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Internal Inductance Correction for Permittivity Measurements of Planar Transmission Lines

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***Abstract*—At ISAP 2014, the authors have shown how measurements of planar transmission lines can be used for the determination of the transmission line's propagation constant as well as substrate permittivity. The work presented in this paper extends the previously presented method to also give a correction for internal inductance related to skin depth and surface roughness. Measurement data for microstrip and grounded coplanar waveguide up to 50 GHz is given and shows good agreement after correction. Small deviations due to nickel plating of the lines are discussed and an estimation for the effective relative permeability of the plating is given.**

1. Introduction

The continuously increasing demand for system integration often restricts fabrication of antennas to planar substrates such as printed circuit board or on-chip substrates. To allow a proper design of these antennas and related structures, the physical properties of the underlying material base have to be known. By application of the method presented in [1], the effective relative permittivity $\varepsilon_{\mathrm{r,eff}}$ of a planar transmission line (TL) can be found by a measurement of the S-Parameters and mapped to the relative substrate permittivity ε_{r} by comparison with simulation data. Using this method and the measurement setup as in [2], measurement data on microstrip (MS) and grounded coplanar waveguide (GCPW) fabricated on the same substrate [3] is given in Fig. 1 (dashed lines). The signal traces are made of copper with thickness $18\,\mu\mathrm{m}$ and low RMS surface roughness ($R_q = 0.5\,\mu\mathrm{m}$) and have been plated with nickel ($0.5\,\mu\mathrm{m}$) and gold ($0.1\,\mu\mathrm{m}$) for passivation. The substrate manufacturer gives a reference value of $\varepsilon_{\mathrm{r}} = 3.1$ for 10 GHz, which is in good agreement with the obtained value for the MS at this frequency. Additionally, ε_{r} obtained from the MS measurement shows a smooth decrease with increasing frequency, which obeys causality and implies a low dispersion [4]. However, the determined ε_{r} for the GCPW deviates significantly from the reference value as well as the MS slope. In the following, the authors will explain how this deviation is related to an increased internal inductance of the GCPW and give a method for correction.

2. Influence of surface roughness on internal inductance

Applying the method of [1], the propagation constant γ and $\varepsilon_{\mathrm{r,eff}}$ of a TL can be determined by a measurement of the S-Parameters. Combining this with the approach shown in [5] for calculating the characteristic impedance

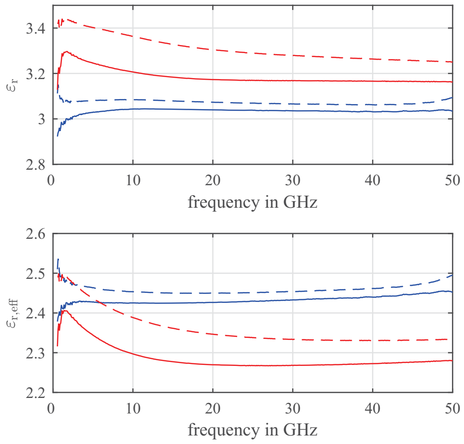

Fig. 1: Effective relative permittivity (bottom) and relative substrate permittivity (top) for MS (blue) and GCPW (red) using the method of [1] without (dashed lines) and with the presented correction method (solid lines).

$$Z_c = Z_0\sqrt{\frac{\mu_{\mathrm{r,eff}}}{\varepsilon_{\mathrm{r,eff}}}} \approx \frac{Z_0}{\sqrt{\varepsilon_{\mathrm{r,eff}}}}, \tag{1}$$

with Z_0 for the free space impedance of the line with ideal conductors and the effective relative permeability $\mu_{\mathrm{r,eff}} \approx 1$, the TL parameters can be calculated:

$$R' + j\omega L' = Z_c\gamma, \qquad G' + j\omega C' = \frac{\gamma}{Z_c}, \tag{2}$$

where R', L', G', and C' stand for the series resistance, series inductance, shunt conductance and shunt capacitance per unit length, $\omega = 2\pi f$ for the angular frequency and j for the imaginary unit.

The resistance R' consists of a DC resistance R'_{dc} for conductors electrically thick compared to skin depth and a term for the RF resistance R'_{rf}, covering the frequency-dependent loss due to skin effect [4]:

$$R' = R'_{\mathrm{dc}} + R'_{\mathrm{rf}} \tag{3}$$

The inductance is

$$L' = L'_{\mathrm{ext}} + L'_{\mathrm{int}} = L'_{\mathrm{ext}} + \frac{R'_{\mathrm{rf}}}{\omega} \approx L'_{\mathrm{ext}} + \frac{R'}{\omega}, \tag{4}$$

which consists of the external inductance L'_{ext} as well as the contribution of the internal inductance L'_{int} per unit length and approaches L'_{ext} for ideally smooth conductors at high frequencies [4]. For rough conductors and skin depths in the order of magnitude of the surface roughness, current flowing at the conductor surface cannot flow in a direct path anymore and needs to traverse the grooves introduced by the roughness, thus increasing the effective path length. As a consequence, not only the loss increases by a substantial amount, but also the inductance, since the grooves along the current path at the surface serve as distributed inductors. The increase in resistance due to skin depth as well as roughness is already modeled in R'_{rf} and included in R' after measurement. However, this is not accounted for in L' in (2), since $\mu_{\mathrm{r,eff}} \approx 1$ has been assumed in (1) for calculation of the TL parameters. This models all changes in phase originally related to $\mu_{\mathrm{r,eff}}$ into the calculated $\varepsilon_{\mathrm{r,eff}}$ and thus C' instead of L', which effectively reduces the measured L' in (2) to $L' = L'_{ext}$. Since L'_{int} and R'_{rf} are related as already shown in (4) and TLs working in the range of skin effect usually exhibit $R'_{\mathrm{rf}} >> R'_{\mathrm{dc}}$ [4], the effective material parameters can be corrected as follows [5]:

$$\mu_{\mathrm{r,eff}} = \frac{R' + j\omega(L'_{\mathrm{ext}} + L'_{\mathrm{int}})}{j\omega L'_{\mathrm{int}}}, \qquad (5)$$

whereas L'_{ext} in this equation is given by the measured L' from (2) and $L'_{\mathrm{int}} = \frac{R'}{\omega}$. Using $\gamma = j\frac{\omega}{c_0}\sqrt{\varepsilon_{\mathrm{r,eff}}\mu_{\mathrm{r,eff}}}$, the effective relative permittivity can be arranged as

$$\varepsilon_{\mathrm{r,eff}} = -\frac{\gamma^2 c_0^2}{\mu_{\mathrm{r,eff}}\omega^2}, \qquad (6)$$

which allows for a correction of $\varepsilon_{\mathrm{r,eff}}$ by $\mu_{\mathrm{r,eff}}$ introduced through skin depth and surface roughness.

3. Discussion of results and remaining deviation

In Fig. 1, both the uncorrected and corrected values for $\varepsilon_{\mathrm{r,eff}}$ and ε_{r} for MS and GCPW are given. The corrected ε_{r} of both TLs agree well with each other with a remaining deviation of about 0.1 or 3% for frequencies higher than 15 GHz. The ε_{r} values for MS show only little difference in offset, which is due to the small surface roughness of the copper being approached by the skin depth with increasing frequency, thus resulting in a small, but constant $\mu_{\mathrm{r,eff}}$ related to the effective increase in current path length due to roughness. The values are close to the reference value given by the substrate manufacturer at 10 GHz [3]. Concerning the material is designed to show low dispersion at microwave frequencies, the small, negative slope is deemed reasonable and causal [4].

Concerning the GCPW, not only a stronger offset correction, but also a slight change in the slope of the curve can be observed, whereas the corrected ε_{r} slope approaches the MS slope for frequencies higher than 15 GHz. The stronger offset correction can be explained by a higher roughness in the GCPW gap, which could be observed during microscopic analysis of the GCPW after plating the copper signal traces with nickel and gold as mentioned in Sec. 1. Beyond 15 GHz, only the offset remains and both corrected values show about the same slope, thus indicating that both TL measurements determined the same frequency-dependent behaviour of ε_{r}.

However, the deviation in offset as well as a different slope for frequencies up to 15 GHz still remains. The authors see the nickel plating as a reasonable explanation for this: As reported by several investigators and summarized in [6], nickel shows a $\mu_{\mathrm{r}} >> 1$ at DC, decreasing to a value slightly above 1 for frequencies higher than about 10 GHz. Since the nickel plating on the top and side surface of the signal traces affects the GCPW stronger than the MS due to the current concentration in the gap region, this explains the extent of the effect for the GCPW. Assuming that the MS current propagates only inside the copper and thus does not exhibit any material-based μ_{r}, the deviation between GCPW and MS can be incorporated into an additional $\mu_{\mathrm{r,eff}}$ accounting for the effect of the slightly magnetic material in the GCPW, see Fig. 2.

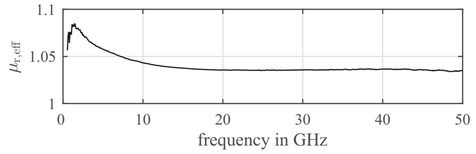

Fig. 2: Additional $\mu_{\mathrm{r,eff}}$ for GCPW due to nickel plating.

4. Conclusion

A method for correction of internal inductance variation due to surface roughness has been presented and applied on measurement data for MS and GCPW. After correction, the ε_{r} measurements of both TLs agree well with a remaining deviation of about 0.1 or 3% for frequencies higher than 15 GHz. The remaining deviation is explained by nickel plating in the gap of the GCPW not covered by the correction method and an estimation for the additional $\mu_{\mathrm{r,eff}}$ due to the plating is given.

Acknowledgment

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References

[1] P. Seiler, B. Klein, and D. Plettemeier, "Broadband characterization of planar transmission line substrate permittivity up to 67 ghz," in *Int. Symposium on Antennas and Propagation (ISAP)*, Dec 2014.

[2] ——, "Influence of microstrip probe pad design on planar measurements using on-wafer probes," in *Int. Symposium on Antennas and Propagation (ISAP)*, Nov 2015.

[3] *Data sheet: Ultralam® 3000 - Liquid Crystalline Polymer Circuit Material*, Rogers Corporation.

[4] H. Johnson and M. Graham, *High Speed Digital Design: A Handbook of Black Magic*. Prentice Hall, 1993.

[5] R. B. Marks, D. F. Williams, and M. B. Steer, "Accurate experimental characterization of interconnects: a discussion of 'experimental electrical characterization of interconnects and discontinuities in high-speed digital systems'," *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 15, no. 4, pp. 601–604, Aug 1992.

[6] S. Lucyszyn, "Microwave characterization of nickel," *PIERS Online*, vol. 4, no. 6, pp. 686–690, 2008.