Accurate Characteristic Impedance Measurement on Silicon

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Abstract- **This paper presents a new method that accurately determines the characteristic impedance of planar transmission lines printed on lossy dielectrics even when contact-pad capacitance and conductance are large. We demonstrate the method on a coplanar waveguide fabricated on fused silica and a microstrip line fabricated on a highly conductive silicon substrate.**

INTRODUCTION

We present a new algorithm for determining the characteristic impedance Z_0 of transmission lines printed on lossy substrates with the calibration comparison method [1]. The algorithm automatically accounts for shunt contact-pad capacitance and conductance. This improves accuracy when parasitic contact-pad capacitance and conductance are the dominant sources of systematic measurement error.

Reference [2] describes an extremely accurate method of determining the characteristic impedance of a printed transmission line. However, the method is based on the assumption that the conductance G per unit length is small and capacitance C per unit length is frequency independent. While the method accounts for all contact-pad parasitics, its assumptions are strongly violated when the transmission lines are fabricated on lossy substrates, such as conductive silicon substrates.

Eo and Eisenstadt [3] proposed what is now the conventional approach to determining the characteristic impedance of printed transmission lines that do not satisfy the criteria of small G and constant C. It determines Z_0 by comparing the transmission line's scattering parameters measured by a probe-tip calibration to those of an ideal transmission line. However, the probe-tip calibration measures not only the scattering parameters of the line, but also of the contact pads or other unaccounted for transition parasitics. This method of determining Z_0 is particularly sensitive to the shunt contact-pad capacitance. To circumvent this drawback, [3] suggests measuring the capacitance of the contact pads separately and subtracting their effect from the data measured by the probe-tip calibration before determining Z_0.

Figure 1a shows a top view of a short microstrip transmission line and its contact pads; Fig. 1b shows a coplanar waveguide (CPW). The figure illustrates the first difficulty with the method of [3]: while constructing the microstrip contact pads and measuring their capacitance is often straightforward, it is not clear how to define a physical structure that we can use to

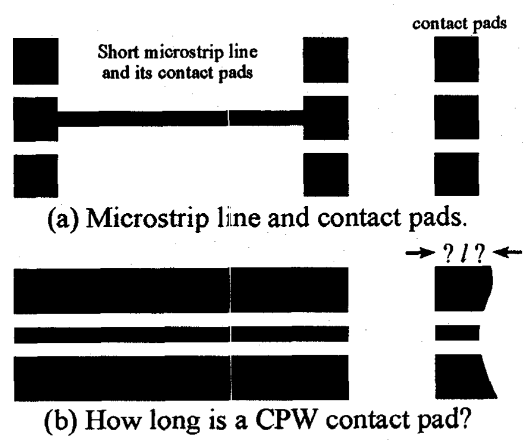

Fig. 1. Top views of microstrip and coplanar waveguide transmission lines.

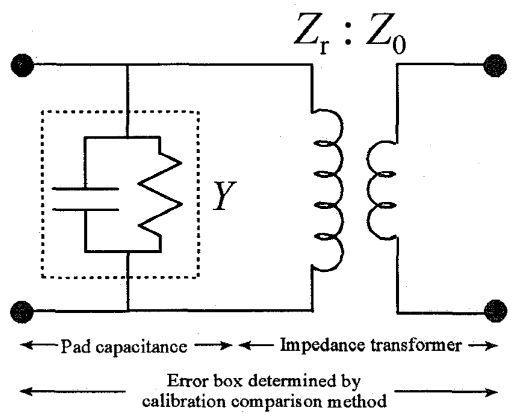

Fig. 2. The equivalent circuit model for the contact pads and impedance transformer.

measure a CPW's contact-pad capacitance. Even in microstrip, the center conductor may be wide, which effects the fringing fields, or the ground metal below and around the pads may have been removed to reduce the parasitic pad capacitance, complicating the choice of test structure used to determine contact-pad capacitance.

Winkel, et al. [4] propose a related method of determining Z_0. This method uses a set of additional measurements to develop a complex electrical model for the contact pads and subtracts the modeled parasitics from the measurements before determining Z_0.

Reference [5] proposes a different approach. Rather than try to subtract the electrical parasitics of the contact pads from the measurements, it uses the calibration comparison method of [1] to reduce the sensitivity of the measured values of Z_0 to those parasitics. The method begins with the performance of a multiline TRL probe-tip calibration [6] with a set of easily characterized reference lines. The reference impedance of this calibration is set to 50 Ω, and its reference plane is moved back to a position close to the probe tips using the methods described in [2].

A second-tier multiline TRL calibration in the transmission line of interest determines a set of "error boxes" relating it to the probe-tip calibration. These error boxes describe not only any contact-pad parasitics not accounted for by the probe-tip calibration, but also an impedance transformer that translates the 50 Ω reference impedance of the probe-tip calibration to Z_0, the reference impedance of the second-tier TRL calibration.

Reference [5] suggests a method of decomposing the error box measured by the calibration comparison method to allow Z_0 to be determined accurately in the presence of an arbitrary reference plane transformation of the probe-tip calibration.

Here we will propose an alternative treatment of the error box measured by the calibration comparison method that determines Z_0 accurately when contact-pad capacitance is large. We will compare the new method to prior methods and show that it accurately determines Z_0 without a separate characterization of the contact pads.

CONTACT-PAD MODEL

Figure 2 shows a simple model for a transition between a probe tip and a transmission-line. The model consists of a lossy shunt contact-pad with admittance Y followed by an impedance transformer mapping the reference impedance Z_r of the probe-tip calibration into the reference impedance Z_0 of the second-tier TRL calibration. The transmission matrix X of the circuit in Fig. 2 is

$$X = \frac{1}{\sqrt{1-\Gamma^2}} \begin{bmatrix} 1 & \Gamma \\ \Gamma & 1 \end{bmatrix} + \frac{Y Z_r}{2} \begin{bmatrix} -1 & -1 \\ 1 & 1 \end{bmatrix}, \quad \textbf{(1)}$$

where

$$\Gamma \equiv \frac{Z_0 - Z_r}{Z_0 + Z_r}. \quad \textbf{(2)}$$

When transition parasitics are dominated by contact-pad capacitance and conductance, the error box X' measured by the calibration comparison method will be approximately equal to X.

Reference [1] estimates Γ as

$$\Gamma_0 \equiv \sqrt{\frac{X_{12}' X_{21}'}{1 + X_{12}' X_{21}'}} \quad \textbf{(3)}$$

and shows that Γ_0 is insensitive to arbitrarily large reference plane transformations of the probe-tip calibration. However, while Γ_0 may not be sensitive to these reference plane transformations, **(1)** shows that it will be sensitive to Y.

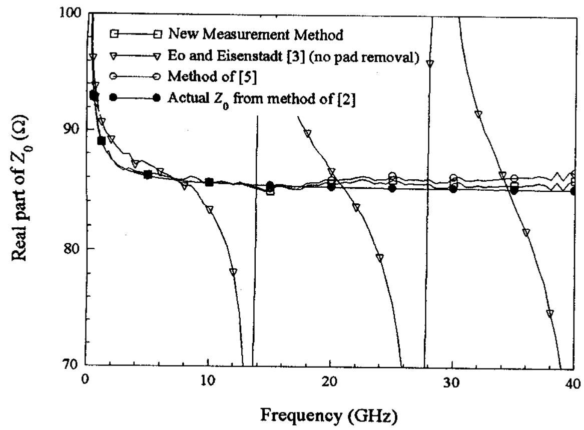

Fig. 3. The real part of the characteristic impedance Z_0 of a CPW measured with several different methods compared to the accurate method of [2]. In this CPW line we could not apply the procedure suggested in [3] to measure the contact-pad capacitance, and did not subtract it from the measurements before applying the method of [3]. The plotted data is from [5].

On the other hand, the term $YZ_r/2$ in (1) adds to X_{21} but subtracts from X_{12}, so its effect cancels completely from the mean $\frac{1}{2}(X_{12}+X_{21})$. Thus, even for very large Y, $\Gamma/\sqrt{1-\Gamma^2} \approx \frac{1}{2}(X_{12}'+X_{21}')$. In the new method we propose here, we will use (2) and the estimate

$$\Gamma_1 \equiv \sqrt{\frac{(X_{12}'+X_{21}')^2}{4+(X_{12}'+X_{21}')^2}}, \qquad (4)$$

which is insensitive to contact-pad capacitance and conductance Y, to determine Z_0.

MEASUREMENT COMPARISON

Figure 3 compares the measurement methods of [2], [3], and [5] to the new method described above for a CPW in which it was not possible to separately measure and subtract the contact-pad capacitance from the data. The transmission line is a CPW with a 73 μm wide center conductor separated by 49 μm wide gaps from 250 μm wide ground planes fabricated on a fused silica substrate. On this low loss fused silica substrate the assumptions of [2] are well met, so we assume that it gives an accurate result. The figure shows that the measurement method of [3] fails badly when the contact-pad capacitance cannot be determined and subtracted from the measurements, while the new method and the method of [5] accurately determine the characteristic impedance of the CPW.

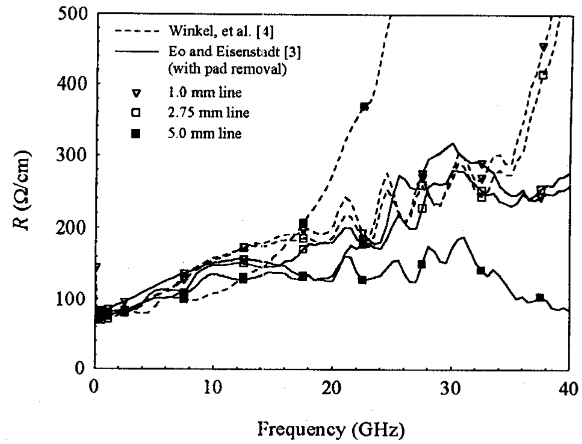

Fig. 4. The resistance R per unit length of a 10 μm wide microstrip on a lossy silicon substrate measured by the methods of [3] and [4]. The contact-pad parasitics were measured and removed following the procedure recommended in [3] and [4].

The resistance R per unit length of a transmission line can be determined from the lines' measured characteristic impedance Z_0 and propagation constant γ via $R+j\omega L \equiv \gamma Z_0$. While γ can usually be measured quite accurately [6], R is particularly sensitive to errors in the measurement of the phase of Z_0.

Figure 4 plots measurements of R of microstrip lines of different lengths printed on a highly conductive silicon substrate determined with the methods of [3] and [4]. These lines had a 50 μm by 50 μm pad connected to a 10 μm wide center conductor fabricated on a 0.5 μm thick oxide layer grown on a silicon substrate with a resistivity of 0.0125 Ω·cm. The microstrip line also employed two 20 μm wide metal rails connected by a continuous 10 μm wide via through the oxide to a 10 μm wide ohmic contact to the silicon substrate. These CPW-like ground returns were fabricated at a distance of 100 μm from the microstrip center conductor to reduce the resistance of the ground return through the substrate.

In this case we were able to define, test, and subtract the capacitance and conductance of the contact pads following the procedure outlined in [3] and to apply the pad model of [4]. Nevertheless, Fig. 4 shows that the methods of [3] and [4] are very sensitive to the particular line used in the experiment.

Figure 5 compares measurements of the R of the

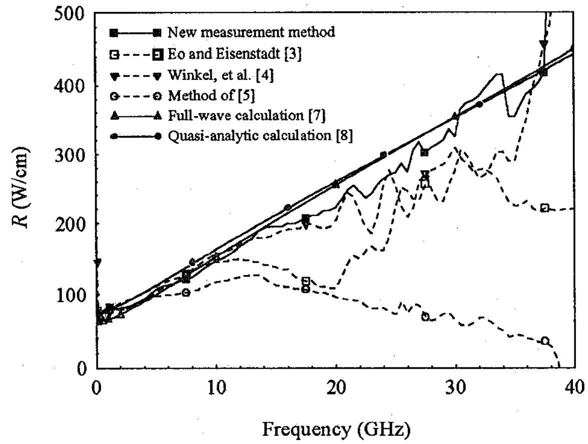

Fig. 5. Measured and calculated values of R of the 10 µm wide microstrip line of Fig. 4 fabricated on a highly conductive silicon substrate.

microstrip lines from the new method described here, the method of [5], the methods of [3] and [4] applied to the 1 mm long microstrip line, and calculations using the full-wave method of [7] and the quasi-analytic method of [8]. Both the methods of [3] and [5] exhibit nonphysical drops in R not seen in the calculations. Only the method of [4], which requires a complex pad model, gives results comparable to the new method.

CONCLUSIONS

We have introduced a new method of measuring characteristic impedance that automatically accounts for large contact-pad capacitance and conductance. The method does not depend on a separate characterization and subtraction of these pad parasitics from the measurements, but rather on a formulation that is insensitive to these parasitics.

The method is well suited to transmission lines fabricated on silicon substrates, where contact-pad capacitance is the dominant source of measurement error. However, it would be expected to fail in measurements situations in which other significant contact-pad parasitics, such as a large contact-pad resistance or inductance, are also present.

The values of characteristic impedance determined by the method could be used to set the reference impedance of TRL calibrations in transmission lines fabricated on lossy substrates, as explained in [9], perhaps improving the accuracy with which network parameters can be measured on silicon.

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