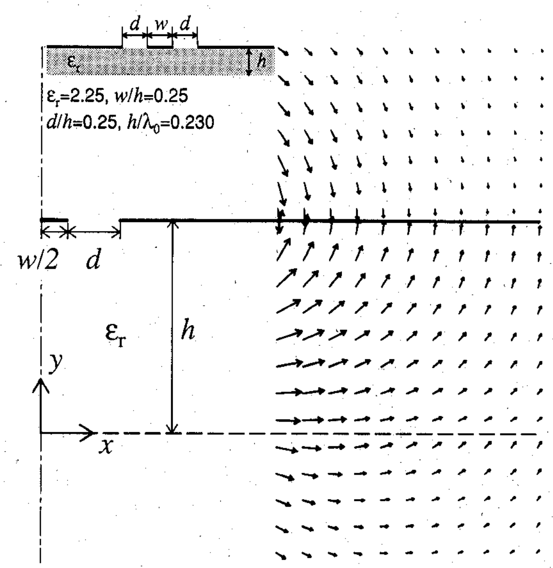

Fig. 9. Plot of the electric field within the box indicated in Fig. 8, but enlarged by a factor of 25. This plot corresponds to frequency ① in Fig. 7, for which there is no leakage.

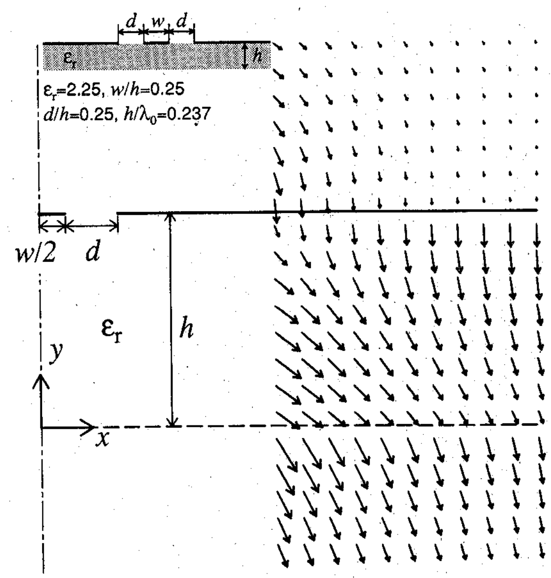

Fig. 10. Electric field plot similar to that in Fig. 9, also enlarged by a factor of 25, but corresponding to frequency ② in Fig. 7, at the top of the sharp leakage peak just after the onset of leakage.

In the enlarged field plot in Fig. 9, we observe that the field decays in the transverse (x) direction, as we would expect since the mode is purely bound for this frequency.

The next field plot, given as Fig. 10, corresponds to point ② in Fig. 7, at the *top of the sharp leakage peak* that occurs just after the onset of leakage. Since the leakage is in the form of the TM_0 surface wave on the grounded dielectric layer outside of the CPW central region, the electric field direction in the dielectric layer under the metal surface should be vertical in the cross-section plane far away from the central region. This is indeed what we find in Fig. 10, which again shows the field vector magnified by 25 times the values seen in Fig. 8. A plot similar to that in Fig. 8, but valid for point ② instead of point ① in Fig. 7, looks almost identical to the one shown in Fig. 8 because the value of the leakage constant is quite small in this example. It should also be noted in Fig. 10 that the field is almost completely vertical at the right hand edge of the plot shown, and that the horizontal component of field decays in the x direction

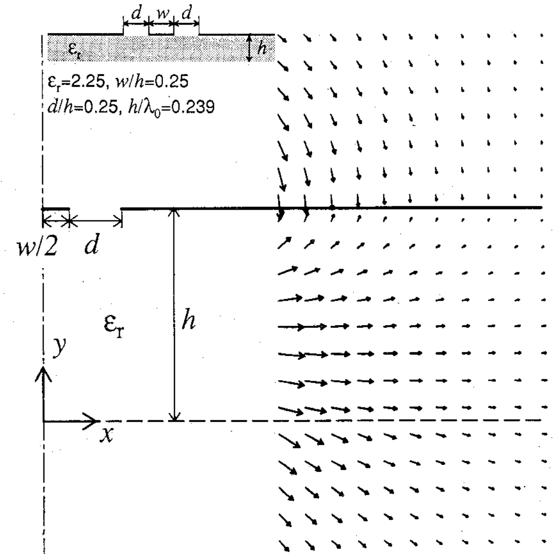

Fig. 11. Electric field plot similar to that in Figs. 9 and 10, also enlarged by a factor of 25, but corresponding to frequency ③ in Fig. 7, which is the cancellation point.

but the vertical component, representative of the leakage field, does not.

The final field plot, in Fig. 11, corresponds to point ③ in Fig. 7, which is the *cancellation point*. Since the value of α / k_0 is very small at this frequency, we might expect that the field plot would resemble the one found in Fig. 9, for which there is no leakage. We find a somewhat different result in Fig. 11, however, in which the field is predominantly horizontal, and decays rapidly as one moves from the central region in the x direction. There is a complete absence of the vertical field component, which is representative of the leakage field, implying that some mechanism is present that has cancelled out the leaking surface wave field.

V. Conclusion

When the frequency of operation of a circuit that utilizes coplanar waveguide is increased sufficiently, leakage of power away from the waveguide occurs in the form of a surface wave. This power leakage can cause unwanted cross talk between neighboring portions of the circuit and produce unexpected package effects. It is therefore important to understand the characteristics of such leakage and its dependence on the dimensional parameters.

Our recent studies of these leakage properties have revealed a number of new behavioral features that are both important from a practical standpoint and interesting on fundamental grounds. Some of the conclusions to be drawn from these studies are as follows.

1) The leakage rate (the power leaked per unit length along the guiding structure) can vary considerably, depending on the frequency and the dimensional parameters. In the frequency region soon after the onset of leakage, it is found that the leakage rate increases substantially as the width c of the CPW is increased. Furthermore, when the CPW has infinite width the leakage rate is higher than that for any finite width value.

2) When the width c is finite, the widths w of the central metal strip region and d of the gap regions play a secondary role in the leakage properties, whereas the width c of the outer strips plays a strong role. When the width c is infinite, changes in the gap width d influence the leakage behavior significantly but the value of metal strip width w affects the behavior minimally.

3) For CPW of finite width, we found the presence of sharp and deep minima in the leakage rate at specific combinations of frequency and outer strip width c. We have proposed an explanation for these sharp minima in terms of a cancellation effect due to the excitation of another surface wave that is multiply reflected between the outer edges of the CPW of finite width.

4) When the CPW has infinite width, sharp and deep minima also occur but their properties are different. The maxima associated with them are also very narrow, in contrast to the case when c is finite, and these effects occur only immediately after the onset of leakage. The explanation for these effects in terms of a cancellation process is hard to verify quantitatively, but the cancellation may be due to another surface wave that produces a reactive resonance in the gap regions. Electric field vector plots verify that a cancellation process is present.

5) As the frequency increases further, other surface waves contribute to the leakage. The transition regions that occur at the onset of these additional contributions are both unusual and very interesting, and we are looking further into their characteristics.

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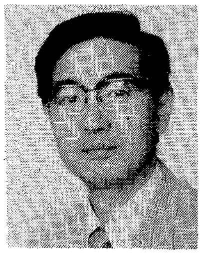

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While at Cornell University, he held a Graduate Teaching Assistantship in the Physics Department and also conducted research on a project of the Office of Scientific Research and Development. He joined the Microwave Research Institute of the Polytechnic Institute of Brooklyn, NY, in 1946, and was made Professor in 1957. From 1966 to 1971, he was Head of the Electrophysics Department; he then became Head of the combined Department of Electrical Engineering and Electrophysics from 1971 through 1974. He was also the Director of the Microwave Research Institute from 1967 to 1981. During the summer of 1964, he was a Walker–Ames Visiting Professor at the University of Washington, Seattle, and during the 1965–1966 academic year he was on sabbatical leave at the Ecole Normale Supérieure, Paris, France, under a Guggenheim Fellowship. During the summer of 1973, he was a Visiting Professor at the Catholic University, Rio de Janeiro, Brazil; in the spring of 1978 he was a Visiting Research Scholar at the Tokyo Institute of Technology, Japan; in the spring of 1980 he was a Visiting Professor at the Huazhong (Central China) Institute of Technology, Wuhan, China; and in the fall of 1982 he was a Visiting Professor at the "La Sapienza" University of Rome, Rome, Italy. Dr. Oliner's research has covered a wide variety of topics in the microwave field, including network representations of microwave structures, precision measurement methods, guided-wave theory with stress on surface waves and leaky waves, traveling-wave antennas, plasmas, periodic structure theory, and phased arrays. His interests have also included waveguides for surface acoustic waves and integrated optics and, more recently, guiding and radiating structures for the millimeter and near-millimeter wave ranges. He is the author of more than 180 papers and the coauthor or coeditor of three books. He served on the Editorial Boards of the journal *Electronics Letters* (published by the British IEE) and the volume series *Advances in Microwaves* (Academic Press).

Dr. Oliner is a Fellow of the AAAS and the British IEE, and he served as the first MTT National Lecturer in 1967. He has received prizes for two of his papers: the IEEE Microwave Prize in 1967 and the Institution Premium, the highest award of the British IEE, in 1964. He was named an Outstanding Educator of America in 1973, and in 1974 he received a Sigma Xi Citation for Distinguished Research. He was a National Chairman of the IEEE MTT Society, a member of the IEEE Publication Board and General Chairman of three symposia. In 1977 he was elected an Honorary Life Member of the IEEE MTT Society, and in 1982 he received the IEEE Microwave Career Award. In 1984, he was a recipient of the IEEE Centennial Medal. He is a member of several Commissions of the International Union of Radio Science (URSI), a past Chairman of Commission 1 (now A), and a past U.S. Chairman of Commission D. He is also a former Chairman of a National Academy of Sciences Advisory Panel to the National Bureau of Standards.