Improving CDM Measurements With Frequency Domain Specifications

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Abstract - Existing Charged Device Model standards have relied exclusively on time domain specifications; but devices discharge in the CDM resonant circuit at different frequencies. Accurate measurements of CDM discharge parameters require that its primary measurement components be specified in the frequency domain. Uniform frequency response measurement components are possible and described.

I. Introduction

The Charged Device Model (CDM) tester is fundamentally a simple circuit which uses a spark discharge to simulate real world ElectroStatic Discharge (ESD) threats to each pin of an IC. The high speed measurement methods for the CDM discharge has only been partially analyzed to identify or improve waveform measurement precision. This work completes the analysis of these measurements. Difficulties in achieving repeatable verification test waveforms have existed since the beginning of this test and have been reported in various published studies. Over the past decade or so variations in current discharge waveform parameters have increased. Our primary concern with CDM measurement accuracy has been the current sensor, although the rest of this measurement chain also affects accuracy and repeatability issues.

The recent combination of JEDEC and ESDA CDM standards into a single JS002 standard forced combining the different response requirements of both current sensors into one standard. We believe that their differences have caused the verification waveform tolerance in the new standard to be wider than necessary.

The availability of wide bandwidth instrumentation in many test facilities provides an opportunity to improve repeatability and accuracy of the CDM discharge waveform.

We are looking at the CDM test in a way that has not been done before. This paper describes the realization that although CDM discharge parameters are correctly identified in time domain parameters, they are actually created in the frequency domain. The highest CDM measurement accuracy will be obtained most easily and most repeatable when each individual component is specified and measured in frequency domain parameters. Improved CDM measurement accuracy will inherently improve repeatability between test facilities.

There have been many different methods of theoretical analysis of the CDM event and test, which were very extensive; but they are outside the scope of the measurements presented here. This work analyzes measurement issues which limit accuracy, and provides new measurement methods to improve the fundamental accuracy of CDM measurements. We explain the new measurement parameters, and new specifications for measurement components which can improve the accuracy of discharge waveform measurements. We leave theoretical analysis methods to those who choose to explore this direction in future work.

The CDM measurement chain consists of four components which define and determine the discharge waveform parameters. They are: the verification module, the current sensor, the scope, and the coaxial cable which carries the discharge waveform to the scope. The original verification method evaluated the CDM test by combining the four measurement components into one time domain specification measured with a 1 GHz scope. It presently includes the combined time domain response tolerances of all four components which does not allow their individual responses to be identified. Because the current sensor is the main component in the CDM test head, those which meet new specifications will produce higher accuracy CDM test data. The basic improvement proposed is to add frequency domain calibration of each individual CDM measurement chain component, and develop a new set of specifications.

II. Background

The original current sensors used a one ohm disk resistor. The quality of its response to provide accurate CDM measurements, was originally measured in the frequency domain by inserting it into a 50 ohm coaxial line. Its response shown below in figure 1, had a reasonably flat frequency response from DC to 3 GHz. The red curve with amplitude variations is re-plotted from the original data taken in 1988. [1] The variations in the original red trace are caused by the very high mismatch between the 50 ohm measurement system and the one ohm current sensor. The smooth blue curve is our best estimate of the disk resistor's frequency response when the measurement system impedances are matched.

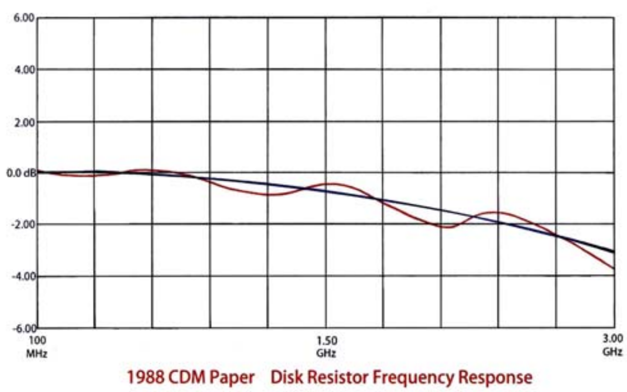

Figure 1. Original Disk Resistor frequency response

This was the first and last time the current sensors were measured in the frequency domain until recently. Twenty years ago a special 50 ohm coaxial adapter shown in figure 2 was designed to measure the pulse response of the CDM current sensors in a 50 ohm system. The data was reported in our 1996 paper. [2] The pogo pin is enclosed in two parallel conductors which form a strip line connection. Its connection directly to the current sensor isolates the pogo pin from the measurement The input to the adapter's SMA connector and the output from the current sensor's SMA connector identifies the response of the current sensor alone.

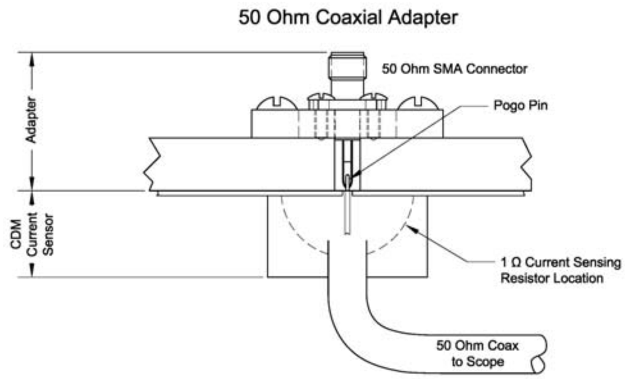

Figure 2. 50 ohm coaxial Adapter

The time domain response of six of the original current sensor units are all shown in figure 3.

Their pulse responses measured with a 20 GHz sampling scope exhibited a total variation of as much as 25 % during the first half nanosecond, which is the approximate time where the peak discharge current occurs in of the CDM discharge.

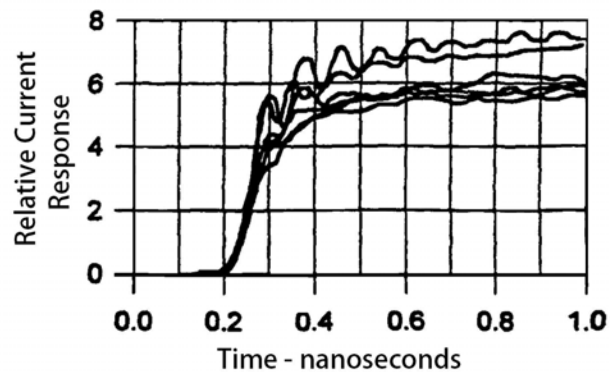

Figure 3: Current Sensor Step Responses

Because the spark resistance in the discharge has significant variations which limit the accuracy with which the discharge can be measured; the pulse response repeatability in an accurate and repeatable measurement system can be in the range of +/- 5% to +/- 8%. Although the ESDA and JEDEC current sensors probably used the same disk resistors, and their verification modules both used FR4 as the dielectric, they were constructed differently. Because of these differences each CDM specification developed different verification waveform parameters. The suggestion at the time was that the uniformity of current sensor response should be improved to minimize data variations as much as possible. [2] Those suggestions were not acted upon and no improvements in data repeatability were realized.

Some years ago the current sensing resistors were changed from disk resistors to a ring of five ohm commercial chip resistors mounted on an FR4 disk. This change produced high frequency responses that further increased the differences between the ESDA and JEDEC discharge current verification parameters.

The verification waveform peak values in the new sensor design were different enough that "tuning" was added to some current sensors to achieve the legacy values. This "Tuning" was accomplished by adding cavities resonant between 10 to 20 GHz in front of the current sensing resistor. This compensated for the sensitivity decrease and allowed these sensors to achieve the required legacy values when measured with the 1 GHz scope.

III. Measurement Techniques

A. CDM Measurement Chain

1. Verification Modules

Verification modules are reference capacitors intended to provide known discharge waveforms.

2. Current sensor

The current sensor inserts one ohm of resistance into the discharge circuit to provide a voltage waveform proportional to the discharge current waveform.

3. Oscilloscope

The scope measures the voltage waveform to identify the discharge current amplitude and width parameters.

4. Coaxial Cable

The CDM discharge waveforms occur at speeds high enough that the skin effect loss of the coaxial cable carrying the discharge waveform to the scope affects measurement chain accuracy.

B. Present Technique

Verification of test system operation uses the discharge waveform captured on the scope produced by a charged verification module (capacitor) to insure that measured peak current is within specifications. The present procedure for CDM Standards combines the response of all four measurement components into a single waveform measured in the time domain. It is used to verify that the tester is operating correctly. The present method ignores the individual and presently unspecified, electrical characteristics of the four measurement components when their responses are combined into one discharge current waveform.

Achieving the combined discharge waveform response at only 1 GHz ignores the frequency response of its individual components.

Adding specifications for the response of each measurement component will improve the accuracy of CDM measurements. A method to identify the individual component response in the time domain is difficult, and has been without any practical specification since the beginning of the CDM test.

C. Improved Techniques

1. Verification Module

Unfortunately, verification modules for both ESDA and JEDEC standards were developed using FR4 as the dielectric material for these reference capacitors. The dielectric constant of FR4 decreases and its dielectric loss factor increases at high frequencies. These variations hardly make FR4 a good or effective dielectric material for reference capacitors. High loss factor will absorb some of discharge energy and decrease the peak amplitude as the discharge frequency increases. Being hygroscopic, its capacitance also depends on its water content which depends on the dew point of the location where it is stored.

The FR4 dielectric constant variations with frequency are shown below in figure 4.

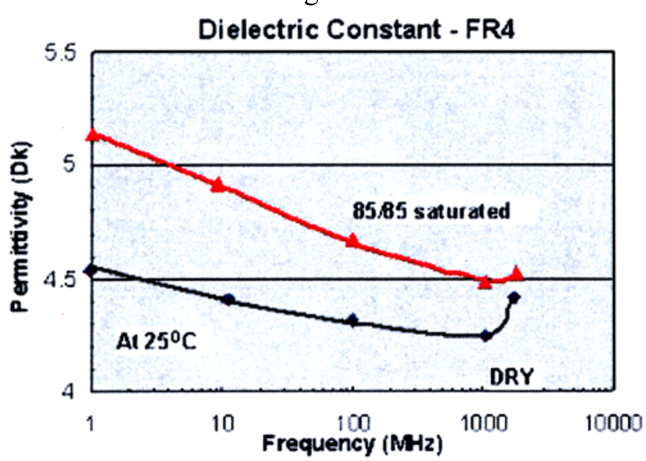

Figure 4. Dielectric properties of FR4.

An analysis of their capacitance variations was provided in 1999. [3] It recommended that the dielectric material be changed to an improved high frequency dielectric material with better dielectric constant and loss qualities.

Alumina was selected for new reference capacitors because of its excellent dielectric properties.

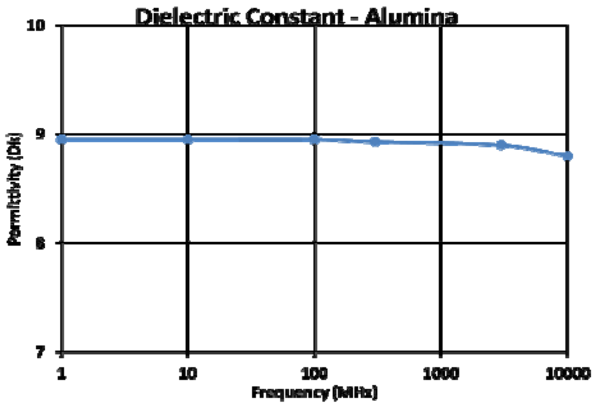

Figure 5 Dielectric properties of >99% Alumina

The dielectric constant of alumina remains almost perfectly constant from DC to 3 GHz. Fixed terminals are fired onto the top and bottom alumina surfaces to insure that its value will remain the same indefinitely. The size of its electrodes on the alumina insulator can be easily adjusted to provide precise values. Uniform frequency dielectric constant will insure that accurate measurements at 1 KHz will be the same at 4 GHz. Unlike the JEDEC coins stacked on the FR4, no assembly is required and variables caused by air gaps between dished coins and the FR4 are eliminated.

Figure 6. Alumina capacitors: 55 pF & 6.8 pF

The photo in figure 6 shows two silver electrodes on a 25.4 mm diameter alumina disk.

The bottom alumina electrode is affixed to the large metal disk which contacts the RCDM3 charge plate directly. Direct contact to the charge plate isolates the existing FR4 dielectric from the circuit. The two capacitors on the alumina dielectric become the verification modules.

Each capacitor has a silver disk on the top silver electrode to provide highly conductive metal surface for pogo pin discharges.

2. Current Sensor

A thorough analysis of the CDM tester makes it clear that while the discharge waveform is measured in the time domain it actually occurs in a resonant circuit and produces a highly damped sine wave. The pogo pin provides a relatively constant value of inductance, which combined with the capacitance of verification modules or device capacitance, determines the circuit's resonant frequency.

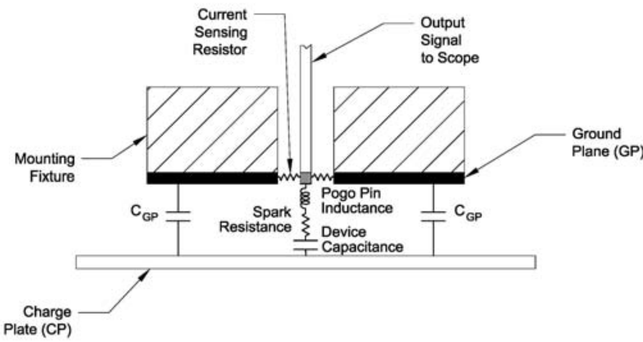

Figure 7: CDM Tester Elements

Figure 7 illustrates the resistive and reactive elements in the CDM tester. Different device size packages have different capacitance values, which produce different resonant discharge frequencies. Device bond-wire and package leads are additional inductive parasitics which will combine with pogo pin inductance, and lower the CDM discharge resonant frequency. Inherent variations in the spark resistance will still limit the repeatability of the peak current discharge amplitude. However, the width of the discharge waveform is primarily determined by the discharge frequency, so its width is that of the first half cycle of the resonant frequency discharge waveform.

An improved frequency response current sensor has been constructed to provide accurate CDM waveform measurements.

Data taken with these sensors will determine practical specifications for an improved standard. The first improved response sensor unit was designed for the RCDM3 tester. Its frequency response is compared with the original sensor disk resistor as shown in figure 8. One ohm current sensors have high reflection coefficients when measured in a 50 ohm system. The amplitude variations are caused by reflections from both ends of the sensor's low impedance. The true values are an average between the ringing waveforms as shown in figure 1, 8, and 13.

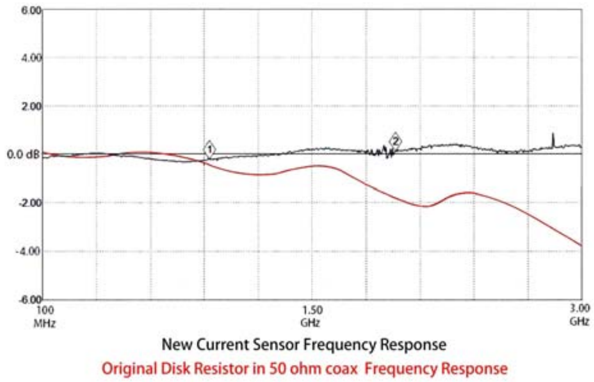

Figure 8. New & original disk resistor responses

We used the wide bandwidth 50 ohm coaxial adapter of figure 2 to identify the frequency response of the new CDM current sensor. The one ohm current sensor measured in a 50 ohm system produces a nominal attenuation of 26/1 V ratio, where 0 dB on the Figure 8 graph is adjusted to -28.30 dB.

As in figure 1., the original disk resistor response, shown in red has its average response sensitivity decreasing with frequency. The 1 and 2 diamond frequency markers are at 1 and 2 GHz. The lower ripple in the black frequency response plot occurred because we used more attenuation to reduce the reflections caused by the one ohm current sensor. The true attenuation is an average of either cyclical amplitude variations. Designing a current sensor utilizing its measured frequency response, allows the design to be adjusted to meet frequency response requirements.

3. Oscilloscope

The previous specifications identified scope bandwidth at 1 GHz without considering that different frequencies were being measured.

More recent data has used wider bandwidth scopes which have less variations in the frequencies of interest. Specific frequency response sensitivity of the scope permits its precise effect on measurement accuracy to be determined and specified. Frequency response specifications of a scope are more relevant to the accuracy of these measurements than bandwidth specification. Unfortunately digital scopes can have less uniform roll off characteristics than analog scopes with their expected Gaussian characteristics which makes this specification even more important. [4]

4. Coaxial Cable

The loss of a the 2 meter length of coax supplied with the RCDM3 tester is shown in figure 9. It is typically within a small fraction of a dB in the frequency range expected from the CDM discharge.

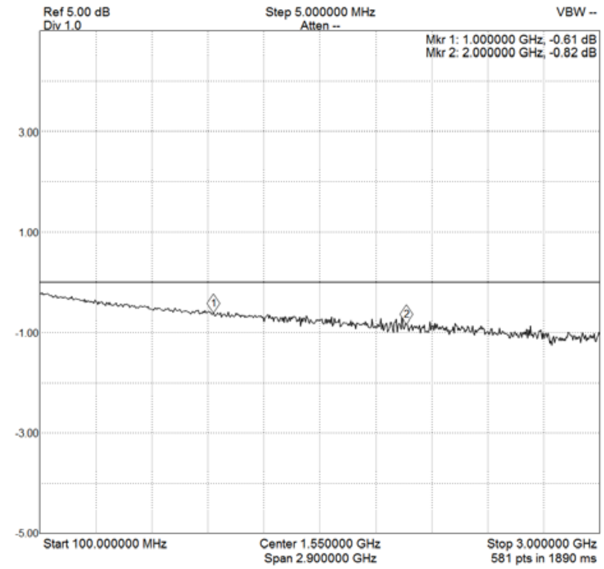

Figure 9. Loss of 2 m. of Sucoflex 104 coax

The small increase in cable loss at higher frequencies can be compensated by reducing the attenuation of the current sensor as a compensating mechanism. When its loss is measured in the frequency domain it can be added to the current sensor response to define the combined response.

IV. Measurements

Discharge measurement of a series of alumina capacitors with values from 1.3 pf to 340 pF were made on our RCDM3 CDM tester. It used the new uniform frequency response current sensor. Multiple discharges of each capacitor were observed until a ringing waveform displayed three or four cycles which was recorded.

The zero crossing periods of multiple sine waves provided sufficient measurement accuracy of each resonant frequency.

A. CDM Frequency Range

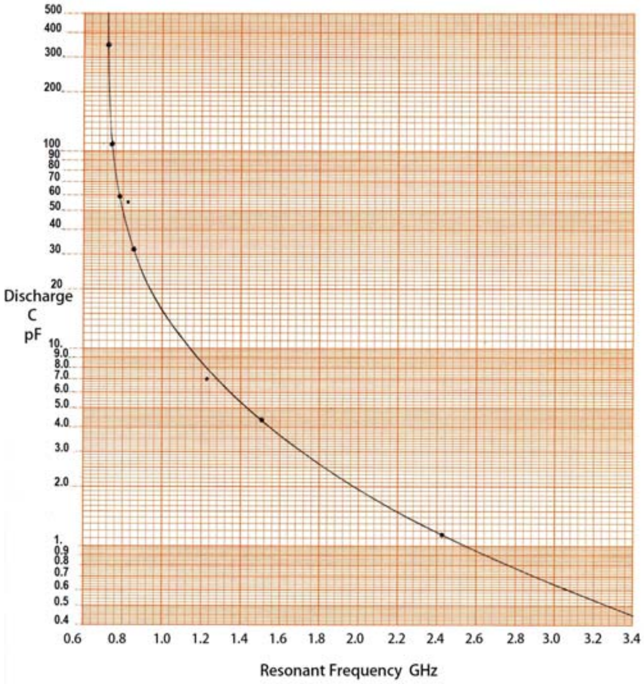

Figure 10. CDM resonance vs. Capacitance

The measurements of these various capacitance values cover the wide range of device sizes and capacitances which are tested with CDM. The CDM resonant circuit is limited to about 750 MHz (.75 GHz) on the vertical axis for the largest capacitance values. However it can reach 2500 MHz (2.5 GHz) for extremely small devices with capacitance values as low as 1 pF.

The highest CDM discharge frequencies occur in very small IC packages that typically have limited CDM failures.

B. Existing current Sensors Response

We used the wide bandwidth 50 ohm coaxial adapter of figure 2 to identify the frequency response of six different current sensors that are used in daily CDM testing.

The response of the JEDEC current sensor shown in Figure 11 had the greatest variation. One of the current sensors had a more reasonable response, while the other four were in between tolerable and unacceptable. Additional high frequency measurement errors are caused by the "tuning" efforts produced by cavity resonators in front of the current sensor as mentioned previously. The frequency response of JEDEC 0506262 unit shown in figure 11 was also measured in the time domain shown in Figure 12.

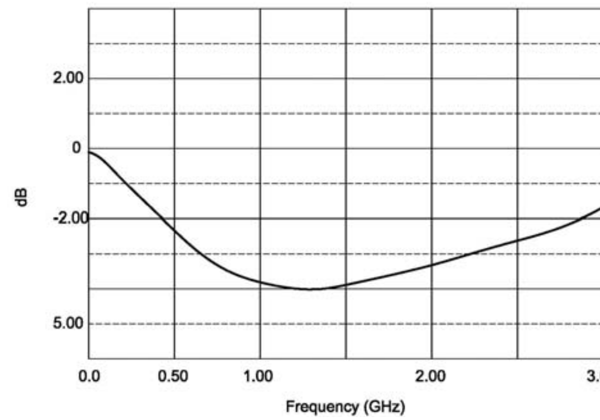

Figure 11: JEDEC 0506262 Frequency Response

The frequency measurement of this current sensor shows an error of -4 dB at 1 GHz which would produce CDM peak current discharge waveform reduced by 58%. However the "tuning" overshoot observed in figure 11 produced by the resonant cavity was probably intentional to decrease the 1 GHz measurement error by an amount sufficient to meet the peak current verification specification.

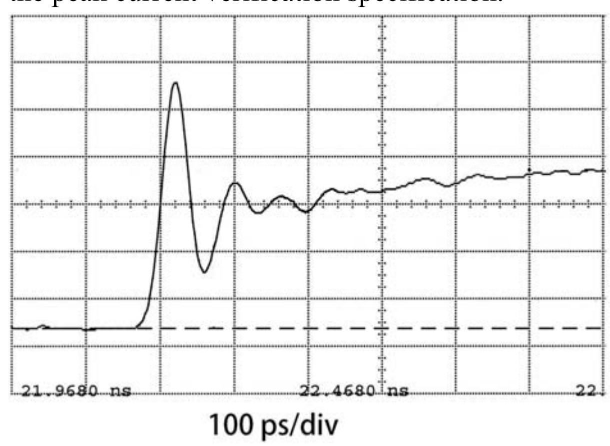

Figure 12: JEDEC 0506262 Pulse Response

Figure 13 shows the operating current sensor with the best frequency response. The other three operating JEDEC current sensors had varying amount of decreased amplitude centered in the 0.5 to 3 GHZ frequency range. Unfortunately there is no general ability to select current sensors with reasonable frequency response from those whose response varies considerably. Other ESDA current sensors from a somewhat earlier time have unusually distorted frequency responses that will not provide accurate measurements.

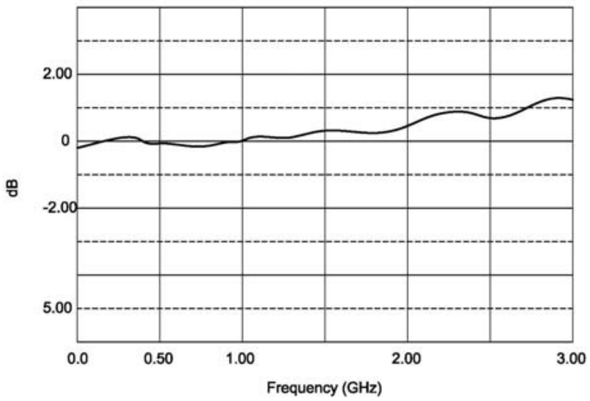

Figure 13: ESDA 0406355 Frequency Response

C. "Tuning" Cavities Issue

The "tuning" described earlier had been added to different current sensors to pull up sagging response at 1 GHz. The greatly increased impedance of a cavity in front of the current sensing resistor assembly distorts the real discharge waveform when measured with scopes of greater than 1 GHz bandwidth. The "tuning" addition to a modern current sensor produces discharge waveform "ringing" distortion when measured with an 8 GHz scope as shown in figure 14. The high impedance of the resonant cavity "tuning" in front of the one ohm current sensing resistor at the beginning of the discharge appears to increase the measured initial current. However the initial current from the device under test (DUT) is actually decreased. Higher initial load impedance decreases the current; but because its sensitivity is greatly increased the measurement erroneously shows the current as being increased. This is an important concern for device failure levels. Will decreasing the initial current out of the DUT, caused by the initial "tuning" circuits impedance distortion, produce the correct failure level?

The voltage inside the package will be distorted in some manner. In VFTLP measurements the Initial Voltage Impulse waveform is the threat to gate oxides. [6] Any change to the initial voltage will affect this TDDB threat to gate oxides in some manner. Distortion of discharge current can affect device failure level; but the magnitude still needs to be determined.

Figure 14 shows the discharge waveforms of the 6.8 and 55 pF FR4 verification modules made with a very fast scope. The extremely fast risetime and ringing are caused by resonant cavity tuning in a particular CDM current sensor. Both waveforms are severe distortions of what should occur.

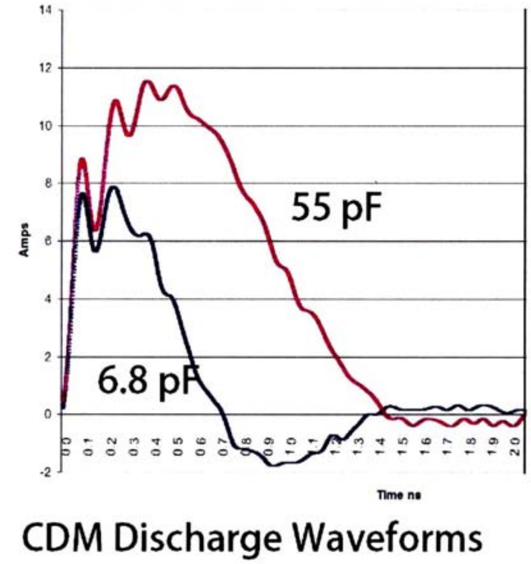

Figure 14: "Tuned" Current Sensor Waveforms

CDM measurements with the DUT Load impedance somewhat greater than one ohm are known to affect device failure levels. [5] Including a tuning cavity of some unknown high impedance value inserted into the discharge circuit will distort the discharge current in unknown ways. Flat response current sensors inherently have one ohm of load impedance inserted into the discharge circuit. One ohm load impedance insures that CDM test systems will produce the same failure levels as occur in real world ESD events.

In Table 1, the resonating capacitance (C_{12}) from the graph in figure 10 can be determined as the series combination of the capacitance between the ground plane (C_{VM}) and the charge Plate (C_{GP}) as shown in figure 15.

V. Spice Analysis

The measured amplitude of the third sine wave peak was 17.3 % of the first peak amplitude. Figure 17 is a Spice model generated with the C_{12}, L, and Frequency values to produce a similar 3^{rd} to 1^{st} amplitude ratio.

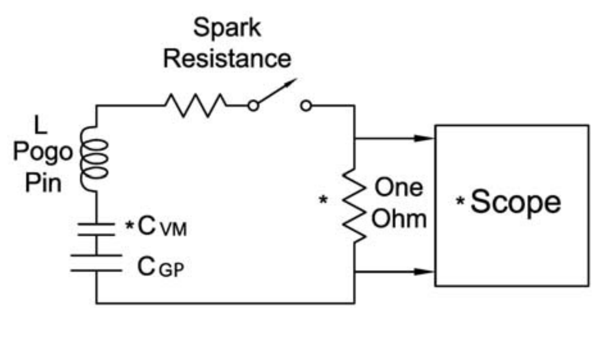

Figure 15: CDM Discharge Circuit

	Pogo Pin Inductance Calculations				
Measure-ment Frequency GHz	C Verification Capacitor on Alumina pF	C_{12} Series combined capacitance pF	L Pogo pin calculated inductance nH	R_{S1} Spice Model Value for >1 cycle Ohms	R_{S2} Spice Model Value for Normal CDM Ohms
2.420	1.15	1.049	4.101	10	38
1.500	4.43	3.236	3.456	7	19
1.310	6.80	4.340	3.370	7	?
0.856	31.80	8.712	3.967	3.85	16.2
0.783	58.30	9.952	4.152	3.60	16.0
0.753	109.00	10.810	4.133	3.64	14.0
0.724	343.00	11.594	4.168	3.22	14.0

Table 1. Capacitance, Inductance and Resistance Values used in Spice Models

The total series resistance for this discharge waveform as shown in Table 1 was 7.0 ohms.

The resonant capacitance consists of the capacitor being discharged in series with the capacitance between the ground plane and the DC charge plate. The discharges were made at 100 volts which produced the low damping ratio with 3 cycles. The Typical CDM waveform for this value capacitor was then measured and is shown in figure 18.

To determine the value of C_{GP}, we measured the capacitance of a standard size ground plane spaced 0.167 inch above a flat aluminum sheet. This identifies the approximate capacitance which is in series with each verification module or device. The measured capacitance value was 10.2 pF. The spacing between the two capacitor electrodes was controlled with 4 Teflon spacers of 0.188” dia. The measured value was then corrected to eliminate the capacitance added by the Teflon spacers to be 10.04 pF.

The capacitance of the combination was used with the measured resonant frequency to calculate the inductance of the pogo pin. Its inductance had a 40% variation over the range of alumina capacitor values. Because the current sensor has additional metal surrounding it, we estimated that the added capacitance would be about 2 pF. Using C_{GP} of 12 pF in Table 1 provided a more reasonable range of calculated pogo pin inductances.

Other sources identify the pogo pin as being 4.0 to 4.1 mm (0.157 to 0.161 inch) long, while our measurements of available current sensors identify the typical pogo pins as extending 0.167 inch above the ground plane.

The values for C_{12} and L were used in simple Spice models to simulate the actual CDM discharge waveforms and identify the series resistance in two different types of CDM discharge circuits. We fit the circuit resistance to match the damping ratio of figure 16 which was produced with an extremely low value of spark resistance in the CDM discharge. Multiple measurements were made at 100 volts until we found waveforms with low damping factors that produced 3 cycles of ringing waveform. We used the ratio of the first peak amplitude to the third peak amplitude. Rs1 resistance value in the model was determined by matching the first to the third peak amplitudes of the decaying sine wave.

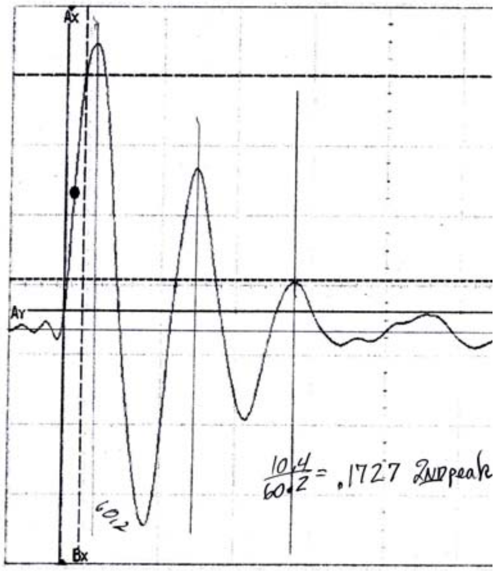

Figure 16. 4.43 pF CDM Ringing Discharge Waveform

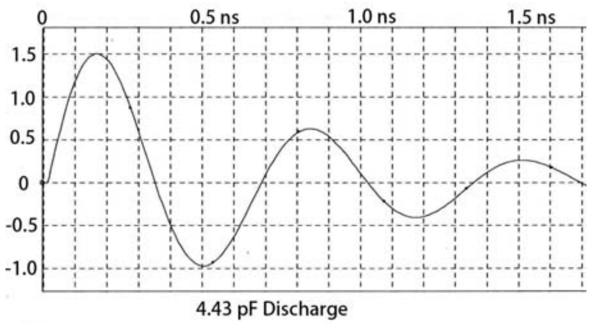

Figure 17. Spice model with 17.5 % of 3rd to 1st peak

Figure 18 shows a typical CDM discharge waveform without multiple cycles of ringing sine waves. The first positive peak to second negative peak was 34.3%.

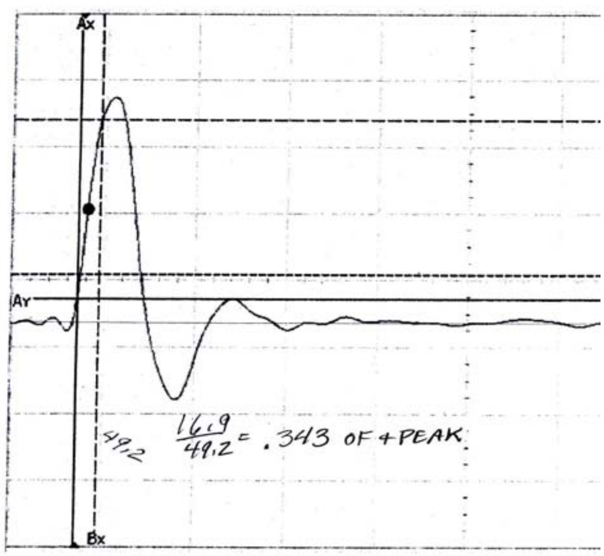

Figure 18. Typical CDM discharge waveform.

The Spice simulation waveform that provides a similar amplitude ratio for the typical CDM discharge is shown below in figure 19.

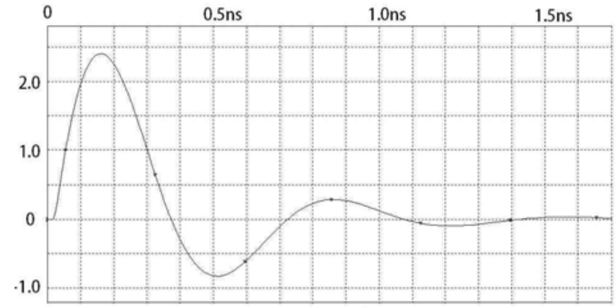

Figure 19. Spice model with 34.4% of 1st (-) to 1st (+)

Figure 19 was generated in the Spice model with the C_{12}, L, and Frequency values to produce the same -2nd o +1st amplitude ratio. The total series damping resistance that produced this waveform was 19 ohms as shown in table 1. The interesting part of table 1 is that either the series resistance increases with frequency to produce the same CDM discharge rate of decay or some other parameter not identified causes this effect.

VI. Future Work

The range of frequencies for device testing can define the oscilloscopes response requirement for the third CDM measurement component.

The effect of the scope bandwidth has been known to affect accuracy, but its frequency response requirement has not been used. Its frequency response now becomes a specific factor in determining the accuracy of the CDM discharge measurement. The frequency response of digital scopes do not necessarily have a uniform Gaussian roll-off at the -3dB point. Further analysis of modern digital oscilloscopes response is needed to complete frequency domain specifications for the standard. [4]

Impedance measurements of the current sensor over the frequency range will require precision network analyzer measurements. Accurate calibration will be needed if we are to identify current sensors dynamic impedance levels near one ohm up to 2.5 GHz. Until sparkless CDM testing is available the ultimate tolerance will ultimately remain limited by spark resistance variations. Skin effect losses in coaxial cables are minimal but can vary depending on the cable size and manufacturer. While these losses are typically about 0.2 dB at 500 MHz they increase to about 1 dB at 2.5 GHz. These errors are fairly consistent with the same make and length of cable. They CDM measurement chain can be corrected for this amount of loss at frequency when needed for precise data.

VII. Conclusion

Accurate CDM time domain data requires known frequency response sensitivity for the complete CDM measurement chain. The validity of the CDM current sensor high frequency response has been the subject of wishful thinking. The information provided by this analysis can be used to clarify the frequency response of the CDM measurement system with specifications for each component. Improvements in the CDM verification module and current sensor measurement components will provide increased accuracy and repeatability when the new CDM metric includes frequency domain specifications. The long history of CDM testing has had few changes which can improve discharge waveform measurements that can be more readily accomplished by adding frequency domain specifications to the new joint standard.

References

1] R.G. Renninger, et. al., “A Microwave-Bandwidth Waveform Monitor for Charged- Device Model Simulators”, EOS/ESD Symposium Proceedings, 1988. pp 162-171.

[2] L.G Henry et. al., “Charged Device Model (CDM) Metrology: Limitations and Problems, EOS/ESD Symposium, 1996. pp 167-179.

[3] L.G Henry et. al., “Issues Concerning CDM ESD Verification Modules - The Move to Alumina”, EOS/ESD Symposium, 1999. pp 203-211.

[4] DA Humphreys, et. al., “Calibration of Wideband Digital Real-Time Oscilloscopes”, June 2015, IEEE Transactions on Instrumentation & Measurement, pp1716-1725.

[5] R. Given et. al. “CDM2 – A new CDM Test Method for Improved Repeatability and Reproducibility”, EOS/ESD Symposium, 2010, pp 359-367

[6] Barth Electronics Website: VFTLP; Initial Voltage Impulse (IVI)