ACCURATE BROADBAND CHARACTERIZATION OF TRANSMISSION LINES

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ABSTRACT

This paper reports a sensitivity analysis of the transmission-line parameters versus the measured S-parameters of a single line element. The results lead to a simple procedure to (1) extract the small parasitic capacitance or inductance of discontinuities, (2) obtain accurate, broadband characteristic impedance of the transmission line, and (3) estimate error bounds of the measured line parameters.

INTRODUCTION

There are many techniques of characterizing transmission lines for their characteristic impedance and propagation constant. The simplest of all is the conventional method [1,2], characterizing the transmission line by measuring the S-parameters of a line segment. It is a broadband technique that calculates the characteristic impedance and propagation constant of the transmission line at every frequency point from the measured S-parameter data. However, the method suffers from relatively large errors in the characteristic impedance values due to the junction discontinuities and measurement uncertainties at frequencies where the line length is near a multiple of half-wave-length.

Recently, the calibration comparison method [3,4] was proposed to avoid this drawback. The method yields a well-behaved and more accurate estimate for the characteristic impedance of the line. However, it requires the fabrication and measurement of two or more line sections of the same transmission line.

In this paper, we re-examine the conventional method with a sensitivity analysis of the transmission-line parameters versus the measured S-parameters. We found that at frequencies where the line-length is a multiple of half-wave-length, the characteristic impedance estimate is very sensitive to small variations in S-parameter values, confirming the observations in previous publications. We also found that **at frequencies where the line-length is an odd-multiple of quarter-wave-length, the characteristic impedance estimate is insensitive to the measurement uncertainties or junction discontinuities**. Based on these observations, **we derive a procedure to (1) extract the small parasitic capacitance or inductance of discontinuities, (2) obtain accurate, broadband characteristic impedance of the transmission line, and (3) estimate error bounds of the measured line parameters**.

METHOD

The equations relating the characteristic impedance, Z_O, and the propagation constant, γ, of the transmission line to the measured S-parameters were outlined in [1] and [2]. We use those equations to study the sensitivity of Z_O and (γl) with respect to the variations of the measured S-parameters. We evaluated their derivatives

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numerically for typical transmission lines used in MIC and MMIC designs. Figures 1 and 2 present calculated results for a typical transmission line. Figure 1 presents the sensitivity of Z_r (real part of Z_o), Z_i(imaginary part of Z_o), αl(real part of γl), and βl(imaginary part of γl) with respect to the phase and magnitude of S21 (i.e., θ21 and A21). The result shows that αl_θ21 and βl_θ21 are well behaved over the broad frequency band. In fact, αl_θ21 ~ 0 and βl_θ21 ~ 0.5. For a typical on-wafer S-parameter measurement, the measurement uncertainty increases (almost linearly) with frequency to about 0.05 radian of phase error at 40 GHz. This translates to a 2.5% uncertainty in βl and about 0.5% uncertainty in b at 40 GHz. Notice that **longer line-segment will result in better accuracy in** β. On the contrary, Z_r_θ21 and Z_i _θ21 are ill behaved, presenting a periodic erratic behavior near frequencies where line length becomes a multiple of half-wave-length. This behavior confirms the observation reported in earlier papers[1,2]. However, we also observe that at frequencies where the line length becomes an odd-multiple of quarter-wave-length, Z_r_θ21 ~ 0 and Z_i _θ21 ~ 0.2. For similar measurement uncertainty mentioned earlier, this translates to 1% uncertainty in Zo at 40 GHz. That is, **accurate Zo can be determined at frequencies when the line length becomes an odd-multiple of quarter-wave-length**.

Figure 2 presents the sensitivity of Z_r (real part of Z_o), Z_i(imaginary part of Z_o), αl(real part of gl), and βl(imaginary part of γl) with respect to the phase and magnitude of S11 (i.e., θ11 and A11). The result shows that all the derivatives are well behaved over the broad frequency band. The measurement uncertainty in S11 does not present problems in the extraction of transmission-line parameters.

Based on the sensitivity analysis, we developed a procedure to extract the small parasitic capacitance or inductance at the discontinuity and obtain accurate, broadband characteristic impedance of the transmission line. The procedure is illustrated in the following example.

EXAMPLE

We fabricated a microstrip test pattern on 100-um GaAs substrate for this study. The line width is designed to be 50-um so as to matching the width of on-wafer probe pad for less geometrical discontinuity. The total length is 9 mm, plus another 100 um for two probe pads at both ends. The calibration of the probe station uses SOLT method with standards fabricated on an alumina substrate.

Based on the measured S-parameters, we calculated the complex characteristic impedance and propagation constant as shown in figure 3. Referencing figure 1, the behavior of the Z_o estimate indicates that the errors are mainly caused by a decrease in the phase of S21. Even though we maintain continuity in the test pattern design, the electrical discontinuity exists at the junction between the probe pads and the microstrip line. The parasitic can be represented by a shunt capacitor. If we remove a shunt capacitance of 4.5 fF, we see a dramatic improvement in the behavior of Z_o, as shown in figure 4. It appears that we need to remove a little more capacitance at the high frequency. By removing the parasitic in the test pattern, we improve the accuracy of the Z_o, but not sufficient for precise application. We then apply the fact that at frequencies where line length becomes an odd-multiple of quarter-wave-length, we can obtain accurate values of Z_o. Broadband representation is obtained by interpolation. In this case, we calculated the distributed capacitance of the line at those frequencies (2.87, 8.61, 14.35, 20.09, 25.82, 31.56, and 37.30 GHz) to be (.1577, .1569, .1569, .1572, .1585, .1531, and .1519 pF/mm), respectively. Using these capacitance and their interpolations to estimate the characteristic impedance based on the propagation constant, we obtain a set of accurate values for Z_o as shown in figure 5.

CONCLUSION

The accurate broadband characterization of the transmission line has been discussed in this paper. The proposed method is based on the sensitivity analysis of the transmission-line parameters and the measured S-parameters of a single line. We have demonstrated the simple procedure to enhance the accuracy of the transmission line parameters by extracting and removing external parasitic from the measurement. We also evaluated error bounds of the measured line parameters and observed the optimum frequency point(odd multiple of quarter-wave-length) to extract the line parameters, which is the least sensitive frequency point to the measurement error.

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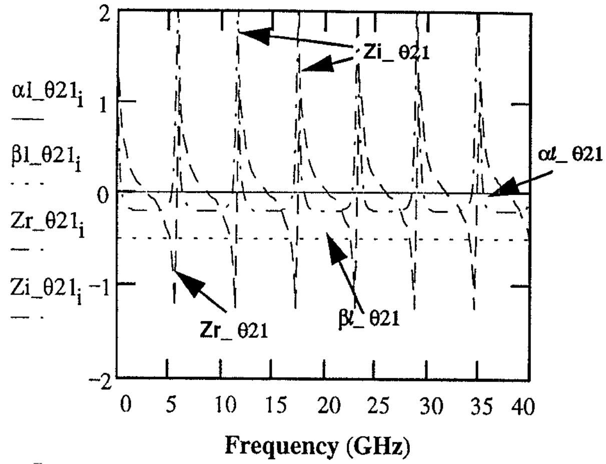

Figure 1. (a) Sensitivity of Zr, Zi, αl and βl with respect to the phase of S21.

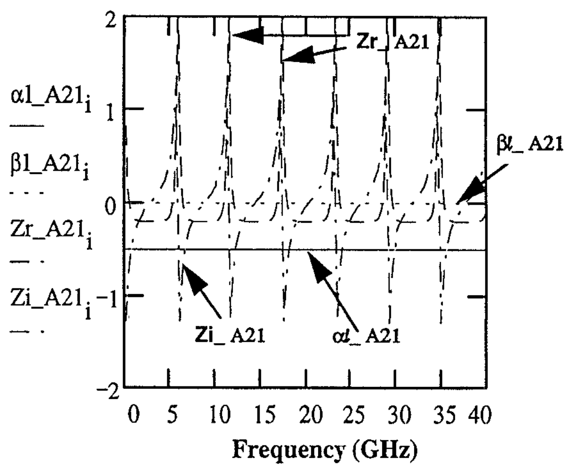

Figure 1. (b) Sensitivity of Zr, Zi, αl and βl with respect to the magnitude of S21.

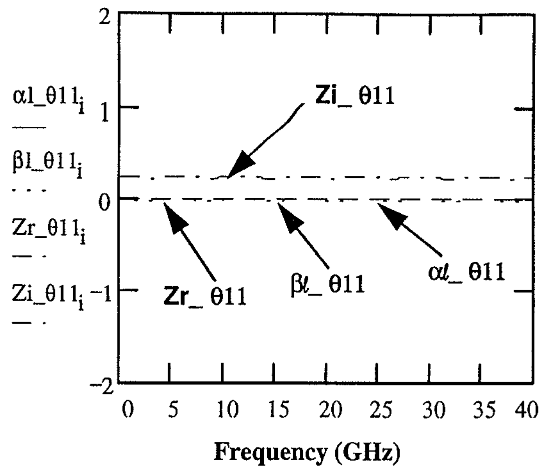

Figure 2. (a) Sensitivity of Zr, Zi, αl and βl with respect to the phase of S11.

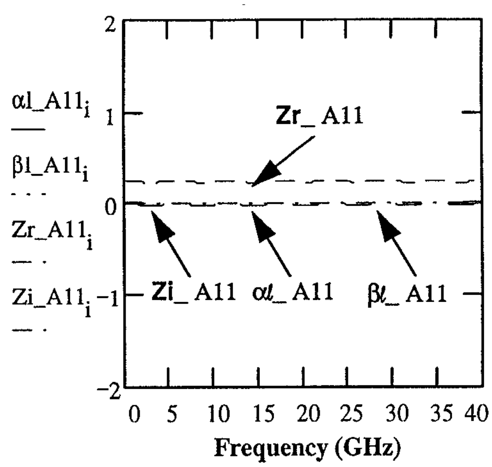

Figure 2. (b) Sensitivity of Zr, Zi, αl and βl with respect to the magnitude of S11.

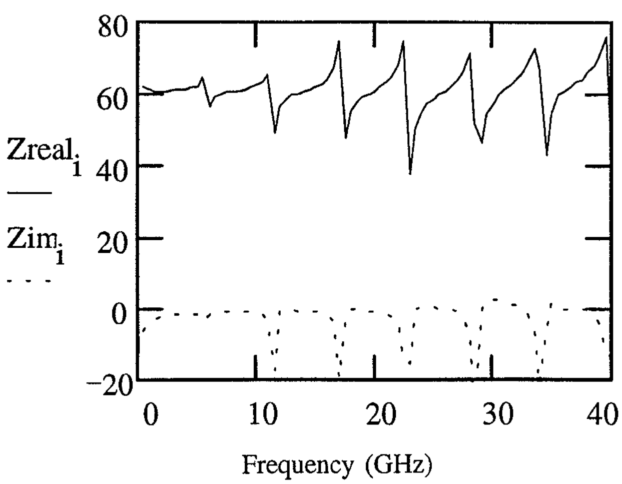

Figure 3. (a) Calculated characteristic impedance based on the measured S-parameters.

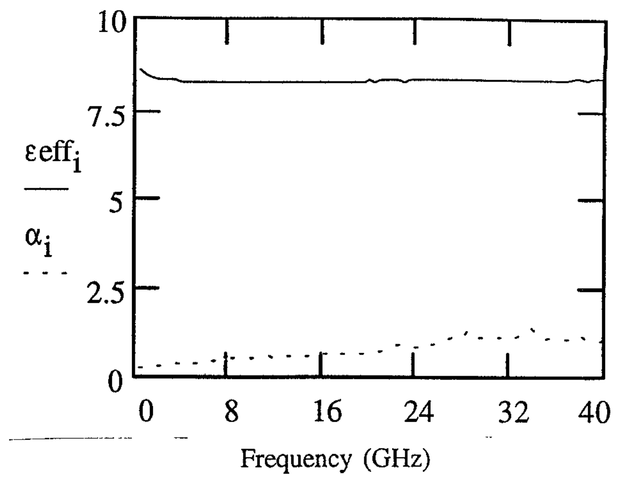

Figure 3. (b) Calculated propagation constant based on the measured S-parameters.

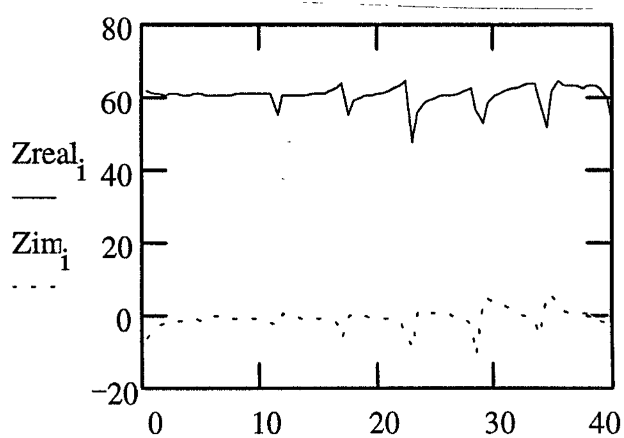

Figure 4. Characteristic impedance after shunt capacitance is removed.

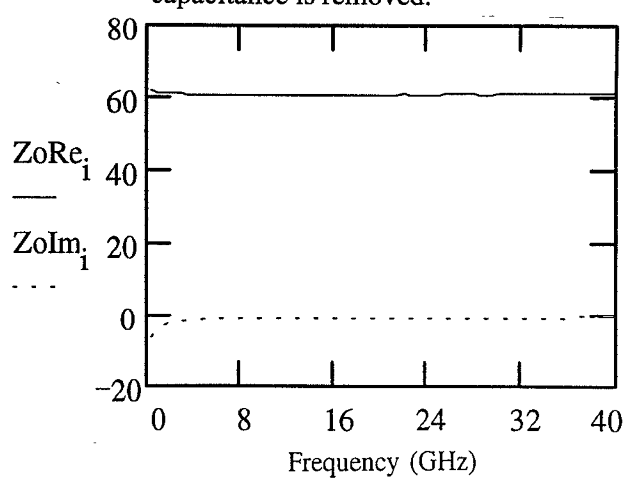

Figure 5. Only odd-multiple of quarter-wave-length frequencies are used for calculation of Z.