# INFLUENCE OF QUASI-PHYSICAL SOLUTIONS ON NEAR FIELDS IN PRINTED-CIRCUIT TRANSMISSION-LINE DISCONTINUITIES

**Hiroshi Shigesawa**(1) **and Mikio Tsuji**(2)

(1)*Department of Electronics, Doshisha University*
*Kyotanabe, Kyoto 610-0321, (Japan)*
*hshigesa@mail.doshisha.ac.jp*
*"As (1) above, but E-mail: mtsuji@mail.doshisha.ac.jp"*

## ABSTRACT

In addition to the bound-real eigen solution (the bound-dominant mode) on printed-circuit transmission lines, there can exist additional real and complex solutions that don't satisfy the physical condition based on a real-source excitation. Therefore, such nonphysical solutions have been always ignored with respect to their influence on the physical field excited by a real source, although the evolution in their properties serves to explain certain changes in the character of the physical modes. In this paper, therefore, we show the quantitative verification of the indirect effect of those nonphysical solutions to the physical fields numerically and experimentally.

## INTRODUCTION

It is well known that a leaky-wave solution in printed-circuit transmission lines is improper but physical and measurable within a sector of space near the guiding structure. On the other hand, the eigenvalue solutions that do not satisfy physical conditions based on a real-source excitation are called nonphysical solution. Therefore such solutions have been ignored with respect to their influence on the physical field excited by a source, although the evolution in their properties serves to explain important changes in the character of the physical modes. While it is true that they do not contribute directly to the excited fields, we have found out that under the right conditions, two types of nonphysical solutions, that is, real and leaky ones can ***indirectly*** influence the physical field in significant but different ways. That is, in spite of an excitation at a frequency where there is only a leaky solution as physical one, we have observed that the field amplitude along the guide axis does not decay according to the leakage constant expected from the eigenvalue of the leaky solution, but remains significantly far away from the source. In this case, the nonphysical real solution behaves as a ***quasi-bound mode*** within some finite distance from a source[1][2]. While in the case of the excitation at a frequency where there is only a proper-real solution (bound mode) as a physical one, we have observed that the field amplitude along the axis does not remain constant, but slowly decay from the real-source point. This effect caused by the behavior of the nonphysical $LM_2$ leaky mode[3] as a ***quasi-leaky mode***, where $LM_2$ leaky mode leaks in the form of two lowest-order surface waves on the surrounding dielectric substrate when its phase constant lies below both the dispersion curves of two surface waves[4]. Actually both phenomena are closely related to the bound-mode behavior that is practically important, so such phenomena may unexpectedly produce serious performance difficulties in microwave and millimeter-wave integrated circuits. In this paper, therefore, we show the quantitative verification of the indirect effect of those nonphysical solutions to the physical fields numerically and experimentally.

## QUASI-BOUND MODE

We consider here the slot line shown in the inset of Fig. 1 that shows the normalized phase constant when the relative slot width is $s/h$=0.4. The other dimensions and material constant are shown in Fig.1. The normalized leakage constant is not shown. The leaky dominant mode (the physical and improper complex solution) appears closely at the point of reversal of the improper-real solution, and goes to high frequencies as shown in Fig. 1. This type of the leaky mode is called here as the $LM_1$ mode that leaks power only into the $TM_0$ surface wave. In addition to this $LM_1$ leaky mode, there exists an additional higher-order leaky mode called as $LM_2$ mode in Fig. 1, but the discussion of the behavior of this mode is included in the next section. Fig. 2 shows the amplitude variation of the $E_x$ component (tangential to the air-substrate interface) along the guide axis at the slot center. As a real source, we have used the vector eigen function of the bound dominant mode at a low frequency on the guide cross section. The field variation shown in Fig. 2 is calculated at the normalized frequency $h/\lambda_0$=0.40 that is in the leakage range. We see that the field amplitude decays exponentially along the red curve given by the leakage constant expected from the eigen value. Such a decaying feature is typical to the ***ordinal leaky mode*** in the range, in which the leaky mode is the only physical solution.

Let us next change the slot width *s/h* from 0.4 to 0.9. Then the evolution of solutions changes significantly in both the improper-real solution and the $LM_1$ solution as shown in Fig. 3. The leakage constant and the dispersion curve of the $LM_2$ mode are again omitted here. The improper-real solution now goes upward to higher frequencies along the $TM_0$ surface-wave curve in the leakage range. Fig. 4 shows the field-amplitude variation, when the slot line is excited at $h/\lambda_0=0.32$, at which the physical solution is only the improper complex (leaky) one. However, the excited field decays unexpectedly slowly along the guide axis in the neighborhood of the source, and then the field remains with mostly same amplitude even at a distance far away from the source. This will be understood as the indirect effect of the improper real solution, which lies closely to the $TM_0$ surface-wave curve or closely to the branch point. Thus, in this case, the ***nonphysical real solution*** behaves like a ***quasi-bound mode*** within some distance from a source point.

## QUASI-LEAKY MODE

Let us consider again the case of the slot width $s/h=0.4$. In this case, we have an additional higher-order leaky mode called as the $LM_2$ mode shown in Fig. 5, and this mode leaks power into both the $TM_0$ and $TE_1$ surface waves. The $LM_1$ leaky solution is physical when its dispersion curve lies between the $TM_0$ and the $TE_1$ surface-wave curves, while the $LM_2$ leaky solution is physical below the $TE_1$ surface-wave curve. Therefore, the $LM_2$ leaky mode is ***nonphysica***l below the frequency $f_{cr4}$ in Fig. 5. Fig. 6 shows the field-amplitude variation, when the slot line is excited by a real source at the normalized frequency $h/\lambda_0=0.25$, at which the physical solution is only the proper-real (bound) one. We see that this result is very similar to that in Fig. 4. That is, the excited field in the neighborhood of the source region decays exponentially, and then the field remains with constant amplitude even at a distance far away from the source. However, the mechanism of the field variation is very different from that in Fig. 4. In this case, the field behavior is understood as an indirect effect of the nonphysical improper-complex $LM_2$ solution. To confirm such field behaviors, we made plots for both the equiamplitude-contour map and the bird-eye view as shown in Fig. 7. In the equiamplitude plot, which is shown only for the right half of the line, it is clearly shown that the field is bound to the slot region without decay in the field amplitude in distant. However the field in the neighborhood of the source region leaks some power in the form of the $TM_0$ surface wave along the slant line with the angle $\theta=30.81$ degrees from the line axis. This angle is corresponding mostly to the angle calculated from the eigen value of the $LM_2$ mode. Thus, in this case, the ***nonphysical complex solution*** behaves like a ***quasi-leaky solution*** within some distance from a source point.

## EXPERIMENTAL RESULTS

In this section, we demonstrate some comparative studies relating to the behavior of the quasi-bound mode. Fig. 8 is the results obtained from the FDTD calculations and our experiments. In Fig. 8, the slot line with the slot width $s/h=0.4$ is examined at the frequency $h/\lambda_0=0.4$, at which the physical mode is only the $LM_1$ solution as seen in Fig. 1. The red curve indicates the theoretical exponential-decay curve, while the dumping sinusoidal plot shows the FDTD result. The experimental result is shown by the blue curve. These three results agree well with each other. On the other hand, Fig. 9 shows the numerical and experimental results for the slot width $s/h=0.9$, but the operating frequency is changed to $h/\lambda_0=0.32$. At this frequency, the physical mode is still only the $LM_1$ solution as seen in Fig. 1. In this case, however, the decay rates of the field amplitude obtained from both the measured and FDTD results are very small than that of the $LM_1$ mode alone. These results show us that the improper-real solution in the case of Fig. 3 can affect unexpectedly the field behavior.

## CONCLUSION

In this paper, we have reported that nonphysical improper real solutions have significant effect to physical field excited by a real source. Also we have discovered that nonphysical leaky solution at low frequencies causes a significant effect to physical near field excited by a real source. These unexpected behaviors produce serious performance difficulties in microwave and millimeter-wave integrated circuits.

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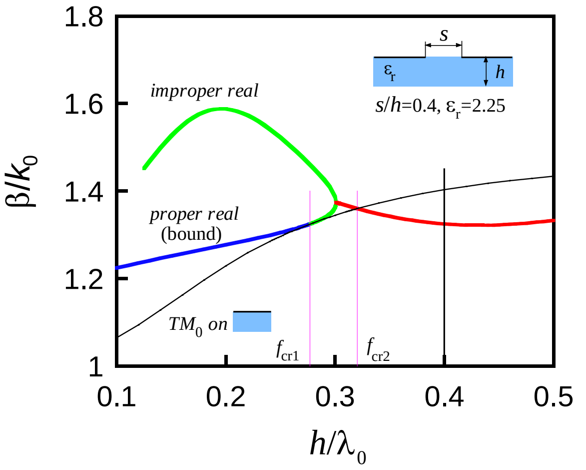

Fig. 1. The normalized phase constant for the slot line when the normalized slot width $s/h$ is selected as 0.4.

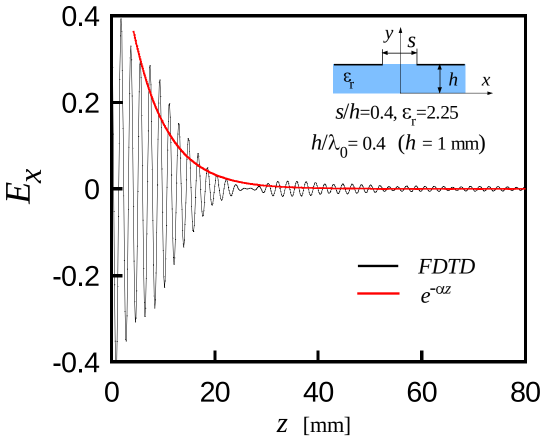

Fig. 2. The plot of the field-intensity variation along the guide center at the normalized frequency $h/\lambda_0$=0.4 of Fig. 1.

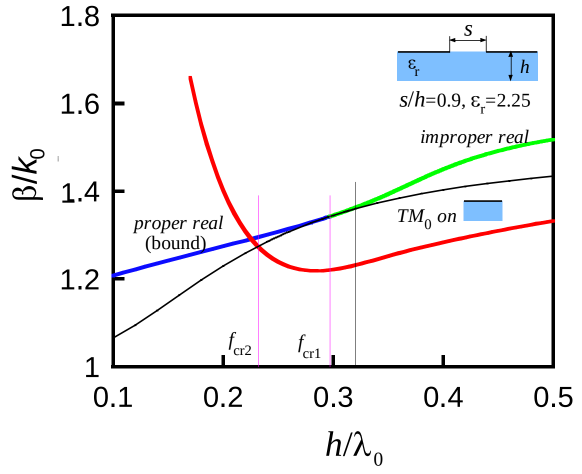

Fig. 3. The normalized phase constant for the slot line with $s/h$ = 0.9. In this case, the improper-real solution goes upward to higher frequencies, and the spectral gap disappears.

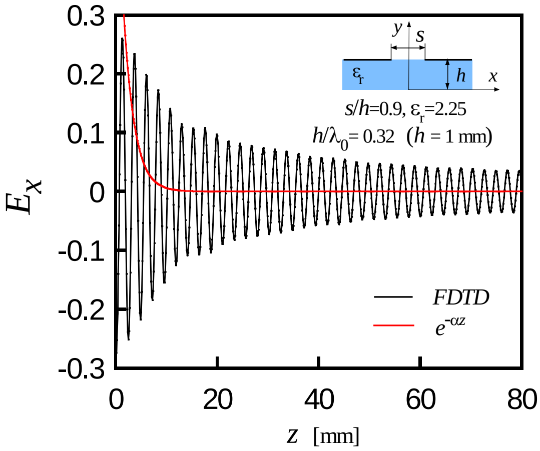

Fig. 4. The plot of the field-intensity variation along the guide center at the normalized frequency $h/\lambda_0$=0.32 of Fig. 3.

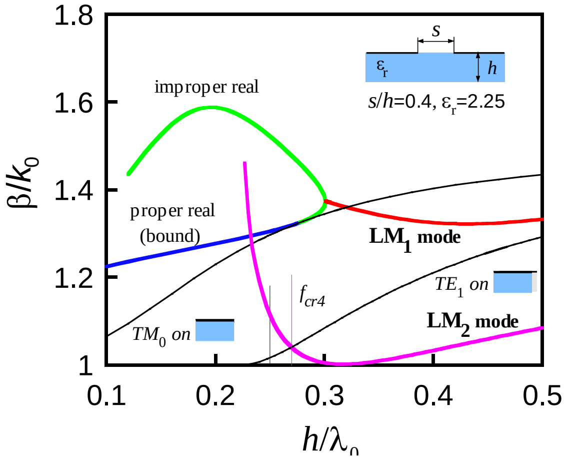

Fig. 5. The normalized phase constant of the $LM_2$ leaky mode for the slot line with $s/h = 0.4$.

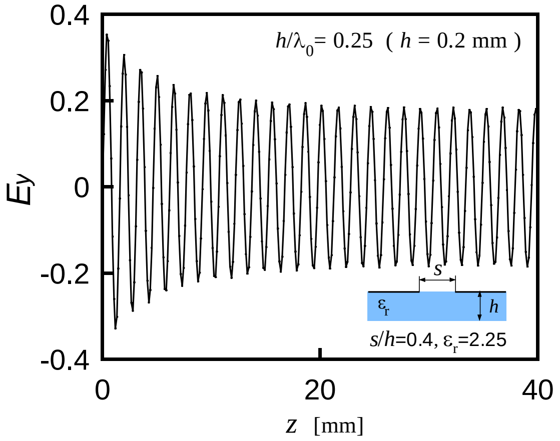

Fig. 6. The plot of the field-intensity variation along the guide center at the normalized frequency $h/\lambda_0 = 0.25$ of Fig. 5.

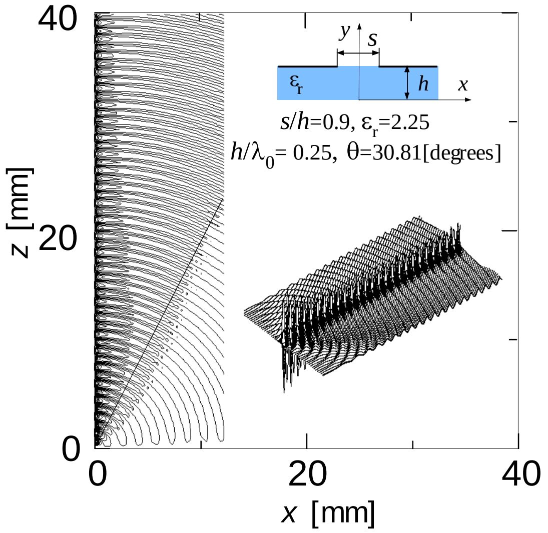

Fig. 7. Field-intensity distribution on the $xy$ plane just below the air-dielectric substrate at $h/\lambda_0 = 0.25$ for the guide of Fig. 5.

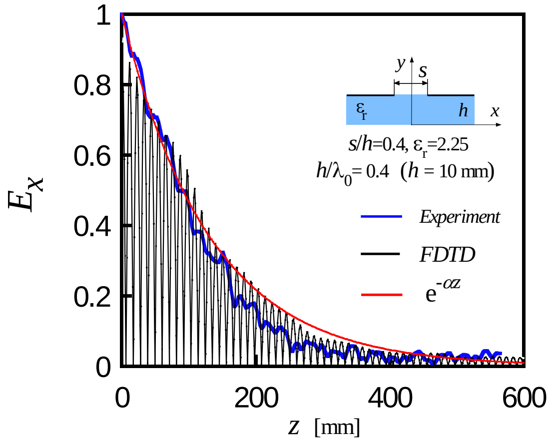

Fig. 8. The measured result of the field-intensity variation along the guide center at the normalized frequency $h/\lambda_0 = 0.40$ for the guide of Fig. 1.

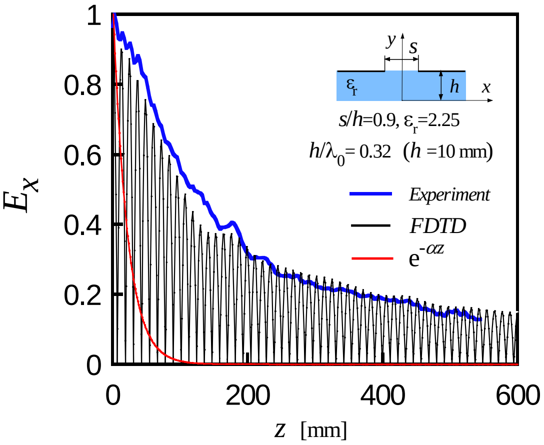

Fig. 9. The measured result of the field-intensity variation along the guide center at the normalized frequencies $h/\lambda_0 = 0.32$ for the guide of Fig. 3.