Performance:
Electrical performance and characteristics

What is Electrical Performance?

• Get signal from point A to point B so that the device works

  – Speed is critical:
    Device calculates A+B, but if it takes too long, it doesn’t work!

Hereafter, performance = electrical
REFERENCE TEXTBOOKS


What’s covered in this lecture:

• Models that describe performance in a package
• Measurements that quantify performance
• Reasonable improvements made by changing the electrical package
• A specific example of electrical performance in an EI product
What’s not covered in this lecture:

• Details of underlying Physics that define performance
• Derivations of formulas
• How to use lab equipment

CUSTOMIZED DEFINITIONS:

• Ideal signal path:
  – connect A & B with wire
  – all signal energy gets to B instantly
  – no unwanted energy gets to B
• Non-ideal = anything that's not ideal
  – non-ideal is not necessarily an error nor is it necessarily changeable
Reality of Physics (and Life)

Nothing is ideal!

Many things prevent the signal path from being ideal

Let’s call them electrical non-idealities

Electrical non-idealities:

• conductive loss: energy dissipated in the copper
• dielectric loss: energy dissipated in the dielectric material
• reflections: energy reflected away from point B
• delay: how long it takes for energy to travel from A to B
• interference: energy that’s not the signal but gets to B
• radiation: energy transmitted into the outside world
Reality of Business

There are other requirements besides performance that influence packaging:

- Cost
- How hot does the device get?
- Many other things

I'm not going to talk any more about these, but the point is that there are other factors.

• At DC, copper wire is nearly ideal
  – Dielectric loss is zero
  – Reflections are zero
  – Delay is zero
  – Radiation is zero
  – Interference is tiny
  – Conductive loss is small

• “High” freq is what's challenging

• Everything gets worse as frequency increases!
Electrical Symbols used in this lecture

- $\mu_o$: magnetic permeability of vacuum, air and most materials
- $\varepsilon_o$: electric permittivity of vacuum
- $\varepsilon_r$: relative electric permittivity of material
- $\varepsilon$: electric permittivity of a material = $\varepsilon_r \varepsilon_o$
- $Z_o$: characteristic impedance of a signal path, (ratio of electric to magnetic field)
- $f_{rq}$: frequency

What is conductive loss?

Energy lost as current flows through the metal

- How is it quantified?
  - resistance (ohms, $\Omega$)
  - Conductivity of copper: $\sigma = 5.8e7 \ 1/(\Omega \text{meter})$
  - $R(\text{wire}) = L/(\text{Area} \times \sigma)$
  - $B = A \times \exp (\ - \frac{R}{2 \ Z_o})$
How does conductive loss change with frequency?

- \( B = A \times \exp\left(-\frac{R}{2Z_0}\right), \sim A \times \exp(-\sqrt{f_{\text{req}}}) \)
- Conductivity may change with frequency

Skin depth will change
  - Skin depth: distance from edge where most current flows (strictly, it is where charge decays by 1/e)
  - Current is pushed to the outside of the conductor
  - Effective conductor area decreases with frequency

- Roughness
  - Combines with skin effect to decrease effective conductor area even further

What is dielectric loss?

Energy lost through the dielectric

- How is it quantified?
  - Dielectric constant: \( \varepsilon_r = 2.7 \) for Rogers 2800
  - Loss tangent: \( \tan \delta = .003 \) for Rogers 2800
  - \( B = A \times \exp(-2\pi f_{\text{req}} \sqrt{\mu_0\varepsilon_r} \tan \delta \times L/2) \)
How does dielectric loss change with frequency?

- Dielectric characteristics, $\varepsilon$, $\tan \delta$, may change with frequency.

- Loss is proportional to frequency:
  - $B = A \times \exp(-2\pi f_{eq} \sqrt{\mu \varepsilon} \tan \delta \times L/2)$
  - $B \sim A \times \exp(f_{eq})$

What are reflections?

Energy bounced back from receiver

- How is it quantified?
  - Reflection co-efficient: $\Gamma$, ratio of reflected voltage to signal voltage.
  - $\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$
How do reflections change with frequency?

- $Z_L$, $Z_o$ may change with frequency
- Reflections are transmission line (t-line) effects; a wire doesn’t become a t-line till $L$ is about the size of a quarter wavelength: $L \geq \frac{\text{speed of light}}{4 \cdot f \cdot \sqrt{\varepsilon_r}}$
- At higher frequencies, more features look like a transmission line

What is delay?

Time it takes for energy from A to get to B

- How is it quantified?
  - Propagation Delay is the time required for a signal to leave a sending circuit and arrive as a valid signal at a receiving circuit
  - Delay = $84.7 \sqrt{\varepsilon_r}$ ps/inch

<table>
<thead>
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<th>Material</th>
<th>Er</th>
<th>ps/inch</th>
</tr>
</thead>
<tbody>
<tr>
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<td>84.7</td>
</tr>
<tr>
<td>ceramic</td>
<td>9</td>
<td>300</td>
</tr>
<tr>
<td>glass/ceram</td>
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<td>200</td>
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<tr>
<td>FR4</td>
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<td>170</td>
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<tr>
<td>teflon(base)</td>
<td>2.5</td>
<td>134</td>
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</tbody>
</table>
How does delay change with frequency?

- $\varepsilon_r$ may change with frequency
- Combines with reflections and loss to make a signal path unusable at frequency that’s too high
  - If the material is not good enough (large reflections, lossy) it may take several excursions of the path to establish a valid signal
  - As frequency increases, the time allowed to establish a valid signal decreases
  - If time allowed is less than time for valid signal, signal path fails

What is interference?

Energy at B, that’s not from the signal

- How is it quantified?
  - Background interference: noise density, power/sqrt(freq)
  - Specific frequencies: peak power @ $f_0$
  - Mutual capacitance and mutual inductance quantify coupling mechanism (how the outside energy gets into point B)
  - Device at B has a spec for how much interference it can handle
How does interference change with frequency?

- Sources of interference can broadcast easier at high frequency, but amplitude is usually smaller (same problems as signal path A to B)
- Coupling factors usually increases with frequency
- Susceptibility at B changes with frequency, Depends on device at B which may be either more sensitive or less sensitive at high frequency

What is radiation?

Energy broadcast into the world (converse of interference)

- How is it quantified?
  - Antenna efficiency: power radiated vs. frequency
  - FCC spec: no radiated power above X in frequency band $Y_0$ to $Y_1$
How does radiation change with frequency?

- SIMILAR TO INTERFERENCE
- Source at A can broadcast easier at high frequency, but amplitude is usually smaller
- Coupling factors usually increases with frequency
- Radiation energy sources at A change with frequency, depends on device at A which may be either stronger or weaker source at high frequency

More detail:
How do we model and describe these non-idealities?

- conductive loss: circuit model, attenuation
- dielectric loss: circuit model, attenuation
- reflections: circuit model, t-line, timing diagram
- delay: circuit model, t-line, timing diagram
- interference: circuit model, antenna coupling, 3D field solver
- radiation: circuit model, antenna coupling, 3D field solver
• THERE’S ALWAYS A CIRCUIT MODEL THAT (APPROXIMATELY) DESCRIBES ELECTRICAL NON-IDEALITIES

• THERE MAY BE BETTER AND/OR SIMPLER MODELS BESIDES CIRCUIT MODELS

More detail:
How do we model and describe these non-idealities?

• Radiation and interference are typically smaller than other effects and largely outside the control of the package signal path

• Focus on Loss, (dielectric and conductive) Reflections, and Delay
Look at a HyperBGA design

• Simplest model

\[ B = \frac{A \times 50}{R + 50} \]

• What’s R ?

More detail, Specific case:
How do we model and describe conductor loss?

\[ R = \frac{L}{(\text{Area} \times \sigma)} \]

L = 15mm, \( \sigma = 5.8e7 \)

Area = t*w = 13u*40u = 5.2e-10m²

\[ R = .49 \]

\[ B = \frac{A \times 50}{R + 50} = .99A \]
More detail, Specific case: Conductor Loss

• More accurate model

\[ B = A e^{-\frac{R}{2Z_o} \left[ 1 + \frac{2}{\pi} \tan^{-1}\left\{1.4 \left(\Delta/\delta\right)^2\right\}\right]} \]

\( \Delta = \) roughness factor, 2 um

\( Z_o = 50 \Omega, f(w,t,h_1,h_2, \varepsilon_r) \)

\( R = \frac{L}{\text{EffectiveArea} \times \sigma}, A_{eff} \sim w\delta \)

\( \delta = \) skin depth = \( \sqrt{\frac{2}{2\pi f_{r_q} \mu_0 \sigma}} \)

RESULT
• \( B = A \cdot \exp(-\pi f_r L \sqrt{\mu_0 \varepsilon_0 \varepsilon_r} \cdot \tan \delta) \)

\( \varepsilon_r = 2.7, \tan \delta = 0.005, L = 15 \text{mm} \)

• More accurate model includes variation of \( \varepsilon_r \) and \( \tan \delta \) with frequency

More detail, Specific case: dielectric loss
RESULT for constant \( \varepsilon_r \), \( \tan \delta \)
Compare lab results with model

Lab data is measured with a Network Analyzer

More detail, Specific case:
How do we model and describe reflections and delay?

Actual snapshots from layout

What’s going on?
More detail, Specific case: Reflections and Delay

- Transmission line model is needed
- \( Z_n = \text{impedance}, Z_1 = 70, Z_2 = 50 \)
- \( V_g = \text{group velocity} = 3e8/\sqrt{\varepsilon_r} \text{ m/s} \)
- Delay of each segment is \( L_n/V_g \)

Characteristic Impedance

Categories of Transmission Lines

- \( Z_0 \) is a different function for each different geometry
- Co-ax \( Z_0 = \sqrt{\mu_0/\varepsilon}/2\pi * \ln (b/a) \)
- Stripline \( Z_0 \sim 60*\ln[1.9*(2h+t)/(.8w+t)]/\sqrt{\varepsilon} \)
- Microstrip \( Z_0 \sim 87*\ln[6h/(.8w+t)]/\sqrt{\varepsilon+1.41} \)
More detail, Specific case: Reflections and Delay

- $Z_1 = 70$, $Z_2 = 50$, $L_1 = 5\text{mm}$, $L_2 = 10\text{mm}$,
- From earlier, $\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$
- $\Gamma_A = 20/120$, $\Gamma_C = -20/120$, $\Gamma_B = 1$

This looks roughly like lab, but there's a discrepancy
- Model says after bump, impedance is exactly 50 ohms, Lab says 55 ohms
More detail, Specific case: Reflections and Delay

Discrepancy between lab and model

What’s going on?
- Multiple reflections! \( \Gamma_A = -20/120 \)

Reflection at C, bounces back at A’

This looks more like lab, not quite exact
- Model says 53 ohms, Lab says 55 ohms
- What else is wrong with the model?
  - DC resistance adds to Zo, makes impedance another 2 ohm higher to get 55 in lab
Package Improvements

Now that we understand and can model the package, how do we make it better?

- Eliminate defects
- Change dielectric material
- Change metal
- Change design dimensions
- Control manufacturing processes better

Package Improvements

Why might we change dielectric material?

- Lower loss tangent means lower loss
- Lower dielectric constant means smaller delay, and slightly lower loss
- Easier or Cheaper manufacturing
Package Improvements

Why might we change the metal?

- Smoother surface means lower loss
  - Electrical Engineers have been waiting for years for a very smooth copper surface that still adheres to dielectric materials
- Higher conductivity means lower resistance
- Easier and cheaper manufacturing

Package Improvements

Why might we want to control manufacturing processes better?

- Reduce variations in the system
- Improve reliability
- Models will predict performance more accurately
Package Improvements

Why might we change the design dimensions?

- Hitting impedance target reduces reflections
- Shorter signal length improves delay, reflections and loss
- We want a structure that is insensitive to any variations in the system (manufacturing, material, etc.)

Package Improvements

How do we make these improvements?

- Eliminate defects
- Change dielectric material
- Change metal
- Change design dimensions
- Control manufacturing processes better

New ideas and technology are needed. You can make it happen!
Conclusion

• All concepts are general, can be applied to PWB, Large-Area-Arrays, HyperBGA, any packaging or semiconductor wafer

• As frequency increases, more and more details can't be ignored

• Conductive, dielectric and reflections are most important and can be improved reasonably in packaging

Conclusion

So Where Are the Challenges (and the jobs?)

• **Materials** – new lower loss dielectric materials, smoother copper that will still stick to dielectrics, materials that are more robust for manufacturing

• **RF Design and High Speed Data Transfer Design**, write your own ticket in many companies

• Knowing the tradeoffs and how to optimize the cost/performance ratio
  – **system architects** must know how to achieve optimal bandwidth (i.e. bus width vs bus speed)
  – all of the tradeoffs between materials, conductor widths, net lengths need to be understood