Technical Brief

Computing Self and Mutual Capacitance and Inductance Using Even and Odd TDR Measurements

Abstract

TDR measurement techniques for IC package characterization have been reported extensively and standardized by JEDEC [1]. In addition, several techniques utilizing differential TDR measurements have been reported in [2]. In this paper, we will present a novel technique for computing self and mutual inductance and capacitance. This technique is based on applying computational procedures as described in [1] to even and odd mode TDR measurements of the device under test, such as a connector or IC package.

Introduction

Differential and common mode TDR measurements involve sending a differential (the same amplitude but opposite polarity) and common-mode (the same amplitude, the same polarity) signals to two pins in the package or connector under test (Figure 1). These two measurements allow the designer to characterize the Device Under Test (DUT), and obtain the impedance, capacitance, and inductance of the DUT, as described in [3].

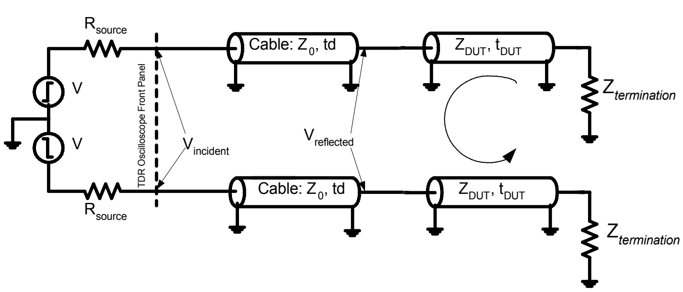


Figure 1. Differential TDR measurement setup.

Reference [3] discusses how to apply the true impedance profile, computed in IConnect® TDR software from TDA Systems, to obtain the self and mutual capacitances and inductances of the connector or the IC package. For example, for a uniform impedance structure, the following equations will apply:

$$L_{self} = \frac{1}{2}\left(Z_{even}t_{even} + Z_{odd}t_{odd}\right) \quad (1)$$

$$L_{mutual} = \frac{1}{2}\left(Z_{even}t_{even} - Z_{odd}t_{odd}\right) \quad (2)$$

$$C_{total} = \frac{1}{2}\left(\frac{t_{odd}}{Z_{odd}} + \frac{t_{even}}{Z_{even}}\right) \quad (3)$$

$$C_{mutual} = \frac{1}{2}\left(\frac{t_{odd}}{Z_{odd}} - \frac{t_{even}}{Z_{even}}\right) \quad (4)$$

where $C_{total} = C_{self} + C_{mutual}$.

For a non-uniform impedance structure (like most connectors or packages), the equations will change to allow for independent integration along the even and odd impedance profile paths. All these computations are automated in IConnect TDR software. However, any analysis based on the true impedance profile relies on the designer to accurately partition the impedance profile waveform into impedance segments for computation in IConnect. In this paper, we propose an alternative procedure, which utilizes computations described in JEDEC standard [1], [2] to compute the even and odd mode capacitance and inductance. The designer can then utilize simple equations derived below to compute the self and mutual inductance and capacitance from even and odd mode inductance and capacitance.

Theory

The odd mode waveform can be obtained by applying a differential stimulus to a pair of pins under test, and acquiring only the positive switching channel on the TDR oscilloscope. The even mode waveform can, in turn, be obtained by applying a common mode stimulus to the same pair of pins under test, and acquiring the same channel as in the odd mode measurement. The pins adjacent to the pins under test must be shorted to ground for capacitance measurements, and left open-ended for inductance measurements. Then the odd mode capacitance can be computed when the odd mode waveform is acquired with the far end of the DUT left open-ended, and the odd mode inductance can be computed when the odd mode waveform is acquired with the far end of the DUT connected to ground, or at least with the two pins under test connected together, by applying the computational procedure described in JEDEC standard [1], [2]. The even mode capacitance and inductance can be computed from the even mode waveform under the same fixturing conditions using the same computational procedure. Thus, we obtain:

$$C_{odd} = \frac{1}{2 \cdot Z_0 \cdot V} \cdot \int_0^{\infty} (W_{open} - W_{odd\_open})dt \qquad (5)$$

$$C_{even} = \frac{1}{2 \cdot Z_0 \cdot V} \cdot \int_0^{\infty} (W_{open} - W_{even\_open})dt \qquad (6)$$

where V is the TDR voltage incident at the lead under test, normally half the TDR source amplitude, and Z_0 equals the characteristic impedance of the measurement system, 50 Ω for currently available TDR instruments. For practical purposes, it is not necessary to integrate to infinity, but only until the difference between the W_{open} and $W_{even/odd}$ is negligibly small.

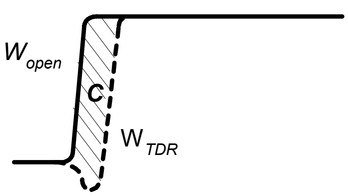


Figure 2. Self-capacitance measurement.

At the same time,

$$L_{odd} = \frac{Z_0}{2 \cdot V} \cdot \int_0^{\infty} (W_{odd\_short} - W_{short})dt \qquad (7)$$

$$L_{even} = \frac{Z_0}{2 \cdot V} \cdot \int_0^{\infty} (W_{even\_short} - W_{short})dt \qquad (8)$$

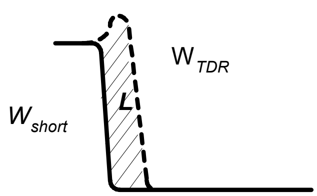
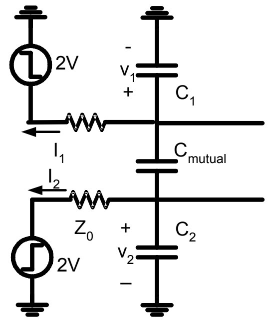


Figure 3. Self-inductance measurement.

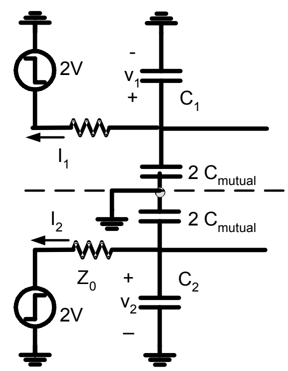
The following figure shows the measurement setup for the odd or even mode capacitance measurement.



In the even mode, there is no the voltage difference across C_{mutual}. Therefore, no current flows through it, making it equivalent to an open circuit. Therefore, applying equation (6) will give us the self capacitance of the circuit:

$$C_{self} = C_{even} \qquad (9)$$

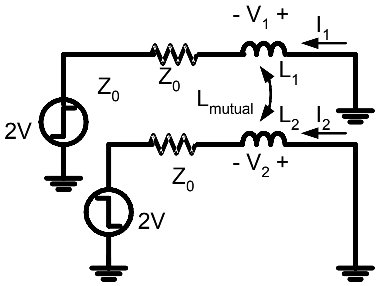
In the odd mode, a virtual ground plane divides the mutual capacitance into two series capacitances of $2C_m$, and the node between them is grounded.



Therefore, if we compute the result of equation (5), we obtain $C_{self}+2C_{mutual}$. Then, C_{mutual} can be found as:

$$C_{mutual} = \frac{(C_{odd} - C_{even})}{2} \qquad (10)$$

The following figure shows the measurement setup for the odd or even mode inductance measurement:



We can see that:

$$V_1 = L_1 \frac{di_1}{dt} + L_{mutual} \frac{di_2}{dt}$$

$$V_2 = L_{mutual} \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \qquad (11)$$

Since in odd mode with differential stimulus, $V_1 = -V_2, i_1 = -i_2$,and $L_1 = L_2 = L_{self}$ we obtain:

$$V = (L_{self} - L_{mutual}) \frac{di}{dt} \qquad (12)$$

This equation, following the derivation for the self inductance of the package lead, gives us:

$$(L_{self} - L_{mutual}) = \frac{Z_0}{2 \cdot V} \cdot \int_0^{\infty} (W_{odd\_short} - W_{short})dt \qquad (13)$$

or,

$$L_{self} - L_{mutual} = L_{odd} \qquad (14)$$

In even mode, on the other hand, $V_1 = V_2, i_1 = i_2$, and $L_1 = L_2 = L_{self}$, and we obtain:

$$V = (L_{self} + L_{mutual}) \frac{di}{dt} \qquad (15)$$

This equation, following the derivation for the self inductance of the package lead, gives us:

$$(L_{self} + L_{mutual}) = \frac{Z_0}{2 \cdot V} \cdot \int_0^{\infty} (W_{even\_short} - W_{short})dt \qquad (16)$$

or,

$$L_{self} + L_{mutual} = L_{even} \qquad (17)$$

Combining equations (14) and (17), we obtain:

$$L_{self} = \frac{(L_{even} + L_{odd})}{2} \qquad (18)$$

$$L_{mutual} = \frac{(L_{even} - L_{odd})}{2} \qquad (19)$$

It is important to keep in mind that the lumped models extracted using the equations (9), (10), (18) and (19) above will only be valid if the electrical length of the package or connector under test, or the given segment of this package or connector, is much shorter than the rise time of the signals propagating through this package or connector:

$$t_{package} < t_{rise}/6 \qquad (20)$$

Measurement Examples

As a measurement example, we measured the input capacitance of a differential pin pair in a package. The test setup included a test fixture board, with the socket mounted in the center of the board. The TDR measurements of the fixture board are shown in the figure below.

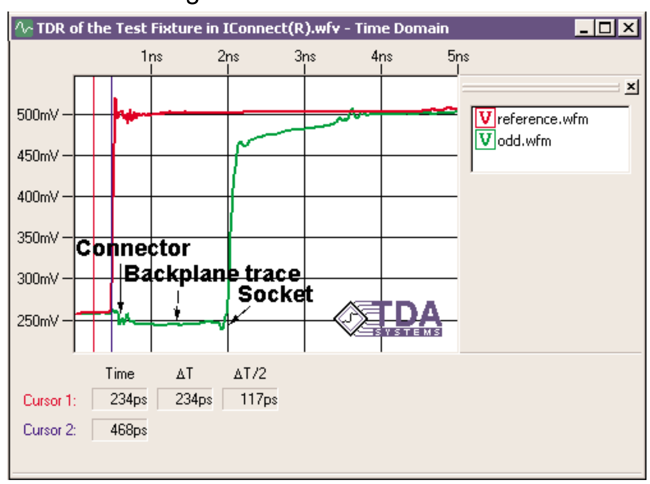


Figure 4. TDR waveform of the test fixture.

We can now use the procedure outlined above to compute the odd mode capacitance using the differential stimulus and the JEDEC procedure. The reference waveform is the odd mode waveform on Channel 1 of the oscilloscope with the socket empty, and the package waveform is the odd mode waveform on Channel 1 with the packaged part inside the socket. The resulting odd mode capacitance, computed using the C_{self} computation in IConnect, is 760fF.

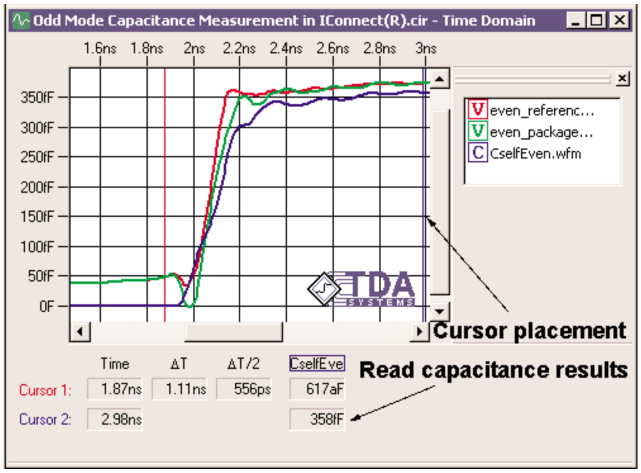


Figure 5. Odd mode capacitance measurement.

We can now compute the even mode capacitance using the common mode stimulus and the JEDEC procedure. The reference waveform is the even mode waveform on Channel 1 of the oscilloscope with the socket empty, and the package waveform is the even mode waveform on Channel 1 with the packaged part inside the socket. The resulting even mode capacitance, computed using the C_{self} computation in IConnect, is 360fF.

Then, we can apply equations (9) and (10), which give C_{self} of 360fF and Cmutual of 200fF.

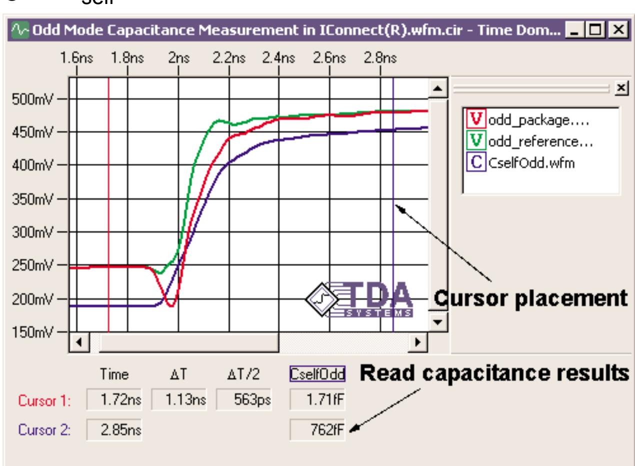


Figure 6. Even mode capacitance measurement.

Summary and Conclusions

In this paper, we proposed a novel procedure for computing the parasitics of a connector or a package using the even and odd mode capacitance and inductance measurements. The advantage of this new procedure is that it is simple and relatively error-proof. However, this new procedure allows the designer to extract only the lumped model for the interconnect in question. Such lumped model is only valid when the length of the package or connector interconnect is much shorter than the rise time of the signals propagating through this interconnect.

Bibliography

[1] Guideline for Measurement of Electronic Package Inductance and Capacitance Model Parameters, – JEDEC Publication #123, JC-15 Committee, October 1995

[2] D.A. Smolyansky, "TDR Techniques for Characterization and Modeling of Electronic Packaging," – High Density Interconnect Magazine, March and April 2001, 2 parts (TDA Systems Application Note PKGM-0101)

[3] D. A. Smolyansky, S. D. Corey, "Characterization of Differential Interconnects from Time Domain Reflectometry Measurements," – Microwave Journal, Vol. 43, No. 3, pp. 68-80 (TDA Systems application note DIFF-1099)

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