Electronic Packaging at Microwave and Millimeter-wave Frequencies
“Applications, Key Components, Design Issues”

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Outline

Goal: Convey The Importance Of Electronic Packaging Considerations For uWave and MMW Products/Components

● Applications
  – What types of systems need it?
  – Components

● Microwave Packaging Issues – Detailed Design Examples
  – Wire bonds
  – Transitions between transmission lines
  – Thermal modeling

Conclude With:

7 Keys to Successful Packaging at Microwave and Millimeter-wave Frequencies
Applications

What Types of Systems Benefit From Electronic Packaging At uWave and MMW Frequencies?
Radar Systems Use Results Of Electronic Packaging at Microwave and Millimeter-wave Frequencies

Commercial Radar Systems

- RADAR is RAdio Detection And Ranging and was heavily used for the first time during WWII.

- A radio signal is transmitted to a target. A portion of the signal bounces off the target and returns to the transmitter. The range and speed of the target, as well as other information, can be determined from the return signal.
Ground Terminals and Satellite Systems Benefit From uWave and MMW Electronic Packaging Technology

Subsystems that benefit from packaging at microwave and millimeter-wave frequencies:

- Amplifiers
- Filters
- Couplers
- Antennas
- Up/Down Converters
Data Back Haul Systems Benefit From mWave and MMW Electronic Packaging

- Back haul system equipment exists from a few GHz to 100GHz.
- That equipment makes extensive use of electronic packaging technology.

FastBackNetworks, 60GHz Radio

Siklu Etherhaul-1200, 71-76 & 81-86GHz
Microwave Hybrids

- Microwave hybrids use:
  - Wire bond interconnects
  - Transmission line transition
  - Transitions to coaxial connectors
  - Vertical transitions from one side of the module to the other
  - Integrated circuits such as MMICs

Source: SemiGen, Inc. Manchester, NH
5G wireless systems will use smart antennas to dynamically change the antenna patterns to optimize user experience. In other words, they will use switch beam systems and phased arrays.

The systems will rely heavily on packaging at microwave frequencies.

Mobile Phones Are An Extreme Example Of uWave Packaging With Coupling Concerns, Antenna, Transitions, and Thermal Issue (and more!)

Transitions between transmission line types

Antennas integrated onto the plastic case

Thermal concerns from high power amplifiers

Miniature RF Connector and Coax (low loss)
Detailed Design Examples Of Packaging Issues at Microwave and Millimeter-wave Frequencies

Wire Bonds
Transmission Line Transitions
Thermal – Heat Transfer
Wire Bonds Are Used Extensively In Microelectronics

- Wire bonds are the back bone for most microelectronic packaging.
- Properly accounting for their effects is critical at microwave and millimeter-wave frequencies.

Example of a wire bonding machine

Example of wedge bonds
The Standard Approach To Wirebond Modeling Is To Approximate Its Electrical Performance As A Series Inductor

- If the simplified electrical model of a wire bond is a series inductor, at what inductance level will the electrical performance be impacted?
- At 25GHz, the answer is that even a small amount of series inductance, as low as 0.2nH, will impact electrical performance.
Let's Investigate Modeling The Wire Bond With Progressively Improving Fidelity

- **Low Fidelity Model**: Simple series inductor. Rule of thumb is that 1mm of wire has 1nH of inductance. This slightly overestimates the inductance in many cases, but can still be useful. Useful to a few GHz only.

- **Moderate Fidelity Model**: Adds shunt capacitance to account for the bond pads and wire shunt capacitance and series resistance of the wire. Useful to 10 GHz or more.

- **High Fidelity Model**: Adds transmission lines at the input to more accurately account for bond pad effects. Useful to over 50GHz.
Let’s Begin The Process Of Developing A Wire Bond Model With A Simplified Wire Bond Model

- The image shows a very simple straight wire bond between two substrates. Of course, this is impractical, but let’s use it as our first step in developing a wire bond model.
Low Fidelity Model Does Not Accurately Capture The Wire Bond Effects On Phase

Where:

\[ L_g = \text{Inductance of a wire over a ground plane} \]
\[ H = \text{Distance of wire above the ground plane} \]
\[ r = \text{radius of the wire} = \frac{d}{2} \]
Assumes \( r \ll H \)

For \( H=0.163\text{mm}, d=0.0254\text{mm}, \) and a wire length of 0.75mm, \( L = 0.489\text{nH} \)

\[ L \approx 2 \ln \left( \frac{2H}{r} \right) \text{nH/cm} \quad (1) \]
The High Fidelity Model Treats The Wire As A Transmission Line For Calculating L, C1 and C2

**Step 1:** Treat wire bond as a transmission line and calculate its line impedance

\[ Z_{ow} = \frac{60}{\sqrt{\varepsilon_{reff}}} \cosh^{-1}\left(\frac{1-u^2+R}{2R}\right) \]  

Where:

\[ R = \frac{2}{4H/a-a/H} \]  

\[ u = \frac{1}{(2H/a)^2-1} \]  

\[ \varepsilon_{reff} = \frac{\ln\left(\frac{2H}{a}\right)}{\ln\left[\frac{2(H-h)}{a}+\frac{2h}{\varepsilon_r}\right]} \]  

**Step 2:** Calculate L, C1, C2, R

\[ L_{dist} = \frac{Z_{ow}\sqrt{\varepsilon_{reff}}}{v_0} \]  

\[ C_{dist} = \frac{\sqrt{\varepsilon_{reff}}}{Z_{ow}v_0} \]  

\[ L = L_{dist} \cdot \text{Wire Length} \]  

\[ C1 = C2 = \frac{C_{dist} \cdot \text{Wire Length}}{2} \]  

\[ R_w = R_{dc} = \frac{\text{Wire length}}{\sigma A} \]  

**Step 3:** Calculate \( Z_{MS}, L_{MS} \)

Use any available transmission line simulator to calculate the impedance of the wire bond pad. \( Z_{MS} \) = wire bond pad line impedance, \( L_{MS} = \) wire bond pad length.

For a gold wire (\( \sigma = 4.1 \times 10^7 \) mho/m) with H=0.163mm, d=0.0254mm, and a wire length of 0.75mm, From Equations 2-4, we obtain:

\( L_{dist} = 651.9nH/m \)  

\( L = 0.489nH \)  

\( C_{dist} = 17.04pF/m \)  

\( C1 = C2 = 0.0064pF \)  

\( R_w = 0.036ohm \).
The High Fidelity Model Results In Excellent Agreement

High Fidelity Model

\[ L = 0.489 \text{nH} \]
\[ C_1 = C_2 = 0.0064 \text{pF} \]
\[ R = 0.036 \text{ ohm} \]
\[ L_{MS} = 0.090 \text{ mm} \]
\[ Z_{MS} = 50.2 \text{ ohms} \left( \varepsilon_{\text{reff}} = 6.01 \right) \]
However, One May Rightly Object That This Wire Bond Model Up To This Point Is For A Simplified Unpractical Case

- This is a valid criticism, but the value of the prior analysis is that it demonstrates the method of wire bond analysis.
- A more complex and practical wire bond mode is shown to the left.
- It shows a GaAs MMIC integrated circuit wire bonded to a package using ball bonds and a ribbon bond.
- Also shown is a 3D model of the ball bond used for our electrical simulations.
The Electrical Model For The Practical Wire Bond Contains Additional Circuit Elements

- The wire bond is approximated by three sections of wire. Each section is analyzed to determine its line impedance.
- LW1 is modeled as a lumped inductor (with $C_{\text{par}}=0$).
- LW2 and LW3 are modeled as sections of transmission line using equations 2-3.
The High Fidelity Model Applied To A Practical Wire Bond Shows Agreement To 50GHz

\[ L_{LW1} = 0.135 \text{nH} \]
\[ Z_{LW2} = 267.9 \text{ ohm} \]
\[ E_{\text{reff}(LW2)} = 1.092 \]
\[ \text{Length}_{LW2} = 0.051 \text{ mm} \]
\[ Z_{LW3} = 235.2 \text{ ohm} \]
\[ E_{\text{reff}(LW3)} = 1.168 \]
\[ \text{Length}_{LW3} = 0.503 \text{ mm} \]
\[ L_{MS} = 0.090 \text{ mm} \]
\[ Z_{MS} = 50.2 \text{ ohms} (e_{\text{reff}} = 6.01) \]

3D EM Model Results Compared To Circuit Model

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Return Loss (dB)          Insertion Loss (dB)          Phase of S21 (degree)
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Transitions Between Transmission Lines: A Few Guidelines and Then A Detailed Example

1. Maintain the same field distribution between transmission lines: If the field distribution between to connecting transmission lines is similar, then the transition has the potential for wide bandwidth.

2. Smoothly transition between transmission line types: Avoid any abrupt changes in features.

3. Use impedance transformation when appropriate: It is possible to include matching circuitry which can be used to tune out undesired inductive or capacitive effects.

4. Minimize stray capacitance: Stray capacitance is one of the primary effects that reduces the bandwidth of microwave and millimeter-wave transmission line transitions.

5. Avoid the excitation of propagating higher order modes: Higher order modes have the potential to increase undesired coupling and increase insertion loss.
How Can A Transition Between Stripline and Microstrip Be Created?

- This is a very common transition since many applications require the signal line to be buried inside the PCB at some point.
- Requires careful design of the transmission lines and transition area between the transmission lines.
Design Of The Stripline Section Requires Careful Attention To Via Placement Detail

Avoiding the two undesired modes results in a limited range for acceptable values for dimension $a$.

Stripline Desired Mode

Stripline Undesired Mode 1

Stripline Undesired Mode 2

Simulate using quasi-static or full-wave simulator to determine change in impedance and effective dielectric constant as a function of spacing between vias.

$$f_{sr1} = \frac{v_0}{2a\sqrt{\varepsilon_r\mu_r}}$$

Allowed Range For Dimension $a$

Line Impedance (ohm)

Onset Of TE01 Resonant Mode (GHz)

Cavity Width, $a$ (mm)

(for $\varepsilon_r=9.8$, b=1mm, w=0.203mm)
The Equivalent Circuit Model Of The Transition Is An LC Network

- $L_1$ = inductance of the via through substrate thickness $h$.
- $L_2$ = inductance of via through the top section of substrate thickness $b$.
- $C_1$ = capacitance created by via passing through the ground plane below the microstrip.
- $C_2$ = capacitance created by the via catch pad at the stripline interface.
The Model Creation Procedure Requires Three Steps

\[ L_{via} = \frac{\mu_0}{2\pi} \left[ h \cdot \ln\left(\frac{h + \sqrt{r^2 + h^2}}{r}\right) + \frac{3}{2} (r - \sqrt{r^2 + h^2}) \right] \] (4)

\[ C_1 = A_1 \cdot \left( h + \frac{b}{2} \right) \frac{\varepsilon_r}{60 \cdot \nu_0 \ln(D/d)} \] (5)

\[ C_2 = \frac{A_{cp} \cdot \varepsilon_0 \varepsilon_r}{\text{spacing}} = \pi \left( \frac{D_{cp}}{2} \right)^2 \frac{\varepsilon_0 \varepsilon_r}{b/2} \] (6)

- **Step 1:** Calculate \( L_1 \) and \( L_2 \) using (4).
- **Step 2:** Calculate \( C_1 \) using (5).
- **Step 3:** Calculate \( C_2 \) using (6)

For LTCC (\( \varepsilon_r = 7.8 \)), \( h = 0.25 \text{mm} \), \( b = 0.5 \text{mm} \), \( D = 0.55 \text{mm} \), \( d = 0.2 \text{mm} \), \( D_{cp} = 0.35 \text{mm} \) which yield \( L_1 = 0.0259 \text{nH} \), \( L_2 = 0.108 \text{nH} \), \( C_1 = 0.102 \text{pF} \), \( C_2 = 0.0781 \text{pF} \).
How Can This Procedure Be Applied To A PCB Which Uses Through Vias

- Follow the same procedure as for the LTCC circuit board, but add a capacitance to account for the capacitive effect of the via stub.

\[ C_3 = A_2 \cdot \frac{b \cdot \varepsilon_r}{2 \cdot 60 \cdot v_0 \cdot \ln(D/d)} \]

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Heat Flux From A GaN MMIC Is Greater Than The Heat Flux From A Clothes Iron Turned To Max Temperature

Heat Flux = $q'' = \frac{Q}{A}$ (W/m²)

Where:
\( Q \) = Power or the Heat Energy Generated (W)
\( A \) = Area Over Which the Heat Energy Is Leaving The Heat Source (m²)

- Heat flux from clothes iron
  \(~ 1500W/(25cm \times 12cm) = 5W/cm^2\)
- Heat flux from GaN HPA
  \(~ 75W/(0.42cm \times 0.055cm) = 3,246W/cm^2\)
**Example of Dissipated Power Calculation For a GaN MMIC**

Consider an X-Band GaN amplifier that delivers output power of $P_{out} = 15\text{W}$ with an input power of $P_{in} = 1\text{W}$ and uses a bias voltage of $V_D = 24\text{V}$ and bias current of $I_D = 1.5\text{A}$.

\[
P_{DC} = V_D \cdot I_D\]
\[
P_{diss} = (P_{DC} + P_{in}) - P_{out}\]

Where:
- $P_{diss}$ = Dissipated power
- $V_D$ = DC bias voltage
- $I_D$ = DC bias current

\begin{itemize}
  \item Consider an X-Band GaN amplifier that delivers output power of $P_{out} = 15\text{W}$ with an input power of $P_{in} = 1\text{W}$ and uses a bias voltage of $V_D = 24\text{V}$ and bias current of $I_D = 1.5\text{A}$.
\end{itemize}

\[
P_{DC} = 24\text{V} \times 1.5\text{A} = 36.0\text{ Watts}\]
\[
P_{diss} = 36\text{W} + 1\text{W} - 15\text{W} = 22\text{W}\]
Once the dissipated heat is known, the junction temperature can be calculated.

Once $\theta_{jc}$ is known (usually supplied by the MMIC fabricator) and the dissipated power, $P_{diss}$, is known, the temperature rise from the MMIC case (bottom of the MMIC) to the junction of the amplifier can be calculated.

Temperature Rise = $\theta_{jc} \times P_{diss} = 2.6 \degree C/W \times 22W = 57.2 \degree C$
The Junction Temperature Is Used To Calculate The Long Term Reliability Based On Empirical Life Testing Of The Devices At High Temperatures

- Empirical testing is used to generate the curve of channel temperature versus MTTF.
- \( E_a \) is then calculated.
- The MTTF at lower temperatures can then be calculated.

\[
E_a = \frac{k \log_{10}(e)}{d \log_{10}(MTTF)} \frac{d(1/T)}{d(1/T)}
\]

\[
MTTF_L = MTTF_H \exp \left[ \frac{E_a}{k} \left( \frac{1}{T_L} - \frac{1}{T_H} \right) \right]
\]

For more information: JEDEC JEP118 publication: "Guidelines for GaAs MMIC and FET Life Testing." Or see: MIL-STD-883 Method 1016 can also be consulted.
The Seven Keys for Successful Electronic Packages and Signal Integrity

1. System Design
2. Proper Material Selection
3. Electrical Signal Integrity (Electronic Packaging)
4. Proper Electrical Modeling
5. Design For Manufacturing
6. Design For Testability
7. Proper Feed Back From Field Failures
Step 1: System Design and Specification

- The system design is the first step after initial top level requirements are known.
- More often than not, the system design and specification are developed in parallel.
- Higher development cost and lost opportunity cost can be significant if specifications and system design are not done properly.
- **RULE:** Detailed design CANNOT start until the system design and specification are completed.
  - More often than I care to recall, this rule has been broken and it has resulted in disaster most every time I have seen it.
**Key 2: Proper Materials Selection**

**RULE:** Never use a material for which reliable material properties do not exist.
**Key 3: Electrical Signal Integrity**

- This is often the killer for package and module development.
- Requires the use of the best modeling tools and experienced designers.
  - 3D electromagnetic simulators
  - Test and measurement of test circuits to confirm simulations
  - Commitment from management is required to get this part of the design correct at the start of the program.
- Develop a library of proven transitions and interconnects.
  - Extremely important to document the library of transitions and interconnects.
  - Will be in a continual process of improvement and expansion.
- **RULE:** When ever possible use two different analysis methods for each transition and interconnect and verify that simulations agree.
Key 4: Proper Electrical Modeling

- Electrical modeling includes any item that will affect the electrical performance such as transitions, interconnects, semiconductors, passives, and package materials.

- It may surprise some, but many designs that I have seen were released to production without models for some (often many) of the components being used.

- The designer should be shot if he or she uses components for which accurate and appropriate models do not exist.

  **RULE:** ONLY use circuits, MMICs, passives, and other items for which confirmed models exist and use them!!

  **Corollary:** If you don’t have a model for something, then don’t use it.
Key 5: Design For Manufacturing

- One benefit of detailed mechanical modeling is that the result can be used to create fabrication ready drawings.
  - CAD programs for circuit boards and ceramic substrates can include design rules and automated design rule checking. These tools should be developed and used to increase the likelihood of designing a manufacturable product.
  - Microelectronic assembly manufacturers include design rules for wire bonds, component placement, wire bond pad size, epoxy squeeze out, etc. Some of these design rules can be difficult to automate and require disciplined design.

- Designer and engineering team must have direct experience with manufacturing processes.
  - Designers must spend time at automatic wire bond machine and the pick and place machine talking to the programmers and operators of the machine to understand the issues and limits of using the machine.

- **RULE:** Design engineer must be responsible for successful transition to production so that he/she must live through poor design choices.
Key 6: Design For Testability

- Design for testability must be appropriate for every stage of the product development process.
  - Design verification stage
  - Reliability testing
  - Burn-In
  - Accelerated life testing
  - Production level testing (may include programming)
  - Build in test functions

- Product design must take into account:
  - Test fixtures
  - Proper heat transfer during test
  - Test probe heads
  - Electrical connections

- **RULE:** Perform a comprehensive testability review BEFORE the T/R prototype modules are release to fabrication.
Key 7: Failure Analysis

- Each field failure is a gem of information for improvement.
- Design engineering team MUST perform or be intimately involved in failure analysis.
  - Ensures that failure information is communicated to the design team for improvement.
  - Closes the loop on accountability for design choices.
- **RULE:** Design engineer must perform or be intimately involved in ALL failure analysis.
**Conclusions**

- The goal of the presentation was to convey the importance of microwave and millimeter-wave electronic packaging
  - We showed why it is important to properly model wire bond interconnects and we examined a method for the wide band analysis of wire bonds that is accurate to at least 50GHz.
  - We examined a method to analyze transitions between transmission lines. We used a microstrip to strip line transition and developed a model that is appropriate for both ceramic with blind vias and laminate packaging with through vias.
- We concluded with 7 keys to successful packaging and uWave and MMW frequencies.