A NEW TYPE OF THE NARROW-PULSE DISTORTION CAUSED BY THE SIMULTANEOUS-PROPAGATION EFFECT OF BOTH BOUND AND LEAKY MODES ON PRINTED-CIRCUIT TRANSMISSION LINES

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Abstract

We report here a new type of the narrow-pulse distortion. Our first two papers [1-2] reported for the first time that the power-leakage effect on most of printed-circuit transmission lines, which was discovered by us [3], caused a serious narrow-pulse distortion. Our investigation [4-5] then discovered also the surprising presence of the simultaneous-propagation effect of both bound and leaky dominant modes on printed-circuit transmission lines. We present here that this effect causes a new type of the narrow-pulse distortion. An important result revealed here is that a narrow pulse inevitably changes into a wide pulse attended with a serious problem relating to the interconnects, even as such a pulse travels along a uniform line.

1. INTRODUCTION

The trend in recent years in MIC and MMIC has been to push the operation to higher and higher frequencies, correspondingly, narrow pulses, already in the subpicosecond range, grow shorter and shorter. Accordingly, the spectral-power distribution of narrow pulses, now spreading over few10GHz, becomes broader and broader. As for the transmission-line characteristics, we now know, contrary to the ordinary belief, that the dominant mode on most of printed-circuit transmission lines are purely bound only at low frequencies [6]. As the propagation frequency becomes greater than some critical value, the bound mode turns into a leaky mode, with power leaking away at some angle in the form of a surface wave on the surrounding substrate. The precise type of surface wave and the conditions governing when leakage begins, depend on the specific structure [6].

When a narrow pulse, of which spectral-power distribution spreads very broadly beyond the critical frequency, excites printed-circuit transmission lines, the degradation in the spectral-power distribution of the pulse necessarily occurs, because the spectral components only above the critical frequency are extinguished by the leakage effect. As a result, some inevitable distortion in the pulse shape comes out even if a narrow pulse travels along a uniform transmission line. On the other hand, the leaked power also introduces unexpected cross talk with neighboring circuits, thus making the inter-connection problem very critical. As a result, it is of great practical importance on the narrow-pulse distortion whether the transmission-line dominant mode is leaky or not. Therefore, such problems of the pulse distortion as well as the dynamic cross talk have been discussed in much detail for the first time by the present authors for the open CPW [1] and for the packaged one [2].

Until recently, everyone thought that the bound and leaky modes are completely separated from each other in the frequency range as mentioned above. Recently, however, we have discovered that this assumption is incorrect, instead, that, under certain circumstances, the dispersion curve for the dominant mode on printed-circuit transmission lines can display behavior quite different from that of earlier belief. Our discovery shows that there can exist a frequency range within which the bound and leaky dominant modes can propagate simultaneously [4]. Our investigation since then revealed that the simultaneous-propagation effect is actually quite general [5], rather than being unique or rare to some transmission line. Thus, we should now investigate the feature of the narrow-pulse distortion in full detail when the bound and leaky dominant modes propagate simultaneously, and such investigation is just the central focus of this paper.

2. SIMULTANEOUS-PROPAGATION EFFECT AND NARROW-PULSE DISTORTION

As mentioned above, the simultaneous-propagation effect was first found in connection with conductor-backed coplanar strips [3], of which cross section is shown in Fig. 1. In this paper, we maintain $\varepsilon_r = 2.25$ and $d/h = 0.25$, and modify the value of w/h. For the narrow strip widths, w/h=0.25, we observe in Fig. 2 that the bound and leaky portions of the dominant mode are clearly separated from each other, which is

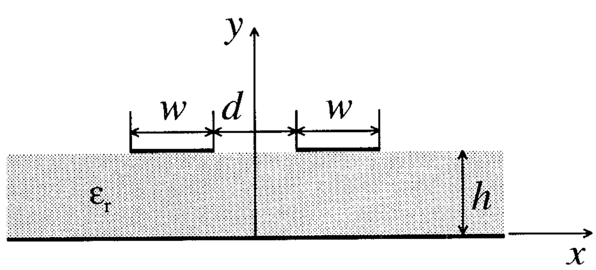

Fig. 1. Cross section of the conductor-backed coplanar strips.

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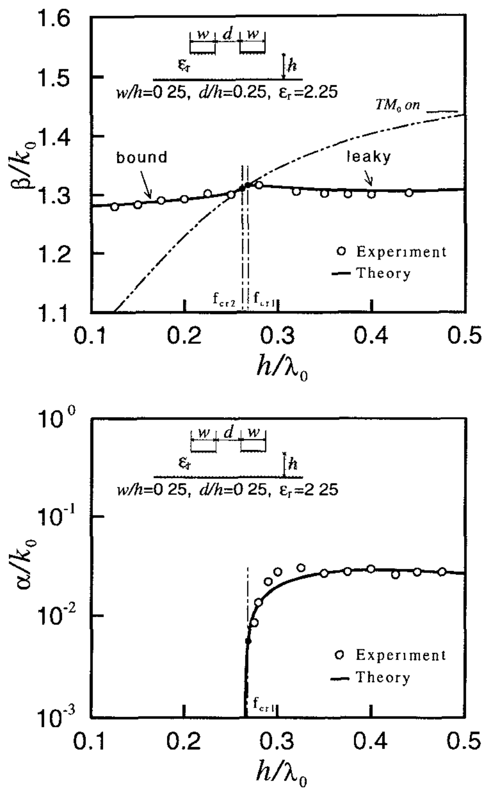

Fig. 2. The normalized phase β/k_0 and leakage α/k_0 constants for conductor-backed coplanar strips, as a function of normalized frequency, h/λ_0, for the case of narrow strips, w/h = 0.25. The bound and leaky modes are completely separated. The circles indicate the measured values.

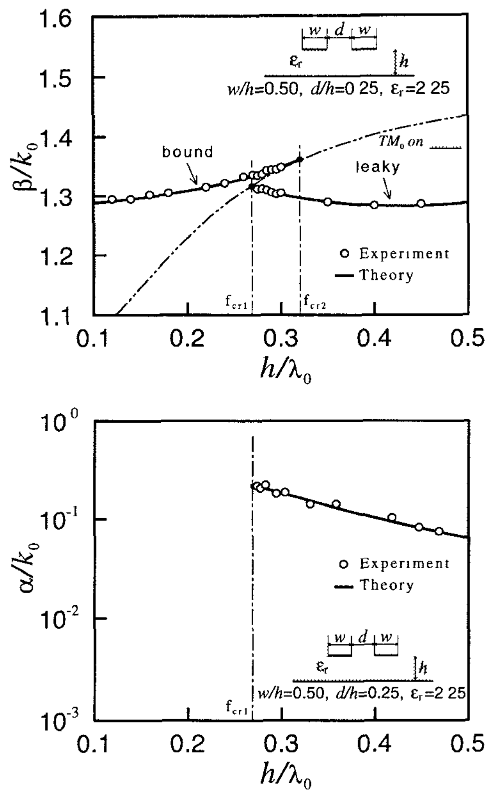

Fig. 3. The normalized phase β/k_0 and leakage α/k_0 constants for conductor-backed coplanar strips, as a function of normalized frequency, h/λ_0, for wide strips, w/h = 0.50. The bound and leaky modes are both present simultaneously in the frequency range between f_{cr1} and f_{cr2}.

the usual situation. Then, the feature of the narrow-pulse propagation on such transmission line is easily understood from our previous work [1-2], and its detail is omitted here due to the limited available space.

When the relative strip width is increased to $w/h = 0.50$, the resulting propagation behavior changes as shown in Fig. 3, where the bound and leaky modes are both present simultaneously in the frequency range between f_{cr1} and f_{cr2}, correspondingly between $h/\lambda_0 = 0.27$ and $h/\lambda_0 = 0.32$ in the normalized frequency. Hereafter, we concentrate our study on this case of the conductor-backed coplanar strips, and discuss how a narrow pulse is distorted on such a transmission line.

Our quantitative discussions here are based on the FD-TD analysis, in which the excitation of the line is performed by applying the pulse electric field horizontally only between the edges of the slot. We investigate here to apply two kinds of the Gaussian pulse; one is the wide pulse with FWHM (Full Width of Half Maximum) of 58.8*psec* and the other is the narrow pulse with that of 11.8*psec*. The frequency spectra of both pulses therefore spread from 0 to 3.75GHz (correspondingly, $0 < h/\lambda_0 < 0.05$) and from 0 to 18.75GHz (correspondingly, $0 < h/\lambda_0 < 0.25$), respectively, as shown in Fig. 4.

It is obvious from Figs. 3 and 4 that the wide pulse has no significant spectral power beyond the critical frequency (h/λ_0 = 0.27) for leakage. Therefore, it is expected that the spectral-power distribution of the wide pulse does not degrade by the power-leakage effect during the pulse propagation, and that the pulse distortion does not occur. Actually, Fig. 5 shows the field plots observed after 300*psec* and 750*psec* from the pulse-peak excitation. These plots show the vertical electric field on the air-substrate interface underneath the strips. Also, Fig. 6 shows the temporal history corresponding to Fig. 5, where the pulse response is observed by the vertical electric field at its maximum point. Thus, we know that these results don't exhibit any significant distortion in the pulse shape as expected from the similar results already shown in [1].

On the other hand, as shown by the solid curve in Fig. 4, the narrow pulse has much spectral power even at high frequencies above the critical frequency f_{cr1}. Then the narrow pulse could excit the leaky mode in two manners. One is the simultaneous excitation of both the bound and leaky modes in the frequency range between f_{cr1} and f_{cr2}, correspondingly between h/λ_0 = 0.27 and 0.32. The other is the excitation of only the leaky mode above the frequency f_{cr2}.

All of the spectral power at the frequencies above f_{cr2} are leaked out from the transmission line after some propagation distance. However, in the finite frequency range between f_{cr1} and f_{cr2} for the simultaneous excitation, both modes will excite the transmission line with almost same amplitude, because both modes have almost same current distributions on the strips. Then, some half of the transmission power is lost by leakage, while another half of the power is transmitted without any loss. Therefore, in this simultaneous-propagation region, the spectral power carried by the bound mode is invariant as the pulse travels, whereas that of the leaky mode is degraded due to leaking out the power from the transmission line. As a result, even if the spectral power of the excited pulse is restricted in the frequency range below f_{cr2}, within which the bound mode can propagate, its distributon is degraded between the frequency range between f_{cr1} and f_{cr2}, and then the excited pulse will be distorted considerably. In addition, when the spectral power lies still beyond the frequency f_{cr2} as that of a narrow pulse is so, only the leaky mode carries the power in the frequency range above f_{cr2}, thereby degrading significantly the spectral power intensity. It is then expected that the spectral power at such high frequencies will mostly vanish at the propagation of some distance. As a result, when the transmission line exhibits the simultaneous-propagation effect, the excited narrow pulse will change into a wide pulse complicatedly distorted.

3. NUMERICAL EXAMPLES

Fig. 7 shows the field plots observed after 250*psec* and 750*psec* from the pulse-peak excitation. We can certainly see the widening effect for the pulse width as the narrow pulse travels. We can also see that the transmission power lost by leakage spreads out on the substrate in the form of the wing-like radiation field of the surface wave. Fig. 8 shows the temporal history corresponding to Fig. 7. We can clearly see the widening in its FWHM of the main pulse, of which the peak value decreases due to the leakage loss as the pulse travels. Also, these results show another behavior in the portion of the pulse tail, which grows to an apparent oscillatory shape as the pulse travels. Such a result will be explained by approximately regarding leakage loss as an intrinsic loss of the guide [7], although the leakage constant α for the present case is frequency dependent.

The pulse distortion we are discussing here is more clarified, if we investigate the spectral-power distribution. Fig. 9 shows the change in the spectral-power distribution that is obtained by Fourier-transforming the spatial pulses observed at different distances. It is apparent from Fig. 9 that the spectral-power distributions in the range below f_{cr1} ($h/\lambda_0 < 0.27$) are conserved independent of the propagation length of the pulse. Then, we know that the pulse power is carried only by the bound dominant mode in this frequency range. On the other hand, we can also see in Fig. 9 that the magnitude of the spectral power in the frequency range between f_{cr1} and f_{cr2} ($0.27 < h/\lambda_0 < 0.32$) decreases gradually as the pulse travels, while that above the frequency f_{cr2} ($h/\lambda_0 > 0.32$) quickly tends to zero even for a short traveling distance (*e.g.*, z = 30*mm*). This gradual change in the spectral-power distribution is caused by the effect of the simultaneous propagation of both bound and leaky dominant modes, while the quick change in the spectral-power

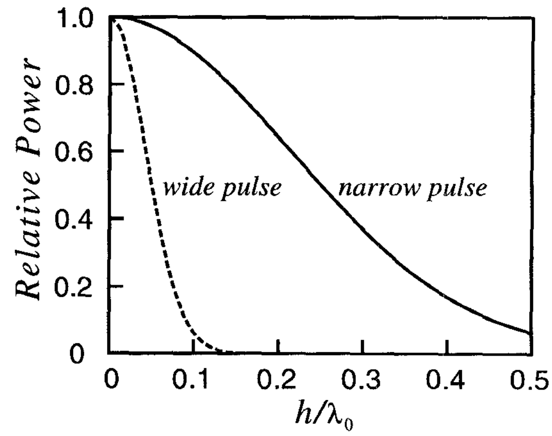

Fig. 4. Spectral-power distributions of two kinds of the Gaussian pulse; One is the wide pulse with FWHM = 58.8*psec* and the other is the narrow pulse with FWHM = 11.8*psec*.

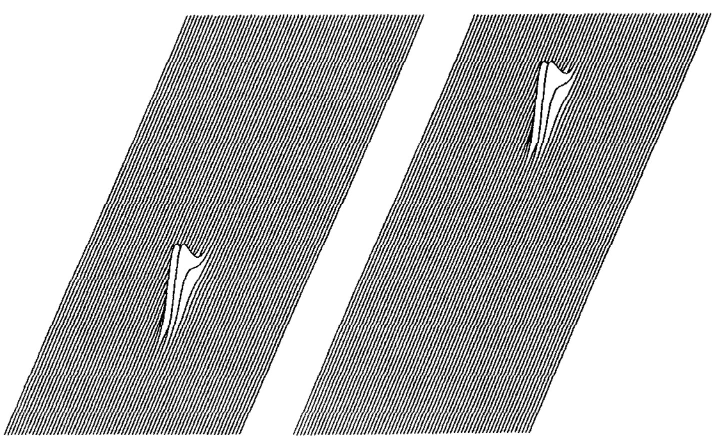

Fig. 5. Spatial history of the wide pulse. The field-intensity distributions of the vertical electric-field component observed at the air-substrate interface just underneath the strips. The left and the right show the pulses observed at t = 300*psec* and 750*psec*, respectively, after the pulse-peak excitation.

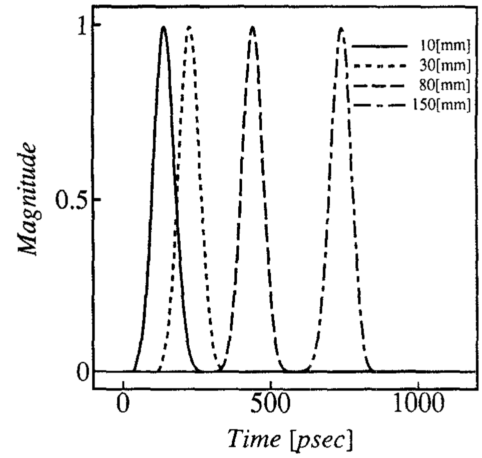

Fig. 6. The temporal history of the wide pulse for the different observation points at z = 10, 30, 80, and 150*mm*.

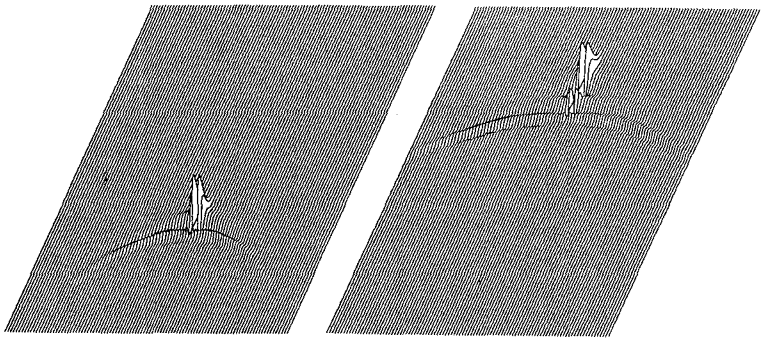

Fig. 7. Spatial history of the narrow pulse. The left and the right show the pulses observed at t = 250*psec* and 750*psec*, respectively, after the pulse-peak excitation.

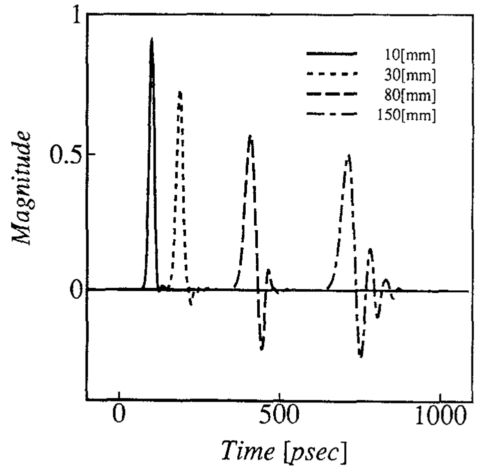

Fig. 8. The temporal history of the narrow pulse for the different observation points at z = 10, 30, 80, and 150*mm*.

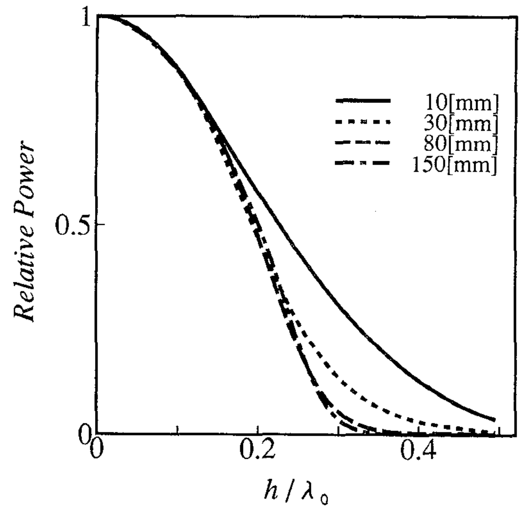

Fig. 9. Variation of the spectral power distribution of the narrow pulse.

distribution can be explained by the power loss due only to the leaky dominant mode at high frequencies (note from Fig.3 that the large attenuation constant α/k_0 is almost frequency independent).

We have obtained the similar results for other printed-circuit transmission lines such as slot line and unbacked coplanar strips, and some of important results will be presented in the talk. All of these numerical results have explained consistently well the physical understanding of a new type of the narrow-pulse distortion mentioned in this paper.

4. CONCLUSION

The feature of the narrow-pulse distortion discussed here has a significant effect on millimeter-wave-circuit performance. The reasons are the following; the first one is that, since the excited narrow pulse changes into a wide pulse as it travels when the transmission lines exhibit the simultaneous-propagation effect, one can not realize intrinsically the high-speed transmission of narrow pulses. The second reason, which relates to the performance of the interconnects, is the complicated dynamic cross talk produced by the leakage power radiated in the form of the surface wave. This performance problem relating to the interconnects will be discussed in the talk.

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