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NEW SURFACE-WAVE-LIKE MODE ON CPWS OF INFINITE WIDTH AND ITS ROLE IN EXPLAINING THE LEAKAGE CANCELLATION EFFECT

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I. INTRODUCTION AND BACKGROUND

At the 1990 International Microwave Symposium we showed [1] that a new mode, not previously recognized, could exist on coplanar waveguide of finite width. This mode can propagate down to zero frequency, and its field distribution resembles that of a TM_0 surface wave on a grounded dielectric layer. We therefore called this new mode a "surface-wave-like," or SWL, mode. We also demonstrated, both theoretically and experimentally, that this mode couples to the dominant CPW mode over a narrow frequency region. Although the frequency corresponding to this coupling region is relatively high, it is lower than the frequency at which the dominant CPW mode changes from a bound mode to a leaky mode. The two modes that couple are therefore real everywhere within the coupling region, so that the coupling behavior is exactly that of the classical forward directional coupling type. The behavior is illustrated in Fig.1, which presents the normalized phase constant as a function of the normalized frequency. Power leaks from the dominant CPW mode in the form of a TE_0 surface wave on the ungrounded dielectric layer outside of the strip region, but that leakage occurs only for frequencies higher than the crossing between the CPW curve and the one for the TE_0 surface wave. In Fig.1 the CPW curve stops at exactly that crossing point.

We also showed previously that at such crossings, where the dominant mode changes from bound to leaky, there is a complicated narrow transition region, which we are now calling a "spectral gap," to distinguish it from other transition regions, such as the coupling region in Fig.1. The term spectral gap is apt, because there exists within it an unphysical nonspectral real solution that is not captured in a steepest descent representation. Such spectral gaps appear for many structures.

At the 1991 International Microwave Symposium, we presented the results [2] of a careful study of leakage effects on CPWs of finite and infinite widths. We found several interesting effects, one of which is the occurrence of unexpected sharp and deep minima, for both finite and infinite widths. We explained these sharp minima in terms of cancellation effects, although the explanation for the infinite-width case was admittedly not clear. In fact, in the expanded published version[3] we state: "The explanation in terms of a cancellation effect here as the cause of these narrow effects is harder to prove."

During this past year, we have examined the region of the sharp minima for CPWs of infinite width much more thoroughly, and the clear explanation that has now emerged is fascinating, in our opinion. It is the result of several things happening simultaneously:

(a) First, a surface-wave-like mode is present here, just as it is for CPWs of finite width, but it is located very close to the TM_0 surface wave curve, in contrast to the finite-width case.

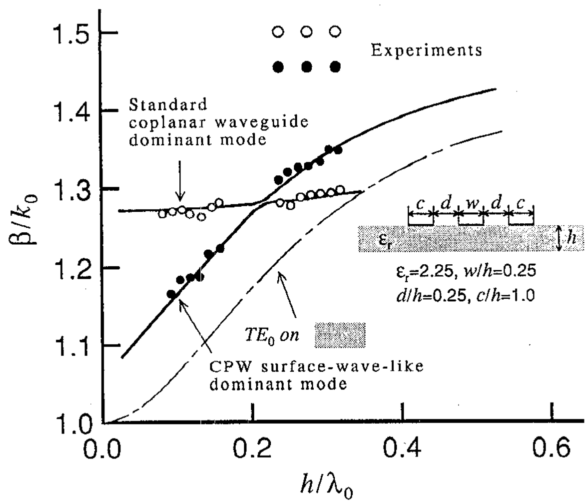

Fig.1. Variation of normalized phase constant β/k_0 with normalized frequency h/λ_0 for coplanar waveguide of finite width, showing the coupling effect between the CPW dominant mode and the surface-wave-like mode. Experimental points are also shown.

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(b) Second, this surface-wave-like mode again couples to the CPW dominant mode, but this coupling occurs just where the CPW mode changes from bound to leaky.

(c) Third, at this transition from bound to leaky, a spectral gap also occurs.

Thus, the coupling region and the spectral gap occur together, making the result something we have never seen before, and appearing very complicated at first. However, we have also made a series of vector electric field plots in the various regions, and they completely confirm the conclusions that we draw from the interpretation of the wavenumber plots. The cancellation-effect explanation of the sharp minima in the leakage constant values as a function of frequency then follows directly and clearly. We have repeated these calculations for several different values of *d/h* (see the inset in Fig.2), and for both a low value (ε_r=2.25) and a high value (ε_r=12.9) of dielectric constant, and all our results are consistent even though the magnitudes change significantly from one case to the other.

We apologize for the need to present so much background information, but we were afraid that our discussion to follow would not be understandable without it.

II. THE VARIOUS WAVENUMBER EFFECTS

A. The Sharp Minima in the Leakage Constant Values

The structure of the conventional coplanar waveguide of infinite width appears in the inset in Fig.2, which also presents the normalized leakage constant values, α/k_0, as a function of normalized frequency, h/λ_0. Values of α/k_0 are shown for three different values of normalized slot width, *d/h*. It is seen that for narrow slot widths, the range in frequency from the onset of leakage to the sharp minimum is also narrow, while this range is larger (but still narrow, since the abscissa scale is expanded) when *d/h* is larger. The magnitudes of the peaks also increase as *d/h* becomes larger. We should also recall that the leakage occurs in the form of the TM_0 surface wave on a grounded dielectric layer, since that is the structure away from the CPW's central region.

In Sec.III we explain how the sharp minima can be understood in terms of a cancellation effect, and we show that the field structure in the frequency range before the minimum is different from that in the frequency range above that minimum. In fact, before the minimum the field is that of the surface-wave-like mode, and after it the field is that of the dominant CPW mode.

B. The New Surface-Wave-Like (SWL) Mode

We mentioned in Sec.I that we had shown for the first time two years ago that a new mode can exist on coplanar waveguide of finite width, and that this new mode

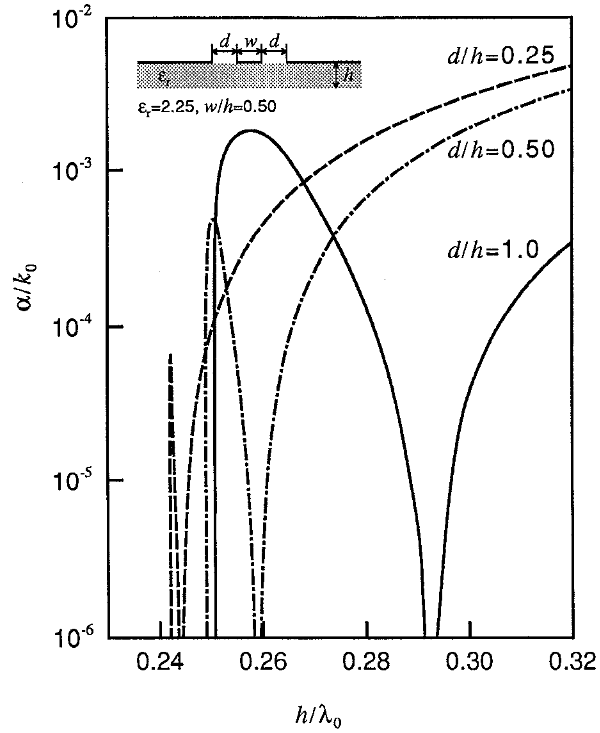

Fig.2. Variation of normalized leakage constant α/k_0 with normalized frequency h/λ_0 for CPWs of infinite width, for three different values of normalized slot width, d/h.

resembles, in field structure, a TM_0 surface wave on a grounded dielectric layer. The dispersion curve for that surface-wave-like (SWL) mode, however, lies some distance to the left of the corresponding curve for the surface wave itself, as seen in Fig.1. We discussed the other important features of the SWL mode at that time[1], and we will quickly review these features during this talk to provide necessary background.

When the CPW has infinite width, the CPW structure is nearly the same as that for a grounded dielectric layer; they differ only in the two slots forming the CPW. This small difference is enough, however, to permit the existence of an SWL mode on CPWs of infinite width, even though the dispersion curve for the SWL mode lies almost on top of the one for the surface wave on a grounded dielectric layer.

Since the CPW dominant mode dispersion curve is relatively flat with frequency, whereas that for the SWL mode is strongly dispersive, the two curves will cross each other at some frequency to produce a coupling effect in the region where they cross. When the CPW has finite width, this crossing occurswell away from the leakage region. Here, for CPW of infinite width, the

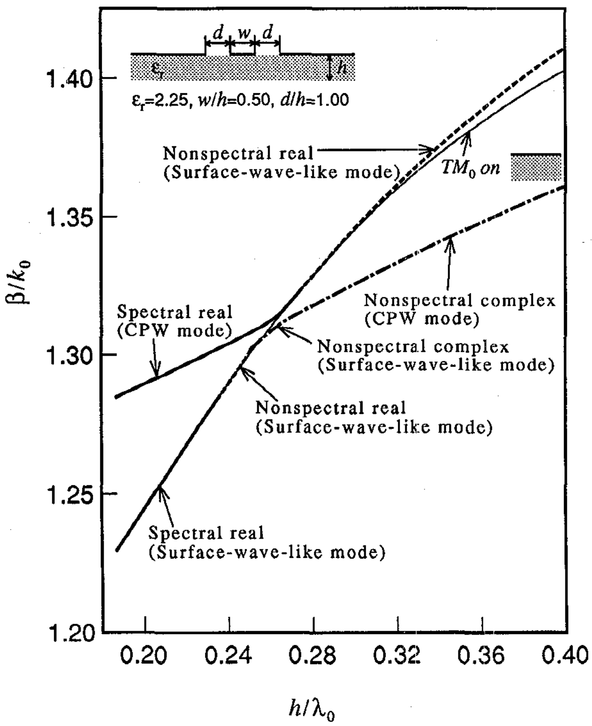

Fig.3. The normalized phase constant behavior as a function of normalized frequency for CPW of infinite width, showing both the CPW dominant mode and the new surface-wave-like mode and their region of interaction. Also superimposed as a thin solid line is the curve for the TM_0 surface wave. The character of the solutions is also indicated: solid lines mean spectral real (bound) modes, dashed lines nonspectral real (nonphysical) modes, and dot-dashed lines nonspectral complex (leaky but physical) modes.

coupling occurs very near to the onset of the leakage, right within the spectral gap region, in fact, making this crossing region quite complicated, and causing the sharp minimum (cancellation effect) mentioned above, as we will see.

C. The Combined Spectral Gap and Coupling Region

As mentioned above, a spectral gap always occurs at the onset of leakage, but in this case the coupling between the CPW dominant mode and the SWL mode also occurs in the same narrow frequency range. The dispersion behavior, in the form of a plot of the normalized phase constant, β/k_0, versus the normalized frequency, h/λ_0, is shown in Fig.3 for a typical case, that for d/h=1.00 and ε_r =2.25. We also made calculations of β/k_0 and α/k_0 for ε_r =12.9, for a GaAs substrate. The behavior is qualitatively similar to that shown in Figs.2 and 3, but we find for the GaAs case that the coupling region is considerably more pronounced, that the maximum value of α/k_0 is more than a decade larger, and that the frequency distance to the minimum is larger as well.

In Fig.3, we first see that there is a coupling region, with two evident separate portions. (The TM_0 surface wave curve passes through the middle of the coupling region, but that curve is added for reference purposes.) In a regular spectral gap region, only a single continuous curve is obtained, as described in detail in [4] for an antenna structure. The characteristics of this single continuous curve will be reviewed in the talk.

In examining Fig.3, we look first at the upper portion. The solid line on the left represents the bound CPW dominant mode, and it turns upward to become tangent to the surface wave curve as it approaches the coupling region. After that tangent point, however, the curve, which is drawn with short dashes, is real but nonspectral (meaning that the field increases transversely) as it continues further. That portion of the solution can be ignored since it is nonphysical.

As we next examine the lower portion, we need to refer to the expanded version of this region in Fig.4. On the lower right, we follow upward the spectral real (bound) solution for the surface-wave-like (SWL) mode, whose curve is almost coincident with the TM_0 surface wave curve, but is slightly to the left of it. When the coupling region is approached, the SWL curve first becomes tangent to the TM_0 surface wave curve, and then moves away from it as the solution becomes nonspectral real (dashed curve) until the curve becomes vertical. At that point, the nonspectral real portion curves back, but a nonspectral complex (leaky but physical) solution, shown dot-dashed, then moves to the right, to higher frequencies. The portion that curves back is not shown in Fig.3. This junction point also represents the onset of leakage.

When we compare the behavior of this lower portion in Fig.4 with that of a regular spectral gap, we observe the rather astonishing result that the spectral gap behavior is associated primarily with the lower portion, and that all of that portion so far involves only the SWL mode, not the CPW mode. We expect, however, that for still higher frequencies the leaky solution must become that for the leaky CPW mode. That is indeed what happens. After the other end of the coupling region is passed, there is a transition from the SWL leaky solution to the CPW leaky solution. The point of transition between these two solutions corresponds precisely to the sharp minimum in the leakage constant. We can now also understand our earlier statement that the fields in the frequency range from the onset of radiation to the sharp minimum are those of the SWL mode, whereas for higher frequencies the fields are those of the CPW mode. We have made vector electric field plots that verify these conclusions.

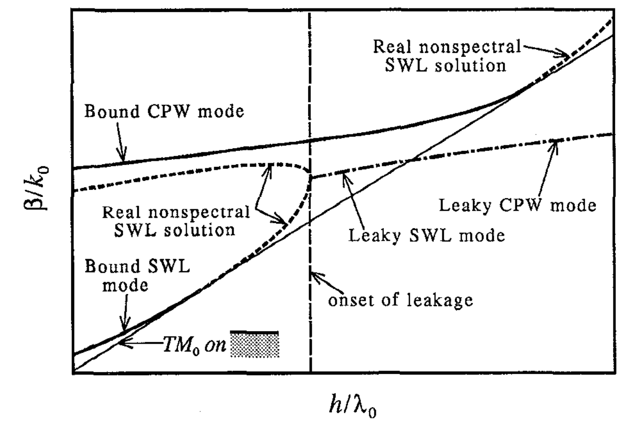

Fig.4. A qualitative sketch of the combined spectral gap and coupling region of the plot in Fig.3 on an expanded scale, showing the character of the solutions in various regions.

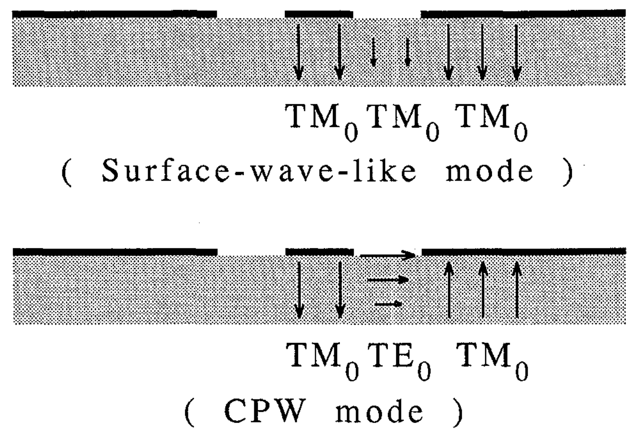

Fig.5. The orientations of the electric fields of the surface-wave-like mode and the CPW of infinite width. Note that in the outer region the field orientations for the two mode types are opposite.

III. THE EXPLANATION OF THE CANCELLATION EFFECT

In the CPW structure with infinite width, the primary electric field orientations under the metal strips are illustrated in Fig.5 for both the surface-wave-like (SWL) mode and the coplanar waveguide (CPW) dominant mode. The most interesting difference between them is that the electric field directions in the outer regions are opposite for the two mode types.

In Sec.II,C, just above, we showed that the onset of leakage occurs when the complex nonspectral (dashed-dot) solution just begins, and that the fields just after the leakage begins would be those corresponding to the SWL mode. At some higher frequency, the fields must change over to those of the leaky CPW dominant mode. Since, as is shown in Fig.5, the electric fields for these two modes are oppositely directed in the outside regions, these fields in the outer regions would cancel each other at the frequency of transition. As a result, there would be little or no leakage power at that frequency, and the value of α would become very small.

We have made vector electric field plots in all of the relevant frequency regions, and those plots verify all of these conclusions. They show, for example, that the field structure just above the onset of leakage is that of the SWL mode, that the fields at higher frequencies are those of the CPW mode, and that in the cancellation region fields exist in the central CPW region but decay transversely in the outer regions. These plots are not shown here but will be presented during the talk.

ACKNOWLEDGMENT

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