Combined Differential and Common-Mode Scattering Parameters: Theory and Simulation

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***Abstract*—A theory for combined differential and common-mode normalized power waves is developed in terms of even and odd mode impedances and propagation constants for a microwave coupled line system. These are related to even and odd-mode terminal currents and voltages. Generalized s-parameters of a two-port are developed for waves propagating in several coupled modes. The two-port s-parameters form a 4-by-4 matrix containing differential-mode, common-mode, and cross-mode s-parameters. A special case of the theory allows the use of uncoupled transmission lines to measure the coupled-mode waves. Simulations verify the concept of these mixed-mode s-parameters, and demonstrate conversion from mode to mode for asymmetric microwave structures.**

I. Introduction

THERE is an emerging need to measure RF and microwave differential circuits. Differential circuits have been important in communications systems for more than 50 years. Recent technological advances have pushed analog differential circuit performance limits into RF and low microwave frequencies.

Typically, differential circuits are designed and analyzed with traditional analog techniques, which employ lumped element assumptions. Examples of such analog differential circuit design and analysis are found in the texts by Gray and Meyer [1] and Middlebrook [2]. RF and microwave differential circuits contain distributed circuit elements, and require distributed circuit analysis and testing. Furthermore, traditional methods of testing differential circuits have required the application and measurement of voltages and currents, which is difficult at RF and microwave frequencies. Scattering parameters (s-parameters) have been developed for characterization and analysis at these frequencies [3], but have been applied primarily to single-ended circuits. A modification of existing s-parameter techniques is needed to measure differential-mode and common-mode circuit performance at microwave frequencies.

Currently, it is possible to measure common-mode s-parameters on wafer with standard ground-signal-ground probes to more than 100 GHz [4]. However, a differential circuit requires a balanced probe to launch differential signals. A balanced probe provided by Cascade Microtech [5] allows some characterization of differential signals with addition of 180 degree splitter/combiners. However, these probes attenuate the common-mode signal, so that it is neglected, although typically non-zero. Testing with separate differential probes and common-mode probes will allow for more complete s-parameter characterization of differential circuits, but until this work, there has been little examination of this subject.

A severe limitation in differential-mode/common-mode circuit characterization is a lack of applicable power wave and s-parameter theory. There is no reported way (known to the authors) to describe s-parameters based on mixed differential-mode/common-mode propagation. Previous work most closely related to this work has been specific to descriptions of coupled transmission lines [6]–[14] and shielded balanced transmission lines. Work by the National Bureau of Standards on balanced transmission lines uses s-parameters to describe differential-mode propagation, but neglects common-mode propagation and any mode conversions [15]. In the literature, the coupled transmission work has been most commonly applied to directional couplers [16]–[19] with Cohn and Levy [20] providing a historical perspective on the role of coupled transmission lines in directional coupler development. Past work on coupled transmission lines has largely focused on voltage/current relationships and Z, Y, and ABCD-parameter descriptions of TEM circuits. One notable exception to the Z/Y/ABCD-parameter approach is work by Krage and Haddad [21] which employs traditional normalized power waves to describe coupler behavior. However, all of the referenced work deals with specific TEM structures, and is not suitable for characterization of a generic differential circuit. The present paper provides the theory behind the mixed propagation mode based s-parameters suitable for general microwave differential circuit characterization, and demonstrates its utility with simulations on Hewlett-Packard's Microwave Design System (MDS) [22].

This paper is organized as follows: In Section II the Mixed-mode two-port circuit is presented, and the definition of the coupled line transmission system is given. Mixed-mode power waves and mixed-mode s-parameters are developed in Section III. Section IV discusses special considerations necessary for mixed-mode measurement systems. Section V presents the ideal mixed-mode two-port measurement system and simulations using MDS. Finally, conclusions are presented in the last Section VI.

II. Mixed-Mode Two-Port Circuit

The concept of a microwave differential circuit is examined in this section. In a practical RF/microwave implementation,

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