Behavioral Feature of Fast-wave Modes on Printed-circuit Transmission Lines of Open and Packaged Types

Mikio Tsuji and Hiroshi Shigesawa

Dept. of Electronics, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan

***Abstract* — Dispersion characteristics of fast-wave modes are deeply investigated for both open and packaged printed – circuit transmission lines. The numerical results conclude that in the packaged guide, the fast-wave mode is mutually connected to the bound mode in the wavenumber behavior, while that for the open guide is completely separated from the bound mode.**

I. INTRODUCTION

We have already shown that the dominant mode on most printed-circuit transmission lines is purely bound to the guide central region at lower frequencies but becomes leaky above the critical frequency at which the dispersion curve for the dominant mode crosses the one for the lowest surface wave on the surrounding dielectric substrate[1][2]. Recently, it has been found that a fast-wave leaky mode can propagate on printed-circuit transmission lines [3]-[5]. This mode calling here the space-wave leaky mode leaks power in the forms of both the surface wave propagating on substrate and the space wave radiating into space. To grasp behavioral feature of this fast-wave mode is very important not only for antenna application but also for the undesired radiation from the discontinuity of the circuit. However, in some case, the analysis of such a mode has been approximately performed in the modified structure introducing the hypothetical wall. If we package the whole of the printed-circuit line, the wavenumber of the fast-wave mode is no longer complex, but is real. As a result, the dispersion curve of the slow-wave bound mode is mutually connected to that of the fast-wave mode in the wavenumber behavior. This fact often leads to misunderstand the wavenumber relation between the bound mode and the space-wave leaky mode in open printed-circuit line. Therefore, the main-discussion point here is to make clear the dispersion behavior of the fast-wave leaky mode, comparing with those for the approximated structure with metal wall. Consequently, we show here that the fast-wave mode in open type is completely separated in other type modes and it is difficult to analyze its dispersion behavior by the approximated structure with the hypothetical wall.

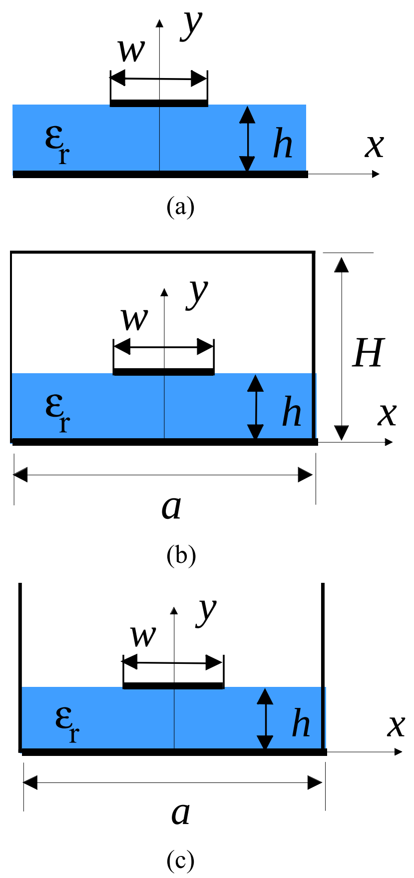

Fig. 1. Microstrip lines of (a) open type, (b) packaged type and (c) with side walls.

II.. STRUCTURE AND THEORY

We discuss the first higher-order (EH_1) microstrip mode as an example. Figure 1 shows three types of the microstrip lines under consideration and the analysis of all the guides are performed by the spectral-domain method. When we seek a space-wave leaky-mode solution of open type shown in Fig. 1(a), we deform the integration path on the transverse-wavenumber (k_x) plane as shown in Fig. 2. This path first runs along the negative $Re[k_x]$ axis on the proper sheet (the negative $Im[k_y]$ plane), and then it cuts

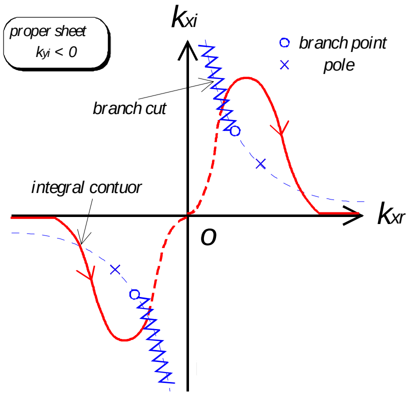

Fig. 2. Integral path for the space-wave leaky mode

the branch cut to enter into the improper sheet (the positive $Im[k_y]$ plane), and again cuts the branch cut to come back on the proper sheet. While, the bound-mode solution is obtained by performing the integration over the entire $Re[k_x]$ axis, and the surface-wave leaky-mode solution is obtained by deforming the integration path to include the pole corresponding to the surface wave into which the mode leaks. On the other hand, the solution on the packaged microstrip lines shown in Fig. 1(b) is obtained by taking the summation on the discrete transverse wavenumber k_x determined by the wall separation a, in place of the integration in open type. Furthermore, the solution on the microstrip line only with the side walls shown in Fig. 1(c) is obtained by the same procedure as that on the packaged guide except for paying attention to the sign of the transverse-wavenumber k_y .

III. Numerical Results

A. open type

Fig. 3 shows the behaviors of the normalized phase and leakage constants as a function of normalized frequency h/λ_0, with the strip widths w/h = 5.0 and the dielectric constant of the substrate ε_r = 2.25. In this figure, four different types of modes are indicated by different colors, that is, the bound mode (blue curve), the improper real mode (green curve), the surface-wave leaky mode (yellow curve), and the space-wave leaky mode (red curve). Although the red dispersion curve of the space-wave leaky mode seems to be connected mutually to the blue one of the bound mode, this curve is actually connected to the dashed red curve of the space-wave leaky mode that possesses the negative attenuation constant (the α/k_0 value is plotted by taking the absolute value in Fig. 3.). Figure

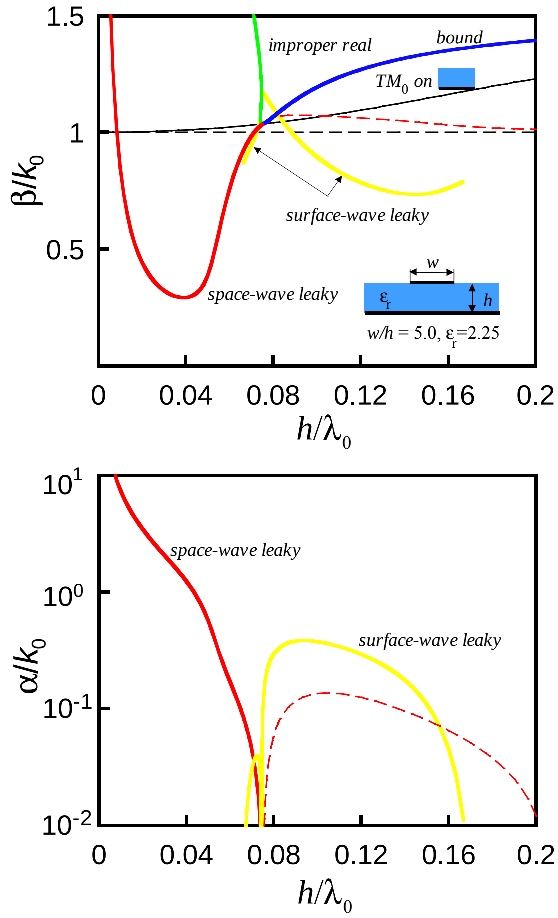

Fig. 3. Normalized phase and leakage constants as a function of the normalized frequency h/λ_0, when w/h is selected as 5.0.

4 on a greatly enlarged scale makes it clearer. We can observe the regular spectral gap among the bound, improper-real and surface-wave leaky modes in the frequency range $f_{cr4} > f > f_{cr3}$. While the space-wave leaky mode exists independently of theses modes. Since the radiation condition into a space wave is given, in good approximation, by $k_0 > \beta$ (the β and k_0 mean the phase constants of the transmitting mode and the plane wave in free space, respectively), the space-wave leaky mode is physical only below a critical frequency f_{cr1}. On the other hand, the surface-wave leaky mode is physical when its phase constant β lies within $k_s > \beta > k_0$ (k_s is the phase constant of the TM_0 surface wave), that is, $f_{cr3} > f > f_{cr2}$. In this case, therefore, there is another spectral gap in the frequency range $f_{cr2} > f > f_{cr1}$.

To make the behavior of the space-wave leaky mode more detailed, we decrease the strip width w/h to 3.0. The resultant dispersion curve is given in Fig. 5. The dispersion curve of each mode is indicated by the same

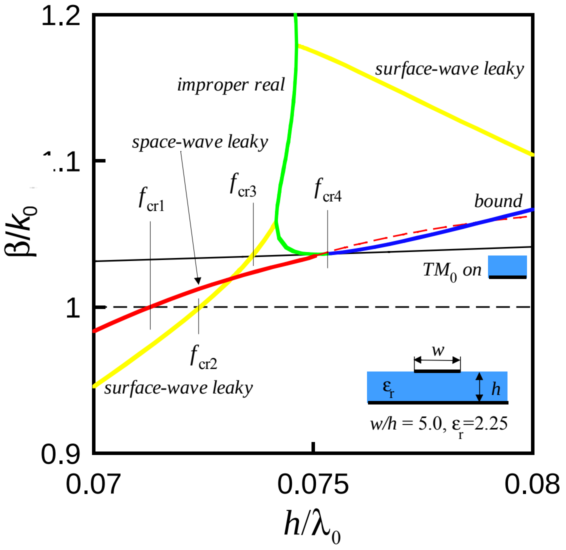

Fig. 4. Expanded plots of Fig. 3 in the spectral-gap region.

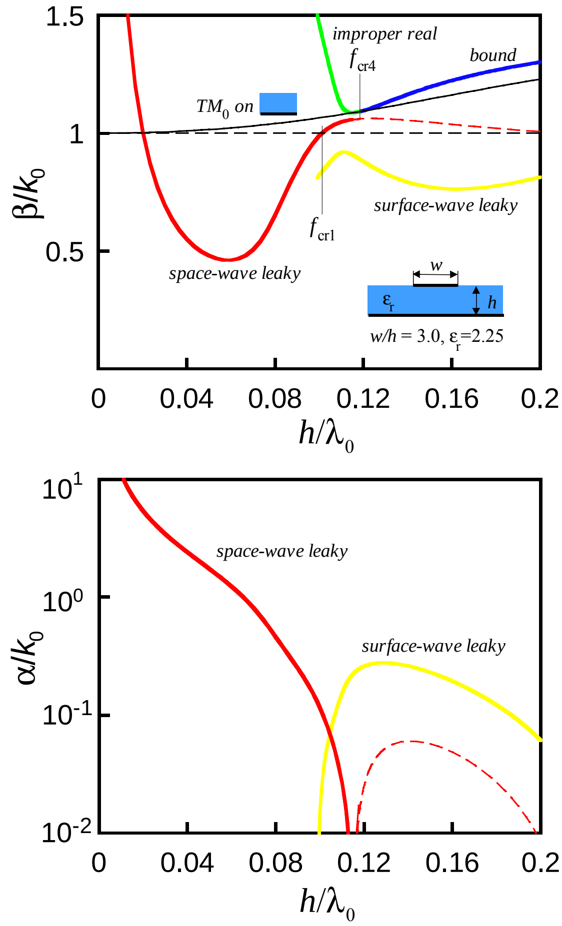

Fig. 5. Normalized phase and leakage constants as a function of the normalized frequency h/λ_0, when w/h is selected as 3.0.

color as Fig. 3. In this case, two surface-wave leaky modes appearing in Fig. 4 meet with and join each other, and then their β/k_0 value comes down to less than unity, so that the spectral gap between the bound and the surface-wave leaky modes disappears. But, a new spectral gap between the bound and the space-wave leaky modes exists in the frequency range $f_{cr4} > f > f_{cr1}$.

Therefore, the space-wave leaky mode is completely separated from the bound mode on the printed-circuit lines of open type.

B. Package wall

To compare with the dispersion behavior on the open microstrip line shown in Fig. 3, Fig. 6 shows that on the packaged one as shown in Fig.1(b). The calculation is performed for three kinds of the package wall, and the dispersion behavior of each guide is indicated by a solid color curve. The dashed color curves show the results of open type in Fig. 3. The package boundaries reflect the leakage power of both the surface-wave leaky and the space-wave leaky modes. As a result, the wavenumber of these modes on the line is no longer complex, but is real above cutoff and imaginary below it. And the dispersion behavior is shown in one curve. The solid red curve shows the dispersion behavior for the guide having the normalized width a/h=10.0 and the normalized height H/h=10.0 of the package wall and it is certainly connected in one line unlike open-type case. While the solid green and blue curves shows the dispersion behavior for guide of which the width and height are increased to H/h=20.0 and a/h=40.0, respectively. In both these guides, we can observe that the bound mode couples to the package guided mode at around h/λ_0=0.07. Therefore, if we make the package wall far away from the microstrip guide, only the bound-mode behavior on the open guide is approximated well by the packaged guide as expected.

C. Side walls

We introduce only the side walls without the top cover as shown in Fig. 1(c). Figure 7 show the dispersion behavior for the guide with the normalized width between the side walls a/h=10.0. In this case, the spectral gap is formed among the bound mode (blue curve), improper real mode (green curve), and the parallel-plate leaky mode (red curve). The improper-real mode for this guide indicated by the green curve possesses the growing-up fields in the y direction, whereas that for the open-type guide (the dashed green curve) possesses such fields in the x direction. Therefore, the feature of both modes are completely

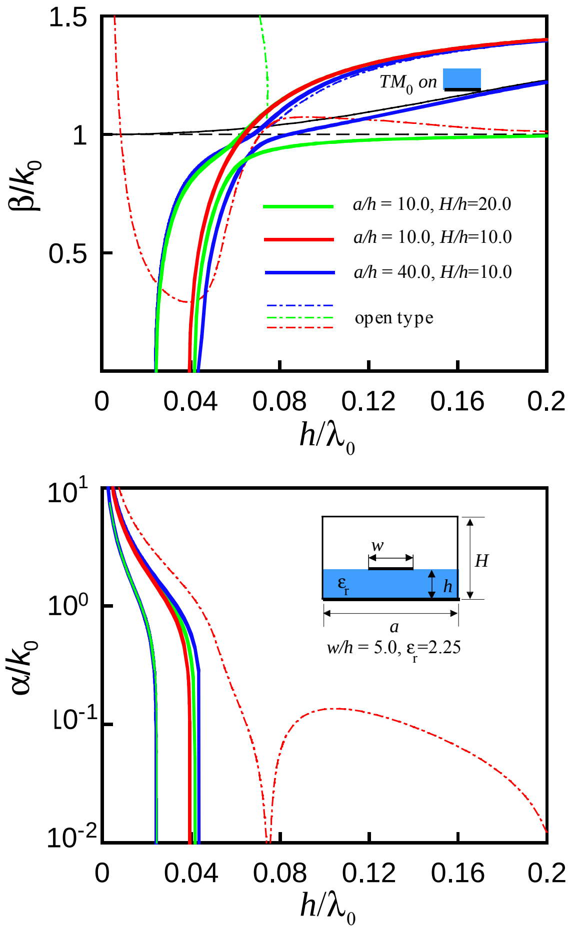

Fig. 6. Normalized phase and leakage constants of packaged microstrip.

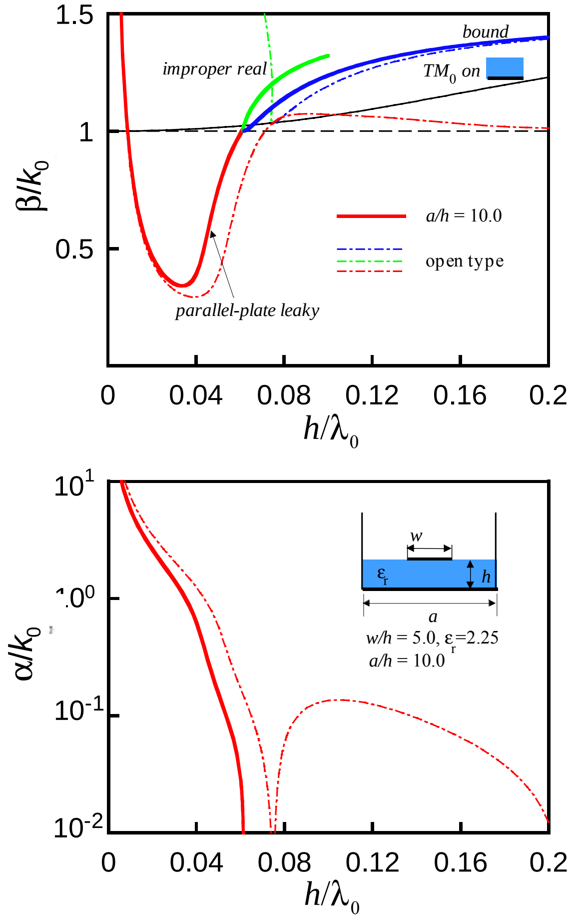

Fig. 7. Normalized phase and leakage constants of microstrip line with metal side walls.

different from each other. The parallel-plate leaky mode indicated by the solid red curve leaks power in the form of the TEM wave towards the *y* direction. Although the dispersion behavior of this mode looks like that of the space-wave leaky mode for open-type guide, both behaviors are considerably different. The detail discussion on this point will be presented at the talk. Anyway, in this structure, the bound mode and the parallel-plate (space-wave) leaky mode are mutually connected through the improper-real mode. This behavior does not appear in the open-type guide.

IV. CONCLUSION

We have deeply investigated the dispersion behavior of the fast-wave mode for the printed-circuit transmission lines with and without package walls. As a result, the fast-wave leaky mode for open-type guide is completely separated from the bound and the surface-wave leaky modes. On the other hand, the fast-wave mode for the packaged guides is mutually connected to other types of modes. These behavioral features will be helpful when the microwave and millimeter-wave printed circuits are designed. This work was supported in part by a Grant-in Aid for Scientific Research (09650432) from Japan Society for the Promotion of Science and by the Grants from the RCAST at Doshisha University.

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