Modeling and Simulation of Via Conductor Losses in Co-fired Ceramic Substrates Used In Transmit/Receive Radar Modules

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Goal Of The Presentation

● Major Goal:
  – Demonstrate the effect of via resistance on vertical transitions within co-fired ceramic substrates.

● Motivation
  – During a product development, it was suggested that via conductor losses may be increasing the insertion loss of the vertical transition. Specifically, the center conductor via for the quasi-coaxial transition.

● Describe the use of vertical transitions in transmit receive modules.

● Show simulation results

● Describe the model developed
T/R Modules Are Used In AESA Radar and Communication Systems

- T/R modules are being used in multiple military systems including airborne, ground based, and sea based systems.
- Commercial applications of T/R modules include communication systems, satellite systems, consumer high data rate mobile.
Typical Transmit Receive Module Showing Location Of Vertical Transition

- **Circulator**
  - Combines RX and TX functions to one radiator port.

- **Limiter and Low Noise Amplifier**
  - Must handle at least the reverse power of HPA output.
  - LNA, G>20dB typ., NF~1-1.5dB

- **Phase Shifter and VGA**
  - 6 bits of phase
  - 5 bits of attenuation

- **Vertical Transition**

- **Power Detector**
  - Detects HPA output power level.

- **Wilkenson Power Divider**
  - Power combines HPA outputs

- **High Power Amplifiers**
  - Two amplifiers

- **Switches**
  - SPDT
  - Used to switch between TX and RX paths.

- **Si and Other Functions:**
  - ASIC, Regulators, Energy Storage, HEXFETs, etc.
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

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

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

Allowed Range For Dimension a

(For \( \varepsilon_r = 9.8 \), \( b = 1 \text{mm} \), \( w = 0.203 \text{mm} \))
The Equivalent Circuit Model Of The Transition Is An LC Network

- L1 = inductance of the via through substrate thickness h.
- L2 = inductance of via through the top section of substrate thickness b.
- C1 = capacitance created by via passing through the ground plane below the microstrip.
- C2 = capacitance created by the via catch pad at the stripline interface.
The Model Creation Procedure Requires Three Steps

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

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

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

C_2 = \frac{A_{cp} \cdot \varepsilon_0 \varepsilon_r}{\text{spacing}} = \frac{\pi \left( \frac{D_{cp}}{2} \right)^2 \varepsilon_0 \varepsilon_r}{b/2} \quad (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 $L_1=0.0259\text{nH}$, $L_2=0.108\text{nH}$, $C_1=0.102\text{pF}$, $C_2=0.0781\text{pF}$
What Effect Does The Conductor Loss Of The Via Have On Performance?

• Approach
  – Convert ohm/sq into resistivity
  – Perform EM simulation
  – Extract insertion loss as a function of metal conductivity
  – Modify circuit model to accommodate via resistance effect.
Co-Fired Ceramic Fabricators Specify Metal Conductivity in Ohm/sq

- Must convert ohm/sq into resistivity or conductivity for EM simulators.

From Definition Of Resistivity

\[ R = \rho \frac{L}{A} = \rho \frac{L}{W \cdot t} \]

From Ohm/Square

\[ R = \left( \frac{Ohm}{Sq} \right) \frac{L}{W} \]

\[ \rho \frac{L}{W \cdot t} = \left( \frac{Ohm}{Sq} \right) \frac{L}{W} \]

\[ \rho = \left( \frac{Ohm}{Sq} \right) \cdot t \]

Area = \( A = W \cdot t \)
The Via Can Be Modeled As A Simple Resistor For Insertion Loss Contribution

- Contribution of resistive part to the insertion loss of the transition can be found from (1), but only if we were just concerned about DC effects (i.e., effects at zero frequency).

- However, (1) does not capture the full story because of the skin depth effect.

Considering DC (i.e., f=0) Current Only

\[ A' = \pi \left( \frac{D}{2} \right)^2 \]

\[ R' = \rho \left( \frac{L'}{A'} \right) \]  \hspace{1cm} (1)
Skin Depth Effect Tells Us That The RF Current Only Penetrates A Small Distance Into The Metal

\[ \text{Skin Depth } \delta = \frac{1}{\pi \mu \sigma f} \]

Where:
- \( \mu \) = permeability
- \( \sigma \) = metal conductivity
- \( f \) = frequency of concern
Because of Skin Depth Effects, The Current Only Travels On The Surface Of The Via

Effective Area Due To Skin Depth Effects

\[ A_{eff} = A' - A1 \]

\[ = \pi \left( \frac{D}{2} \right)^2 - \left( \frac{D - n\delta}{2} \right)^2 \]

\[ R' = \rho \left( \frac{L}{A_{eff}} \right) \] (2)

n= number of skin depths to include

• Using (2) provide a more accurate estimate of the

\[ S21(dB) = 20 \cdot \log_{10} \left( \frac{2}{2 + R' / Z_0} \right) \]
When Skin Depth Effects Are Taken Into Account, The Lumped Model Agrees With HFSS
Simulations Were Performed Using HFSS From Ansys

- Results show a steady increase in insertion loss as a function of frequency and via conductivity.
- Roll off above 10GHz is due to mismatch losses.
Conclusions

- The goal of the presentation was to show the effect of the center conductor resistivity for vertical transitions.
- We showed:
  - 1) For good conductivity metals, the contribution of the center conductor to overall insertion loss of the vertical transition is less than approximately 0.1dB.
  - 2) The skin depth effect must be accounted for when calculating the resistive part of the via transition.
- Suggestions For Further Study:
  - 1) All the vias including the ground vias in the location of the transition should be taken into account.
  - 2) A analytical solution for $n$ should be calculated.

![Modified Model](modified_model_diagram)