Humidity-Dependent Loss in PCB Substrates

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Abstract
Increasing operating frequency of IO busses for computing has highlighted the importance of transmission line loss. For FR4 PCB mother boards computing at speeds above 1 GHz this is dominated by dielectric losses. FR4 dielectrics are epoxy based materials which absorb moisture and are subject to dielectric loss variation due to absorption of ambient moisture. Resonator measurements of the substrate alone are useful for modeling but they do not take into account PCB design variables that influence absorption rates. Transmission line loss data and analysis obtained from two PCB designs subjected to a program of drying and moisture absorption are presented. A model to predict absorption rates and transmission line loss is presented. FR4 materials will be compared and contrasted with a low-loss substrate material.

Introduction:
Moisture in electronics has been and continues to be a significant concern for system reliability due to its impact on mechanical stresses during thermal cycles, ability to alter adhesion properties, and its corrosive nature when mixed with ionic compounds such as salts. Moisture also affects the electrical properties of a dielectric by altering its dielectric constant and loss tangent [1]. As IO bus speeds exceed 1GHz and move toward 5GHz and beyond it is becoming critical to system designs that the change in loss with respect to moisture be quantified. At these signaling speeds, small changes in the dielectric material properties can result in failure of electronics systems to communicate across an IO bus. A complicating factor for designers is that the electrical impact due to the moisture concentration within the dielectric is time-dependent and atmospheric condition dependent.

The electrical properties of a material are partially a function of the amount of moisture in the material. The extent to which a material absorbs moisture is characterized by its moisture diffusivity and saturated moisture concentration. Moisture diffusivity describes rate of change of a material's moisture concentration. The saturated moisture concentration provides an expression for the limit to the amount of moisture that a material can contain. It is important to note that both are a function of temperature and relative humidity. Another measure of a material's susceptibility to moisture is its maximum moisture uptake. This is typically reported on material data sheets as %weight and is related to the saturated moisture concentration.

Common PCB dielectrics, such as FR4, are epoxy-coated glass-reinforced composites typically distinguished by the construction of the reinforcement material. Moisture diffusion will only occur through the epoxy, as the reinforcement glass does not readily absorb moisture. As a result, the moisture absorption characteristics of PCB dielectric materials will vary by construction. The glass reinforcement will act as a barrier to restrict flow and impact the diffusivity between two different constructions. Also, the varying glass-to-resin ratios between different constructions will result in varying measures of moisture concentration and maximum moisture uptake. In this paper all loss and diffusivity data are denoted by temperature, humidity conditions and construction.

System designers need to be able to determine the typical, minimum, and maximum impact of moisture on transmission line loss. This will depend on the system design. Surface microstrips and embedded microstrips are more susceptible to humidity conditions in the environment than striplines. Measurable changes in µstrip losses occur in hours as moisture concentrations change quickly. Transmission lines placed between reference planes, such as striplines, are significantly slower to respond to humidity conditions in the environment. The response time of striplines is measured in weeks or months and is dependent on the continuity and perforation of the reference planes as these provide a barrier to the diffusion of moisture.

Moisture Impact on Transmission Line Loss

A set of test boards were designed to determine the maximum impact of moisture on transmission line loss. In actual computing designs, the power and ground planes are not continuous barriers to moisture absorption perpendicular to the plane of the board. There are anti-pads around each via pad that carry signals between layers and those that provide attach points for thru-hole connectors. These provide a path for moisture to diffuse through the PCB. To simulate actual product designs in this experimental design there were via anti-pads regularly distributed across the ground planes, except directly under the transmission lines as shown in figure 1. Multiple test boards were fabricated and tested with varying distributions of anti-pads to simulate the different levels of plane coverage. All data presented in this section is from test boards having 90% ground plane coverage.

Test boards for this experiment were 8-layers with symmetry across the midplane of the board. Three stackups were used: 1080 FR4, 7628 FR4 and Rogers 4350 ™ High Frequency Circuit Material. All single-ended (SE) lines were designed to have 50 ohm characteristic impedance. Striplines were connected to the surface layers using microvias to minimize via parasitics and improve the frequency response of the test structures.

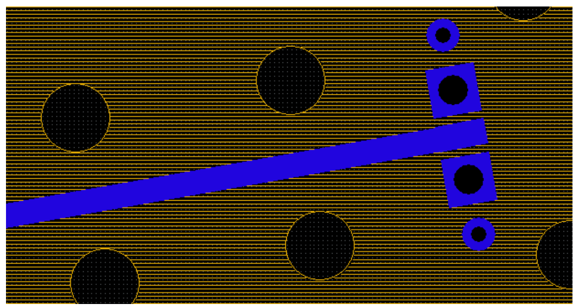

Figure 1 - 90% power plane coverage

All boards were preconditioned for one week at 65 degrees C to remove any residual moisture. All boards were then stored in a dry box at less than 10% relative humidity (RH) and room temperature while dry measurements of S-parameters were made. When this was complete the boards were placed in an environmental chamber kept at 38 degrees C and 95% RH. Measurements of S-parameters were made at regular increasing intervals until the loss reached equilibrium.

Measurements of S-parameters were made using an Agilent ™ 8722ES S-parameter analyzer (VNA). It was calibrated daily using an SOLT calibration standard. The VNA connections to the PCB trace were made using microprobes. Before the experiment was started a 3-day, 3-operator, multiple-sample metrology capability analysis was performed that indicated that the measurements were not operator sensitive and that daily calibration sufficed for our purposes.

The S11 measurements were not significantly affected by moisture. Figure 2 shows the S21 measurements from the microstrip transmission lines for the three materials at their preconditioned dry state and saturated equilibrium state. The measured loss of microstrips on Rogers RO4350™ demonstrated the smallest magnitude shift and smallest percentage change due to moisture. The 7628 FR4 had a lower overall loss compared to the 1080 FR4 at each state and demonstrated similar increased loss due to moisture. The measured line losses equilibrated within days to a couple of weeks, depending on material type and thickness of microstrip structure.

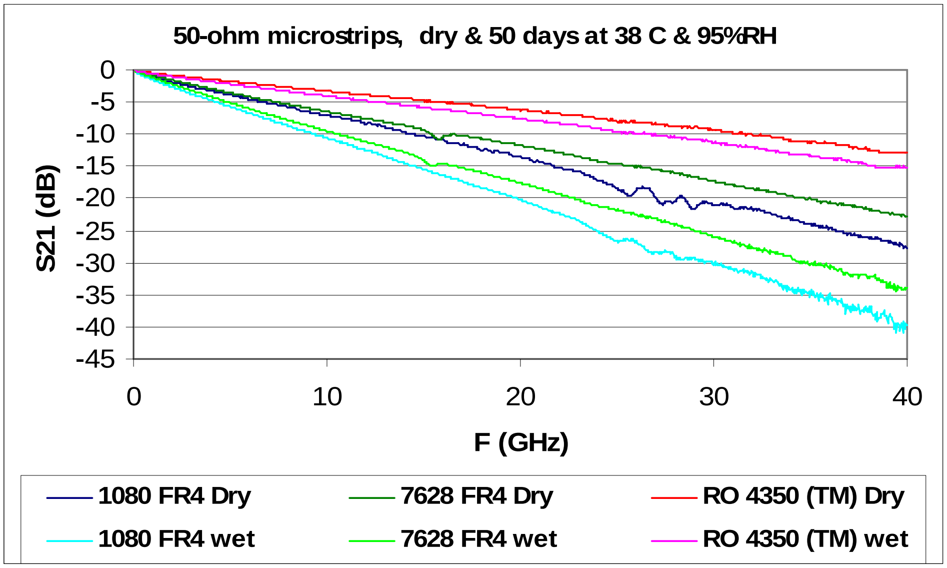

Figure 2 - S21 of 1080 FR4, 7628 FR4 and Rogers 4350 ™ microstrip

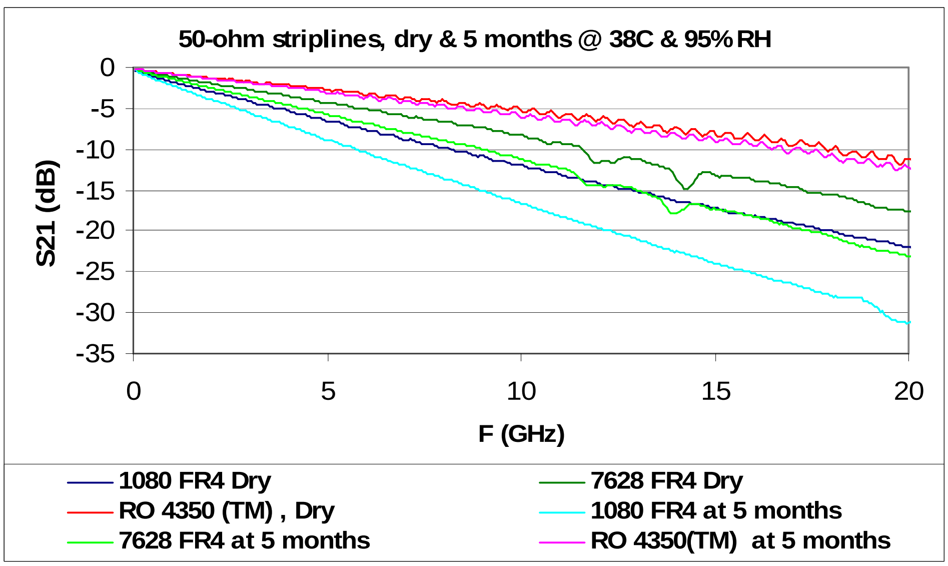

Figure 3 - S21 of 1080 FR4, 7628 FR4 and Rogers 4350 ™ striplines

Figure 3 shows S21 measurements for striplines on layer 3 of the same boards as those in figure 2. Equilibrium delay time for striplines was affected by both their depth into the board and the coverage of the power and ground planes between them and the surface. The measured loss on some combinations of material and ground plane coverage had not reached loss equilibrium after 5 months of testing. As with the microstrip structures, the Rogers RO4350™ demonstrated the smallest magnitude shift and smallest percentage change due to moisture. The longer equilibrium delay time for the stripline structures was expected as the striplines were partially shielded by copper planes. Also, striplines are typically positioned further from the surface of the PCB, forcing moisture to diffuse through the surface substrates to reach the stripline structure.

Fick's law of diffusion was utilized to model the equilibrium delay time and rate of change of measured loss for the microstrip structures.

Impact of Moisture on Loss Tangent and Dielectric Constant

The preceding analysis presented the effect of moisture diffusion into the substrate on transmission line loss by direct measurement and reflected the loss contributions of solder mask, conducting trace, and substrate. To characterize the loss of only the PCB substrate, a split-post dielectric resonator (SPDR) was used to measure loss tangent (tan δ) and dielectric constant (ε_r) of bare PCB substrate materials[4]. No copper or solder mask was present on these PCB samples. The core PCB material was conditioned in two different environmental conditions until equilibrium before measuring ε_r and tan δ. The measured values of tan δ and ε_r measured after equilibrium at 20^0C & 10% RH and measured again after equilibrium at 38^0C & 95% RH are shown in table 1.

Table 1 - Values of tan δ and ε_r measured using split-post dielectric resonator

	20^0 C 10% RH				36^0 C 95% RH			
7628 (FR4)	**1.2 GHz**	**3.2 GHz**	**7.2 GHz**	**10.2 GHz**	**1.2 GHz**	**3.2 GHz**	**7.1 GHz**	**10.2 GHz**
tan δ	0.01255	0.0126	0.0129	0.0125	0.0180	0.0193	0.0197	0.0197
ε_r	4.5	4.55	4.47	4.24	4.65	4.725	4.58	4.475

As seen in Table 1, moisture had a significant impact on the loss tangent. The dielectric constant increased slightly with absorption of moisture. The measured loss tangent increased for each measured frequency by 43-58% between the two conditions. The change in loss tangent is significant as its magnitude is high and it is directly proportional to the dielectric loss component of measured transmission line loss.

Modeling Moisture Dependent Loss

Fick's law of diffusion is a close analog of the method of Fourier for characterizing and predicting heat flow [2]. Fick's law characterizes the time and distance dependent concentration of a solute in a solvent. In the case of modeling moisture dependent loss in PCB substrates, atmospheric moisture is the solute and PCB materials are the solvent. Fick's Law assumes a homogeneous isotropic material as the solvent, but it has been shown to adequately model PCB composites. Fick's law for single-dimensional diffusion is shown in equation 1.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad \text{(Equation 1)}$$

Equation 1 states mathematically that the time rate of change of concentration "C" of a solute in a solvent is proportional by constant "D" to the derivative of the concentration gradient of the solute. The constant "D" is known as diffusivity and has units of area/time. Solving equation 1 by method of separation of variables leads to the general form shown in equation 2.

$$C = \sum_{m=1}^{\infty}(A_m \sin\lambda_m x + B_m \cos\lambda_m x)\exp(-\lambda_m^2 Dt) \qquad \text{(Equation 2)}$$

Where exp(n) denotes the base of natural logarithms, "e", raised to the power of "n". The solution of equation 2 is dependent on the boundary and initial conditions and the geometric dimensions of the sample being modeled. In the case for which the material starts dry and is placed in an environment of temperature and humidity, the diffusion of moisture occurs from the outer boundary of the material inward. Since the material is much wider than thick, all diffusion is treated as if it were in the x direction only. The material is modeled as an infinite plane of thickness twice "l" as shown in figure 4.

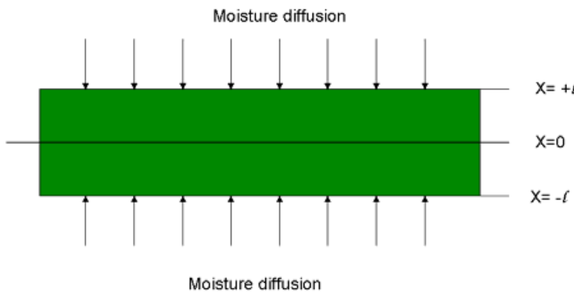

Figure 4 - Fick's Law Diffusion model

Solution of equation 2 using partial fractions and the boundary and initial conditions for two-sided diffusion into an infinite plane is shown in Equation 3.

$$C = Co - \frac{4Co}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\frac{(2n+1)\pi x}{2l}\exp(-D(2n+1)^2\pi^2 t/4l^2) \quad \text{(Equation 3)}$$

Where:

C = concentration of solute at time "t" and distance from material center "x"
D = diffusivity (mm^2/sec)
x = distance from the center of the material (mm) as in figure 4
l = ½ thickness of the material (mm) as in figure 4
t = time (seconds)
Co = equilibrium concentration of the solute at the surface [2]

As seen from equation 1, diffusion is gradient-driven. The center of the plane (x=0) has a zero gradient. Hence, the concentration at any depth except the center at x=0 is from diffusion from one side of the plane. One could place an impermeable plane in the middle of the sample and have no affect on diffusion and concentration at any location for |x| >0. In other words, all diffusion into the top half of the material is from the top surface downwards. All diffusion into the bottom half of the material is from the bottom surface upwards. Thus, an impermeable reference plane below a measured trace can be considered a "virtual center" for the purposes of this model and will be at the location x=0 for the purposes of modeling change in transmission line loss due to moisture absorption with Fick's law.

Obtaining Diffusivity from PCB Trace Loss Measurements:
The magnitude of S-parameters measured using a Vector Network Analyzers (VNA) for the desired range of frequencies is often expressed in decibels (dB). Figure 5 shows an example of the increase in S21 over time for a measured microstrip transmission line on 7628 FR4 that had been preconditioned to a dry state then exposed to 37 degrees C and 95% RH. Similarly, the S11 parameter also changes over time with exposure to the same environmental conditions due to changes in the dielectric constant. To fit S-parameter data to Fick's law it is necessary to convert the S21 and S11 parameters from dB to linear scale as in equation 4.

$$S21, linear = 10^{(S21, dB/20)} \quad \text{(Equation 4)}$$

Using linear values for S21 and S11, the identity for a lossless transmission line is shown in equation 5. Therefore, in the case of a lossy transmission line, the loss is defined as shown in Equation 6.

$$S21^2 + S11^2 = 1 \quad \text{(Equation 5)}$$

$$loss = 1 - S21^2 - S11^2 \quad \text{(Equation 6) [3]}$$

The humidity-induced change in transmission line loss is defined as the difference between the measured loss and the measured loss at its initial condition. For experimental purposes of this paper, the initial condition was the preconditioned dry state. This humidity-induced change in loss from the dry state is labeled "hloss" and shown in equation 7. For an experimental condition of placing the test boards into an environmental chamber, hloss will be zero at time zero for all frequencies as no absorption has taken place. At a particular frequency, hloss changes with time until it reaches equilibrium.

$$hloss = loss - dryloss \quad \text{(Equation 7)}$$

Figure 6, shows the difference in loss between dry and saturated states and the resulting hloss as a function of frequency. As seen in figure 6, impact of moisture increases is small for low frequencies below a few hundred megahertz. The impact of moisture is substantial for between 1GHz and 15GHz. Therefore, at the targeted IO bus speeds of current and projected designs, moisture concentration and moisture absorption will need to be considered.

The change in hloss over time was modeled using the solution to Fick's law in equation 3 and considering hloss to be analogous to concentration. Hence equilibrium concentration Co becomes equilibrium hloss and C(t) becomes hloss(t). The diffusivity constant "D" was renamed "D_l "as it was obtained from loss measurements rather than mass change used to develop Fick's law. The measured loss in a PCB transmission line is a function of the distributed electric field generated within the substrate and the dielectric properties of the substrate. Therefore, the overall transmission line loss will not reach equilibrium until the substrate between it and its reference plane furthest from the surface are saturated at the experimental conditions. As a result, the measured data was modeled using x=0 instead of the physical location of the transmission line being measured.

Thus, Equation 3 was used to fit hloss to Fick's law using the following transformation:
C = hloss which is a function of time "t"
D_l = diffusivity (mm^2/sec)
x = 0 (based on virtual center)
l = distance from the surface of the material to the reference plane below the trace. (mm)
t = time (seconds)
Co = equilibrium hloss of the trace.

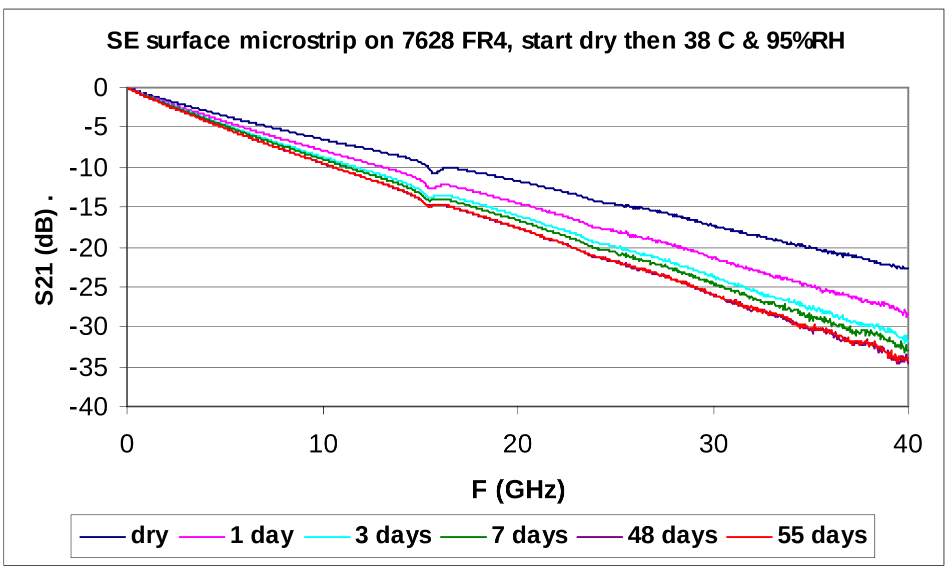

Figure 5 – S21 measurements of a sample trace

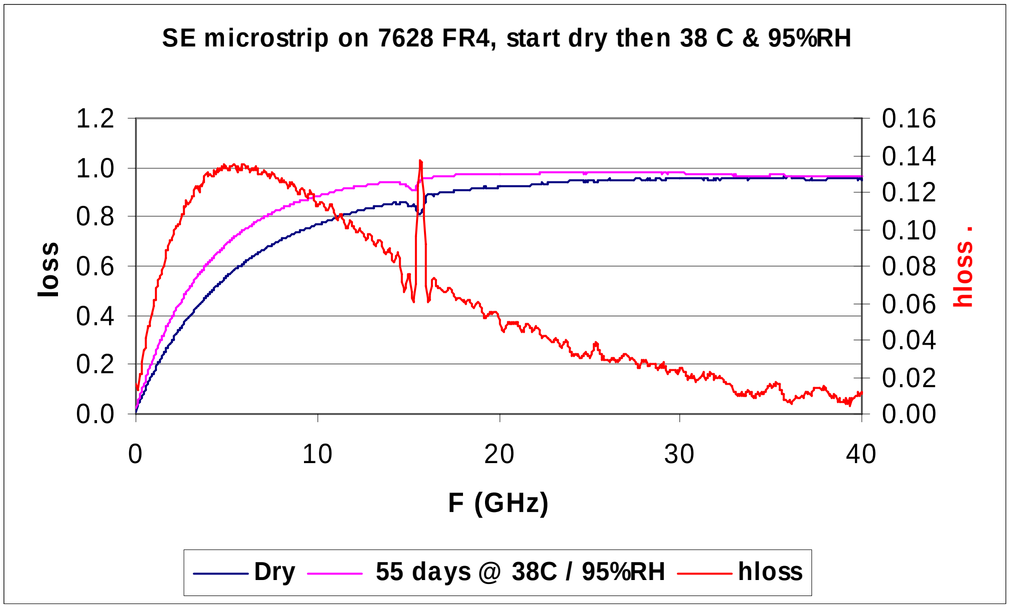

Figure 6 - Loss and hloss for dry and saturated microstrips over frequency.

The obtained value for D_l can be used to visualize and understand the effect of moisture on transmission line loss for different structures in the same material. Figure 7 shows a plot of the modeled normalized hloss for a microstrip as a function of time as the distance from the surface to the reference plane changes. This plot uses equation 3 and the diffusivity obtained for 2116 FR4.

As shown in figure 7, as the distance from surface to the reference plane becomes larger, the time required to reach equilibrium loss increases. As the distance becomes smaller, the time to reach equilibrium decreases as moisture has less distance to diffuse from the surface into the substrate. At t=0 there is no measurable change as the sample is at dry equilibrium. The modeled hloss in figure 7 predicts that the 2116 FR4 material would saturate in approximately 5-6 days for distances less than 0.5mm from the surface at 85C/85RH.

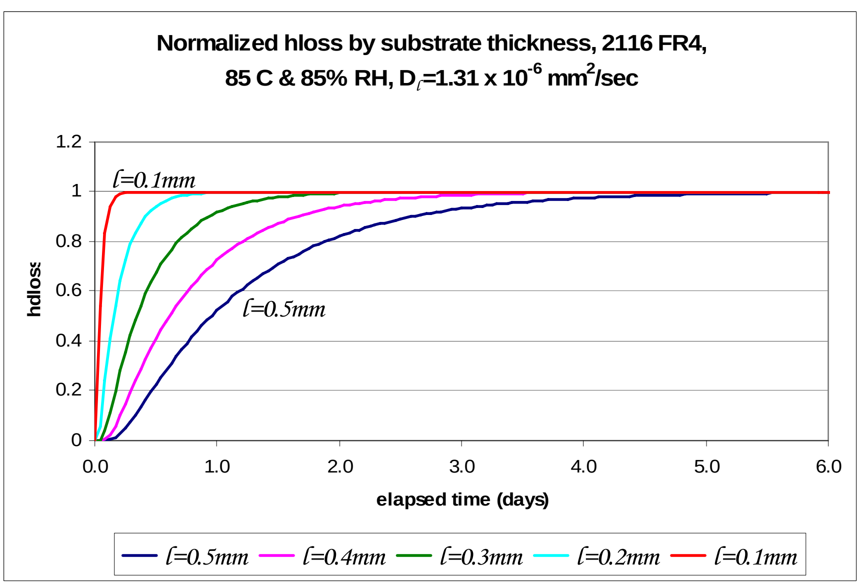

Figure 7: Normalized hloss for various values of distance from sample center.

Measuring Diffusivity

A set of test boards was designed to obtain the diffusivity constant D_l describing moisture dependent transmission line loss for 2116 FR4 at different constructions. By adjusting the layer placement of the transmission line and the reference plane, various depths within the board were obtained for testing. In this design, the distance from the top of a trace to the surface of the board was varied to obtain three unique structures with the distance between a trace and its corresponding reference plane held constant, see figure 8. By keeping the distance between the trace and reference plane constant, the electric field between the trace and plane was held fairly consistent between the three structures. The magnitude of the measured loss of each structure was expected to increase as the representative traces moved further from the surface. There were multiple traces of different lengths designed into each structure. The traces located within structure A are closest to the board surface and expected to respond quicker to changes in environmental conditions. The traces of structure C are farthest from the surface and thus expected to respond slowest to changes in environmental conditions. The ground planes were continuous with the exception of the antipads required for the connecting vias of the transmission line termination points, thus moisture diffusion was limited to one direction.

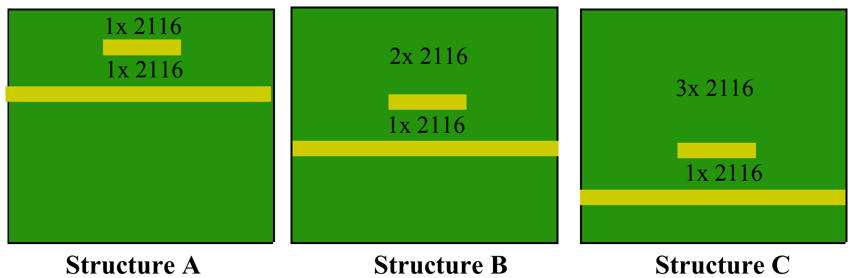

Figure 8 - Example test board design using 2116 construction

S-parameter measurements were made using a HP 8510C VNA. Calibration of the VNA was accomplished using a standard coaxial SOLT kit prior to each experimental run. Measurement of fixed attenuators during preliminary testing indicated that calibration drift was negligible for the planned test period. The test boards were connected to the VNA through a Kiethley RF Mux that allowed in-situ measurements at the desired environmental conditions. This allowed finer time resolution between measurements. The system also allowed the measurement of multiple structures within the same test board and measurements across multiple test boards without changing termination conditions and without removing test samples from an environmental chamber for measurement. As a result, it was possible to measure changes in transmission line loss during short environmental transitions such as changes in temperature.

The test boards were placed in an environmental chamber and connected to the measurement system. Prior to the boards being exposed to high humidity conditions, the boards were baked at 105 °C and RH <10% for approximately nine days. This was to ensure the boards contained no initial moisture. After the preconditioning bake, the environmental chamber conditions were ramped down over 8 hours to 15°C to measure the temperature impact on transmission line loss in the dry PCB. The environmental chamber was then set to 85C/85RH until saturation across all structures was obtained. The temperature in the environmental chamber was again then ramped down over 8 hours to 15°C which provided measurement of temperature impact on transmission line loss in a moisture saturated PCB.

During conditioning at 85C/85RH, transmission lines at the different depths reached equilibrium at different times. This can be seen in a plot of hloss for the three structures in figure 9. The magnitude of the hloss varied by structure and increased with the depth of the structure. The Fickian fit for each structure shown in figure 9 was obtained by using the structure geometries and selecting the loss diffusivity based on the best fit to the measured data. A normalized plot of hloss in figure 10 shows the difference in rise time between structure C and structure A. As predicted, structure A with trace closest to the surface responded quickest to a change in the environmental conditions and reached saturation before the other structures.

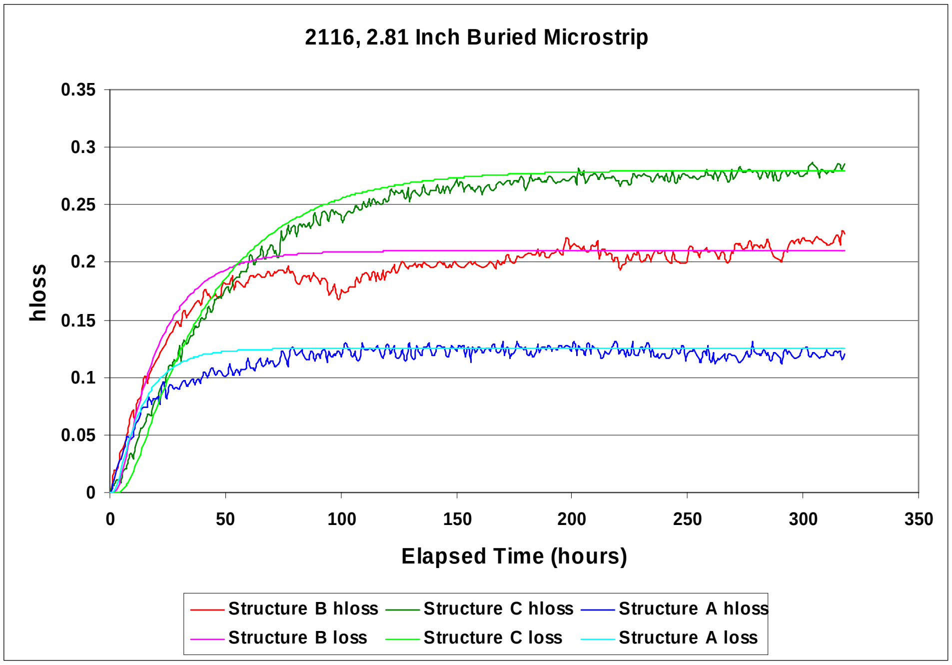

Figure 9 - Hloss for 2116 FR4

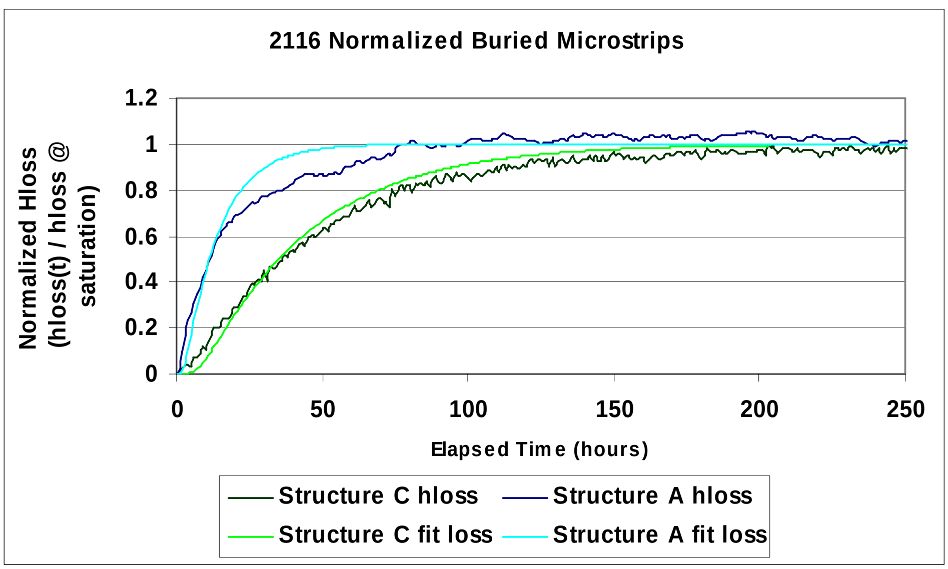

Figure 10 - Normalized hloss for 2116 FR4

Since loss diffusivity, D_l, was derived from trace loss measurements, the variability of the method across different frequencies, trace-to-trace within the same structure, and between structures was examined. Figure 11 shows the results of measuring 6 individual microstrip traces on 7628 FR4 at three frequencies. This data reflects a change from 20 degrees C and dry to 38 degrees C and 95% RH. The D_l derived from loss measurements was consistent between different traces and across selected frequencies. Figure 12 shows the variance in derived D_l for 2116 FR4 using different line lengths and structures. No significant length or structure dependencies were observed. As a result, loss diffusivity was calculated for each tested material that adequately described the loss behavior over time and between different structures. For the 2116 FR4 material, the typical diffusivity was calculated to be 1.31 $X10^{-6}$ mm^2/sec at 85C/85RH. Using a weight based method, Fremont et al obtained moisture diffusivity values for an unspecified FR4 at 85C/85RH of 1.51 $X10^{-6}$ mm^2/sec [4]. This initial comparison shows close agreement between loss diffusivity derived from fitting hloss to Fick's law and moisture diffusivity.

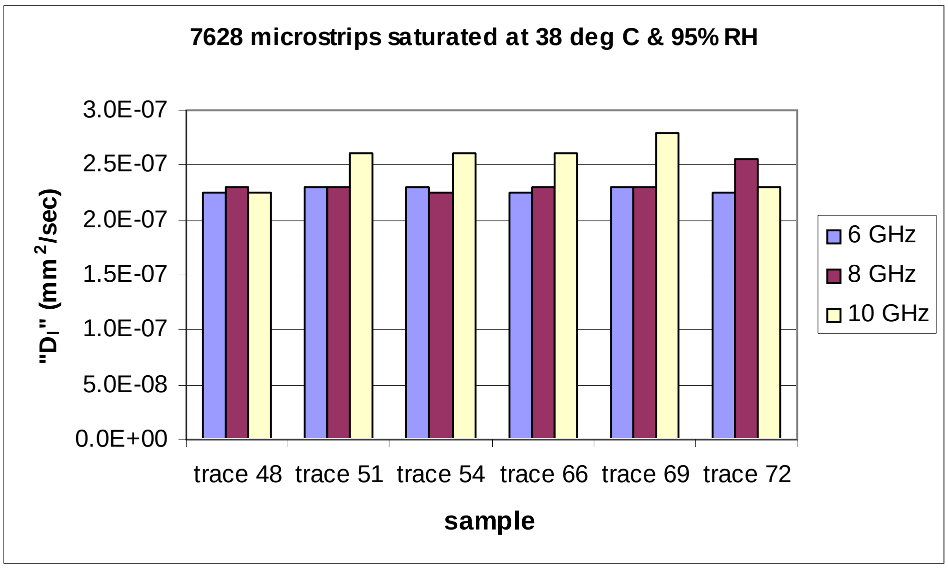

Figure 11 - D_l for 7628 FR4

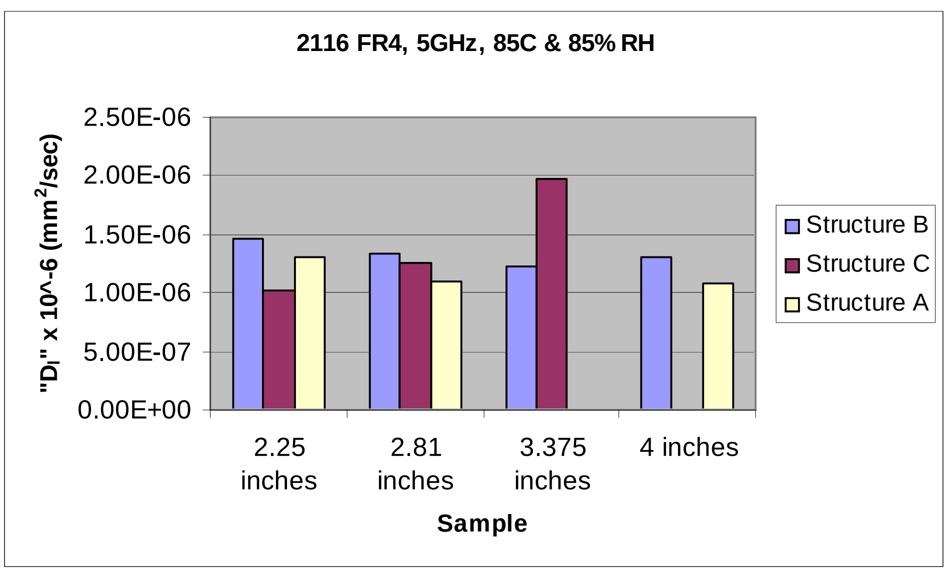

Figure 12 - D_l for 2116 starting cool and dry

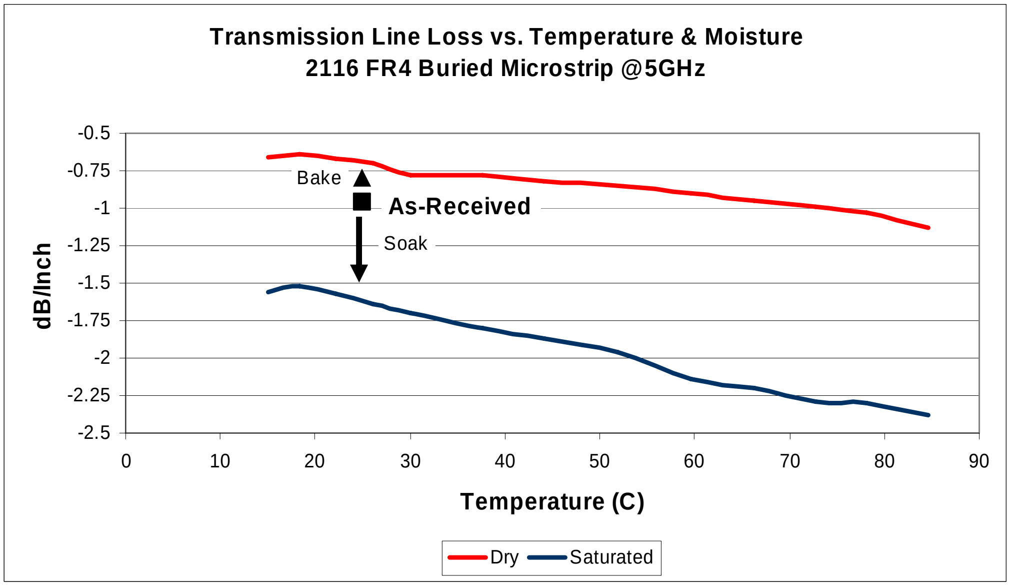

Figure 13 - Temperature Impact on Loss at Dry and Saturated conditions

The loss diffusivity measured for 7628 FR4 and 2116 FR4, shown in Figure 11 and Figure 12 respectively, can not be directly compared as each was derived from different environmental conditions. Diffusivity is a function of temperature and relative humidity. At lower temperatures and lower relative humidity the moisture diffusion through the PCB substrate is slower. This was observed in the diffusivities calculated for 2116 FR4 at 85C/85RH of 1.3×10^{-6} mm^2/sec and the diffusivity calculated for 7628 FR4 at 38C/95RH at 2.3×10^{-7} mm^2/sec. It is noted, that even at same environmental conditions, 2116 FR4 and 7628 FR4 would have slightly different diffusivities due to differences in glass fabric construction.

The transmission line loss is a function of temperature and humidity and must be considered during system design and validation. As noted, the temperature was ramped prior to any change in relative humidity. This provided a measurement of the transmission line loss as a function of temperature at the dry and saturated states as shown in figure 13. For comparison, the measured loss for the 2116 FR4 as received was 0.95dB/inch at 25°C. At 25°C, drying improved the transmission line loss by ~0.3dB/inch and moisture increased the loss by 0.65dB/inch when fully saturated. Temperature had a significant affect on loss across the range 15°C to 85°C. And when saturated with moisture, the impact of changing temperature was more pronounced. When dry, the loss changed 0.5dB/inch between 15°C and 85°C. When saturated, the loss changed by 0.85dB/inch between 15°C and 85°C. In relatively small temperature ranges, the critical loss factor was moisture.

Conclusions:

It has been shown that moisture has a significant impact on the transmission line loss characteristics within a PCB substrate. It has also been shown that temperature affects transmission line loss and influences the significance of humidity dependent loss. As a result, expected environmental conditions need to be considered during system design and validation. PCB substrates respond to changes in temperature faster than changes in relative humidity. Microstrip transmission lines are more sensitive than striplines as they respond quickly to changes in the relative humidity of the environment and reach saturation within a few days. Striplines change more slowly, with moisture saturation taking weeks and sometimes months. As a result, striplines may not be susceptible to seasonal changes; but, variations would exist between two locations due to the average environmental condition.

It has been demonstrated that Fick's law of diffusion can be used to model the humidity dependent losses of a PCB trace. The method provided can be used to determine the loss diffusivity of a desired PCB substrate. The loss diffusivity allows the designer to model the rate of change in transmission line loss due to humidity and thus predict the electrical performance risk across different environmental conditions. The loss diffusivity also appears to be close to moisture diffusivity; but, additional experimental work is required to confirm. It is also shown that the humidity dependent loss does vary with frequency.

Due to the magnitude of humidity dependent loss, end user environmental conditions will must be taken into account as they affect board performance. The impact of moisture on the transmission line loss has been confirmed with both direct VNA measurements and split post dielectric resonators (SPDR) on unclad dielectrics. The SPDR measurements confirm that moisture absorption increases the dielectric dissipation factor (tan□) of a PCB substrate. This change in tan□ as a function of moisture can be included during electrical simulations to determine the design risk across environmental use conditions.

In addition, the dielectric constant of the material has also been shown to change with moisture absorption and should be included when modeling moisture impacts during system design and validation. The magnitude of humidity dependent loss in PCB substrates is affected by material selection. It has been shown that a low moisture absorbing material such as Rogers 4350 ™ is not as susceptible to moisture dependent losses as compared to FR4.

The work presented in this paper allows the likelihood of humidity dependent loss in transmission lines under various environmental use conditions to be evaluated. During system design and validation the loss diffusivity and Fick's law can be used to predict the rate at which hloss increases. The impact of humidity dependent loss on electrical performance can be modeled by adjusting the values of dissipation factor (tan□) and dielectric constant of the PCB substrate used with transmission line simulation tools.

Acknowledgements: Discussions with and ideas from our Intel associates have materially contributed to this work. These teammates include Dennis Miller, Stephen H Hall and Bryce Horine. Mark Beaudoin has spent many patient and careful hours executing experiment #1. The authors are obliged for their help.

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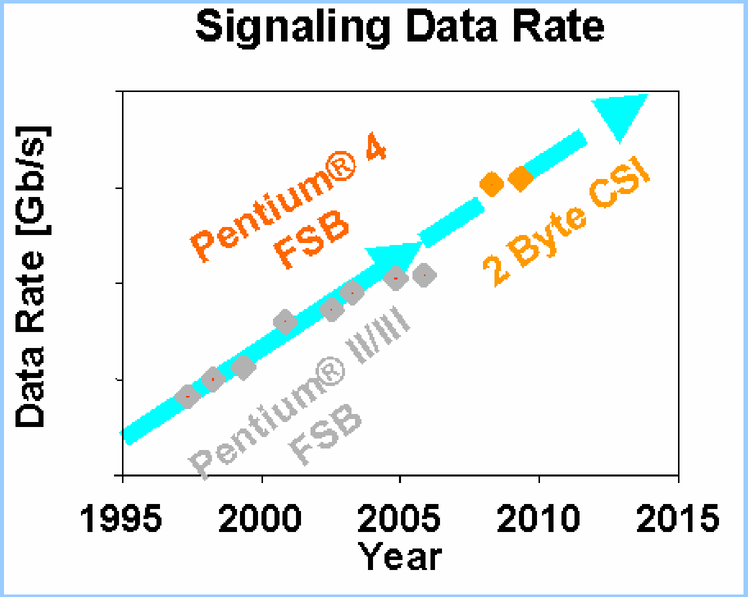
Agenda

- Overview: frequency, material and humidity-dependent loss
- The experiments
- PCB t-line loss data
- Fick’s Law model
- Conclusions

Overview

- Bus speeds are increasing
  - PCB transmission line loss is frequency and humidity dependent
  - Soon OEMs will specify PCB trace loss for some boards as they specify impedance now
  - Uncontrolled increases in loss can cause bus slowdown or failure



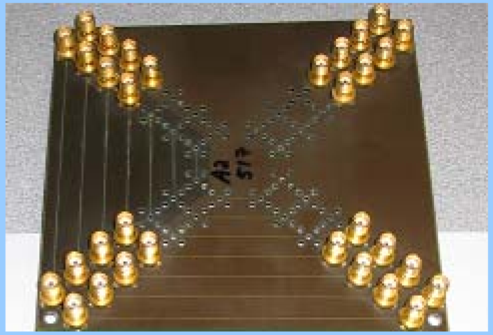
- Substrate materials do not have same loss
  - Differing FR4 stackups have different resin concentrations
  - Different dielectrics (low-loss, FR4, other polymers) have differing loss
- Other issues
  - Moisture absorption is a factor in reliability of PCBs
  - Manufacturers cannot control the humidity of the air that cools their products

Conditioning and measurement

Test boards

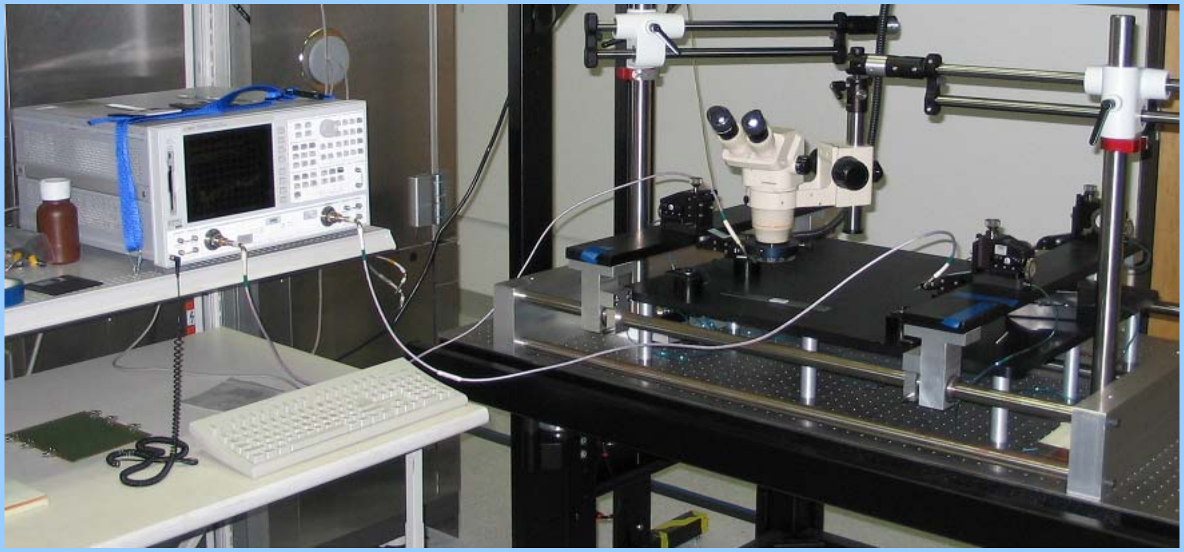
Surface µ-strips
w/ solder mask

Environmental chamber

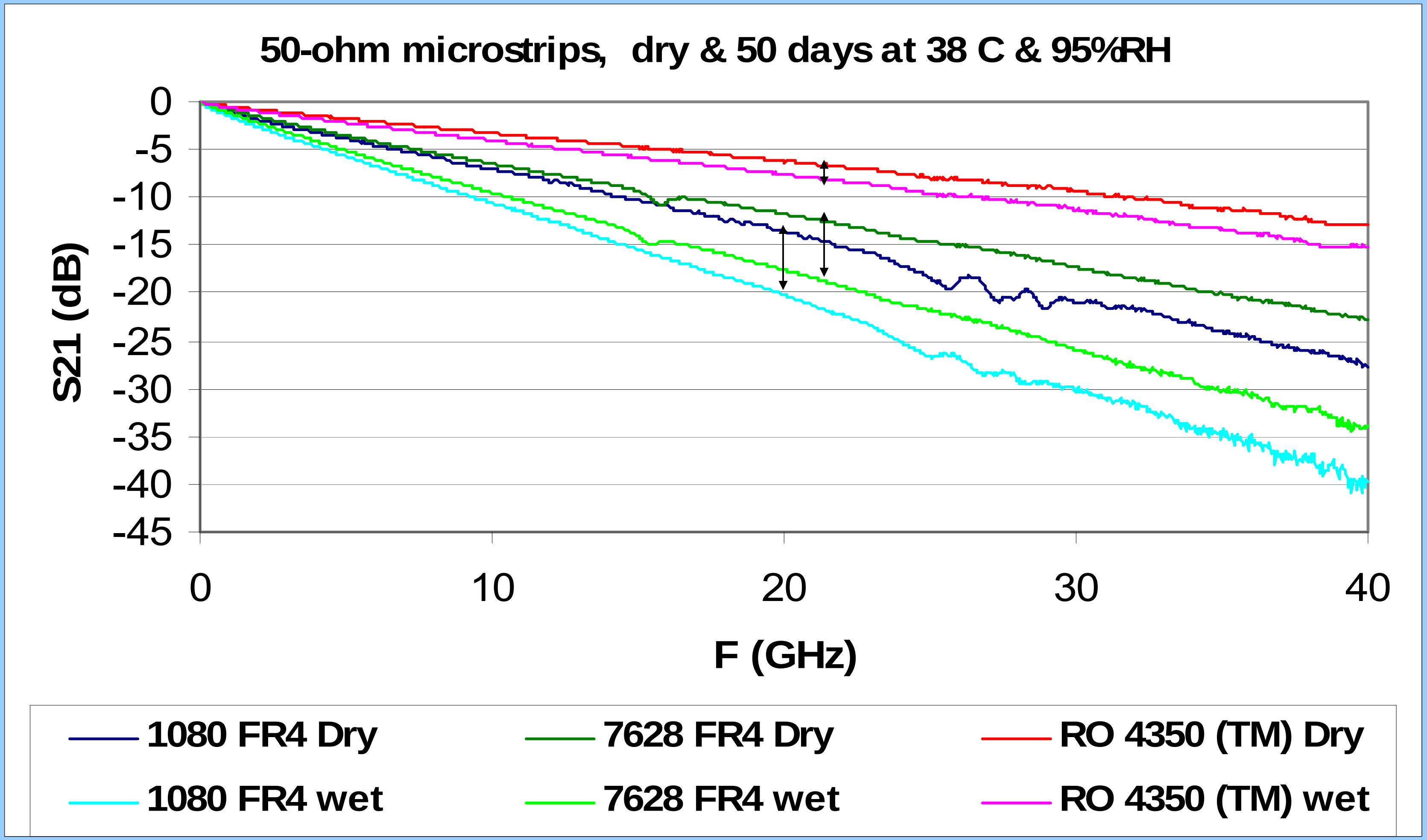


Embedded µ-strips
No solder mask

8722ES S-parameter analyzer & micro-probing



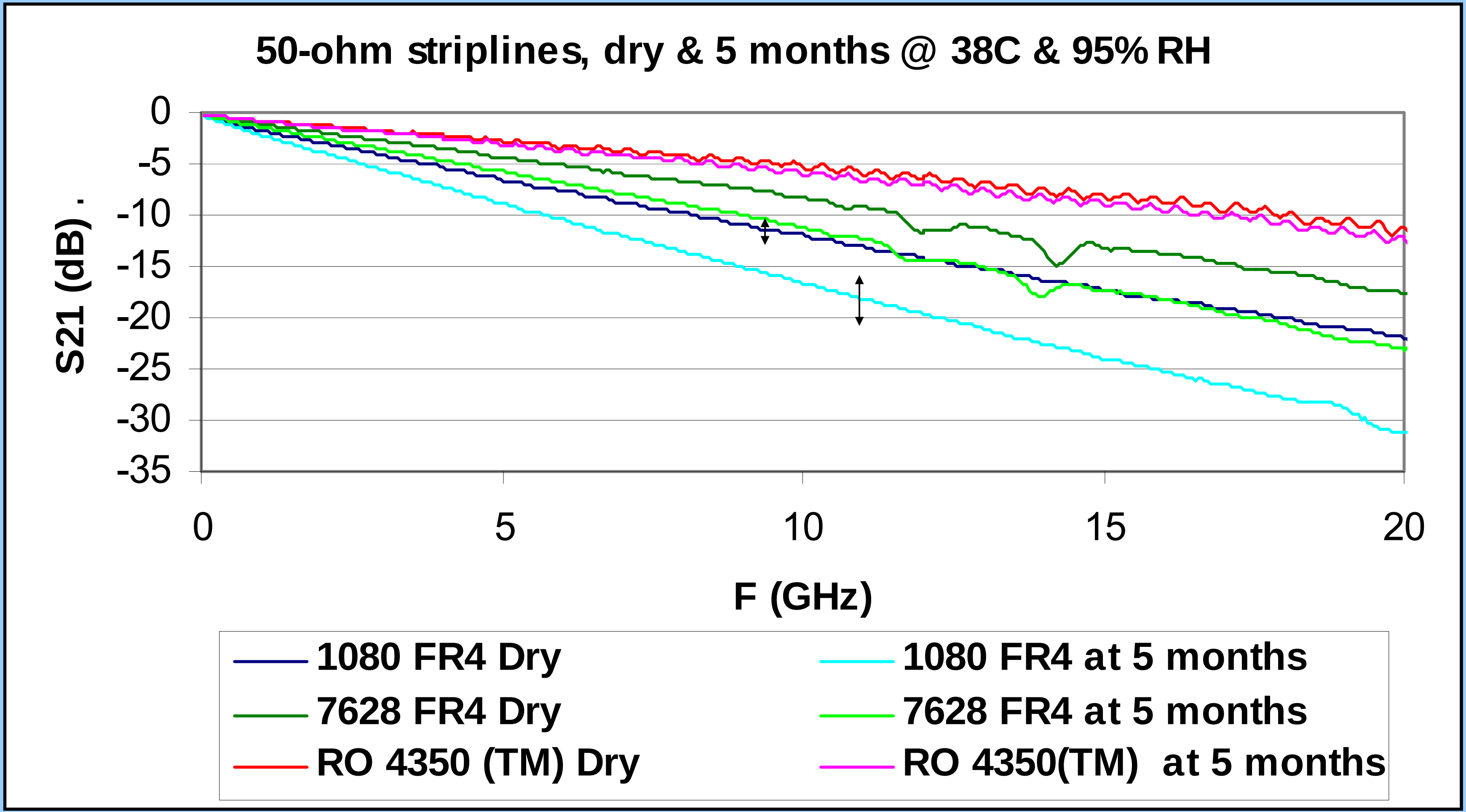
15-cm microstrips



substrate	Δ S21 (dB) @ 10 GHz	% change in S21 (linear)
1080 FR4	3.64	34.2
7628 FR4	3.07	29.8
RO 4350 ™	0.77	8.5

Key Message
Loss depends on:
- Frequency
- Humidity
- Material

15-cm striplines



substrate	Δ S21 (dB) @ 10 GHz	% change in S21 (linear)
1080 FR4	4.76	42.2
7628 FR4	3.0	29.1
RO 4350 ™	0.82	9.0

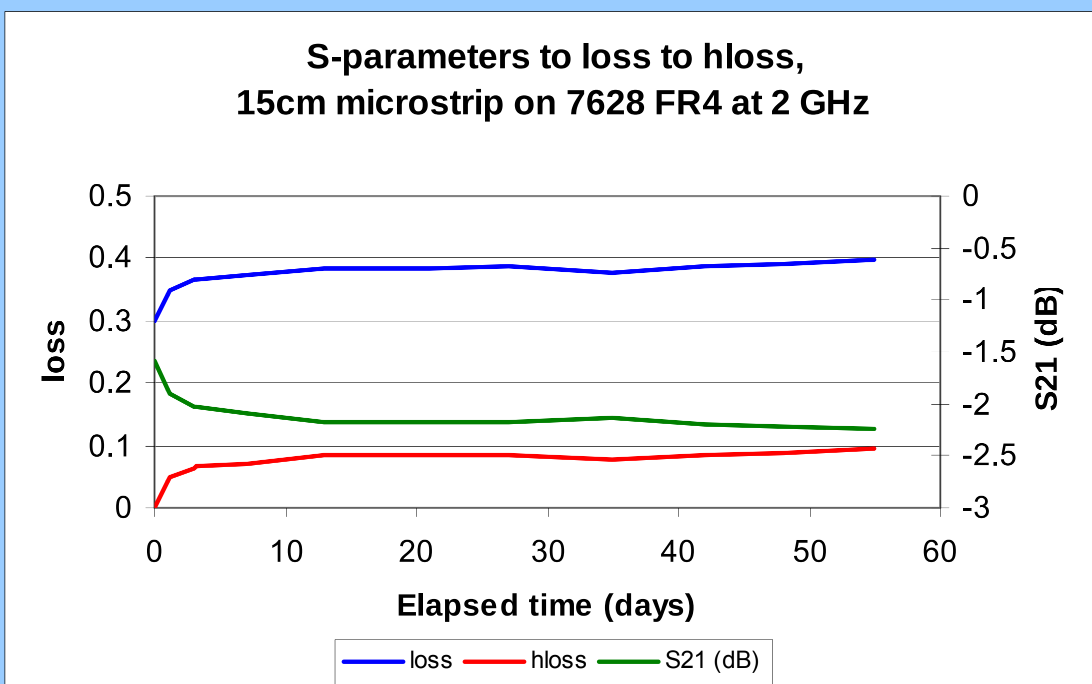
Key Message:
Striplines are not immune to humidity-dependent increases in loss

Converting S-parameters obtained using VNA to "hloss"

S-parameter primer

Assume port 2 is perfectly matched (i.e..: no reflections)

$$S11 = \frac{reflected}{incident} = \frac{b1}{a1} \qquad S21 = \frac{transmitted}{incident} = \frac{b2}{a1}$$



$$S21, linear = 10^{(S21,dB/20)}$$

$$S21^2 + S11^2 = 1$$

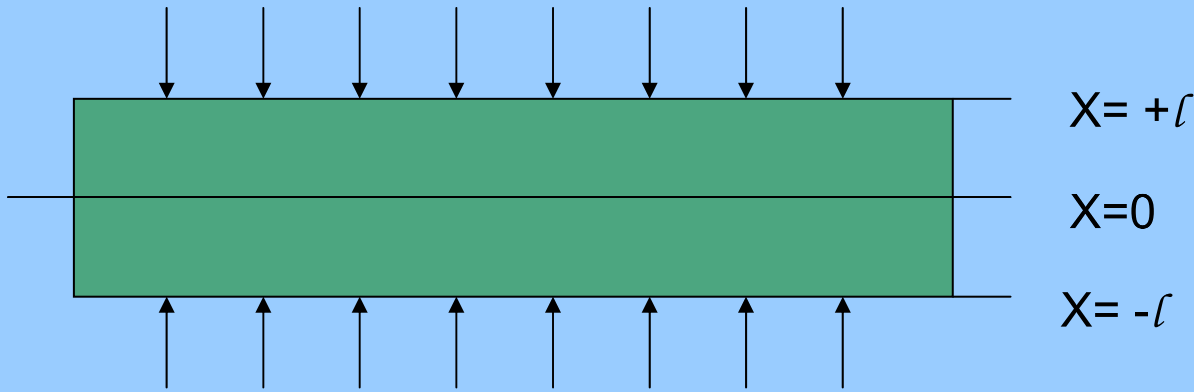
$$loss = 1 - S21^2 - S11^2$$

$$hloss = loss - dryloss$$

Fick's Law applied to dry PCBs placed in humid environment

Fick's Law of Diffusion

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2}$$



Moisture diffusion

Most general solution

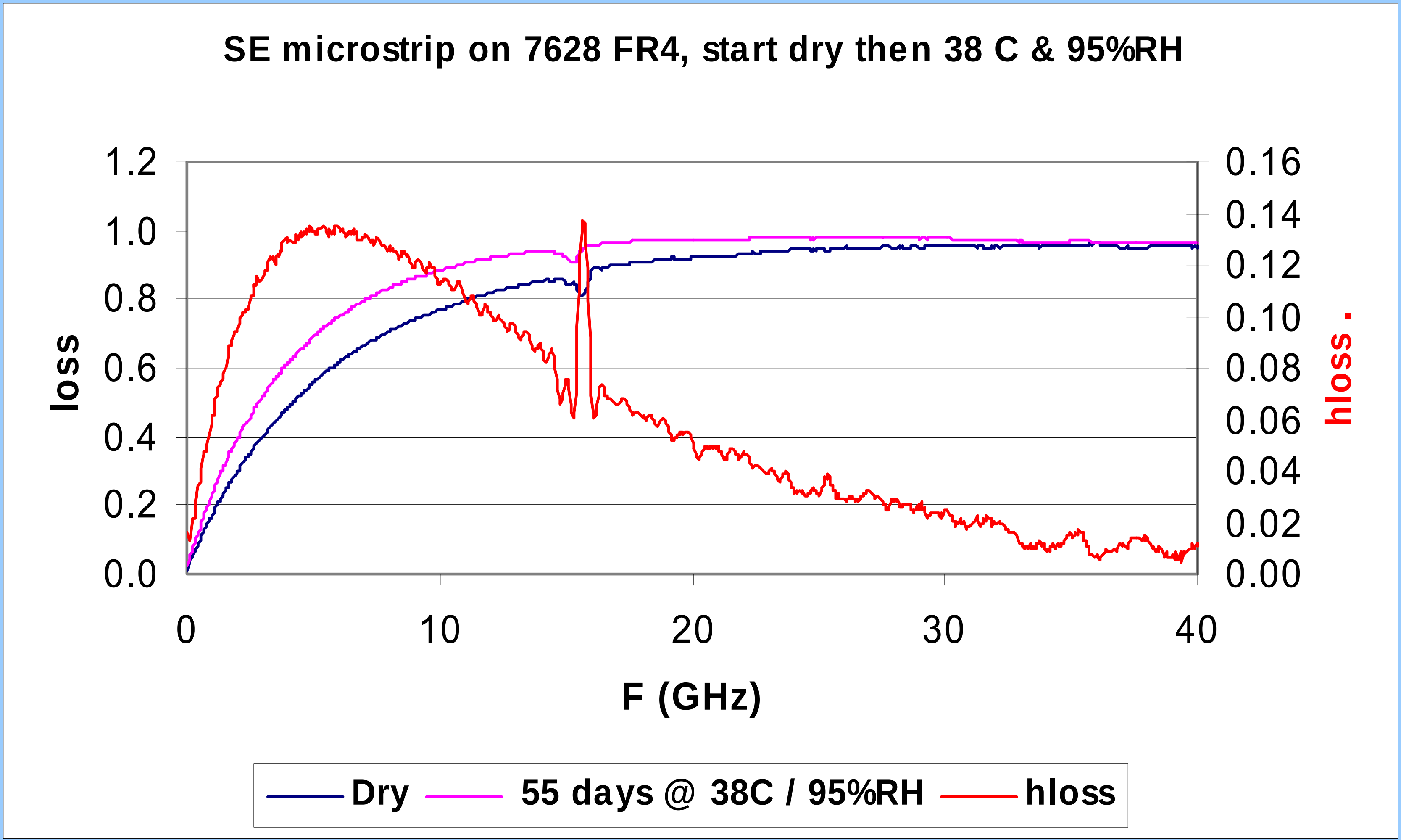
$$C = \sum_{m=1}^{\infty} (A_m \sin \lambda_m x + B_m \cos \lambda_m x) \exp(-\lambda_m^2 Dt)$$

Specific solution for our initial and boundary conditions

$$C = Co - \frac{4Co}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos \frac{(2n+1)\pi x}{2l} \exp(-D(2n+1)^2 \pi^2 t / 4l^2)$$

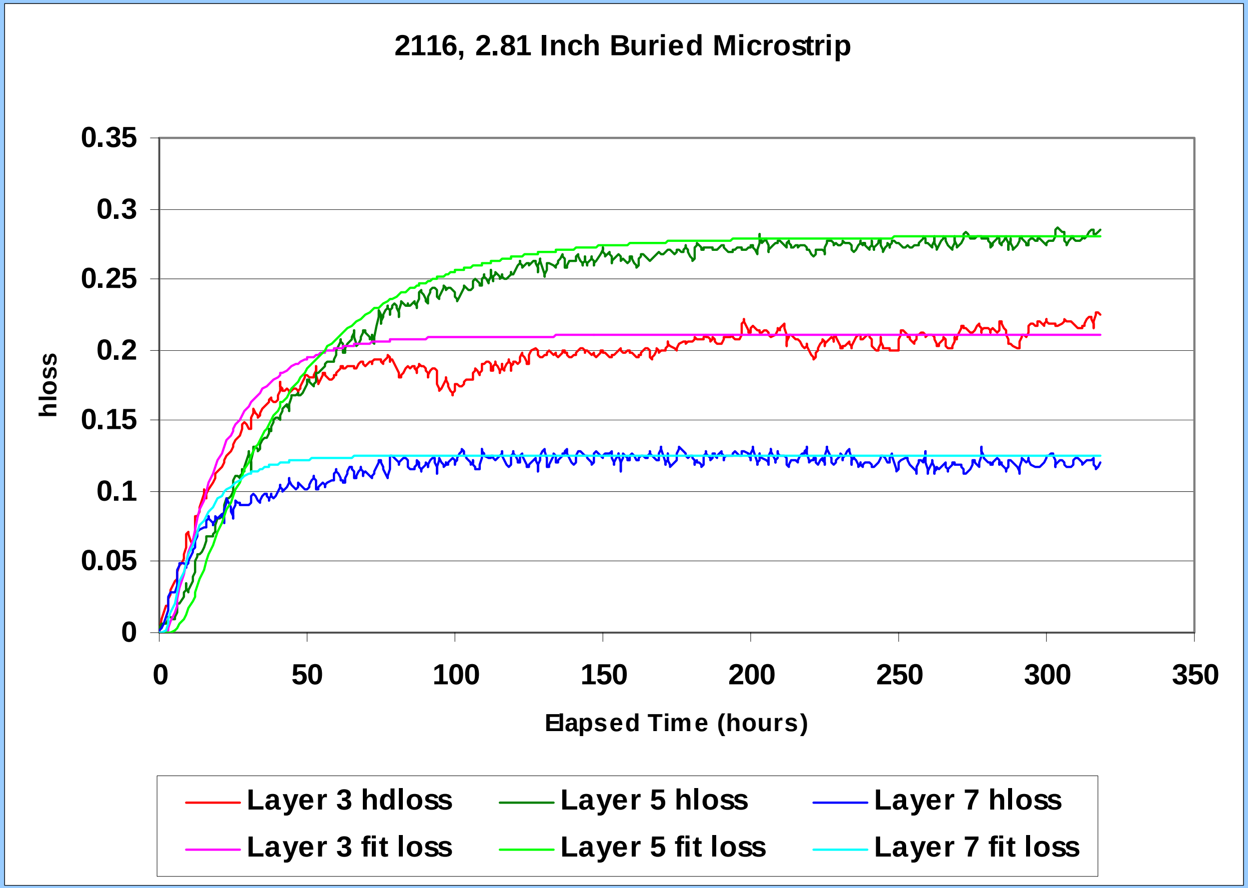
Source: "The Mathematics of Diffusion", J. Crank, Oxford Press

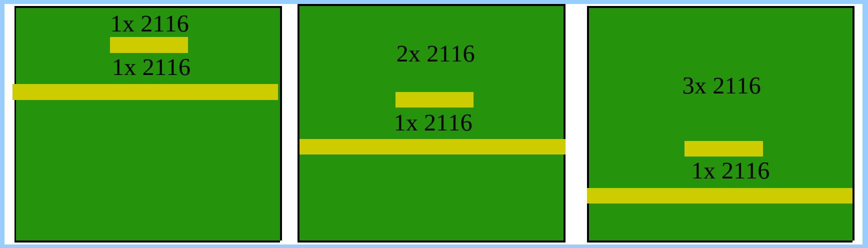
Humidity-induced loss is not constant with frequency



Key Message: maximum impact of humidity-induced loss
Is around 5 GHz (10GT/s), this is on very near design horizon.

Three microstrip configurations



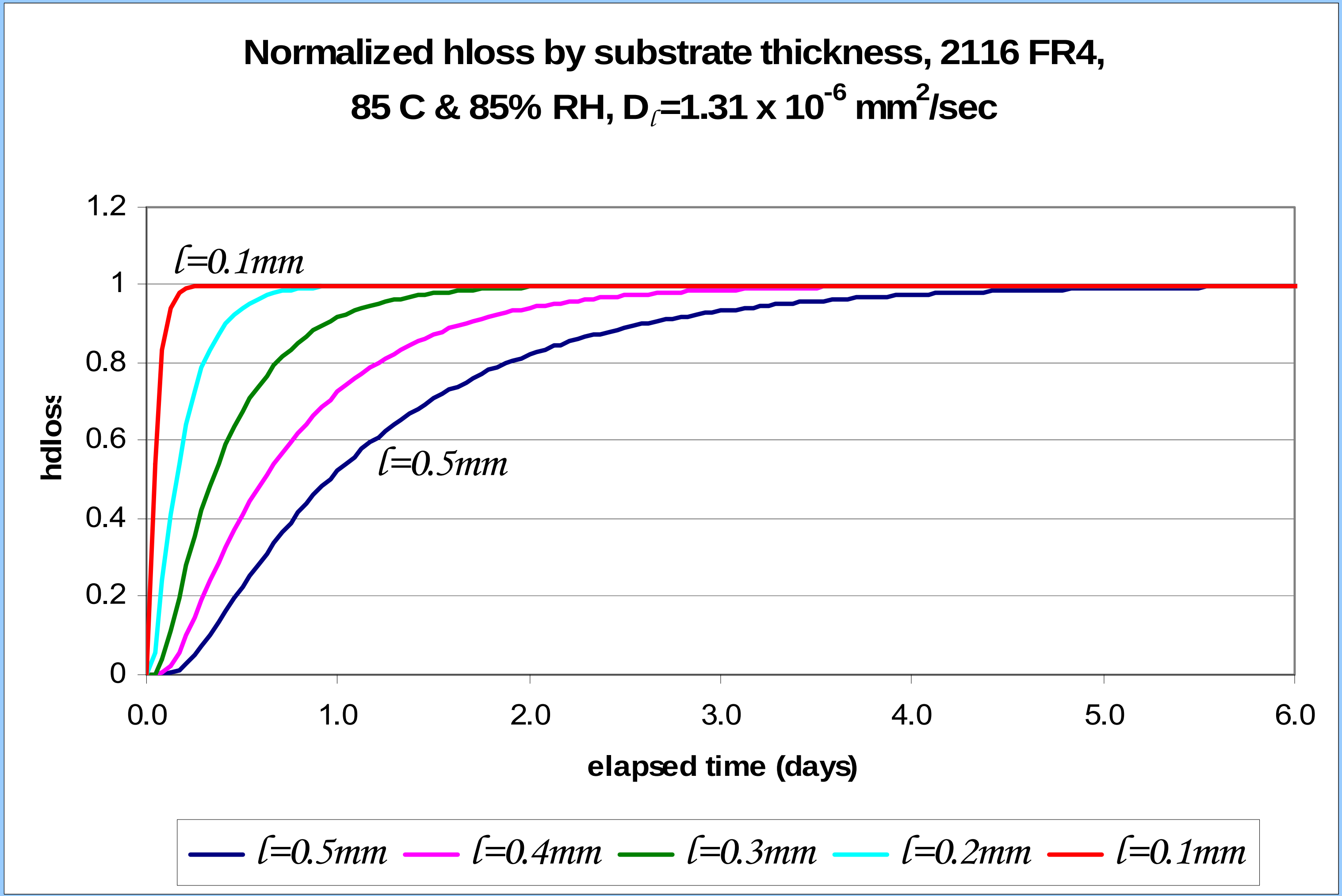


A B C

Key Messages:

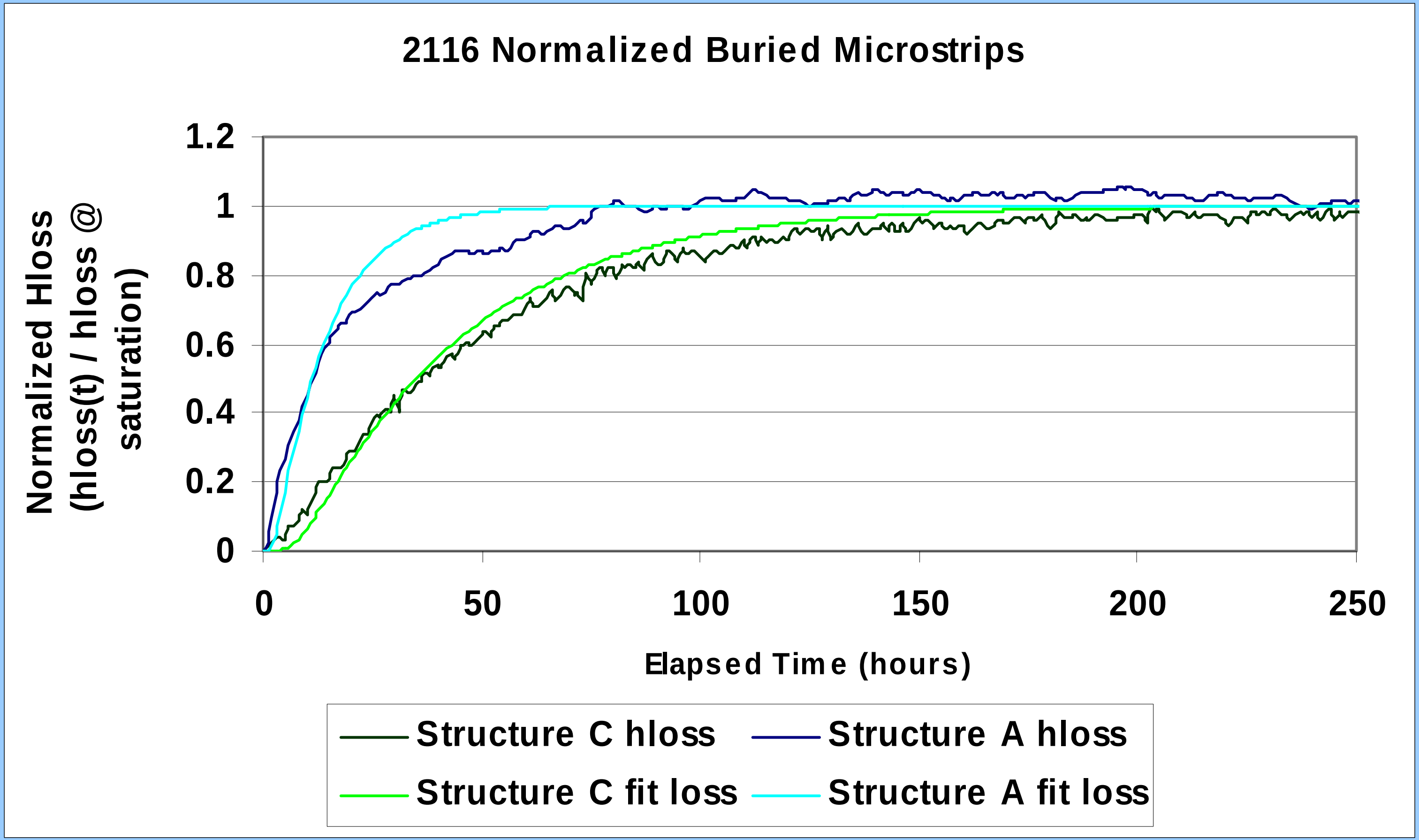
- hloss fits well to Fick's Law
- thickness influences equilibrium loss
- Slope of curve in linear region determines diffusivity

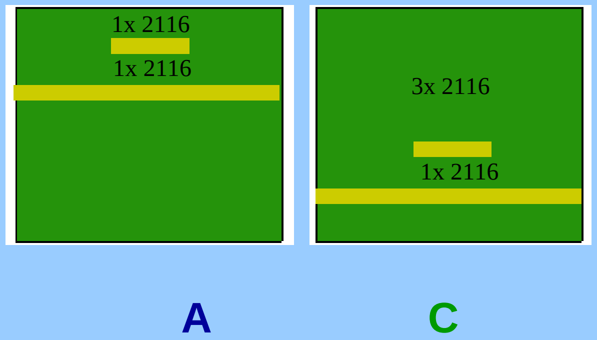
Humidity effect is faster for thin materials: model predictions



$$C = Co - \frac{4Co}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\frac{(2n+1)\pi x}{2l}\exp(-D(2n+1)^2\pi^2 t/4l^2)$$

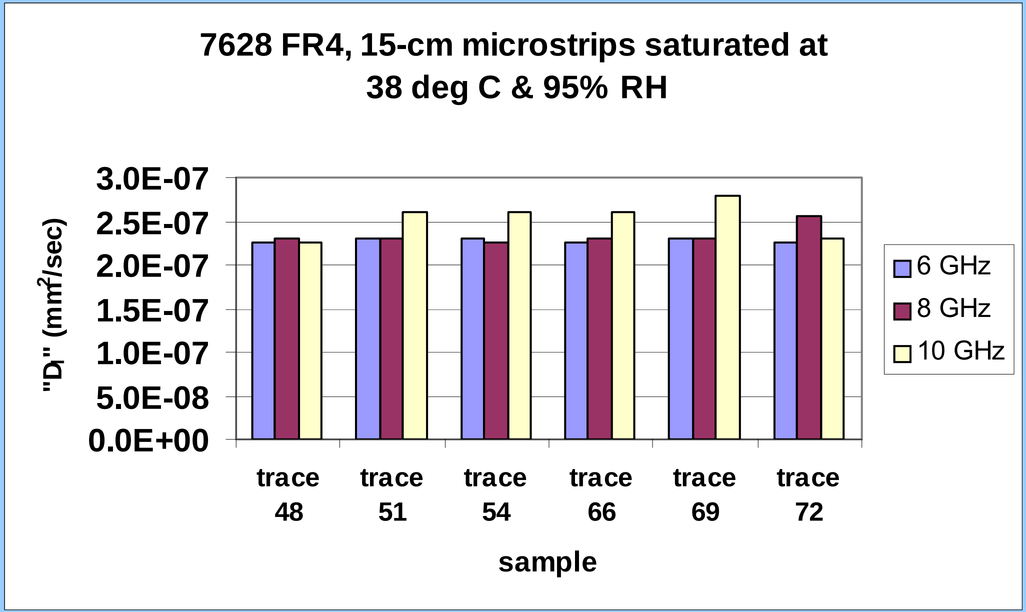
Humidity effect is faster for thin materials: measurements





Key Message: Measurement trends match modeling

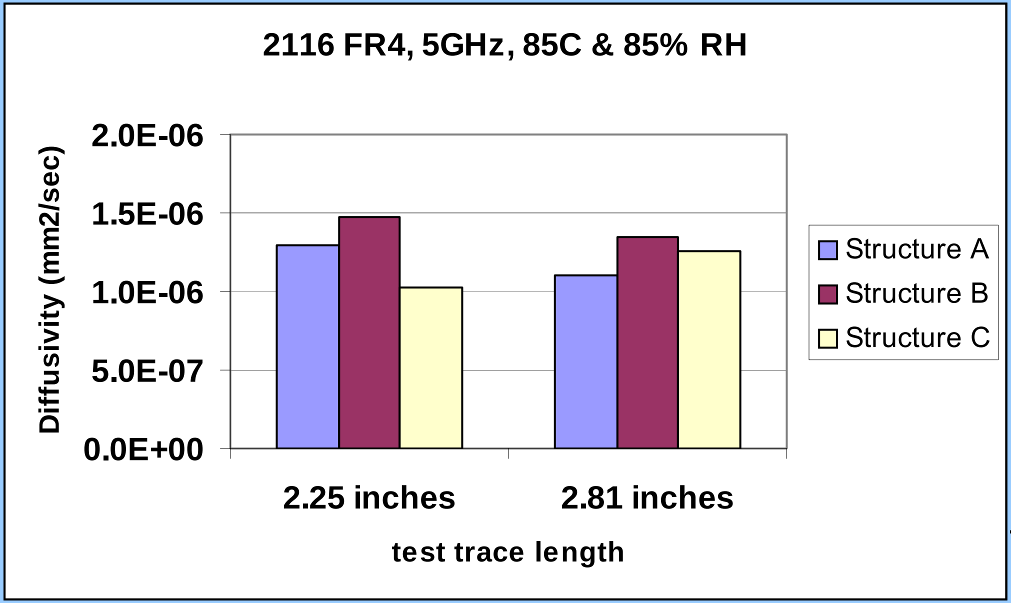
Diffusivity is condition and material dependent



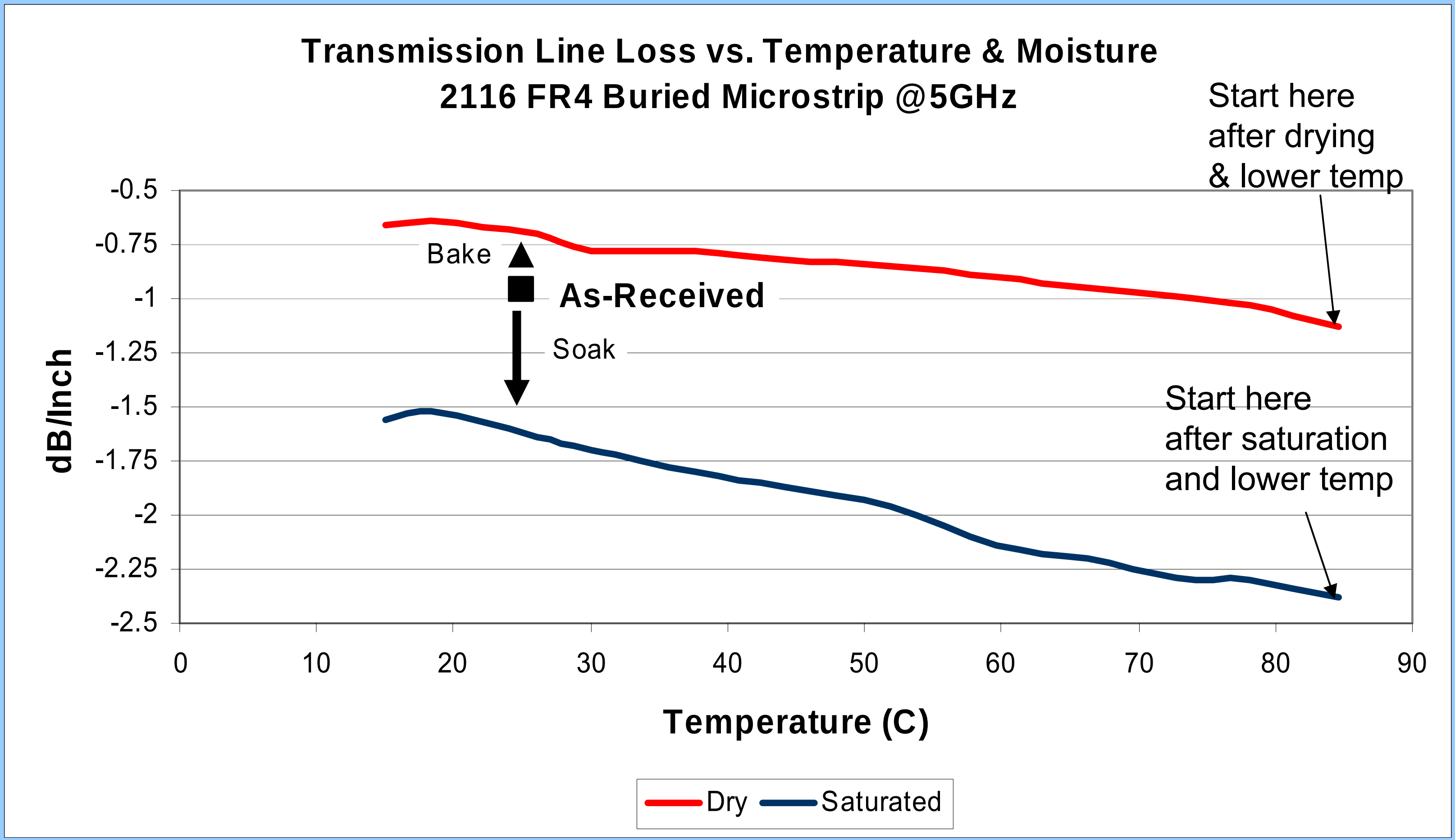
While these FR4 types differ, material differences are insufficient to account for differences in diffusivities obtained at 85C & 85%RH compared to 38C & 95%RH.

Embedded μ-strips w/o s.m. @ 85 C & 85% RH

Surface microstrips w/ s.m. at 38 C & 95% RH



Temperature influence



Conclusions

- Loss matters
  - The need to predict, control and measure PCB loss at board fabricators is on the near horizon.
  - Loss is the next new PCB acceptance criteria
  - IPC D24b committee working on loss measurement using TDR
- Loss is influenced primarily by
  - Substrate material & solder mask
  - Humidity
  - Frequency
  - Temperature
- Further questions:

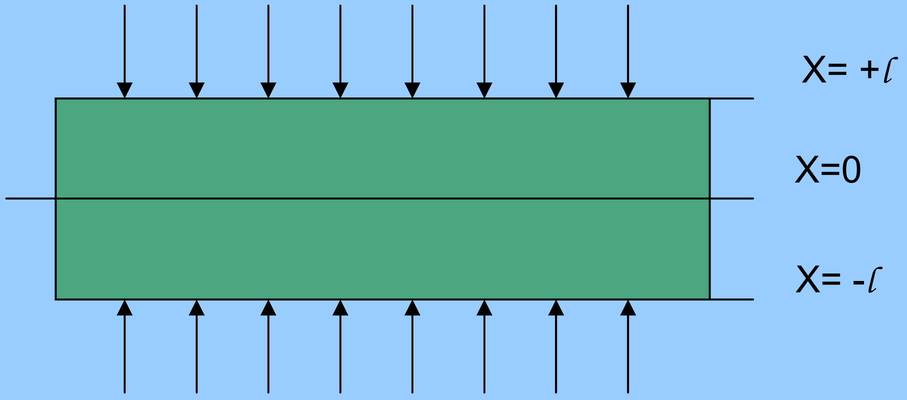
  - paul.c.hamilton@intel.com 503-696-9532
  - gary.a.brist@intel.com 503-696-7426

Backups

“Virtual Center” concept

- Fick’s Law is a gradient-driven expression for concentration (concentration changes with distance from surface)
- There is no gradient across the center of a symmetrical plane immersed in homogeneous medium.
- We can place an impermeable foil at the center of a lamination of two planes without disturbing the diffusion from both exposed surfaces of the plane.
- So we can make our model of even an asymmetric PCB symmetric by twinning the side we are interested in, flipping it and joining the two, creating a mirror image.

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}$$

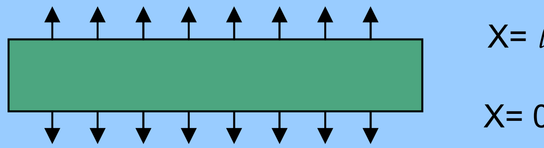


Moisture diffusion

Boundary & initial conditions determine form of final solution obtained from general solution

General solution $$C = \sum_{m=1}^{\infty} (A_m \sin \lambda_m x + B_m \cos \lambda_m x) \exp(-\lambda_m^2 Dt)$$

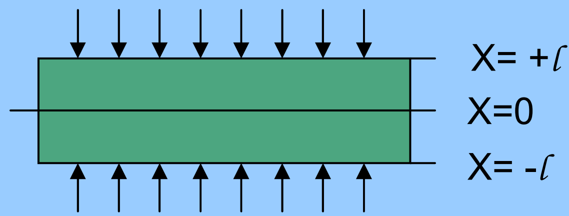
$$C = \frac{4Co}{\pi} \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin \frac{(2n+1)\pi x}{l} \exp(-D(2n+1)^2 \pi^2 t^2 / l^2)$$



Moisture diffusion

Material starts at uniform (non-zero) starting concentration C_0 in solute
Surrounding medium @ C=0

Material starts at zero concentration in solute
& Co in surrounding medium



$$C = Co - \frac{4Co}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos \frac{(2n+1)\pi x}{2l} \exp(-D(2n+1)^2 \pi^2 t / 4l^2)$$

Moisture diffusion

Variable substitutions

- C = Conc. of diffusing substance = f(x,t) — hloss =f(x,t)
- D = Diffusivity (mm2/sec) — D_{ℓ}
- x = distance of C from center — 0 (virtual center)
- ℓ = half the thickness of the material — ref. plane to surface
- t= time (seconds) — no change
- Co = conc. of diffusing substance at surface — equilibrium hloss

$$C = Co - \frac{4Co}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos \frac{(2n+1)\pi x}{2l} \exp(-D(2n+1)^2 \pi^2 t / 4l^2)$$

Fick's Law fit process

- Assume a diffusivity
- Using the equilibrium value of Co and MatLab ® calculate a Fick's Law curve using:

$$C = Co - \frac{4Co}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\frac{(2n+1)\pi x}{2l}\exp(-D(2n+1)^2\pi^2 t/4l^2)$$

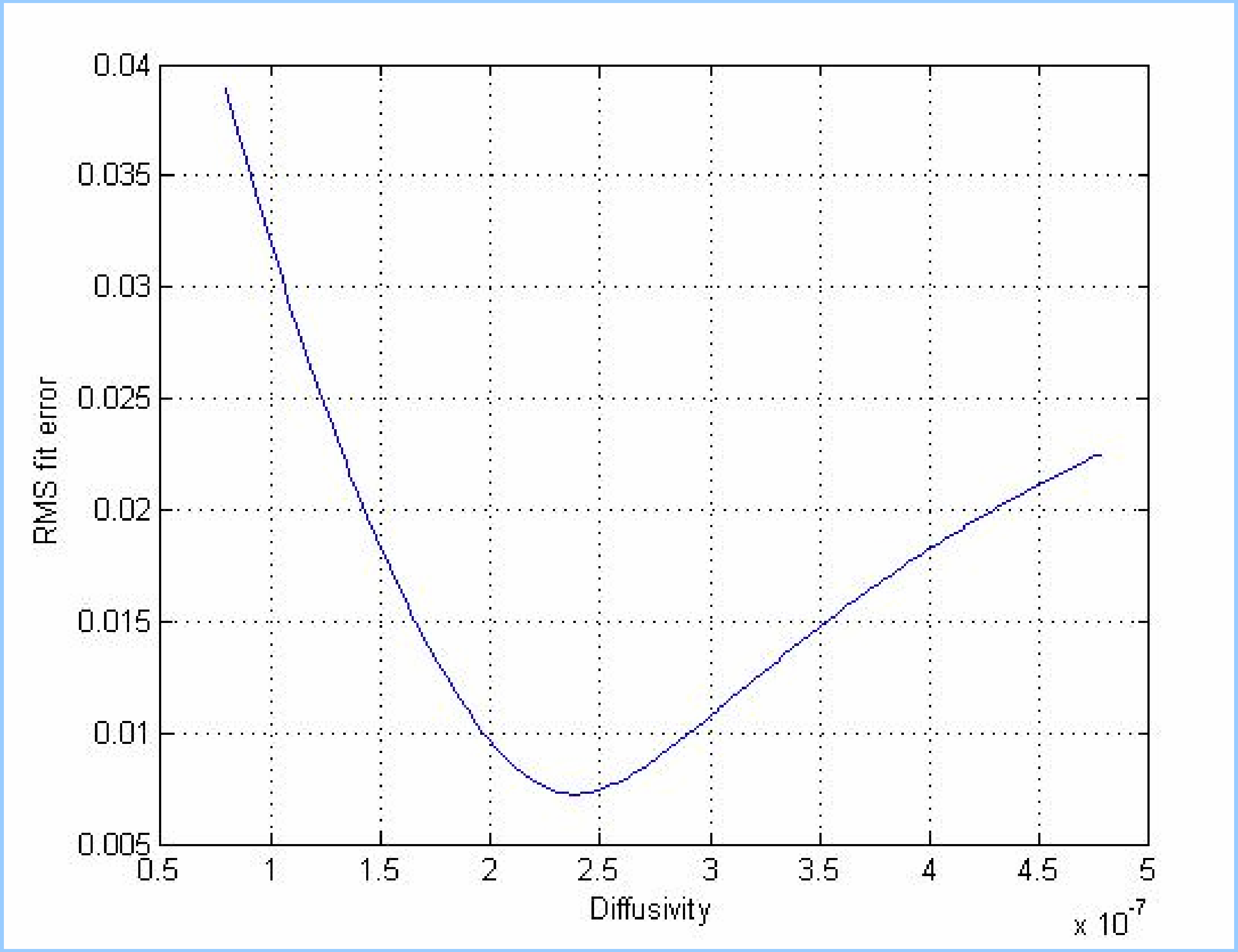
- Calculate the RMS error as:

$$RMS\_error = \sqrt{\frac{\sum_{i=0}^{n}(measured - calculated)_i^2}{n}}$$

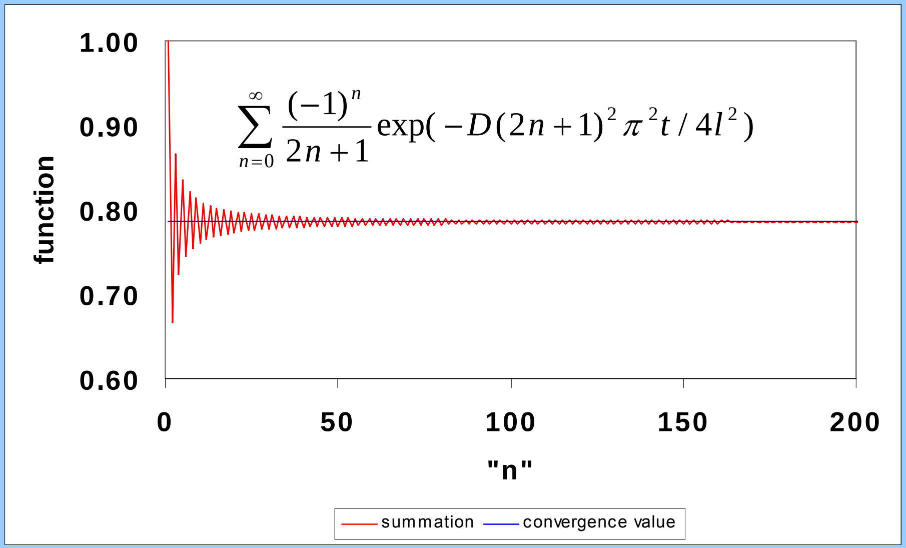
between the measured data and the Fick's Law fit for data points between t=0 and t=1 time constant

- Increase diffusivity by a small step & iterate until RMS error reaches a minimum.
- Use the diffusivity value that minimizes the RMS error between the Fick's Law fit and the measured data from t=0 and t=1 time constant

Iterative curve-fit solution of Fick's Law



End-point analysis on Fick's Law solution



$$C = Co - \frac{4Co}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \boxed{\cos\frac{(2n+1)\pi x}{2l}} \exp(-D(2n+1)^2 \pi^2 t / 4l^2)$$

$$C = Co - \frac{4Co}{\pi} \boxed{\sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp(-D(2n+1)^2 \pi^2 t / 4l^2)}$$

“Ambient Conditions” are not humidity controlled , office space in Oregon