Common-mode and Differential-mode Analysis of Common Mode Chokes

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Abstract

In this paper three methods for the measuring common-mode and differentia-mode S-parameters of common mode chokes are presented. The three methods involve (1) ABCD chain matrix, 2) using hybrid couplers and 3) modal decomposition. Each measurement method provides a specific level of accuracy. The modal decomposition method can work up to 10 GHz.

Given a full characterization of a common mode choke, a passive equivalent circuit model can be synthesized that provides a fundamental understanding of the physical performance. SPICE equivalent circuit model of common mode chokesand the extraction of model parameters are provided.

Keywords

Common mode chokes, hybrid couplers, common-mode insertion loss, differential-mode insertion loss, mixed mode S-parameters, ABCD chain matrix, equivalent circuit model

I. INTRODUCTION

Common mode chokes (CMCs) are widely used as suppression filters against interference of common mode noise in the high-speed differential signaling; such as LVDS, IEEE1394, USB2.0 and many other computer interfaces. Their recent application in mobile equipment has driven CMCs to operate at RF and microwave frequencies. However, traditional S-parameters do not lead to easily understandable characteristics of CMCs. The need for an accurate measurement and complete characterization of CMCs in the modal domain has become necessary.

The performance of CMCs can have strong effects on the system performance. A common mode choke coil that effectively removes common mode noise without influencing signal waveforms is desirable in high-speed differential signal transmission. Manufactures of CMCs often characterize CMCs by specifying common-mode and differential-mode impedance. The higher the common-mode impedance, the smaller the common-mode noise signal that can get through the CMCs.

This paper presents a full characterization of CMCs in terms of common-mode and differential-mode insertion loss. Mode analysis helps the designer to reduce mode conversion, improve symmetry and take full advantage of the enhanced performance that differential devices can offer. The paper is organized as follows. In Section II, three methods of measuring common-mode and differential-mode insertion loss of differential circuits are presented. Section III introduces the results for the three measurement methods. SPICE compatible equivalent circuit model of CMCs and parameter extraction of the model are provided in Section IV. A SPICE equivalent circuit model promotes a fundamental understanding of the physical performance of CMCs. Finally, conclusions are presented in Section V.

II. MEASUREMENT SETUP

While vector network analyzers are typically used to measure single-ended S-parameters of an RF component, they do not supply common-mode and differential-mode signals into the devices. Measuring multi-port components in the differential mode cannot be accomplished without applying some type of hardware or mathematical transformation. In the experiment, three methods are presented. Each measurement method produces a specific level of accuracy and is valid over a certain frequency range.

1. ABCD Chain Matrix

Common mode chokes can be considered as a special type of transformer. It is comprised of two magnetically coupled inductors. At low frequencies, it is easy to determine the common-mode and differential-mode insertion loss from measured ABCD chain matrix. A two-port ABCD chain matrix of CMCs can be obtained directly by short, open and load terminations as shown in Figure 1. Conversion from the two-port chain matrix to a four-port chain matrix, and calculation of the common-mode and differential-mode insertion losses from the four-port chain matrix have been well explained in [3][4].

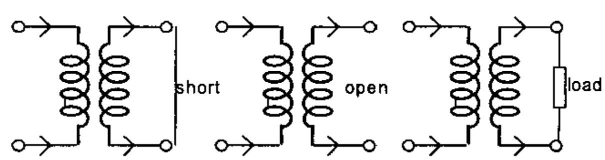

Figure 1. Two-port ABCD matrix measurement

2. Using Hybrid Couplers

Traditionally, network analyzers are comprised of two RF ports that connect to a device under test (DUT). The hybrid-based method requires the hybrid couplers to be placed between the differential ports of the DUT and the RF ports of the analyzer. The CMCs are excited into common mode when connected with a 0-degree hybrid coupler and differential mode with a 180-degree hybrid coupler. Two 0-degree hybrids will measure the common-mode insertion loss of the DUT, two 180-degree hybrids will measure the differential-mode insertion loss, and a 180-degree hybrid and a 0-degree hybrid will measure the conversion loss from differential-mode to common-mode. The measurement setup of the hybrid method is shown in Figure 2. It is difficult to realize the measurement plane at the terminals of the DUT because there are neither calibration standards nor a standard error correction methodology for the hybrid couplers. This technique measures the combined performance of the CMC and the hybrid couplers.

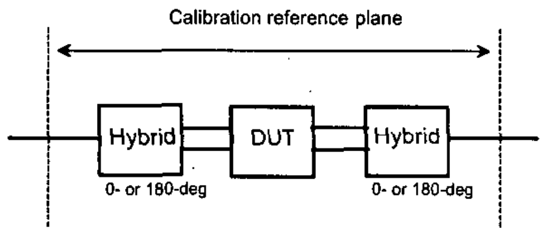

Figure 2. Measurement setup using 0-degree or 180-degree hybrid couplers

The accuracy of the method is highly dependent on the characteristics of the hybrid couplers. The amplitude balance, phase balance, bandwidth, insertion loss, return loss, and port isolation of the hybrids are limiting factors of the measurement techniques. The hybrids used in the experiment are power combiners/splitters working from 10 Hz to 2 GHz with a 3-dB insertion loss, amplitude imbalance within 0.2 dB, phase imbalance within 5 degree and port isolation of about 20 dB. To improve the matching errors, 5-dB attenuators are used on each side of the hybrid coupler. The overall dynamic range of the setup, connecting hybrid couplers without the DUT, is shown in Figure 3. A minimum of 30 dB of dynamic range is obtained at 2 GHz.

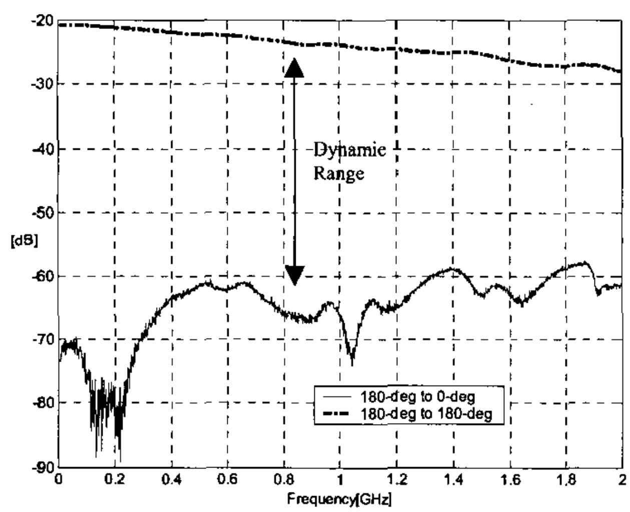

Figure 3. Dynamic range of measurement setup

3. Modal Transformation

Bockleman and Eisenstad [1][2] have demonstrated a method to convert the standard single-ended S-parameters to the mixed mode S-parameters using a mathematical transformation. This transformation provides a basis for using a traditional Vector Network Analyzer (VNA) for measuring differential circuits. Standard single-ended S-parameters of a CMC can be measured from a VNA, and then converted to mixed mode S-parameters. This conversion uses the same algorithms that have been applied in the de-facto market standard of Agilent's N444x Balanced-measurement system. Both the mixed mode S-parameters and the standard S-parameters contain complete characterizing information of the differential circuit. Mixed mode S-parameters show the measurement of the differential circuit in the modal domain, namely the common-mode and differential-mode S-parameters, and S-parameters for mode conversion between common and differential modes.

III. MEASUREMENT RESULTS

The common-mode and differential-mode insertion loss of a common mode choke can be measured directly by the hybrid method, as well as can be derived from the two-port ABCD matrix and the modal decomposition method. Figure 4 shows the comparison of measurement data from the three methods over the frequency from 10 MHz to 1 GHz. The dashed bold line shows the ABCD matrix results. It agrees very well with the other two methods below 300 MHz. At high frequencies, where parasitic components of the PCB board come into effect, the chain matrix cannot be used to predict the insertion loss precisely.

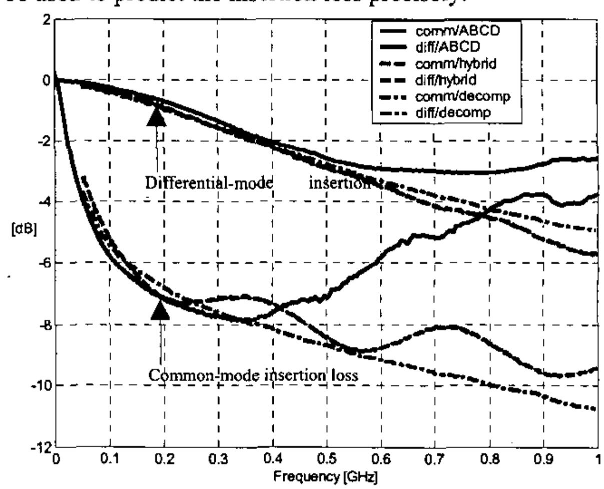

Figure 4. Forward insertion loss of the three methods up to 1 GHz

Figure 5 shows two of the common mode chokes measured with the hybrid method. Common mode chokes are used to attenuate the common-mode signal without influencing the differential-mode signal. So, a high common-mode forward insertion loss and low differential-mode forward insertion loss would be expected for a good common mode choke.

The darker lines of CMC #2 show a better performance in both the common and differential modes.

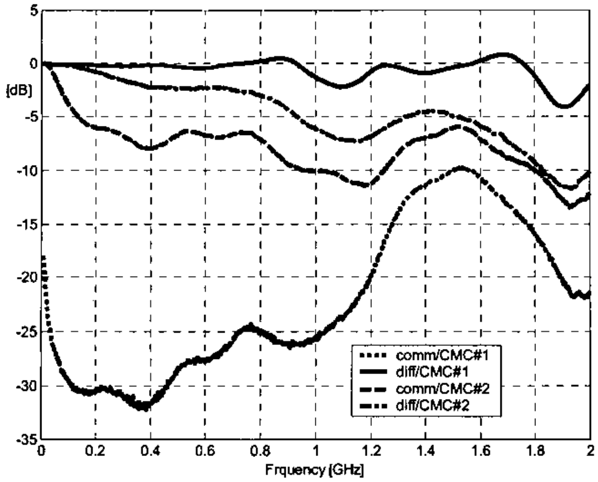

Figure 5. Forward insertion loss of two chokes

Figure 6 shows the differential-mode and common-mode insertion losses obtained by the hybrid and modal decomposition methods up to 2 GHz. The two methods matched very well over this frequency range. However, the two approaches did not yield equally accurate data for the CMC. The undulations shown in the common-mode insertion loss of the hybrid method are most likely caused by impedance mismatches at transitions from SMA connectors to the microstrip lines and from SMA connectors to the hybrid couplers.

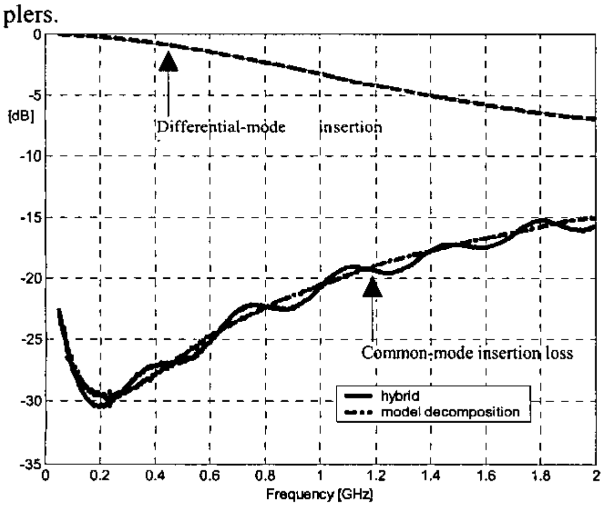

Figure 6. Forward insertion loss up to 2 GHz

It has been shown that the modal decomposition method has an accuracy advantage over the other two methods for characterizing CMCs. Insertion losses obtained from the hybrid measurement and the two-port ABCD matrix measurement exhibit higher levels of uncertainty than that produced by the modal decomposition method. In principal, there is no frequency limit for transforming from standard S-parameters to mixed mode S-parameters. In practice, the uncertainty level of the mathematical transformation will increase as the frequency goes up, and influence from the microstrip lines and residual errors in the calibration become significant. Figure 7 shows the measurement of S_{dd21}, the differential-mode insertion loss, and S_{cc21}, the common-mode insertion loss, for some CMCs up to 10 GHz. In the interest of space, only two of the mixed mode S-parameters are included for the test, yet the agreement of the remaining parameters is very similar. Since the measurement device is symmetrical along the longitudinal and transverse axis, there are only six unique mixed mode S-parameters.

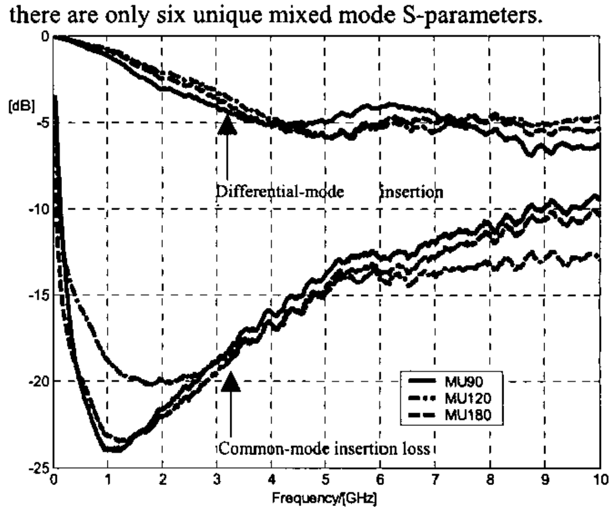

Figure 7. S_{DD21} and S_{CC21} of a series CMCs

IV. EQUIVALENT CIRCUIT MODEL and PARAMETER EXTRACTION

Circuit simulation is dependent on both the validity of the device model and the accuracy of the values used as model parameters. In order to successfully design circuits with CMCs at frequencies in the gigahertz range, the behavior of the CMCs must be modeled accurately up to those frequencies. The lumped SPICE equivalent circuit model for CMCs is shown in Figure 8. The center part in the model is based on transformer model of simple common mode chokes, which includes the internal resistance R_2, self-inductance L_2, and parasitic capacitance C_2. The shunt capacitance C_2 and parasitic elements of the leads are included in the model for operation at high frequencies.

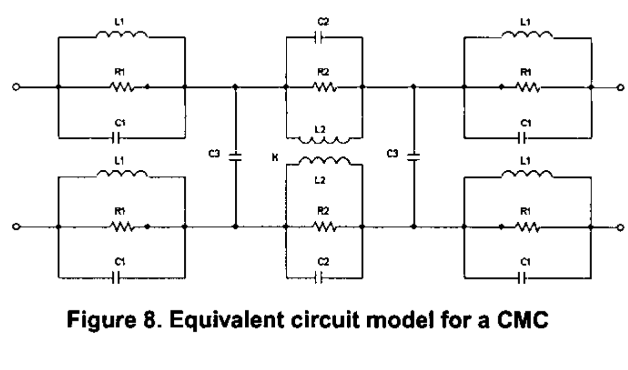

Figure 8. Equivalent circuit model for a CMC

Extraction of an optimum set of device model parameter values is crucial to characterizing the precise relationship between the device model and the measured behavior. Optimal equivalent circuit models for CMCs were derived from the measured mixed mode S-parameters. The optimizing process in the HSPICE, involving Levenberg-Marquardt method, is used for the parameter extraction. Predicted mixed mode S-parameters for the optimized equivalent circuit are then obtained from HSPICE simulator. The difference between the measured and predicted S-parameters over the frequency range is used as the measure of the accuracy of the optimization results. The optimization solves for a set of model parameters that produce simulated data that optimally approximates the measured data.

The derivation of equivalent circuit models is very useful to designer to incorporate the complex behavior of the devices into a system level circuit simulation. However, the process of obtaining the optimal parameters for the equivalent circuit model is usually a slow and computationally challenging task. Simplifications of the equivalent circuit model need to be made in order to run a success on its optimization. For the CMCs, this leads to the use of a symmetrical, balanced circuit model and identical parameters for the leading elements of the model. The mode conversion terms are set to zeroes. Also, regarding the accuracy of the model, it needs to be considered that a characterization of a CMC without taking the landing pads and the board stack-up into account leads to reducing the accuracy above a few GHz. As the board influence is part of the measurement data, the equivalent circuit will incorporate these effects into the model parameters for the board used.

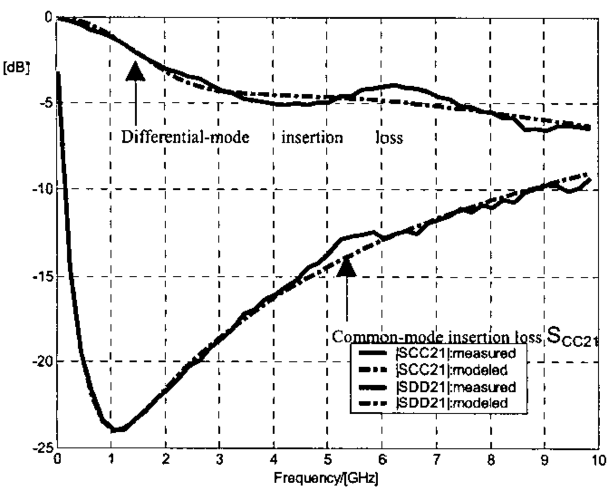

Figure 9. S_{DD21} and S_{CC21} of equivalent circuit model vs. measured data

After optimization, the measured and predicted common-mode and differential-mode S-parameters of a CMC are shown in Figure 9. The agreement between modeled and measured data is good. The optimized values of the circuit components for five different CMCs of interest are listed in Table 1. Each CMC requires the extraction of seven passive device values from the measured mixed mode S-parameters.

Table 1. Optimized equivalent circuit model parameters

Parameter	M900	M121	M181	T201	T900
$R_1(\Omega)$	18.7	35.5	24.2	35.3	71.4
$R_2(\Omega)$	1471	864	1399	1691	870
L_1(nH)	1.76	1.74	1.48	3.39	3.02
L_2(nH)	154	149	255	311	84
C_1(pF)	2.53	0.643	1.54	1.86	0.486
C_2(fF)	68.1	53.5	60.8	68.7	82.4
C_3(fF)	245.3	64.9	175	408	50.1
κ*			1		

*κ is set to 1.

V. CONCLUSION

Three methods for characterizing CMCs as differential circuits are presented. The two-port ABCD matrix method is simple and accurate below 400MHz. The hybrid method provides another alternative way for characterizing CMCs up to 2GHz. Its measurement system is constructed from readily available test equipments. The modal transformation method has demonstrated the usefulness of the concept of the mixed mode S-parameters and the good accuracy of the measurement system compared to the other two methods. For a good common mode choke, it should have a very high common-mode insertion loss and low differential-mode insertion loss.

Equivalent circuit model parameters of CMCs are provided. This data is useful for optimizing the choke design, noise propagation and filter studies.

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