Structural Conditions for Offering High-performance Printed-circuit Devices in Millimeter-wave Range

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Abstract: **The power leakage effect on printed-circuit transmission lines often produces serious performance difficulties in millimeter-wave integrated circuits. One of difficulties is that the critical frequency only for the fundamental bound mode propagation becomes lower in millimeter-wave range. Such a critical frequency for single-mode operation changes significantly depending on the structural dimensions of a line cross section. In this paper, therefore, we discuss for the first time this important issue systematically and deeply for transmission lines frequently used, and present several useful results that offer us the preferable structural dimensions of a transmission line suitable for developing high-performance millimeter-wave devices.**

I. Introduction

As the operating frequency of integrated circuits is increased higher and higher, we often meet with unexpected wave-propagation phenomena [1]. They have relevance to power-leakage effect on printed-circuit transmission lines. It is now known that guided mode purely bound to the structure changes into a radiating leaky mode as the frequency is raised past some critical value (for some structures, the leakage occurs at all frequencies). Such a modal behavior is basically common to most printed-circuit transmission lines, including coplanar strips, slot line, coplanar waveguide, and microstrip line on an anisotropic substrate [2]. However, the detailed behavior often becomes complicated for each transmission line because it has a danger of causing the spectral-gap phenomenon or the simultaneous- propagation phenomenon at around the critical frequency. Under these complicated situations, however, millimeter- wave transmission lines are still desirable to be free from power-leakage phenomenon [3], so that a circuit designer should try to push a critical frequency as high as possible. However, such a critical frequency changes significantly depending on the structural dimensions of a line cross section. In this paper, therefore, we discuss for the first time this important issue systematically and deeply for transmission lines frequently used in practice, and present several useful results that offer us the desirable structural dimensions of a transmission line suitable for developing high-performance millimeter- wave circuit devices.

II. Spectral Gap And Simultaneous Propagation

Figure 1 shows the behavior of the normalized-phase constant β/k_0 (k_0 is the free-space wavenumber) for conductor-backed coplanar strips, for which the structural parameters are w/h=0.375 and d/h=0.25 with ε_r=2.25 (low dielectric constamt). The leakage constant α is not shown there. We can see a typical spectral gap, which involves a short frequency range, in which, at the lower frequency end, the mode remains purely real but becomes improper (nonspectral), and, at the upper frequency end, the mode becomes complex and leaky, but is nonphysical. The spectral gap actually appears between two critical frequencies labeled f_{cr1} and f_{cr2} in the β/k_0 plot. Thus, for guiding structures with a common (or regular) spectral-gap pattern, the fundamental bound mode can be observed only below the frequency at which the spectral gap sets in, and only the frequency range below f_{cr1} can be used for usual circuit design.

When we further increase the parametric value of w/h, for example, to 0.5, we experience a surprising change in the behavior of the normalized-phase constant β/k_0. The bound-mode solution moves to higher frequency,

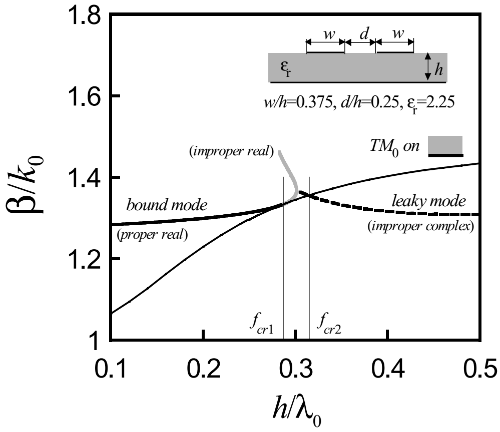

Fig. 1. The variations of β/k_0 *vs.* h/λ_0 for conductor-backed coplanar strips with w/h=0.375.

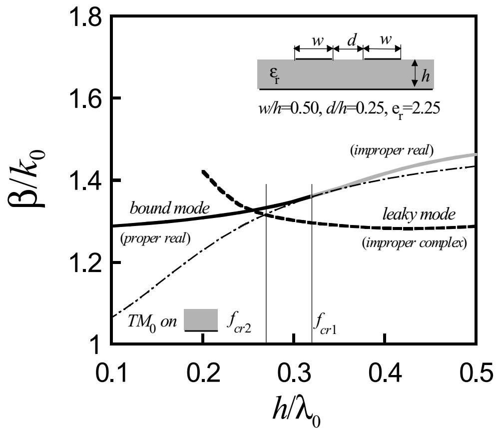

Fig. 2. The variations of β/k_0 *vs.* h/λ_0 for conductor-backed coplanar strips with w/h=0.50.

while the leaky solution moves down and extends to lower frequencies. Then, the critical frequencies f_{cr1} and f_{cr2} are reversed on the frequency axis, producing a range of simultaneous propagation as shown in Fig. 2. This overlap region, within which bound and leaky modes can propagate simultaneously, becomes very wide as the strips are made wider. For example, when w/h is increased only a bit more, to 0.70, the value of f_{cr1} becomes more than twice that of f_{cr2}. The practical importance of this result is that, if the transmission-line circuit is designed on the assumption that only bound mode is present, but unexpectedly a leaky mode is there as well, the source designed to excite the bound mode will also excite the leaky mode with comparable amplitude because both modes have similar strip current distribution. Therefore, the use of this simultaneous-propagation range is not recommended for circuit design, and only the frequency range below f_{cr2} should be used.

III. Structural Parameters Offering High-performance Devices

In the previous section, we have found that for conductor-backed coplanar strips the patterns of the wavenumber behaviors around the critical frequency depend strongly on the dimensional parameters of transmission lines. Therefore, for designing high-performance millimeter-wave circuit devices, it is necessary to investigate precisely the behaviors of two critical frequencies f_{cr1} and f_{cr2} on the structural parameters vs. the frequency or in other forms. For this purpose, we have calculated accurately these relations by the spectral-domain method (SDM) for several important transmission lines.

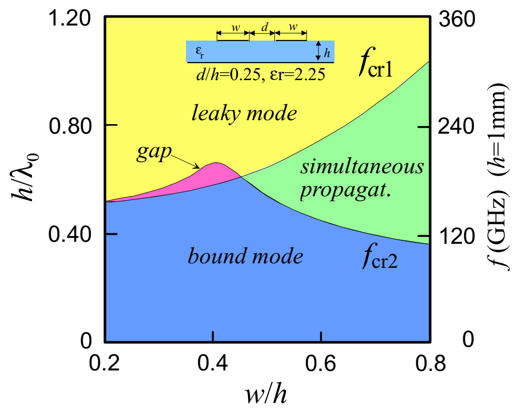

Fig. 3(a). Variations of two critical frequencies on the plane of the structural parameter w/h *vs.* h/λ_0, when dielectric constant ε_r =10.0 and d/h=0.25.

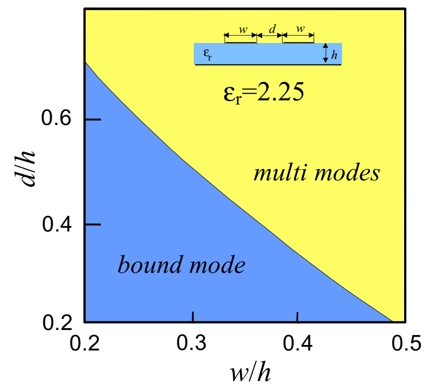

Fig. 3(b) Zoning of the single-mode (the fundamental bound mode) operation and the multi-mode (leaky mode and others) operation on the structural-parameter plane of d/h and w/h for a substrate with ε_r=2.25.

Here, we again take the conductor-backed coplanar strips on the dielectric substrate with ε_r=2.25 as an example transmission line. The plot of Fig. 3(a) presents the variation of the critical frequencies f_{cr1} and f_{cr2} as a function of w/h. For the range in which $f_{cr1} < f_{cr2}$, a spectral gap must of course be present, while the simultaneous-propagation region corresponds to the range, where $f_{cr1} > f_{cr2}$. We see that this simultaneous-propagation range between f_{cr2} and f_{cr1} increases rapidly as w/h is made larger. Then the critical values satisfying $f_{cr1}= f_{cr2}$ are given by w/h=0.454 and h/λ_0=0.608. They lead w=454μm and f_{cr1}=f_{cr2}=182.4GHz for the substrate with the thickness h=1mm. The frequency scale corresponding to the normalized frequency h/λ_0 is shown on the vertical axis of the right-hand side of Fig. 3(a). These values mean the upper limits for both of w and f_{cr1}

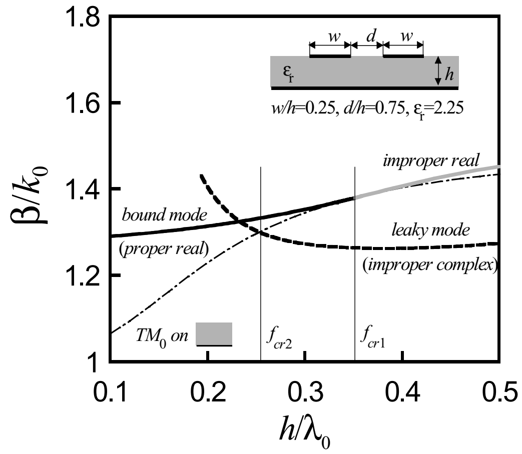

Fig.4(a). The variations of β/k_0 *vs.* h/λ_0 for conductor-backed coplanar strips with w/h=0.375 and ε_r=2.25. This structure exhibits the simultaneous- propagation phenomenon in the wide frequency range between $f_{cr2} < f < f_{cr2}$. For this case, we have the total width of the guide ($2w+d$)=1.25.

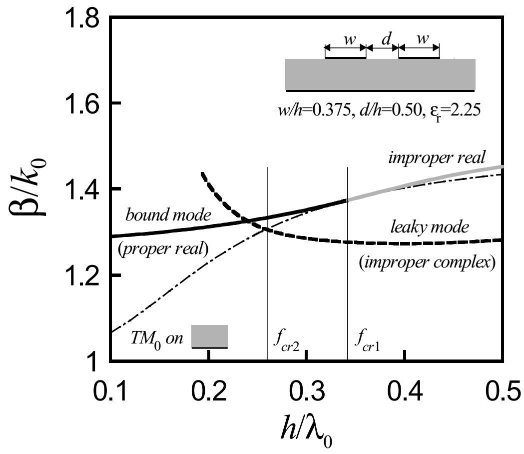

Fig.4(b). For this structure, we have changed the structural parameters from those selected in Fig. 4(a). But, the total width of the guide ($2w+d$) is kept to the same value 1.25 of Fig. 4(a).

satisfying the operation only by the fundamental bound mode. We have also calculated the variation of the critical frequencies f_{cr1} and f_{cr2} as a function of d/h, keeping w/h constant. However, these results are omitted here due to the limited available space.

The second plot shown in Fig. 3(b) shows the boundary curve of the parametric relation between d/h and w/h of a transmission-line structure, where a transmission line with the structural parameters of d/h and w/h lying on this curve satisfies $f_{cr1} = f_{cr2}$. For the region below this boundary curve, the propagation range for the fundamental bound mode is distinctly separated from that for the leaky dominant mode by the spectral gap, while, for the region above this curve, both bound and leaky modes are present simultaneously on the conductor-backed coplanar strips, and the circuit performance of transmission lines with the structural dimensions given by the parameters in this region could be affected significantly.

Here, we notice that the boundary curve shown in Fig. 3(b) corresponds nearly to a straight line given by ($2w+d$) = constant, where the value ($2w+d$) is the total width of the strips and the central gap. To confirm the generality of this "straight-line rule" of the boundary curve, we have selected two kinds of the conductor-backed coplanar strips with different structural parameters. One of them, as shown in Fig. 4(a), has w/h=0.25 and d/h=0.75, and the other, as shown in Fig. 4(b), has w/h=0.375 and d/h=0.50. The dielectric constant ε_r=2.25 is common to both cases. Although the structural dimensions are different each other for these two cases, we find in Fig. 4 as if the wavenumber behaviors are identical each other. Such a result is due to the straight-line rule of the boundary curve as mentioned above. Actually, two different transmission lines mentioned above satisfy the conditional relation ($2w+d$)/h=1.25 common to both cases. Thus, we can conclude that the simultaneous propagation behavior of the conductor-backed coplanar strips may be almost determined not by the strip width w, but by the total width ($2w+d$).

We have next investigated for the conductor-backed coplanar strips on the dielectric substrate with the dielectric constant ε_r=10.0 as a typical value of high dielectric constant for millimeter-wave device use. The plot of Fig. 5(a) presents the variation of the critical frequencies f_{cr1} and f_{cr2} as a function of w/h. The plots are very similar with those of Fig. 3(a). In this case of ε_r=10.0, the critical values satisfying f_{cr1}=f_{cr2} are given by w/h=0.336 and h/λ_0=0.135. They lead w=67.2 μm and f_{cr1}=f_{cr2}=202.5GHz for the substrate with the thickness h=200μm. We have also calculated the variation of the critical frequencies f_{cr1} and f_{cr2} as a function of d/h, keeping the w/h value constant. However, these results are again omitted here due to the limited available space. Fig. 5(b) shows the same plot as Fig. 3(b), but for a high dielectric constant ε_r=10.0 instead of 2.25. We can again confirm the straight-line rule given by ($2w+d$) = constant, even for a high dielectric constant.

We have further investigated for the conductor-backed coplanar strips on the dielectric substrates with different dielectric constants. From these many results, we have confirmed that the rule of ($2w+d$) = constant is actually effective to understand the parametric region of only the fundamental bound-mode operation. Similar results have been obtained for other printed-circuit transmission lines. Further discussions, including slot line, coplanar waveguide and so on, will be presented at the talk.

IV. CONCLUSIONS

We have discussed the causes reducing the upper frequency limit for the fundamental bound mode alone, because this limiting frequency becomes the upper limit circuit devices. As one of the causes, we have shown the reduction of the critical frequency of the bound mode end. Such a reduction is caused by the power-leakage effect alone as seen in the region of small values of w/h in Fig. 3(a). As another cause of reducing the usable frequency limit, we have shown the generation of the simultaneous-propagation phenomenon. As we can see also in Fig. 3(a), this phenomenon has reduced the maximum usable frequency limit for the bound mode alone by about 15~20% at large values of w/h as compared to the case of small w/h value. Thus, a millimeter-wave circuit designer may need to keep the causes reducing the maximum usable frequency in mind.

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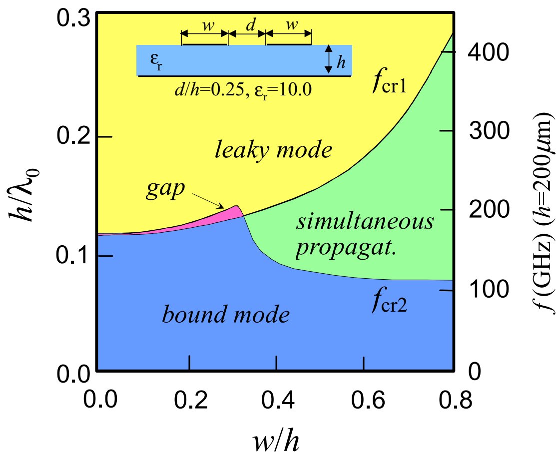

Fig. 5(a). Variations of two critical frequencies on the plane of the structural parameter h/λ_0 *vs.* w/h, when dielectric constant ε_r =10.0 and d/h=0.25.

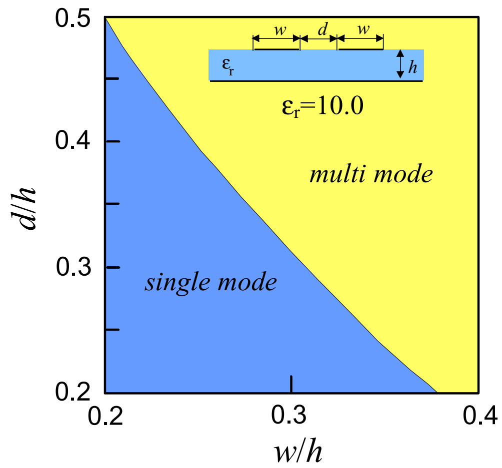

Fig. 5(b). Zoning of the single-mode (the fundamental bound mode) operation and the multi-mode (leaky mode and others) operation on the structural-parameter plane of d/h and w/h for a substrate with ε_r=10.0.