Practical Characterization and Analysis of Lossy Transmission Lines

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High-Performance System Design Conference

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Abstract

As on board clock frequencies exceed 500 MHz in computer systems, and telecommunications products reach into the 10 Gbps regime, the losses in the circuit board and cable transmission lines can be ignored only at great peril.

These lossy effects result in rise time degradation, added delays, bandwidth reduction and most importantly, pattern dependent noise, often referred to as collapse of the eye diagram. Even though these problems are becoming more common, there is still much confusion in the industry about what the effects are, how to model and simulate them, and how the materials and geometry of real boards and cables affect them.

Because there is so little data and practical analysis techniques available, there is still a fundamental debate about how important are the frequency dependence of the dielectric constant and dissipation factor as well as the resistive losses.

In this paper, we eliminate the confusion by showing that using off the shelf Time Domain Reflectometer (TDR) instruments, measurements on standard test structures can be used to fully extract the material properties of any lossy line. These material parameters can then be used with a lossy line simulator to accurately simulate the behavior of any transmission line based on this interconnect technology.

This is a practical approach which can be used by any end user to evaluate their interconnects and establish realistic specs that can be used by any interconnect fabricator.

Authors/Speakers

Eric Bogatin

Current Activities
Eric is the president of Bogatin Enterprises, specializing in training for signal integrity and interconnect design. His company offers a complete curriculum in short courses and training materials to help accelerate engineers and managers up the learning curve to be more effective in activities related to signal integrity. The corporate web site also has reference material relevant to many aspects of signal integrity.

Background
Eric received his PhD in Physics from the University of Arizona in Tucson in 1980 and his BS in Physics from MIT in 1976. He has worked in the corporate world at companies such as AT&T Bell Labs, Raychem Corp, Advanced Packaging Systems and Sun Microsystems. For 20 years, he has been involved in various aspects of signal integrity and interconnect design, from the materials side, manufacturing, product design, measurements, and most recently education and consulting.

Mike Resso

Current Activities
Mike Resso is a Product Manager in the Lightwave Division of Agilent Technologies. He is responsible for technical training of Agilent field engineers, symposium lecturing and creation of sales tools that will expand the worldwide market growth of high bandwidth oscilloscopes. His current activities include developing novel signal integrity measurement techniques as related to high-speed digital design applications, identifying new test methodologies in the communications field and interfacing with Agilent R&D engineers to bring innovative products to the marketplace.

Background
Mike has over 15 years of experience in the design and development of electro-optic test instrumentation. He has published over 20 technical papers in diverse fields such as infrared detector probe systems, linearly variable optical filters, and electrically conductive antireflection coatings. He has provided consulting and application support to European and Asian marketing centers and applications engineers throughout his career at HP. Mike received his

bachelor's degree in Electrical and Computer Engineering from University of California.

Steve Corey

Current Activities
Steve Corey is a Principal Engineer at TDA Systems. He is responsible for Research and Development work at TDA Systems. This includes the software for the creation of models for IC packages, printed circuit board transmission lines and connectors used in high speed busses.

Background
He has been doing research on interconnect characterization and modeling since 1993 and has published a number of papers in this area. During 1994-96, he worked on applications solutions and did development work for the Tektronix IPA-510 Interconnect Parameter Analyzer, which used TDR/TDT measurement techniques to extract electrical models of interconnects. Dr. Corey holds the Ph.D. degree from University of Washington, and is an IEEE member since 1996. His research interests are in automatic measurement-based model extraction.

Slide - 1

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Lossy lines are becoming increasingly important in high speed digital and telecomm applications. Yet, there is much confusion in the industry about the origin of the losses and how to account for their effects in practical ways.

This paper reviews the general features of lossy transmission lines and how they can be characterized with traditional TDR (Time Domain Reflectometry) instruments and simulation tools.

Slide - 2

Overview

- Describing Lossy Lines
- Practical Analysis Approach
- Measurement, Simulation
- Conclusions

First, we'll start out discussing the origin of losses in transmission lines. What does it mean to have loss and what affect do the losses have on signal performance. Then we will look at how to analyze the various lossy effects in a practical way that leverages commercially available simulation tools.

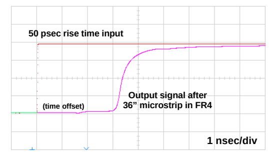
Finally, we'll show how measurements with a TDR can be used to verify this practical approach and how to extract the important material properties of lossy lines with the use of measurements, coupled with simulations.

Slide - 3

Why Worry About Lossy Lines?

Impact from lossy lines in high speed digital systems:
- ✓ Rise time degradation
- ✓ Collapse of the eye diagram

Situation analysis:
- ✓ Performance measured in time domain
- ✓ Lossy effects more easily analyzed in the frequency domain



Measured with Agilent 83480A Mainframe TDR/TDT

The most important effect arising from a lossy transmission line is rise time degradation. The losses behave in a way that cause higher frequency components of the signal to be attenuated more than low frequency components. This means that after propagating down a line, the bandwidth of the signal will decrease and the rise time will increase.

The measurement in the slide above dramatically shows the impact on rise time from the losses in an FR4 substrate. In this example, a step edge with a rise time of 50 psec was launched into a 36 inch long microstrip in FR4.

This length is often found in backplanes that have daughter cards connected. A backplane trace might be as long as 24 inches, with 6 inches of run in each of two daughter cards.

By the time the signal has exited the 36 inch run, the rise time has been degraded to longer than 500 psec. This rise time degradation will give rise to a collapse of the eye diagram. It is lossy effects that will ultimately limit the bandwidth of the interconnects, when using FR4.

One of the commonly used methods of getting around these losses is to use "pre-equalization" filters that attenuate the low frequencies exactly opposite to what will happen to the high frequency components. By the time this pre-distorted waveform is received at the far end, the attenuation has equalized the amplitudes and the sharp rise time is restored. This method can be implemented only if the amount of distortion expected is well known and predictable.

In addition, when evaluating expected system performance, for timing or signal integrity analysis, it is critical to take into account the lossy effects and their impact in transient simulations. For these reasons, it is important to have a practical way of analyzing lossy lines and incorporating their properties in time domain simulations.

Slide - 4

Practical Solution

- Model losses as simply as possible: (suitable for ***some*** transient simulators)
  - ✓ Dielectric constant (constant in frequency)
  - ✓ Dissipation factor, tan(δ) (constant in frequency)
  - ✓ R_{DC} (constant in frequency)
  - ✓ $R_{AC} \sim \sqrt{f}$
- Resistance terms can be predicted very well from field solver
- Use TDR/TDT measurements to extract material properties
- Verify assumptions by comparing simulations to TDR/TDT measurements

The method reviewed in this paper starts with the simplest description possible. We model the material properties in terms of the dielectric constant and dissipation factor, both of which we assume are constant with frequency. This assumption must be checked for each new material, as it is not a fundamental principle for any dielectric material.

The resistive losses we model in terms of a DC component and an AC component. The AC component is frequency dependent and is proportional to the square root of frequency, arising from skin depth effects.

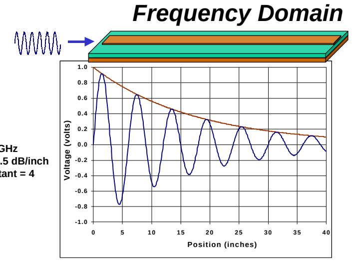
The two resistance terms can be well predicted using a 2D field solver to extract, for any conductor configuration, the DC and AC components. It's the material terms that are harder to come by.

We propose to use measurements with TDR (time domain reflectance) and TDT (time domain transmission) measurements to extract the dielectric properties of test lines. Using these assumptions we can simulate the TDR and TDT behavior of an interconnect and use the comparisons to the measurements as a way of evaluating the accuracy of the simple model.

Slide - 5

Signal Propagation in the Frequency Domain

Conditions:
Amplitude = 1v
Frequency = 1 GHz
Attenuation = 0.5 dB/inch
Dielectric constant = 4



$$V(x) = V_0 10^{(-A_{dB})} = V_0 10^{\left(-x\frac{\alpha_{dB}}{20}\right)}$$

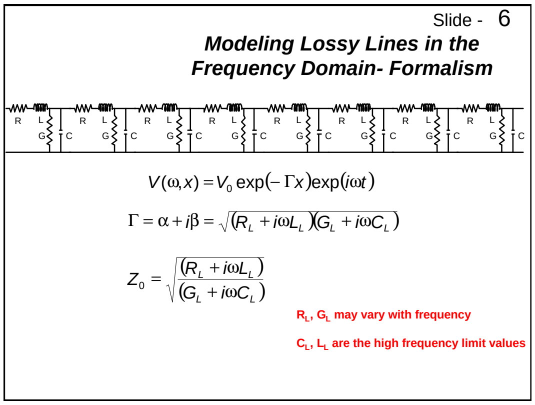
A_{dB} = attenuation in dB
α_{dB} = attenuation per length in dB/length

Analyzing the lossy effects in transmission lines is much easier in the frequency domain. Of, course, in the frequency domain, the only signals that exist are sine waves.

When a sine wave is launched into a transmission line, the frequency of the sine wave propagates unchanged, but the amplitude will drop off. As it propagates, the amplitude will be exponentially attenuated. This can be described with an attenuation per length coefficient, with the units of dB per inch, for example.

The attenuation coefficient is usually denoted as a positive term, the negative sign explicitly placed in the exponent, to give rise to attenuation, as opposed to gain.

How much attenuation is too much? This obviously depends on the specific applications, but in most cases, for typical differential receivers, an attenuation more than 3 dB at the first harmonic will not be acceptable. If the total path length is on the order of 30 inches, the maximum acceptable attenuation per length would be about 0.1 dB/inch. This is a good estimate of when to be concerned.



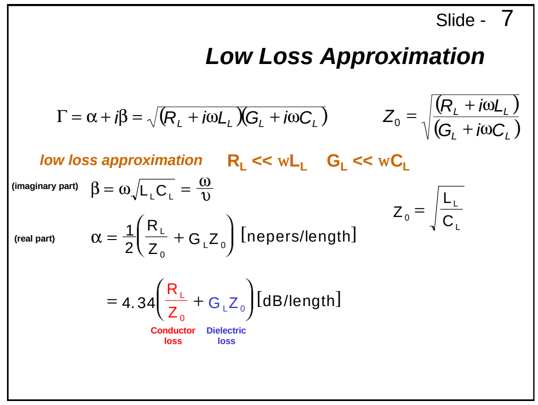
To model attenuation in a transmission line, we need to add the lossy elements of the series resistance per length and the shunt conductance per length to the typical lossless equivalent circuit model for a transmission line. This model is shown in this figure. The conductance term is really a resistor that represents the AC loss of the dielectric.

Given this equivalent circuit model, it is possible to solve for the propagation of sine waves. What we find is that sine waves will propagate as sine waves, with a propagation constant, usually termed Gamma, that is complex. The real part of the propagation constant, usually termed alpha, is the attenuation per length. The imaginary part, usually termed beta, is related to the wave velocity.

In addition, the characteristic impedance of the lossy line can be calculated and depends on the lossy terms.

In general, we will be assuming that R and G may be frequency dependent, but C and L will be constant in frequency, and will use the high frequency limits for these terms. As we shall see, frequency dependence of inductance can be accounted for in the resistance term.

In general, these two equations, while perfectly correct, are rather complicated to use because they have so many terms. Luckily, we can make a few simplifying assumptions that make these relationships much easier to use and from which to gain insight.

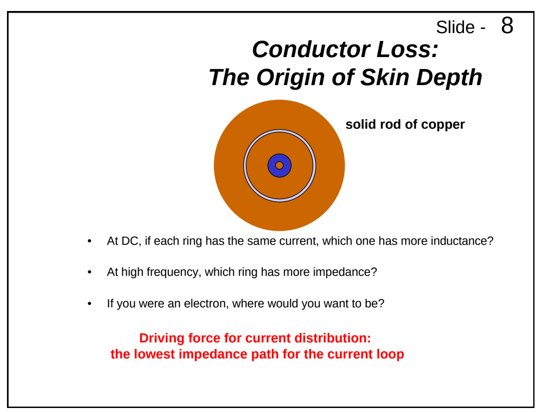


To convert these equations into a form that can yield useful insight, we make the assumption that the losses are small. As we shall see, this is a very good assumption for even the most lossy material, FR4. If this assumption is not good, the losses are probably so high that the interconnect would not be useful anyway.

This low loss approximation is only used to gain insight. In the actual extract software, the exact values for the complex characterization and propagation term are still used.

With the low loss approximation, the propagation term reduces to the lossless value, from which the velocity of the wave can be extracted. The characteristic impedance reduces to the lossless value as well.

The attenuation term reduces to a simple form that includes the attenuation from the resistive losses and the dielectric losses. We will look at each of these terms and how to find values for them in a practical way.



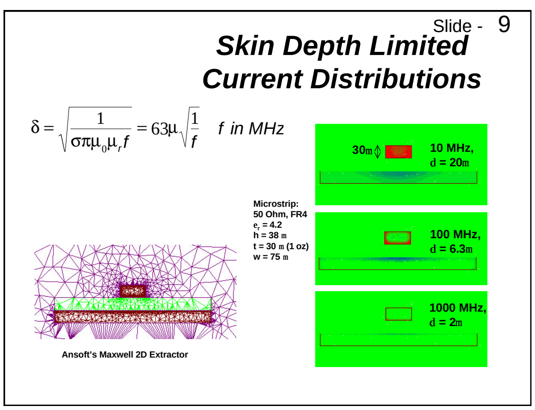
The resistive losses are dominated by skin depth effects. Though skin depth is discussed a lot in

the signal integrity community, it seems almost like a mystical effect to most engineers. In fact, its origin can be very simply understood based on the principle of inductance.
First consider the current distribution through a solid rod of copper, for DC current. Of course, the current distribution will be uniform over the cross section.

Imagine two annular rings, each of equal area, one near the center and one near the outer edge. Though at DC each has the same total current, one path has more inductance than the other.

The center path has the highest inductance since it has all the field lines of the outer ring plus the field lines that are between it and the outer ring. In general, the self inductance of the current path will decrease as you approach the outer edge.

This means that at higher frequencies, the inner paths have higher impedance and the outer paths have lower impedance. As frequency increases, there will be a greater tendency for current to take the lower impedance paths, which are toward the outer edge. This is the fundamental origin of skin depth.

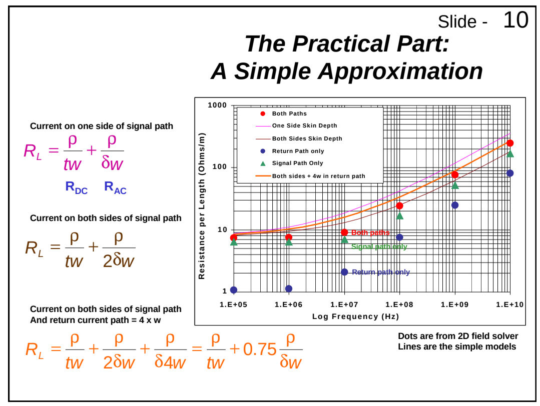


The effective thickness of the cross section of current flow is actually termed the skin depth and can be approximated by the equation above. For copper with 1 GHz sine waves, most of the current flows in a region about 2 micron thick.

Using the Ansoft Maxwell 2D Extractor field solver, we can calculate the current distribution in any arbitrary cross section transmission line. In this example, we are looking at the current density at three sine wave frequencies, 10 MHz, 100 MHz and 1 GHz.

At the highest frequency, most of the current is flowing in a very thin region of the signal path and the return path. In the signal path, even though the structure is a microstrip, the current distribution uses both sides of the conductor.

As the frequency increases, the cross sectional area available for current flow decreases. This will cause the resistance per length to increase with frequency. Based on the field solver results, we can create a simple approximate model for this frequency dependent resistance.

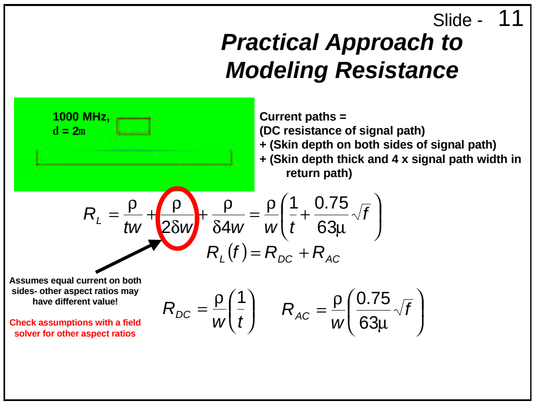


The resistance per length can be calculated from the cross sectional area. We assume a simple behavior that the resistance is a DC term that is just related to the geometrical cross section and an additional term that is the cross section corresponding to the skin depth thickness.

Using the field solver, we can calculate the series resistance per length for the contributions of the signal path and the return path and the sum. These calculations are shown as the individual data points in the graph above. The return path is about half the resistance of the signal path.

The best model for the high frequency resistance is for the case of assuming the current flows on both surfaces of the signal conductor, and spreads out in the return path to a width equal to 4 times the width of the signal path. If this were a stripline configuration, the return path resistance would be reduced due to the parallel combination of the second return current path.

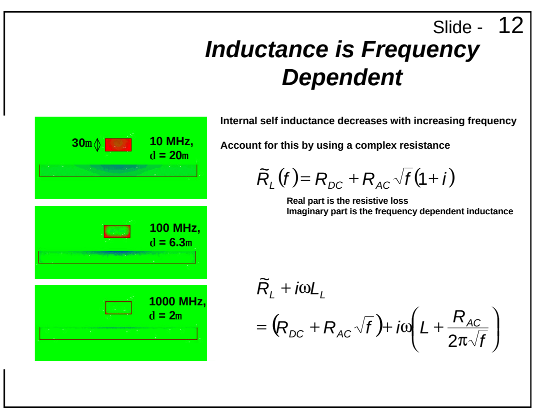
This simple model matches the resistance values from the field solver very well in the GigaHertz regime, where the series resistance is important.



This simple model illustrates the features of the resistance. There is a DC term that is due to the geometrical cross section, and there is an AC term that is proportional to the square root of frequency. Both of these terms can be calculated directly, given the resistivity and the geometry of the transmission line.

The approximation offered here is for a particular aspect ratio and cross section. In general, these terms should be extracted using a field solver. Depending on how much current flows in the top surface, this term could vary by as much as a factor of two.

However, the form of the frequency dependence will be the same. This is the basic assumption used by a few SPICE like simulators that incorporate frequency dependent losses in a transient simulation. We see that based on field solver simulations, this is a reasonable assumption.

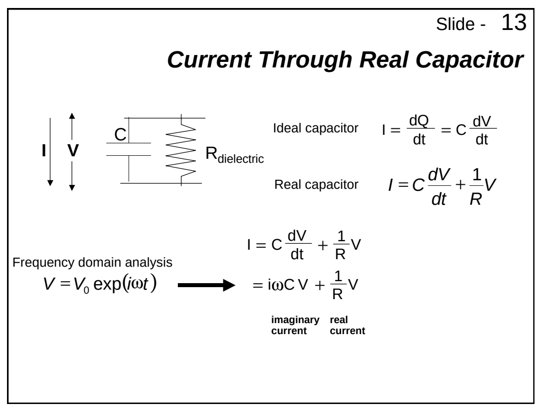


For the same reason that resistance is frequency dependent, the inductance will be. The current distribution changes and the internal self inductance of the current loop will decrease at higher frequency.

This effect can be automatically taken into account by using a complex formulation for the resistance. The real part of the resistance is the lossy term, while the imaginary part of the resistance has the frequency dependent inductance in it.

In all situations, the resistance appears with the inductance as R + i omega L. By using the complex form of R, the inductance per length now accounts for the decreased value, as long as we take L as the high frequency, skin depth limited inductance.

In typical SPICE based simulators that handle the frequency dependence of R, such as HSPICE, the frequency dependence of L, is included in this same way. Including this effect does not complicate the model nor increase the effort in analyzing the lossy line.



The second loss term is the dielectric loss. The easiest way to think about the dielectric loss is to model a real capacitor filled with real dielectric as an ideal lossless capacitor and a resistor that gives rise to resistive loss of energy.

In the model of an ideal lossless capacitor, the current is just C times dV/dt. In this parallel circuit, the current through the combination is the current through the ideal capacitor and the resistor.

In the frequency domain, the current has two terms, an imaginary term that is what we are used to thinking about for lossless capacitor, and a real term, which is what would contribute to loss of energy.

The real part of the current is what arises from the lossy nature of the dielectric material.

Slide - 14

Complex Dielectric Constant

$C = \varepsilon C_0$ C_0 is the empty space capacitance

describe ε as complex: e(w)=e'(w) - i e"(w) tan(d) = e¢ / e¢

Dissipation Factor

$$I = C\frac{dV}{dt} = C_0(i\omega V)\{\varepsilon(\omega)\}$$

$$I = i\omega C_0 V(\varepsilon'(\omega) + i\varepsilon''(\omega))$$

$$= \underbrace{i\omega C_0 V\varepsilon'(\omega)}_{\text{imaginary current}} + \underbrace{\omega C_0 V\varepsilon''(\omega)}_{\text{real current}}$$

The real part of the dielectric constant relates to “dielectric” or “displacement” currents
The imaginary component of the dielectric constant relates to "resistive" or lossy currents through the capacitor.

To take advantage of the properties of complex numbers, this real and imaginary current through a real capacitor can be modeled by changing the nature of what is commonly referred to as the dielectric constant.

We re-define it to be a complex number. What we are used to thinking of as the dielectric constant is really the real part of the complex dielectric constant. The imaginary part, as we shall see, is related to the dielectric losses.

Given this new definition of the complex dielectric constant, we can further define the tangent of the angle between the real and imaginary component as the dissipation factor. In the complex plane, this is the angle between the complex dielectric constant and the real axis.

The dissipation factor is what is usually used to refer to the dielectric losses, rather than the imaginary part of the dielectric constant. However, given the dissipation factor and the real part of the dielectric constant, the imaginary part can be simply found.

With this new definition of complex dielectric constant, and the definition of the current through a capacitor, we can re-write the imaginary and real current through a capacitor in the frequency domain.

Here we see that the real part of the dielectric constant relates to the ideal current through a capacitor and the imaginary part of the dielectric constant relates to the resistive current through a capacitor.

Slide - 15

Dissipation Factor and Conductance

$$I = \underbrace{i\omega C_0 V\varepsilon'(\omega)}_{\text{imaginary current}} + \underbrace{\omega C_0 V\varepsilon''(\omega)}_{\text{real current}} \qquad I = C\frac{dV}{dt} + \frac{1}{R}V$$

$$R = \frac{1}{\varepsilon''(\omega)\ \omega\ C_0}$$

Define conductance as: $I = C\frac{dV}{dt} + GV$

$$G \equiv \frac{1}{R} = \varepsilon''(\omega)\ \omega\ C_0 = \omega\ \tan(\delta)\ C$$

$$G = \frac{\sigma}{\varepsilon_0}C_0 \qquad \sigma = \omega\varepsilon_0\varepsilon_r'' = \omega\varepsilon_0\varepsilon_r'\tan(\delta)$$

Even if tan(d) is constant in frequency, G is linear in frequency

The resistive current through a capacitor can be represented by a resistor that is frequency dependent. Because this resistor is shunting the capacitor, it is often referred to not as R, but as a conductance, G. The value of the conductance is related to the imaginary part of the dielectric constant or the dissipation factor.

It is important to note that even if the dissipation factor is constant with frequency, G will be frequency dependent, with a linear dependence on the frequency.

Slide - 16

Dissipation Factor is ~ Constant in Frequency

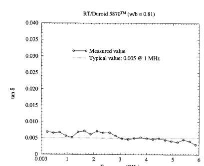


Fig. 9. Measured dielectric loss tangent versus frequency for RT/Duroid 5870.

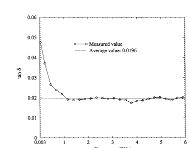


Fig. 11. Measured dielectric loss tangent versus frequency for Novolac epoxy.

From:
“Dielectric Constant and Loss Tangent Measurements Using a Stripline Fixture”, H. Yue, K. L. Virga and J. L. Prince, IEEE Trans CPMT, part B, vol 21 (4), Nov 1998

Most dielectric materials have a dissipation factor that is roughly constant with frequency. In this example, a Duroid® material and an FR4 sample were measured and the dissipation factors are seen to be constant above about 800 MHz.

The assumption of having the dissipation factor be constant is not a bad one. However, there is no fundamental principle that would force all materials to have a dissipation factor constant with frequency, so this assumption must be tested for each material.

Slide - 17

Attenuation due to Dielectric

$$a = 4.34\left(\frac{R_L}{Z_0} + G_L Z_0\right)$$

Conductor loss — Dielectric loss

$$G_L = \omega \tan(\delta) C_L \qquad Z_0 = \frac{\sqrt{\varepsilon_{eff}}}{\text{speed of light } x\ C_L}$$

$$\alpha_{dielectric} = 4.34\, G Z_0 \qquad G Z_0 = \frac{\omega \tan(\delta)\sqrt{\varepsilon_{eff}}}{\text{speed of light}}$$

$$\alpha_{dielectric} = 2.3\, f \tan(\delta)\sqrt{\varepsilon_{eff}} \quad \text{dB / inch} \quad (\text{f in GHz})$$

Even if tan(d) is constant in frequency, a is linear in frequency

We have a way of describing each of the loss terms, the resistance and conductance per length of the lossy line. These two terms factor into the attenuation of the line.

The conductance per length has the same geometrical factors as the characteristic impedance, but inversely. These geometry effects cancel out and the attenuation for the dielectric losses are not geometry dependent. They depend only on the material properties.

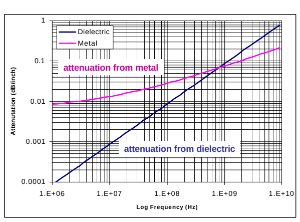
Even if the dissipation factor is constant in frequency, the attenuation due to the dielectric loss will still increase linearly with frequency.

Slide - 18

Relative Importance of Dielectric and Metal Loss

$$a = 4.34\left(\frac{R_L}{Z_0} + G_L Z_0\right)$$

Conductor loss — Dielectric loss



Conditions:
t = 30m (1 oz)
w = 8 mils
tan(d) = 0.02
e_{eff} = 3.5
Z_0 = 50 Ohms

General guide: above 1 GHz, and w > 8 mils, dielectric loss dominates

Based on these simple models for the resistance and dielectric loss, we can approximate the attenuation from each of the sources.

For the typical case of 8 mil wide traces, in FR4 with a dissipation factor of about 0.02, we see that above about 700 MHz, the dielectric losses dominate over conductor losses. For many typical applications, and in the multiple GHz range, dielectric losses will dominate.

If losses are an issue, and conductor losses dominate, one quick fix is to increase the line width, and the dielectric thickness, and thus reduce the conductor losses.

There is no change in geometry which will decrease the dielectric loss. It is simply a material selection issue. If dielectric losses dominate, and the attenuation must be decreased, the only way of doing this is by changing the PCB laminate material.

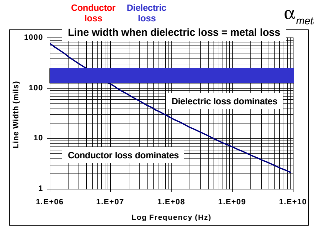
Slide - 19

Where Dielectric Loss Dominates

$$a = 4.34\left(\frac{R_L}{Z_0} + G_L Z_0\right) \qquad \alpha_{diel} = 2.3 f \tan(\delta)\sqrt{\varepsilon_{eff}}$$

Conductor loss — Dielectric loss

$$\alpha_{metal} = 4.34 x \left(\frac{\frac{\rho}{w}\left(\frac{1}{t} + \frac{0.75}{63\mu}\sqrt{f}\right)}{Z_0}\right)$$



Wide lines more sensitive to dielectric loss

Conditions:
t = 30m (1 oz)
tan(d) = 0.02
e_{eff} = 3.5
Z_0 = 50 Ohms

From this simple model, we can evaluate at what line width will dielectric losses equal resistive losses, for a 50 Ohm line. At any frequency, there will be a line width where these two terms are equal.

For example, at 100 MHz, in FR4, a 25 mil wide line has comparable conductor loss as dielectric loss. In designing a test vehicle that allows extraction of dissipation factor, in the 100 MHz range and above, a wide 50 Ohm line should be used.

Slide - 20

Practical Method of Analyzing Lossy Properties of a Transmission Line

- TDR/TDT measurement
- Fit Z_0, TD, tan(δ), R_{DC}, R_{AC}
- Compare Simulated and Measured TDR/TDT

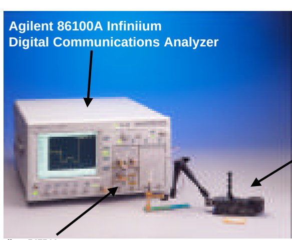
A simple process has been developed to extract the dielectric properties of a test line and verify this model.

We start with TDR and TDT measurements on a test line. Using software from TDA Systems, we fit the value of five parameters to the measured data.

Using these five parameters, we simulate the expected TDR and TDT response. The agreement between the measured and simulated is a good indication of how accurate the simplified model is.

Slide - 21

TDR Equipment



Terminology

TDR:	Time Domain Reflection
TDT:	Time Domain Transmission
DTDR:	Differential TDR
DTDT:	Differential TDT

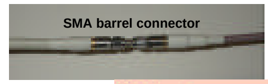
Agilent N1020A TDR Probe

Agilent 54754A
Differential TDR Module
Two independent TDR channels
- Single-ended or Differential
- TDR or TDT

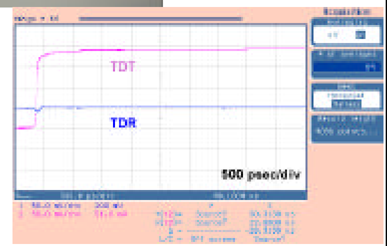
To perform the measurements, an Agilent 86100A Infinium Digital Communications Analyzer mainframe was used. An Agilent 54754A differential TDR plug in was used to take the TDR and TDT data.

Slide - 22

TDR/TDT of the Cabling



Intrinsic rise time with the cables < 50 psec



The first step is evaluating the performance of the cabling that will hook up to the device under test (DUT).

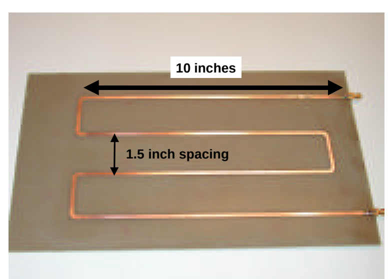
High quality SMA cables were used. Each of them was approximately 1 meter long. In evaluating the transmission properties, an SMA barrel connector was used to connect the step pulse from one channel to the input receiver of the other channel.

In the TDR trace, the small, lower impedance region of the barrel, is clear. The received signal in the TDT channel shows a rise time of about 50 psec, only slightly degraded from the approximately 39 psec of the source.

This thru measurement was used as the reference exiting source by the extraction software. The propagation of this measured signal through the modeled interconnect was simulated and compared with the actual measurements. This effectively takes into account the real cable losses in the measurement system.

Slide - 23

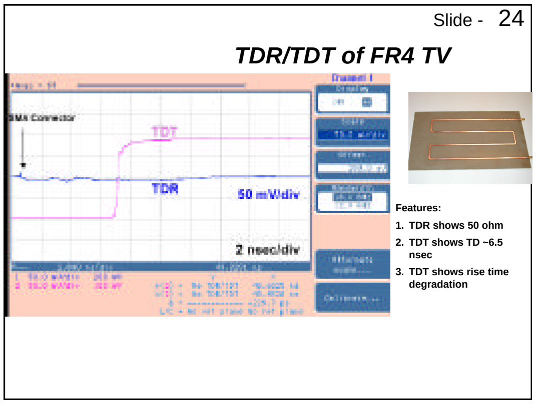
42 inch Long FR4 Test Vehicle



Conditions:
Len = 42.25 inches
t = 30m (1 oz)
w = 120 mils
h = 62 mils
e_r ~ 4.6
tan(d) ~ 0.02
Z_0 ~ 50 Ohms

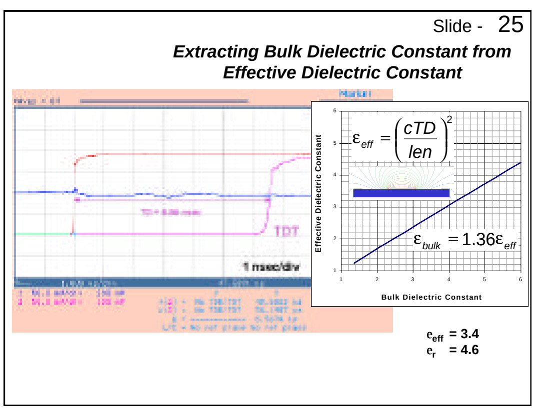
The DUT is a custom manufactured serpentine microstrip on an 062 mil thick FR4 substrate. In order to be 50 Ohms, the line width was set at 120 mils.

The total length is 42.25 inches. It is designed with four legs in a meander. The spacing was chosen so that the far end cross talk coupling was less than 1%.



The measured TDR and TDT response from the DUT are shown above. The TDR shows the DUT to be about 47 Ohm impedance.

The TDT shows a TD of about 6.5 nsec, with some rise time degradation over the original 50 psec edge.

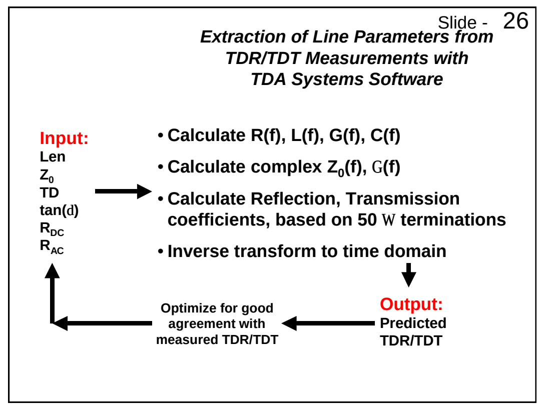


From the TDT measurement on an expanded scale, we can make an estimate of the TD (Time Delay). Taking the mid point as the reference position, the TD is measured as 6.56 nsec.

Given a value of the TD, we can calculate the effective dielectric constant. This should not be confused with the bulk dielectric constant. In a microstrip, some of the field lines see air and some see the bulk material. The effective dielectric constant is reduced from the bulk values, depending on the cross section.

However, using the Ansoft Maxwell 2D Extractor, the bulk dielectric constant can be back extracted from the measured effective dielectric constant. Using the cross section information for this meander, the bulk dielectric constant is found to be 1.36 x the effective dielectric constant. Of course, a different cross section will give a different factor.

We estimate the bulk dielectric constant to be 4.6.

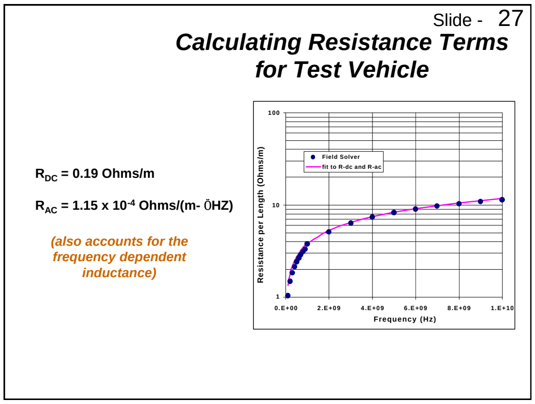


The extraction software that allows the prediction of TDR and TDT measurements, was developed by TDA Systems. The basic algorithm is to select values of the basic parameters that describe a lossy line: the length, the characteristic impedance, the time delay, the DC resistance, the term proportional to root frequency and the dissipation factor.

These terms are used to calculate the frequency dependent R, L, C and G terms. With these terms, the exact complex characteristic impedance and propagation term are calculated. From these terms, the frequency dependent reflection and transmission coefficients are calculated, based on 50 Ohm terminations.

Finally, the frequency domain response is converted to a transient response with an inverse Fourier transform. This is the TDR/ TDT predicted response based on the input line parameters.

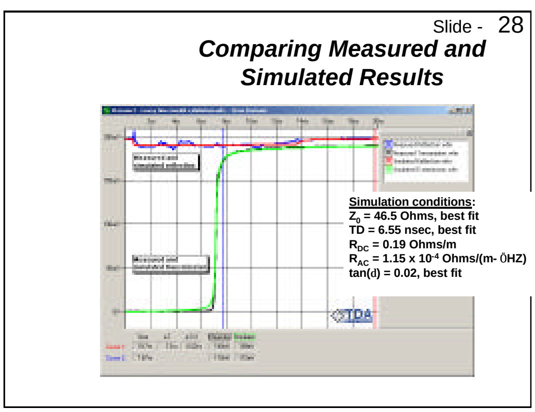
The process for using this tool is to optimize the characteristic impedance and time delay to the measured data, use values of the resistance from the field solver, and optimize a value for the dissipation factor based on the measured data. If the final agreement between predicted and measured TDT is good, we have confidence the value of the dissipation factor used was accurate enough.



The resistance terms for the meander test pattern can be extracted with a 2D field solvers, such as the Ansoft Maxwell 2D Extractor.

From the extracted values of resistance per length and frequency, we can fit the resistance behavior modeled by a DC value and a term proportional to root frequency. We can see that the fit is very good, so we have confidence the resistance can be modeled with this simple approach.

These values of R_{DC} and R_{AC} are input into the extraction tool's input. In addition, the extractor will use these terms to calculate the frequency dependence inductance.

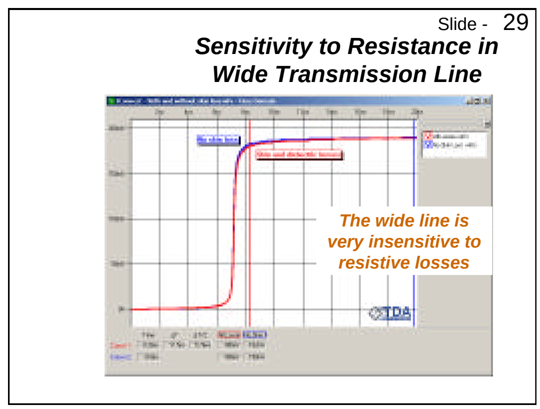


We use the resistive losses from the field solver and optimize the values of TD and the dissipation factor to give the best agreement with the TDR/TDT measured data.

We find the extracted values are TD = 6.55 nsec and dissipation factor = 0.02. The excellent match of the predicted TDT and the measured result is an indication that the simple model proposed here is a very good, practical model for describing the transient performance of lossy lines.

The approximations used to describe this lossy line are easily good enough for all practical situations.

Further, by using the measured TDR/TDT data as the target value, we are able to extract an optimized value for the dissipation factor of this substrate. This can be used as input to any SPICE based simulation tool to predict performance of interconnects using this same substrate material.

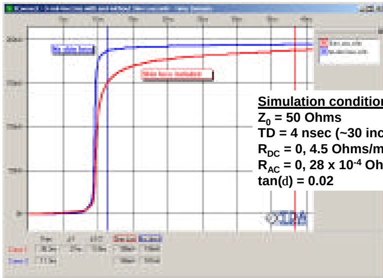


In this particular example, we designed the test vehicle to be insensitive to the resistive loss so we would be more sensitive to dielectric loss. We can confirm this by comparing the predicted response with no resistance used in the input and with the values suggested by the field solver.

As can be seen, there is very little impact from keeping or turning off the resistance terms. This confirms that resistance plays very little role in these measurements of this particular wide trace interconnect.

Slide - 30

Effect of Losses in 5 mil Wide 50 Ohm Line



Simulation conditions:
Z_0 = 50 Ohms
TD = 4 nsec (~30 inches long)
R_{DC} = 0, 4.5 Ohms/m
R_{AC} = 0, 28 x 10^{-4} Ohms/(m- $\sqrt{HZ}$)
tan(d) = 0.02

In typical back plane or large motherboard applications, the line width might be on the order of 5 mils. In this case, the resistive losses play a dominate role.

Using the extraction tool from TDA Systems, and the extracted values for the dissipation of this FR4 substrate material, we can predict the transmitted waveform at the end of a 30 inch interconnect.

With no resistive losses, the dielectric loss gives a relatively fast edge. However, with the resistive losses, as predicted by a 2D field solver, turned on, they clearly dominate and dramatically increase the rise time.

Without considering both resistive and dielectric loss effects, and compensating for them, this sort of lossy behavior would result in unacceptable performance at GigaHertz rates.

Slide - 31

Summary

- Lossy Lines play a critical role on backplanes at clock frequencies > 1 GHz
- A simple model can be used to accurately describe lossy effects: R_{DC}, R_{AC}, constant dielectric constant and constant dissipation factor
- Resistance terms can be extracted with a field solver
- Dielectric constant and dissipation factor can be extracted from TDR/TDT measurements by matching simulation and TDR/TDT measurement
- These values of resistance, dielectric constant and dissipation factor can be used with other SPICE based simulators

We have shown in this paper that a simple model can be used to accurately predict the transient behavior of lossy lines. The assumptions of a resistance proportional to root frequency, and a dissipation factor constant with frequency, are good enough for practical applications.

We illustrated that the frequency dependent resistance can be extracted with a field solver for any arbitrary cross section.

Finally, we showed that using TDR and TDT measurements of test patterns, the material properties of a substrate can be extracted on a routine basis by anyone with the instruments and the extraction software.

These values of resistance and material properties can be used in versions of SPICE that allow frequency dependent losses in transient simulations. With such a tool, the lossy properties of transmission lines can be simulated for all high speed signals.

Slide - 32

Resources

- www.BogatinEnterprises.com
  - ✓ Training for Signal Integrity and Interconnect Design
  - ✓ Complete continuing education curriculum of courses in signal integrity and interconnect design
  - ✓ Resources on the web include bibliography, journal links and conferences, in addition to papers and publications for download
- www.GigaTest.com
  - ✓ GigaTest Labs offers a full line of measurement services
  - ✓ Capabilities include IC package modeling and lossy line characterization
- www.Agilent.com
  - ✓ Full line of TDR high speed products and accessories
- www.TDASystems.com
  - ✓ Software for analysis of TDR and DTDR structures

For more information and training about signal integrity and interconnect design, please contact Bogatin Enterprises. Our web site is a resource center for many topics related to signal integrity and interconnect design, including a bibliography, list of relevant conferences and trade journals and a listing of important webs sites and vendors.

For information about instrumentation used in this study, contact Agilent Technologies. Agilent provides high precision TDR/TDT instruments as well as a full line of high speed instrumentation.

TDA Systems offers a complete line of software tools to extract high speed circuit models of interconnects from measured data. The extraction tools used in this paper are available through TDA Systems.

GigaTest Labs is available for contract measurements of lossy lines and other high speed interconnects.

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