Limitations due to systematic phase errors on the extraction of loss tangent from micron-sized transmission line test structures

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Abstract

When two-port S-parameters are used to characterize microstrip test structures, finite phase measurement precision and small reference plane offsets can significantly limit the ability to extract loss tangent from transmission lines with finite series resistance.

Introduction

New dielectrics are being developed for integrated circuit applications. These materials must be characterized to determine both dielectric constant and loss. A common figure merit for dielectric loss is loss tangent (tan δ), which is related to the conductivity σ of the dielectric, the real part of the dielectric constant ε, and the angular frequency ω by

$$\mathrm{Tan}\delta = \frac{\sigma}{\omega\varepsilon}. \qquad (1)$$

Loss tangent is a convenient measure of dielectric loss since it is roughly frequency independent for many materials.

Transmission lines are often characterized by their per unit length series resistance R, series inductance L, shunt capacitance C, and shunt conductance G. For a microstrip test structure with conductor thickness less than a skin depth over the frequency range of interest, R, L and C will be frequency independent. When the microstrip is embedded in a uniform lossy dielectric the relation between G and C is simply

$$G = \omega C \cdot \mathrm{Tan}\delta. \qquad (2)$$

Hence, G will linearly increase in frequency for a frequency independent loss tangent. If a measurement can determine G and C with sufficient precision the loss tangent can be extracted.

Methodology

To study the influence of finite measurement accuracy and precision on the extraction of R, L, C, and G, an idealized microstrip was used as a model test structure. Here we first find the values of R, L, C and G from the geometry using Wheeler's microstrip model [1], and then convert to complex propagation constant γ and complex characteristic impedance Z_0. For a specified length of line l, γl and Z_0 are converted to "exact" S-parameters referenced to 50 ohm test ports. The S-parameters are then perturbed using the systematic errors discussed below. The perturbed S-parameters are then converted back to "measured" γl and Z_0, and finally the extracted R, L, C, and G are determined. The "measured" loss tangent is then calculated from the extracted G and C.

Microstrips of two different cross sectional dimensions were studied. The first, referred to as the 0.3 μm geometry, had a 0.3 μm wide, and 0.3 μm thick signal conductor. The signal to ground separation was also 0.3 μm. The other geometry, referred to as the 1 μm geometry, had metal thickness, width, and height above ground plane all of 1 μm. Both lines were assumed to be above a perfect ground plane, embedded in a uniform dielectric with $\varepsilon_r = 4$. The signal metal conductivity was assumed to be 5.8×10^7 S/m (bulk copper), while different values of frequency independent loss tangent were considered. The two cross sections will have the same L, C, and G per unit length because the shrink is the same in all dimensions. The R will be a factor of 11 higher for the 0.3 μm line compared to the 1 μm line. Two different lengths, 1 mm and 10 mm, were studied for each cross section.

Types of Errors

S-parameters can have errors in both magnitude and phase, but the errors in phase are simpler to model as a function of frequency and are the only ones considered in this paper. The two types of systematic phase errors considered here are finite phase measurement precision (essentially a round-off error in the phase) and a reference plane offset.

"Round-off" error is caused by the finite precision with which the phase of an S-parameter can be measured. For instance, the approximate phase precision under favorable conditions for an HP 8510C network analyzer is 0.01 degree [2]. Under less favorable conditions, the limit may be only 0.5 degree. To simulate this error, the phase of the calculated S-parameters (S11 and S21) were rounded to the appropriate decimal place. The transmission line parameters can then be extracted from the rounded S-parameters. Two representative phase limits, 0.01 degree and 0.1 degree, are considered here.

Another source of systematic phase error is reference plane offset. This can occur anytime the test setup changes between calibration and measurement. Calibrating a network analyzer sets a reference plane to which all measurements are referred. This allows the test cables and the probes to be mathematically removed from the measurement. If the plane moves after the calibration, all measurements will have an error because the effective DUT will now be the actual DUT plus the offset in the reference plane (either plus or minus). Two possible causes of an offset error are thermal variations in and bending of test cables.

The thermal expansion or contraction of the center conductor, shield conductor, and dielectric of the test cables causes the effective electrical length of the cables to change. If a shift occurs sometime between the calibration and the measurement, the calibration will remove the wrong amount of electrical length from all the measurements. Typical microwave test cables have a phase vs. temperature dependence of approximately 10 ppm per degree Celsius at room temperature. Since phase and length are directly proportional at a given frequency, the phase shift of 10^{-5} can also be interpreted as a length shift of 10^{-5}. In on wafer probing it is often necessary to use test cables of significant length: approximately1 meter of cable between test port and probe tip is not uncommon. For a 1 meter long cable, a 10^{-5} error would produce a 10 μm shift in the effective electrical length per degree Celsius temperature change.

Bending of the test port cables is also frequently unavoidable, as the probes must be moved to measure different DUTs. Any flexing of the cable between calibration and measurement will also shift the reference plane. The combination of these unavoidable reference plane shifts (temperature stability and bending) suggests that a 10 μm reference plane shift is a reasonable expectation in most measurements. Greater offsets are likely in many cases. For this reason we consider reference plane offsets of both 10 and 100 μm. We only consider the case where both S11 and S21 are affected by the offset, since this case is an upper bound on the other possible cases.

Results

The goal of these simulations is to determine the conditions under which loss tangent can be accurately measured. Many different variables could be considered but certain examples were chosen because they clearly illustrate the main dependencies.

The first consideration is the effect of systematic phase error on the extraction of the per unit length transmission line parameters R, L, and C. Figures 1, 2, and 3 show the extracted parameters R, L, and C, respectively, for the worst case phase error of 100 μm offset and 0.1 degree round-off. The simulations were run for both long (10 mm) and short (1 mm) lines for three different loss tangents (10^{-3}, 10^{-2}, and 10^{-1}). The 0.3 μm geometry is shown, but the 1 μm geometry case is similar. Only the extracted R parameter showed any significant variation due to changing loss tangent over the three orders of magnitude considered. All three parameters showed a dependence on length of DUT. This is not unexpected because the phase round-off of S21 should have a greater effect on the 1 mm long line than on the 10 mm long line. The extracted L is the worst of the three parameters, but this should be expected given the resistance of the line [3]. As the figures show, R and C can be "measured" to within 10 percent over most of the frequency range, although round-off error makes C at low frequency somewhat difficult to extract accurately.

The precision of the phase (round-off) affects the extracted loss tangent as shown in Figure 4. The 0.3 μm geometry is shown for a loss tangent of 10^{-2} and a length of 10 mm. The reference plane offset is assumed to be zero for this case. As expected, the less the precision, the worse the error in the extracted parameter. The results look "noisy," but it is important to note that the results are due to a systematic error as opposed to a random one; the behavior at low frequency is the direct result of limited precision causing the "measured" phase to appear to remain constant over a range of frequencies, leading to an extracted parameter that appears frequency dependent.

The effect of differing reference plane offsets is illustrated in Figure 5. Again, the 0.3 μm geometry and 10 mm length case is shown, and with no round-off error (i.e., infinite precision). Both offsets generate large errors in the extracted loss tangent, particularly at high frequency. The 10 μm offset produces less than 40% error, but the 100 μm offset is off by a factor of 4.5.

The effect of cross sectional geometry is shown in Figures 6 and 7. The 0.3 μm geometry for two line lengths and three loss tangents is shown in Figure 6, while Figure 7 shows the same information for the 1 μm geometry case. For both geometries the length dependence is less important than the other variables. A loss tangent of 10^{-1} can be extracted for either geometry. Lower values of loss tangent are hard to extract for the 0.3 μm geometry, though a loss tangent of 10^{-2} might be extractable at low frequencies. The 1 μm geometry can be used at low frequency to extract both 10^{-2} and 10^{-3} loss tangents.

Discussion

The simulations point out the difficulty of determining loss tangent from microstrip lines with large series resistance using S-parameter measurements with finite phase precision and accuracy. Some guidelines can be identified, however. Not surprisingly, a higher loss tangent is easier to extract, although "high" in this case is around 10^{-1}, which is a very lossy dielectric. Lower loss tangents may be estimated, but phase errors lead to an extracted frequency dependent loss tangent, even though the actual loss tangent was frequency independent. Lower series resistance (i.e., larger conductor cross section) lines can allow smaller loss tangents to be extracted and allow the extraction to higher frequency. Line length for a given cross-sectional geometry does makes a difference, but the simulations to date do not indicate definitively whether long or short lines are better under all circumstances.

Acknowledgements

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References

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[2] Hewlett-Packard, *HP Test & Measurement 1999 Catalog*, pp. 299, 1999.

[3] R. J. Friar and D. P. Neikirk, "Experimental Determination of the Importance of Inductance in Sub-Micron Microstrip Lines," presented at 1999 International Interconnect Technology Conference, San Francisco, 1999.

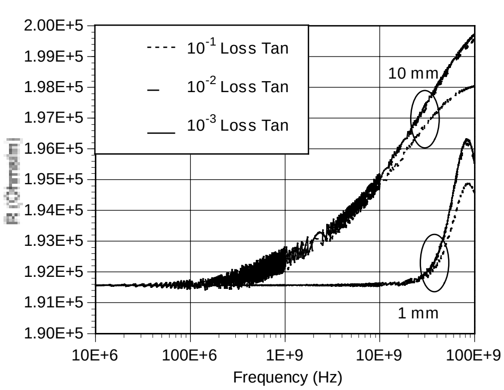

Figure 1: R per unit length for three loss tangents and two lengths. 0.3 μm cross sectional geometry, 0.1 degree phase round off, and 100 μm reference plane offset for all cases.

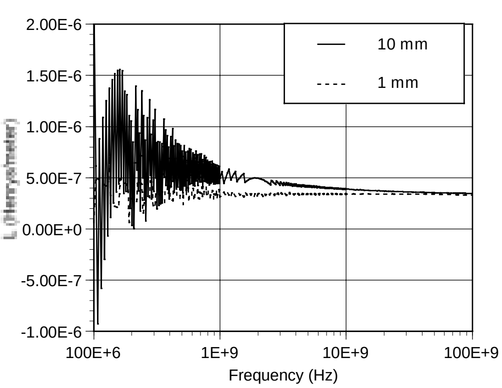

Figure 2: L per unit length for two lengths. 0.3 μm cross sectional geometry, 0.1 degree phase round off, and 100 μm reference plane offset. Loss tangents of 10^{-2} and 10^{-3} produce similar results and are not shown here.

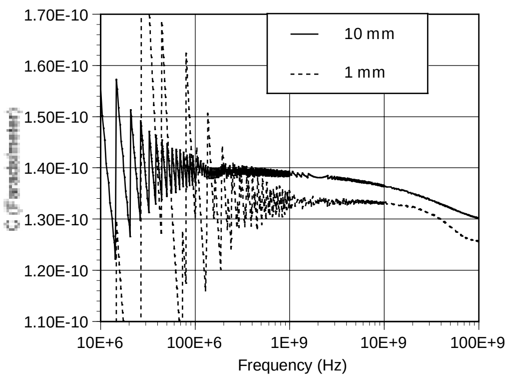

Figure 3: C per unit length for two line lengths with loss tangent of 10^{-1}. 0.3 µm cross sectional geometry, 0.1 degree phase round off, and 100 µm reference plane offset. Loss tangents of 10^{-2} and 10^{-3} produce similar results and are not shown here.

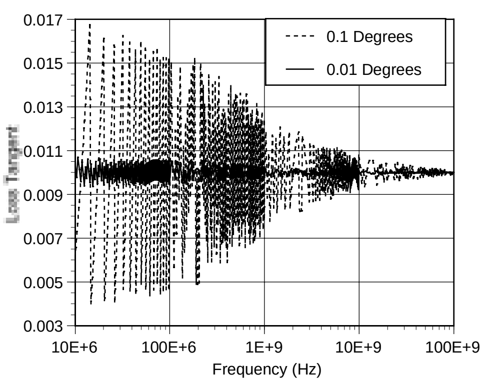

Figure 4: Extracted loss tangent for two different phase round off errors; 0.3 µm cross sectional geometry, 10 mm long, and zero reference plane offset. Actual loss tangent used was 10^{-2}.

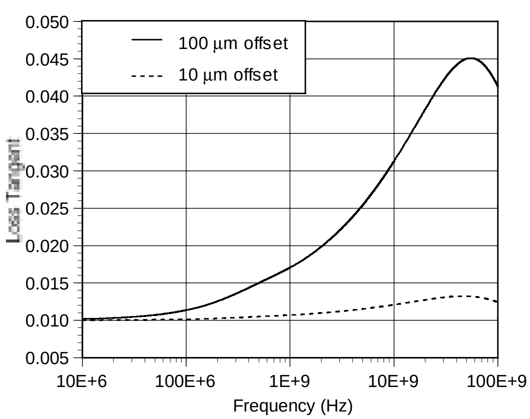

Figure 5: Extracted loss tangent for two different reference plane offsets; 0.3 µm cross sectional geometry, 10 mm long, and zero phase round off error. Actual loss tangent used was 10^{-2}.

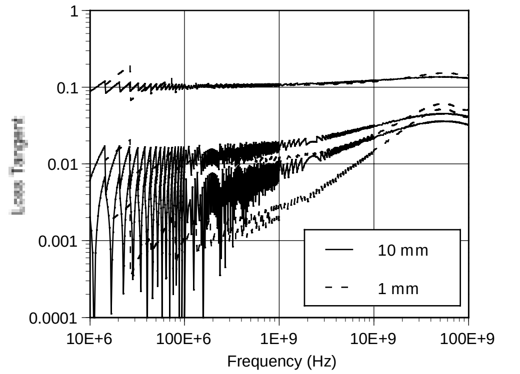

Figure 6: Extracted loss tangent for 0.3 µm cross sectional geometry, 0.1 degree phase round off error, 100 µm reference plane offset, for three different actual loss tangents and two lengths.

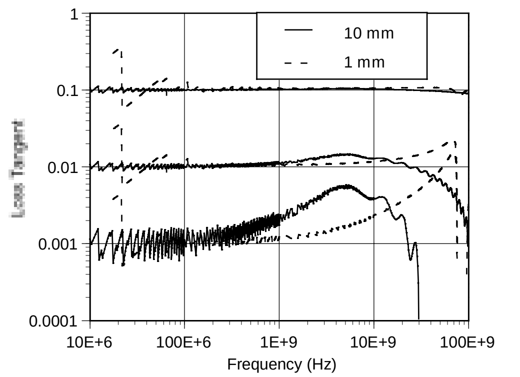

Figure 7: Extracted loss tangent for 1 µm cross sectional geometry, 0.1 degree phase round off error, 100 µm reference plane offset, for three different actual loss tangents and two lengths.