Accurate Electrical Measurement of Coupled Lines on Lossy Silicon

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***Abstract*- In this paper we apply a measurement method designed for asymmetric coupled lines to determine the broadband propagation characteristics of symmetric coupled lines fabricated on a highly conductive silicon substrate. We show that the matrices of frequency-dependent propagation constants and characteristic impedances, as extracted from calibrated four-port S-parameter measurements, agree very well with data predicted by numerical calculations.**

INTRODUCTION

Most recent measurement methods involving coupled transmission lines on conductive silicon substrates have been restricted to the case of symmetric coupled lines. The method presented in [1], which is based on the procedure introduced in [2], was demonstrated for the more general case of asymmetric coupled lines fabricated in CMOS technology. However, no results have been reported for the case of symmetric coupled lines. The purpose of this paper is to investigate the applicability of method [1] to the symmetric case.

References [3] and [4] report on measurement results for test structures similar to the ones investigated in this work, thereby allowing for a direct comparison to method [1]. A cross section of the lines studied is shown in Fig. 1. A more detailed view of the geometry can be found in Figs. 1 and 2 of Ref. [3]. The only significant difference in the experiments of [3] and [4] was the line width of the two coupled lines: in this work, the two coupled lines have a width of 10 µm and are separated by a gap of 5 µm, whereas in [3] and [4] the line width was 5 µm.

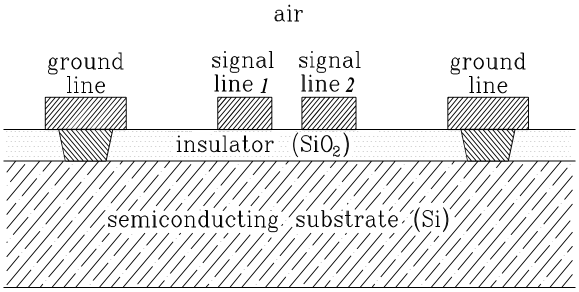

Fig. 1. Cross section of the investigated coupled lines.

This work was partially supported by an ARFTG Student Fellowship.

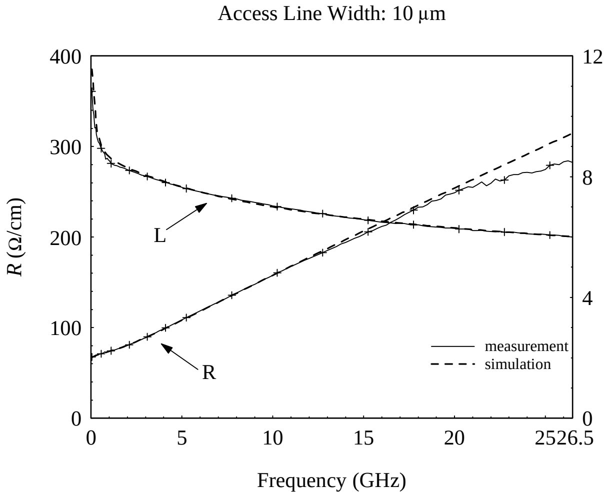

Fig. 2. Resistance and inductance per unit length of the access lines.

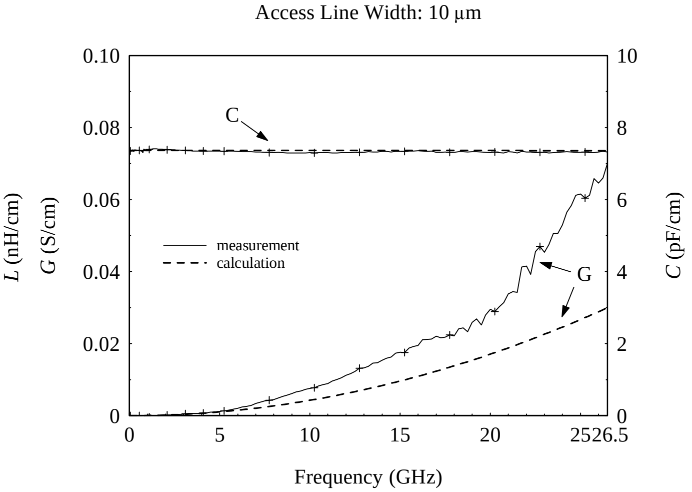

Fig. 3. Conductance and capacitance per unit length of the access lines.

In our experiments, the metal thickness is 0.665 µm, and the metal conductivity is 23.15×10^6 S/m. The symmetric coupled lines are surrounded by 20 µm wide grounds that are electrically connected to the substrate. The highly conductive silicon substrate has a resistivity of 0.0125 Ω-cm. We used on-wafer probes to connect to 50 µm by 50 µm contact pads. These contact pads are connected to the coupled line segment with access lines 10 µm wide and 250 µm long. The coupled line segment was built in various lengths ranging from 0.5 mm to 5.0 mm. Since the coupled lines are embedded in access lines and contact structures with large parasitic effects, these effects must be accounted for in a rigorous way.

MEASUREMENT AND DEEMBEDDING PROCEDURE

We used two-port measurements to characterize the contacts and access lines and four-port measurements to characterize the coupled line system. We employed the method of [5] to measure the characteristic impedance Z_0 of the access lines, which is designed to account for large contact-pad capacitances on lossy substrates. We determined the propagation constant from a multiline TRL calibration [6], and verified the measurements using the quasi-analytic calculations described in [7].

Figures 2 and 3 show that the measured and calculated line parameters per unit length of the 10 µm wide access lines agree well. Only the values of conductance per unit length differ significantly. We believe that this is due to the fact that the method of [7] neglects the influence of substrate skin effect in the calculation of the admittance parameters per unit length.

The calibration procedure used for the four-port measurement is described in [8]. It eliminates the need for orthogonal calibration standards, and requires only three in-line calibrations. To this end we again used the multiline TRL procedure [6]. Since the initial reference plane position of the four-port calibration [8] is near the probe tips, we required an additional deembedding step for the access lines. We employed a second-tier TRL calibration in the access lines for this purpose, using the propagation constant from the TRL calibration to locate the reference planes at the beginning of the coupled line segment, and the calibration comparison method [5] to set the reference impedance to 50 Ω.

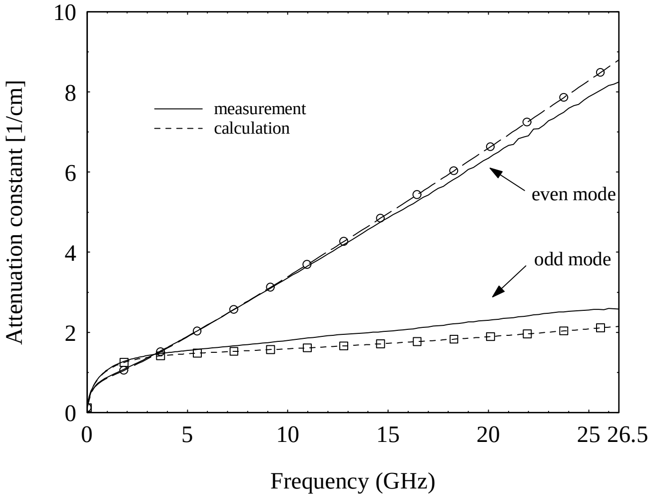

Fig. 4. Attenuation constants of the symmetric coupled-line system.

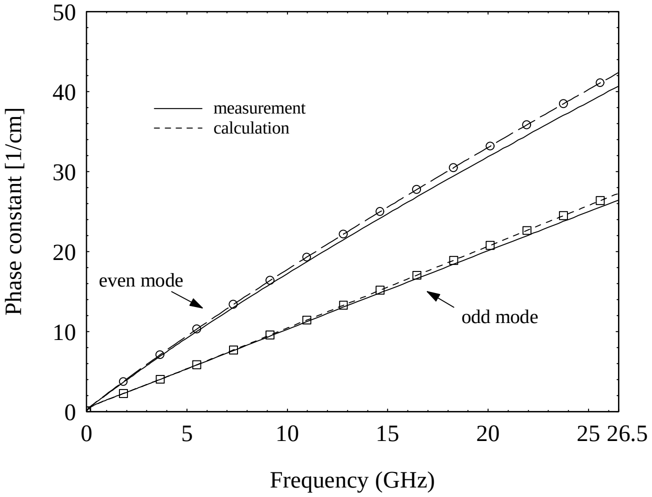

Fig. 5. Phase constants of the symmetric coupled-line system.

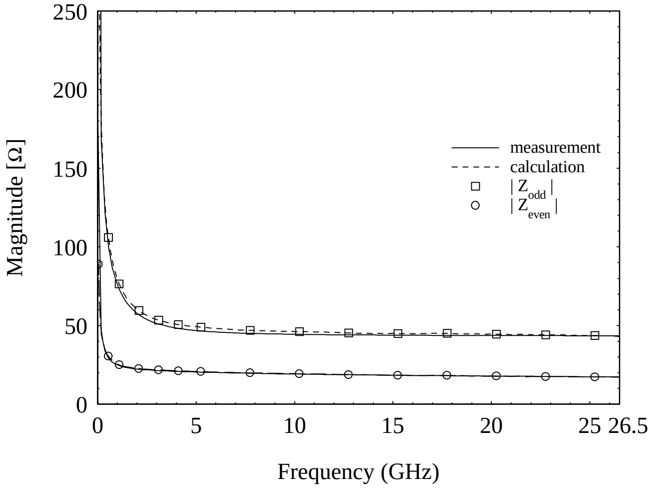

Fig. 6. Magnitude of characteristic impedances of the symmetric coupled-line system.

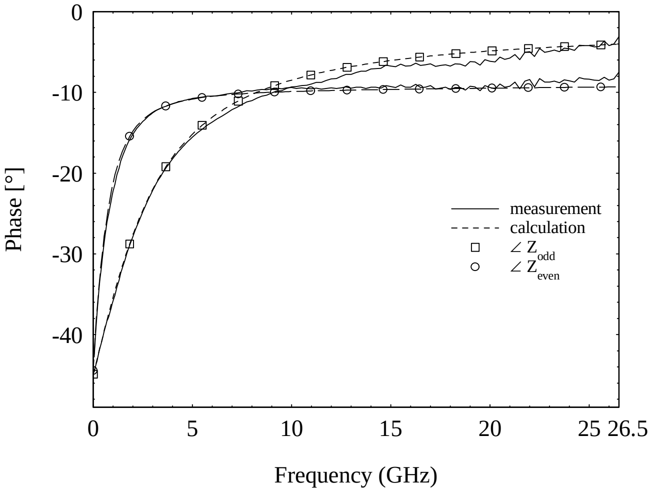

Fig. 7. Phase of characteristic impedances of the symmetric coupled line system.

EXPERIMENTAL RESULTS

The coupled lines support two dominant modes, which are commonly called the even and odd modes. We determined the matrices of the line parameters $\boldsymbol{R}_c$, $\boldsymbol{L}_c$, $\boldsymbol{G}_c$, and $\boldsymbol{C}_c$ in the conductor representation of [9], choosing voltage paths between each of the two conductors and ground. In our analysis we ignored the four-port error boxes that represent the discontinuities between the single-mode access lines and the multi-mode coupled line segment.

We first estimated the line parameter matrices from the four-port measurement data using ODRPACK, an implementation of the weighted orthogonal distance regression algorithm of [10], using the procedure described in [1]. This procedure solved for all of the elements of the line parameter matrices at each frequency independently. Then we calculated the matrices of the propagation constants and characteristic impedances from the measured values of the line parameters.

Figures 4-7 compare the measurement results with calculated quasi-analytic data for the coupled line system. The agreement between measured and calculated values is good over the entire frequency band despite the fact that the nonlinear optimization was performed with regard to the line parameters, not the quantities shown in Figs. 4-7. The measured real and imaginary parts of the propagation constant (Figs. 4 and 5) as well as the measured magnitude and phase of the characteristic impedance (Figs. 6 and 7) show that the method of [1] can also be used for the accurate characterization of symmetric coupled lines on substrates of a high conductivity. Furthermore, the results achieved for the even- and odd-mode characteristic impedance values in Figs. 6 and 7 appear much more accurate than the results reported in [4].

REFERENCES

[1] U. Arz, D. F. Williams, D. K. Walker, J. E. Rogers, M. Rudack, D. Treytnar, and H. Grabinski, "Characterization of Asymmetric Coupled CMOS Lines", *2000 IEEE MTT-S Symposium Dig.*, pp. 609-612, June 11-16, 2000.

[2] D. F. Williams, J. E. Rogers, and C. L. Holloway, "Multiconductor Transmission Line Characterization: Representations, Approximations, and Accuracy", *IEEE Trans. Microwave Theory Tech.*, vol. 47, no. 4, pp. 403-409, April 1999.

[3] T.-M. Winkel, L. S. Dutta, H. Grabinski, and E. Grotelüschen, "Determination of the Propagation Constant of Coupled Lines on Chips Based on High Frequency Measurements", 1996 *IEEE MCMC Conf. Dig.*, pp. 99-104, February 6-7, 1996.

[4] T.-M. Winkel, L. S. Dutta, and H. Grabinski, "An Accurate Determination of the Characteristic Impedance Matrix of Coupled Symmetrical Lines on Chips Based on High Frequency S-Parameter Measurements", 1997 *IEEE MTT-S Symposium Dig.*, pp.1769-1772, June 11-16, 1997.

[5] D. F. Williams, U. Arz, and H. Grabinski, "Accurate Characteristic Impedance Measurement on Silicon", *1998 IEEE MTT-S Symposium Dig.*, pp. 1917-1920, June 9-11, 1998.

[6] R. B. Marks, "A Multiline Method of Network Analyzer Calibration", *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, no. 7, pp. 1205-1215, July 1991.

[7] E. Grotelüschen, L. S. Dutta and S. Zaage, "Quasi-analytical Analysis of the Broadband Properties of Multiconductor Transmission Lines on Semiconducting Substrates", *IEEE Trans. Comp., Packag., and Manufact. Tech.-Part B*, vol. 17, pp. 376-382, Aug. 1994.

[8] D. F. Williams and D. K. Walker, "In-line Multiport Calibration", *51st ARFTG Conf. Dig.*, pp. 88-90, June 12, 1998.

[9] D. F. Williams, L. A. Hayden, and R. B. Marks, "A Complete Multimode Equivalent-Circuit Theory for Electrical Design", *J. Res. Natl. Inst. Stand. Technol.*, vol. 102, no. 4, pp. 405-423, July -Aug.1997.

[10] P. T. Boggs, R. H. Byrd, and R. D. Schnabel, "A Stable and Efficient Algorithm for Nonlinear Orthogonal Distance Regression", *SIAM J. Sci. Stat. Comput.*, pp. 1052-1078, Nov. 1987.