Nickel Characterization for Interconnect Analysis

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Outline

- Nickel characterization at microwave frequencies
- Anomalies in ENIG plated interconnects
- Identification of nickel parameters
  - GMS-parameters extraction from measured data
  - Electromagnetic model for plated traces
  - Landau-Lifshits model for ferromagnetic metal
  - Nickel parameters identification
- Effect of Nickel on multi-gigabit digital signals
- Conclusion

Nickel characterization at microwave frequencies

- From S. Lucyszyn, Microwave Characterization of Nickel, PIERS online, vol. 4, N 6, 2008, p. 686-690.

Results from different authors show drop in permeability of nickel at microwave frequency range – though the data are inconsistent due to differences in the identification techniques and differences in the investigated material

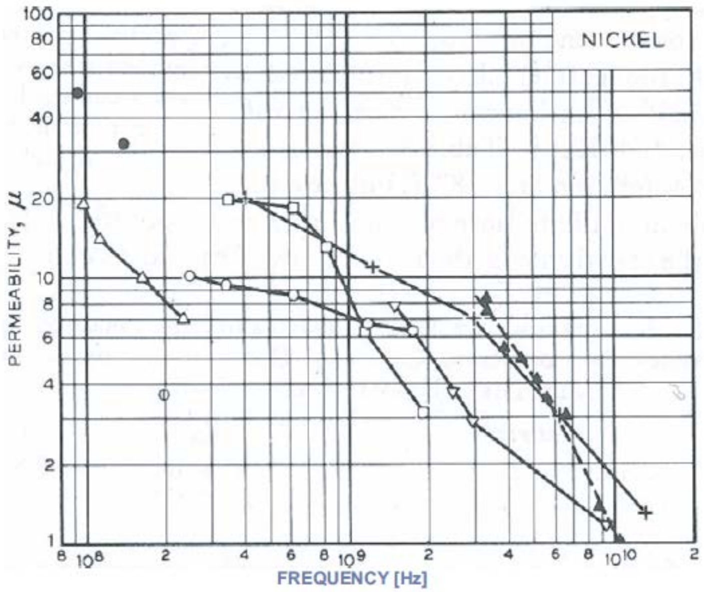


Figure 1: Measured frequency characteristics of initial permeability for nickel [10]. (+ Arkadiew [11], ∇ Simon [12], ▲ Hodsman et al. [13])

10. R. M. Bozorth, *Ferromagnetism*, D. Van Nostrand Co. Inc., 1951.
11. W. Arkadiew, “Absorption of electromagnetic waves in two parallel wires," *Ann. Physik*, Vol. 58, 1919.
12. I. Simon, “Magnetic permeability of Ni in region of cm waves," *Nature*, Vol. 157, 735, June 1946.
13. G. F. Hodsman, G. Eichholz, and R. Millership, “Magnetic dispersion at microwave frequencies," *Proceedings of the Physical Society Section B*, 377{390, 1949.

Plated Nickel effect: Case 1

- J. Moreira, M. Tsai, J. Kenton, H. Barnes, D. Faller, PCB Loadboard Design Challenges for Multi-Gigabit Devices in Automated Test Applications, DesignCon 2006

Anomaly in attenuation for case of thin Au layer over Ni is clearly visible between 2 and 4 GHz (black curve)

Nickel modeled as non-dispersive metal with permeability varying from 1 to 100 – no anomaly observed in such model

Effect of nickel plating on 10 Gbps signal degradation is shown experimentally

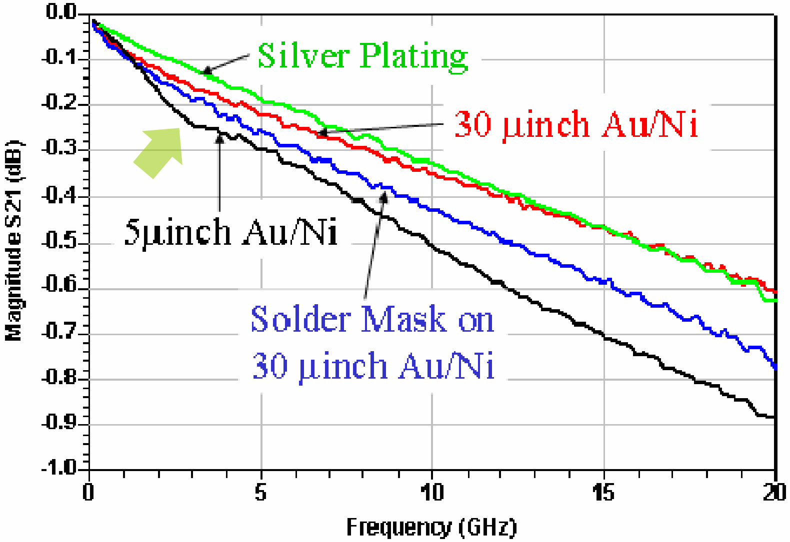


Figure 13: Measured loss per inch for Ag plating, OSP, electroplated 30 µinches Au and 15 µinches Au, soldermask and immersion 5 µinches Au [6].

Plated Nickel effect: Case 2

- X. Wu, D. Cullen, G. Brist, and O. M. Ramahi, Surface Finish Effects on High-Speed Signal Degradation, IEEE Trans. On Adv. Packaging, Vol. 31, No 1, Feb. 2008, p. 182-189.

Anomaly in attenuation for case of Au layer over Ni is clearly visible between 1 and 3 GHz (red curve)

Simulation shows substantial differences in the insertion loss (black curve)

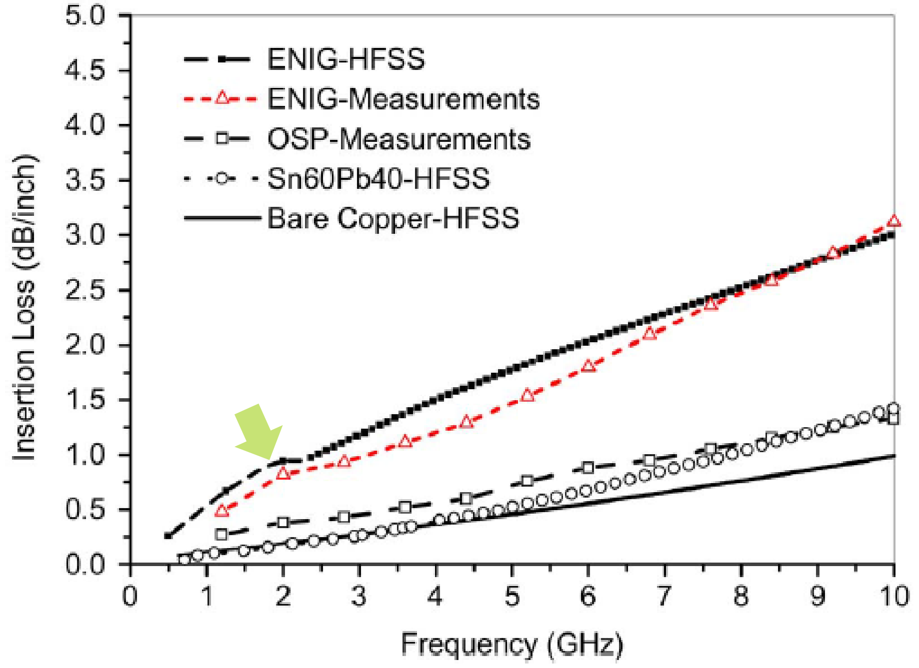


Fig. 10. Simulation and measurements of differential pairs with ENIG and OSP finishes applied.

Plated Nickel effect: Case 3

- A. Aguayo, Advances in high frequency printed circuit board materials, Microwave Engineering Europe, Dec. 2009, p.11-14.

Anomaly in attenuation for case of Au layer over Ni is clearly visible between 1 and 5 GHz (magenta curve)

Simulation did not reproduce the anomaly

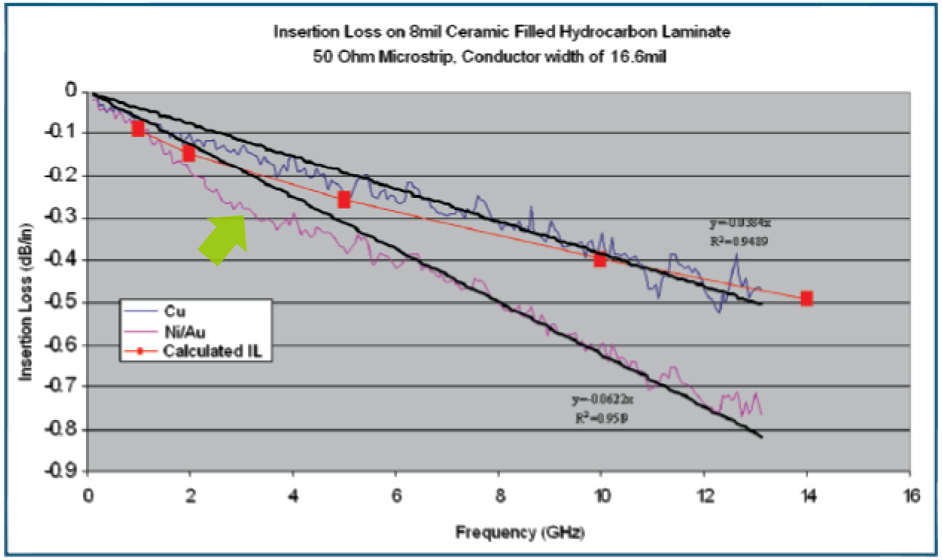


Figure 3: Data showing insertion loss versus frequency of copper only as compared to copper plated with ENIG (electroless nickel/immersion gold).

From Internal Rogers Corporation study, “Increased Circuit Loss due to Ni/Au”, Dr. Al Horn, January 2006.

Plated Nickel effect: Case 3.1

- X. Chen, “EM modeling of microstrip conductor losses including surface roughness effect,” *IEEE Microwave and Wireless Components Letters,* v. 17, n.2, p. 94, February 2007

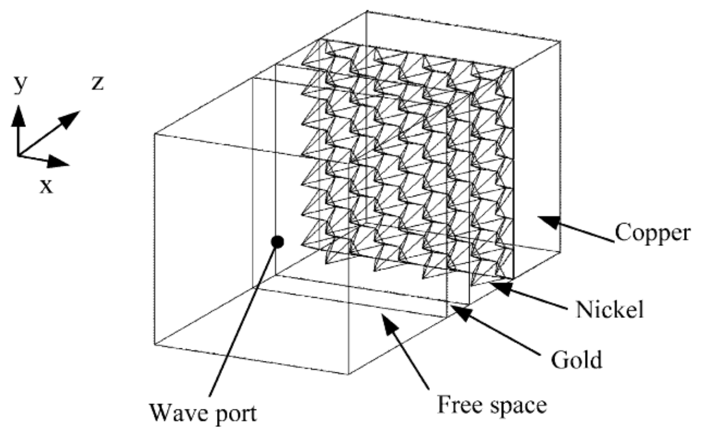


Fig. 2. 3-D HFSS model to obtain effective conductivity of the Au–Ni–Cu metal system. Surface roughness is considered.

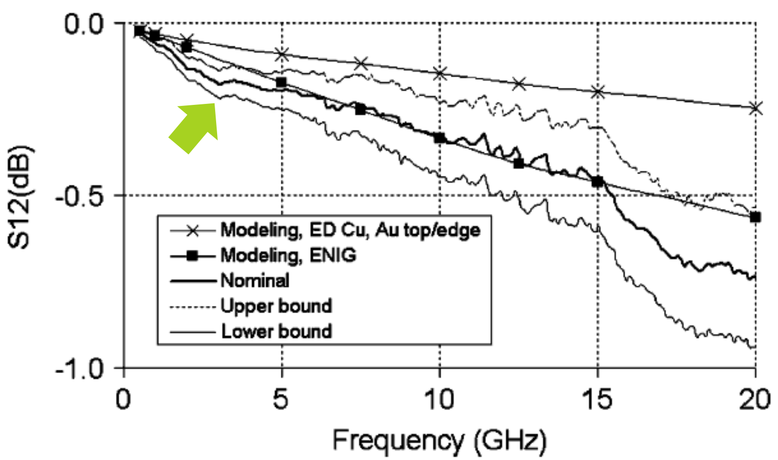
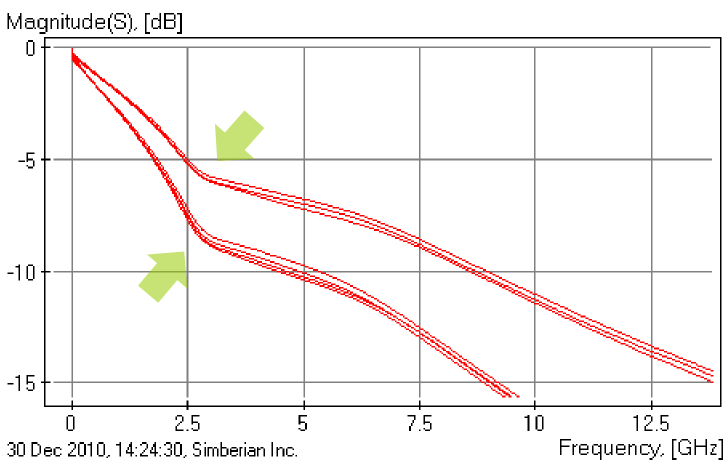


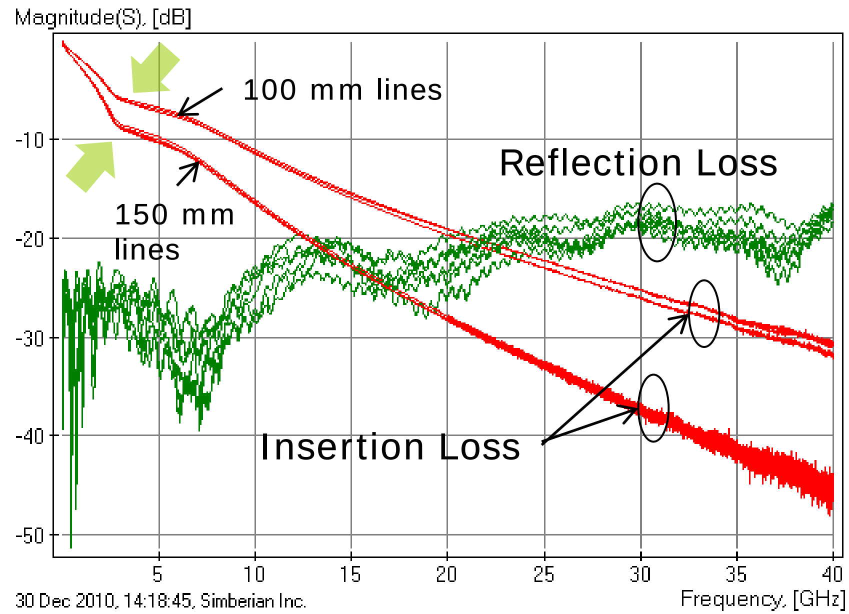
Fig. 5. Calibrated and HFSS simulated insertion loss of a 1-in long 50-Ω microstrip.

Plated Nickel effect: Case 4

- S-parameters of single-ended microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper

Anomaly in attenuation around 2.7 GHz – cannot be reproduced with regular metal models





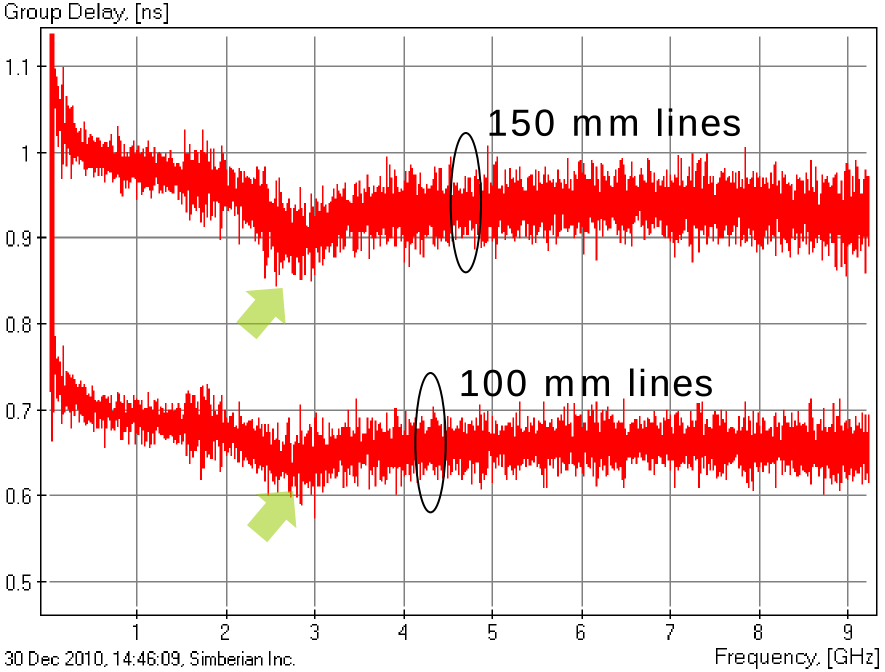
S-parameters for three structures with 100 mm microstrip line segments and for four structures with 150 mm segments are plotted

Plated Nickel effect: Case 4

- S-parameters of single-ended microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper

Anomaly in group delay around 2.7 GHz - not previously reported!

Cannot be reproduced with regular metal model



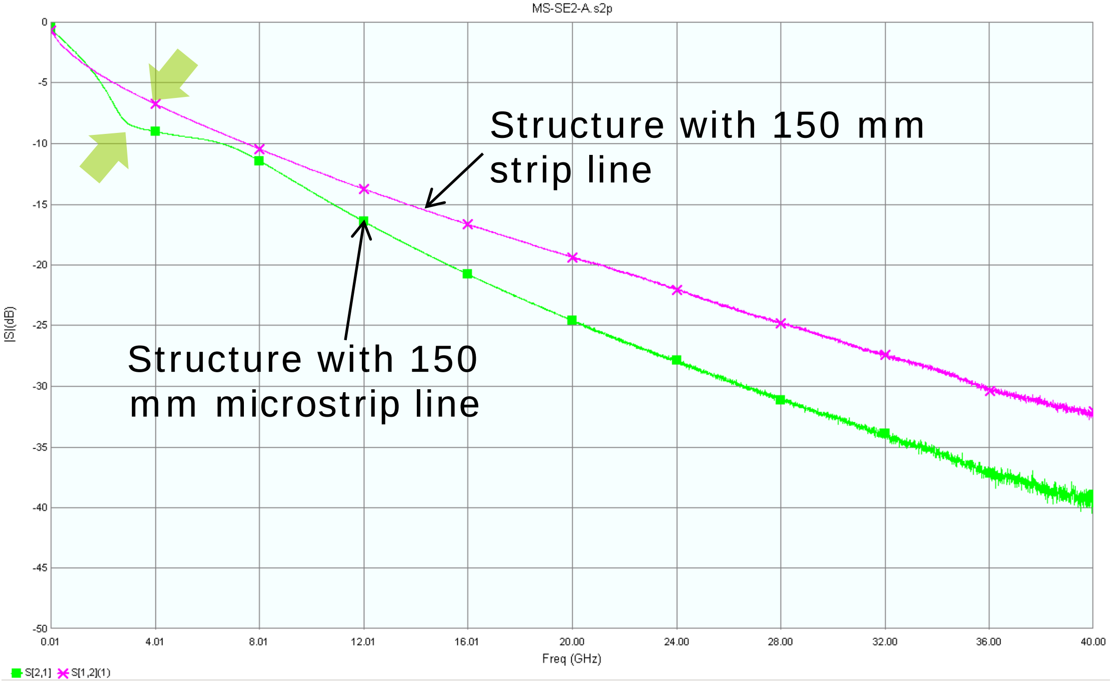
Group delays for three structures with 100 mm microstrip line segments and for four structures with 150 mm segments are plotted

Plated Nickel effect: Case 4

- S-parameters of single-ended microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper

Structures with strip lines did not show any anomaly in IL and GD – it is clearly the effect of plating

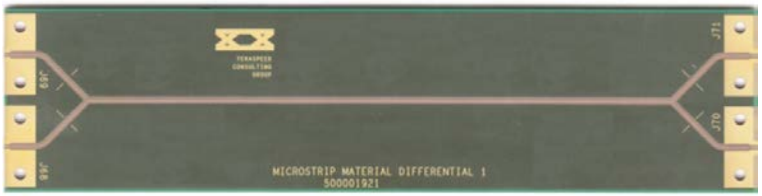
Strip line structures can be used to identify dielectric properties



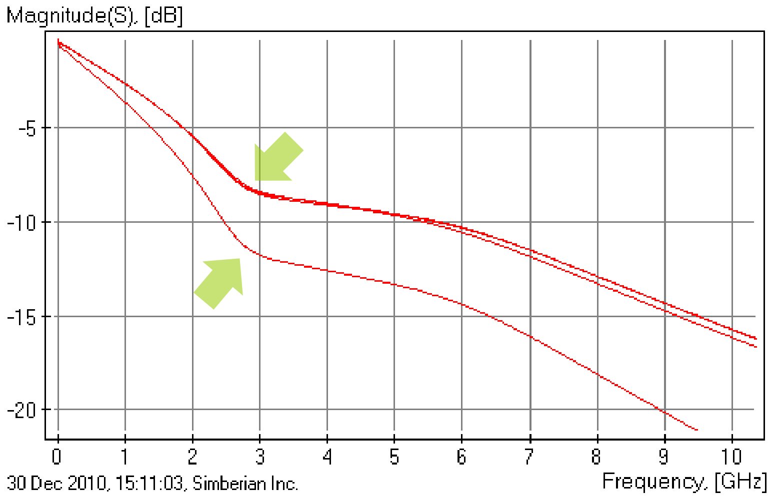
Dielectric parameters were identified with GMS-parameters of the strip line structures as wideband Debye model with DK=3.x and LT=0.01x at 1 GHz

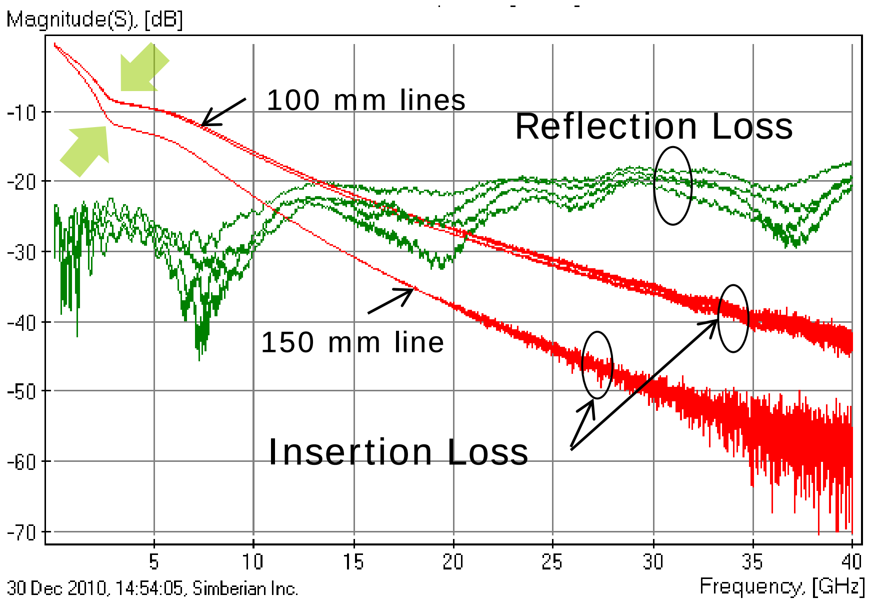
Plated Nickel effect: Case 5

- S-parameters of differential microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper



Anomaly in attenuation around 2.7 GHz – cannot be reproduced with regular metal models

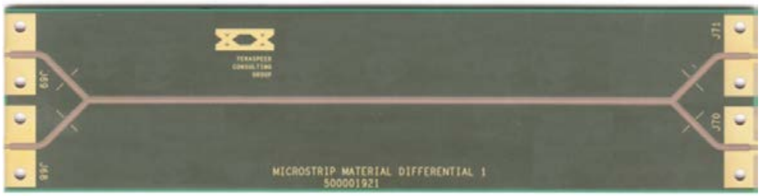




Differential S-parameters for three structures with 100 mm microstrip line segments and for one structure with 150 mm segments are plotted

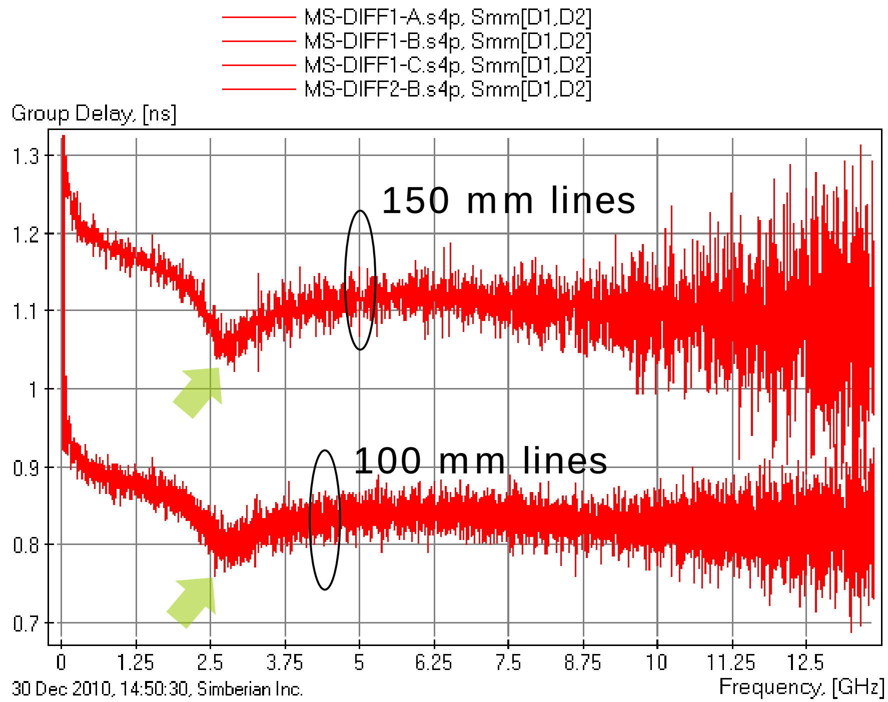
Plated Nickel effect: Case 5

- S-parameters of differential microstrip lines with ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper



Anomaly in group delay around 2.7 GHz - not previously reported!

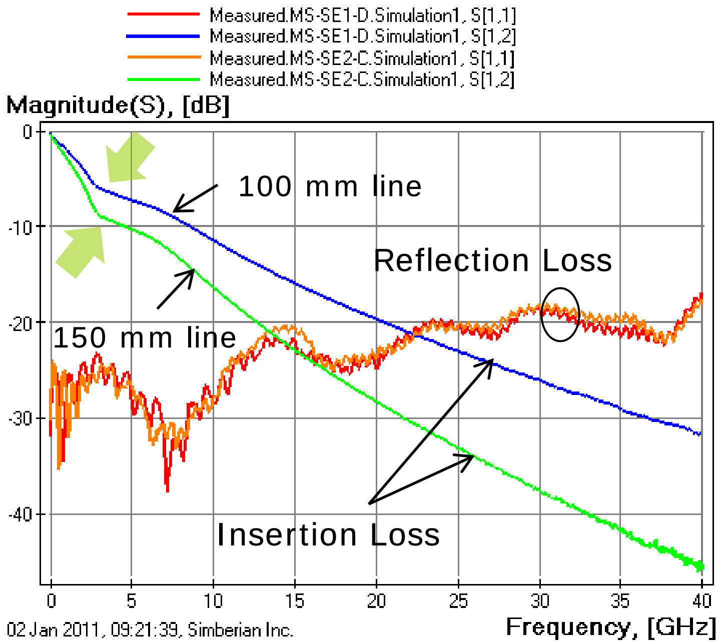
Cannot be reproduced with regular metal model

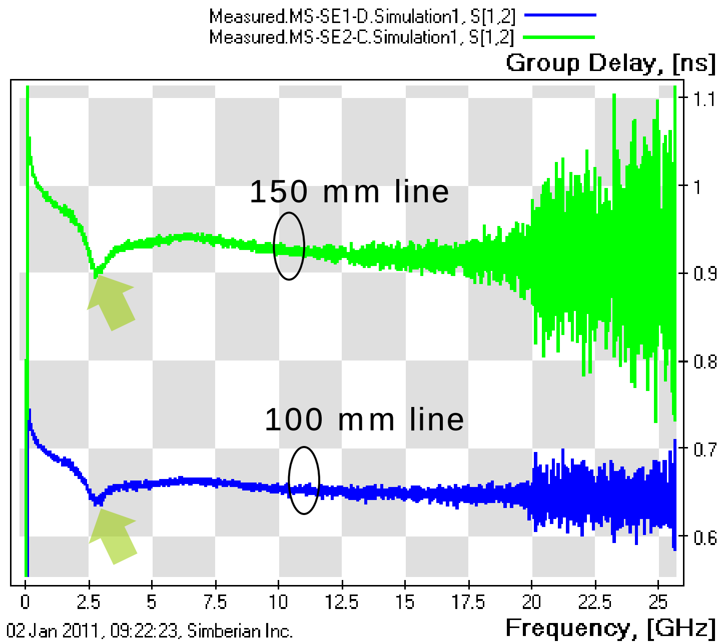


Differential group delays for three structures with 100 mm microstrip line segments and one structure with 150 mm segments are plotted

Structures for Nickel Model Identification

- Two structures suitable for the identification – contain 100 mm and 150 mm segments of microstrip line – both structures show anomalies around 2.7 GHz

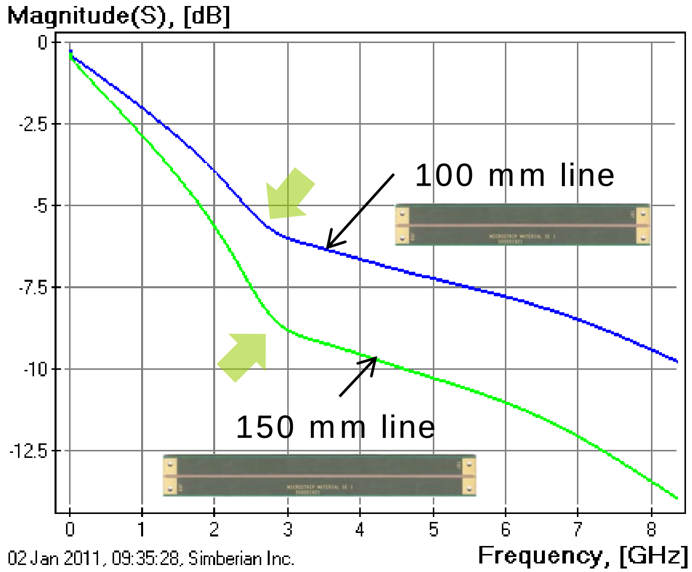


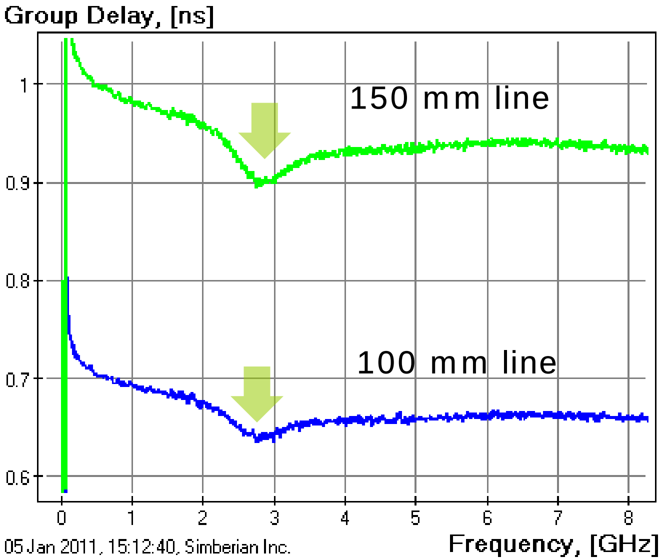


ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper
Microstrip width 74 um, thickness 15 um, substrate 30 um, wideband Debye model DK=3.x and LT=0.01x at 1 GHz

Anomaly in IL and GD is clearly due to Nickel plating

- Deviation 2-3 dB from Insertion Loss expected with regular conductor
- Deviation 40-60 ps from Group Delay expected with regular conductor



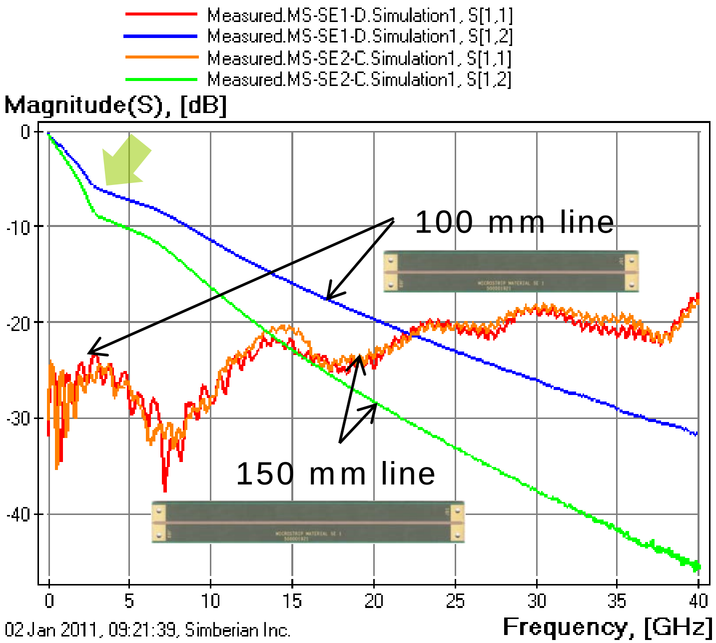


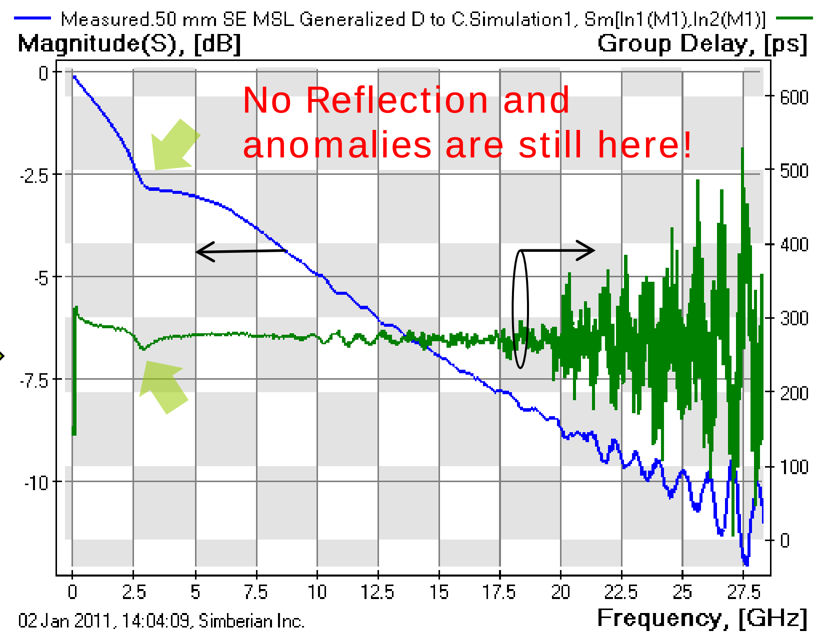
ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper
Microstrip width 69 um, thickness 12 um, substrate 30 um, wideband Debye dielectric model: DK=3.x and LT=0.01x at 1 GHz

GMS-parameters (reflection-less) can be extracted from these two models for identification

Generalized Modal Scattering (GMS) Parameters

- S-parameters of reflective structures with 100 mm and 150 mm segments of microstrip line can be converted into GMS-parameters of 50 mm segment





Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Practical identification of dispersive dielectric models with generalized modal S-parameters for analysis of interconnects in 6-100 Gb/s applications, DesignCon 2010.

GMS-parameters are noisy at high frequencies due to non-identities of probes/launches and cross-sections of two test structures (see more on sensitivity in app note #2010_03, www.simberian.com)

Landau-Lifshits Model of Ferromagnetic Metal

L. Landau, E. Lifshits, On the theory of the dispersion of magnetic permeability in ferromagnetic bodies, Phys. Zeitsch. der Sow., v. 8, p. 153-169, 1935

- Magnetic permeability dispersion equations are derived from description moving boundaries of oppositely magnetized layers in ferromagnetic metal

$$\mu(f) = \mu_h + (\mu_l - \mu_h) \cdot \frac{f_0^2 + i \cdot f \cdot \gamma}{f_0^2 + 2i \cdot f \cdot \gamma - f^2}$$

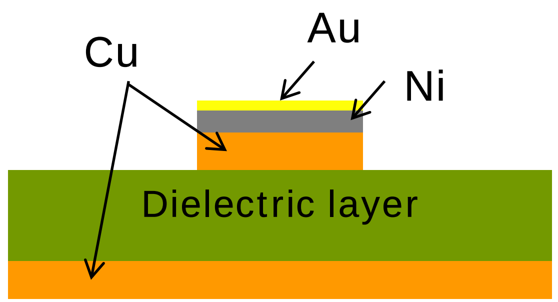
μ_l – *permeability at low frequencies*; μ_h – *permeability at high frequencies*;

f_0 – *resonance frequency* [Hz]; γ – *damping coefficient* [Hz]

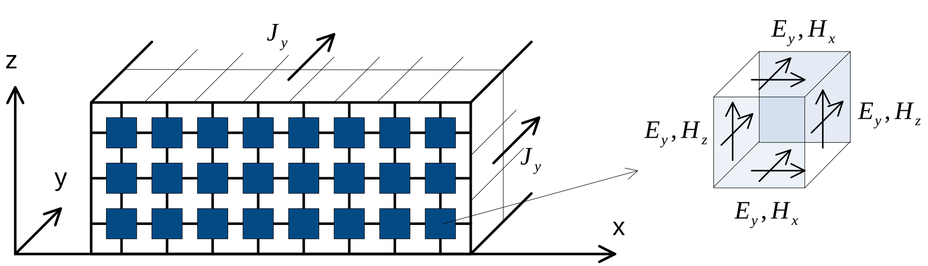
- Usable at microwave frequency band
- Lorentz model may be also acceptable for resonance description (2-nd order Debye)
- Can be combined with Debye model at lower frequencies and Lorentz model at the millimeter frequencies

Electromagnetic model of microstrip line

- Hybrid model has been constructed to simulate segment of transmission line
- Method of Lines (MoL) is used for multi-layered dielectric and plane layer – produced grid Green's function (GGF) (*)
- Multi-layered conductor interior meshed with Trefftz-Nikol'skiy finite elements and matched with the GGF (*)
- Method of simultaneous diagonalization is used to extract modal and per unit length parameters of microstrip line (*)



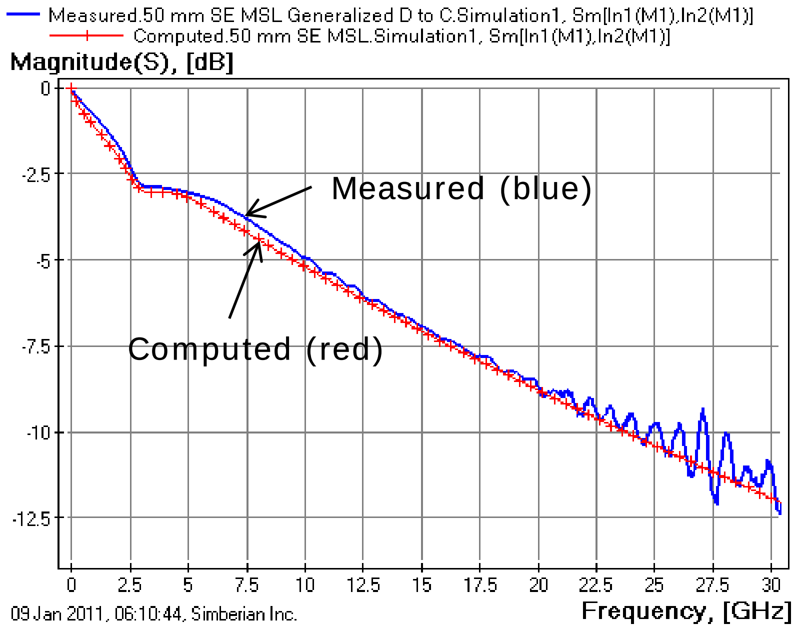
Conductor interior model

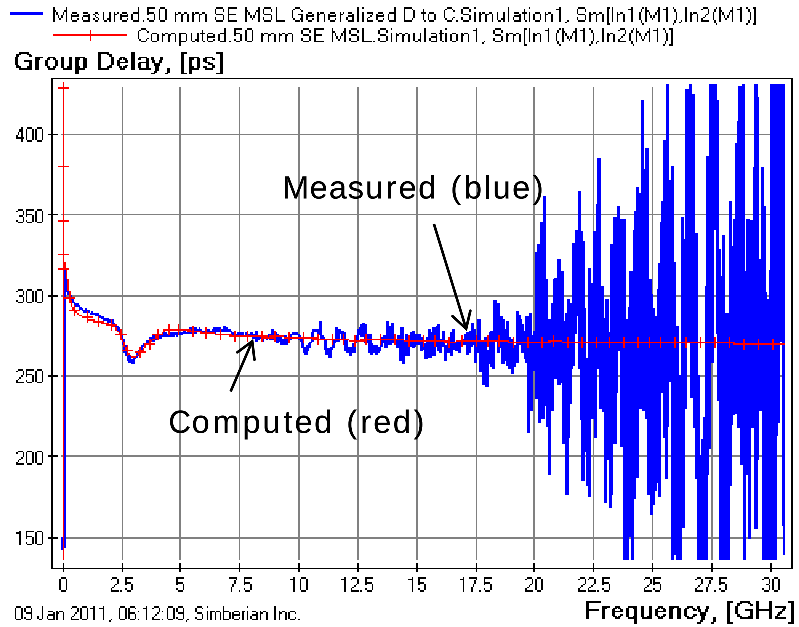


(*) References are in the paper
Model is implemented in electromagnetic signal integrity software Simbeor 2011 – available at www.simberian.com

Plated Nickel Model Identification

- Adjust Ni model parameters to match measured and computed GMS-parameters for 50 mm segment of microstrip line, strip width 69 um, thickness 12 um

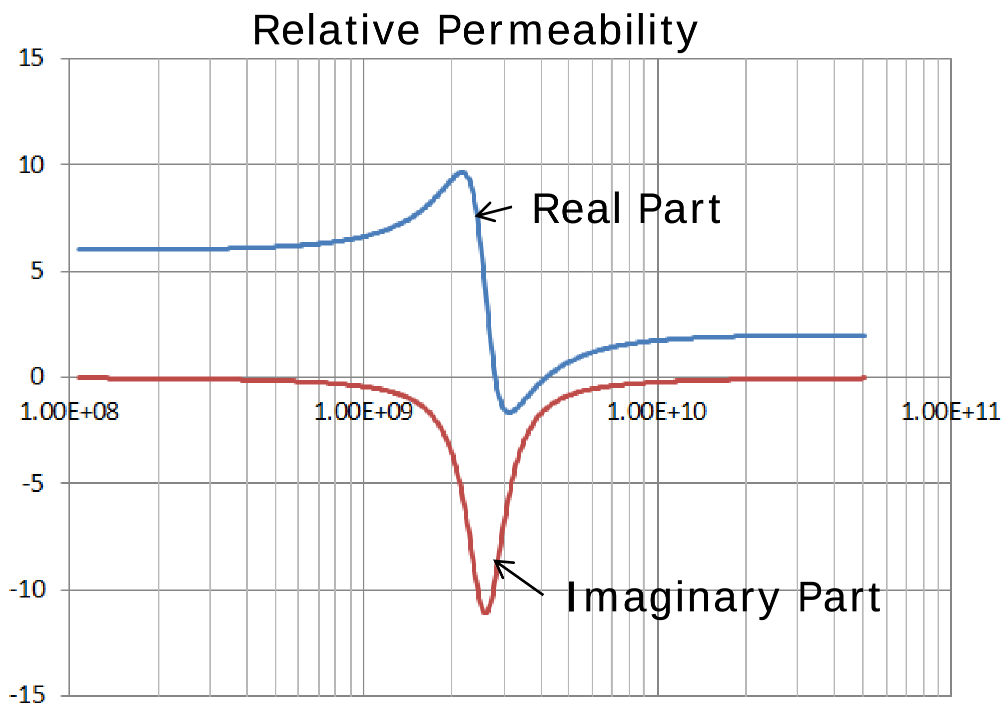




ENIG finish with about 0.05 um of Au and about 6 um of Ni over the copper
Substrate dielectric DK=3.x and LT=0.01x at 1 GHz, wideband Debye model
Landau-Lifshits model for Nickel: Mul=6, Muh=2, f0=2.6, dc/f0=0.18, relative resistivity 6

Identified Model for Plated Nickel

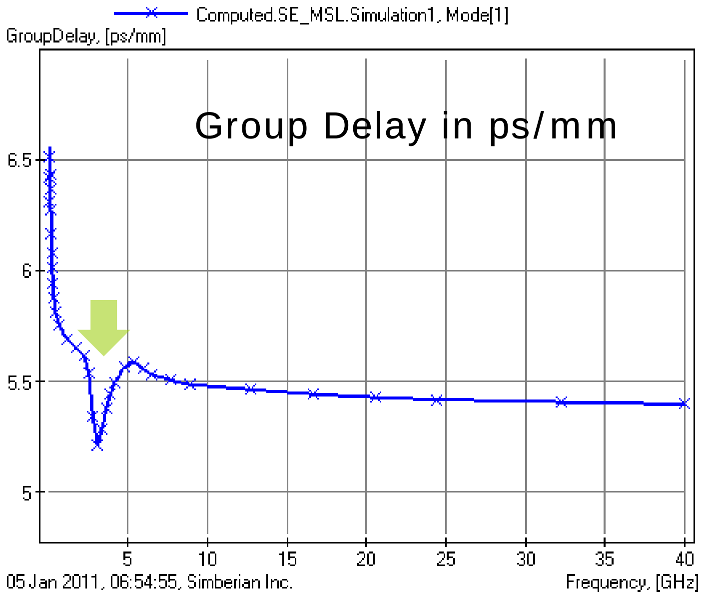
- Resistivity 1.0e-7 Ohm*meter
- Landau-Lifshits Permeability Model: Mul=6, Muh=2, f0=2.6, dc/f0=0.18

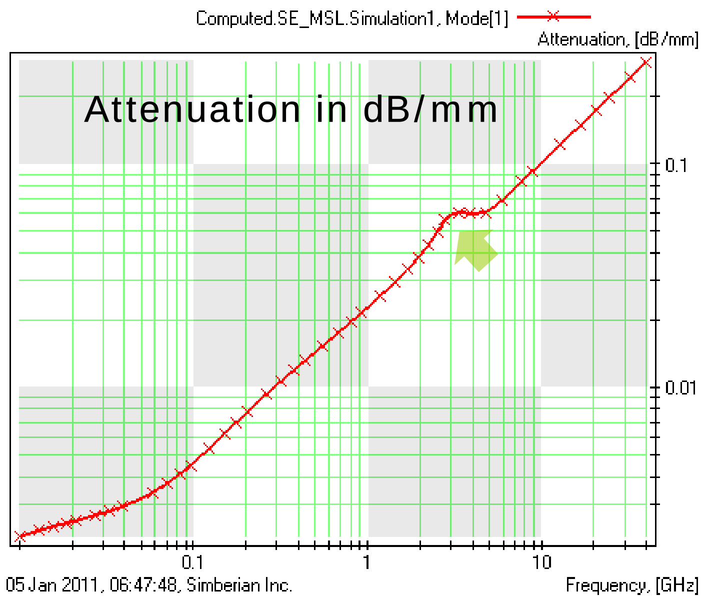


May be further refined with a dedicated experiment with more defined geometry

Effect of nickel on t-line parameters

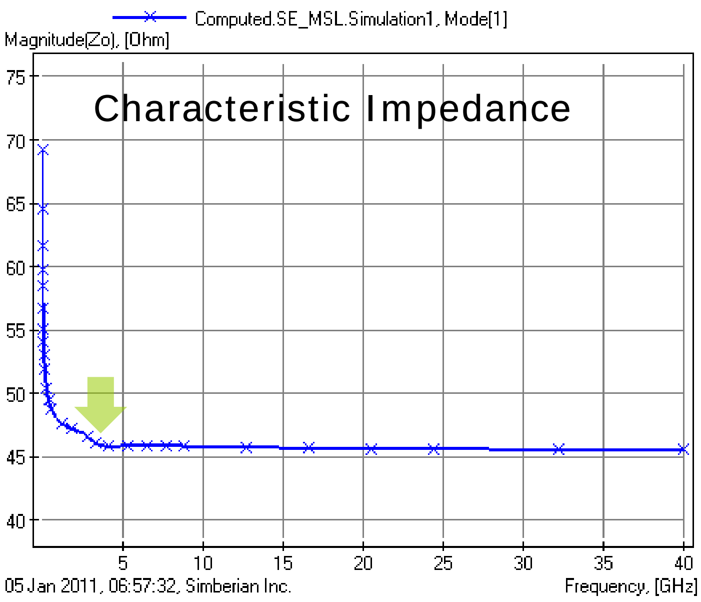
- We can observe decrease of group delay and increase in attenuation per unit length

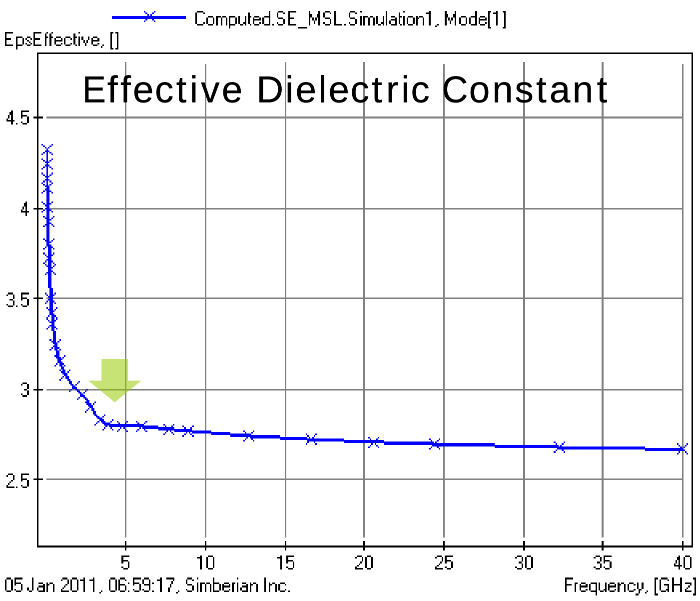




Effect of nickel on t-line parameters

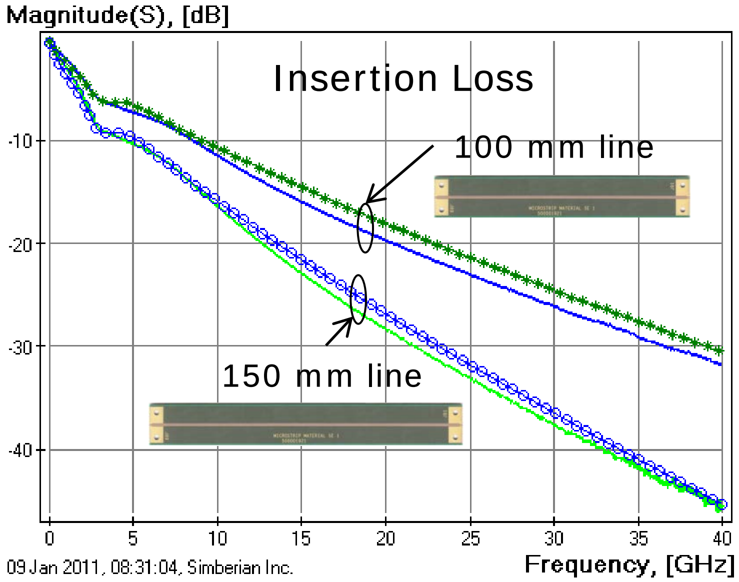
- The effect is less visible on the characteristic impedance and effective dielectric constant

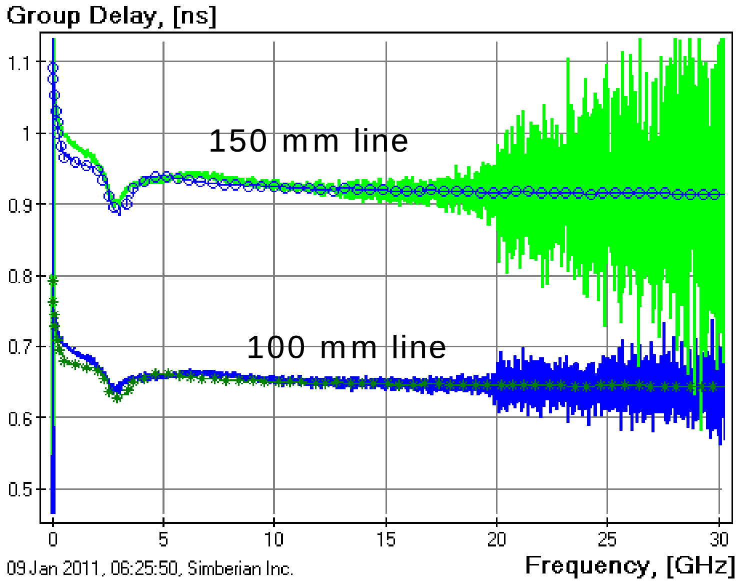




S-parameters of test fixtures

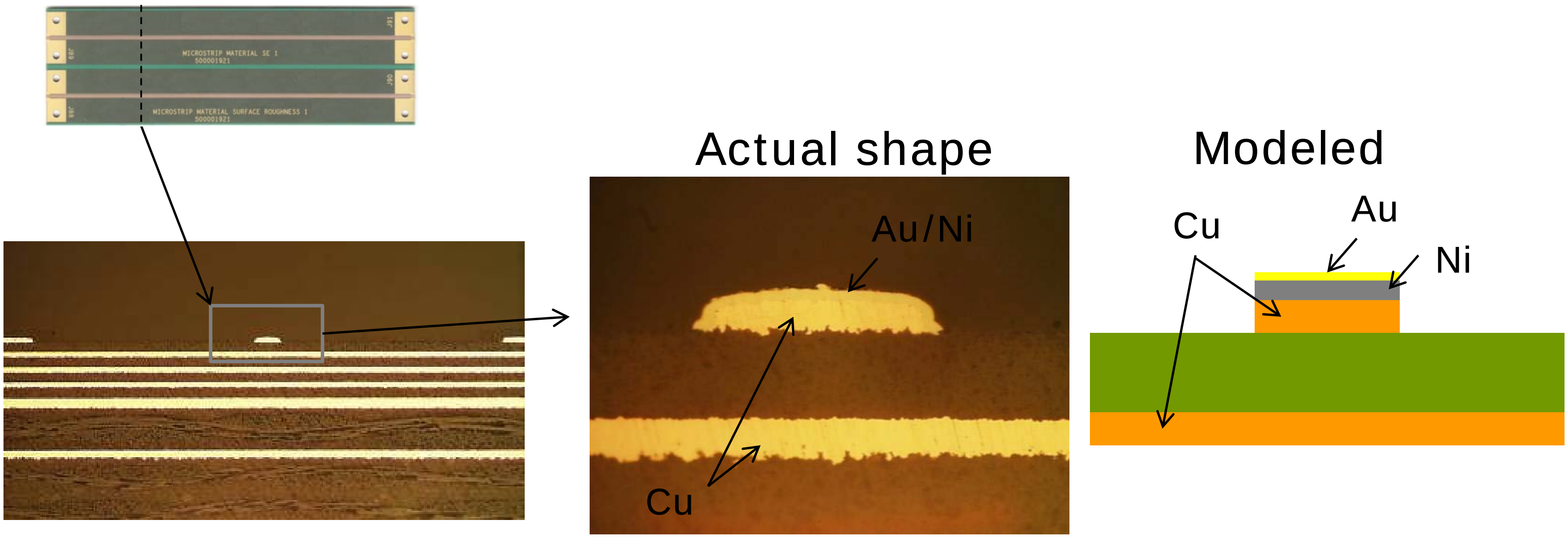
- Nickel: resistivity 1.0e-7 Ohm*meter, Landau-Lifshits Permeability Model: Mul=6, Muh=2, f0=2.6, dc/f0=0.18





Possible sources of discrepancies

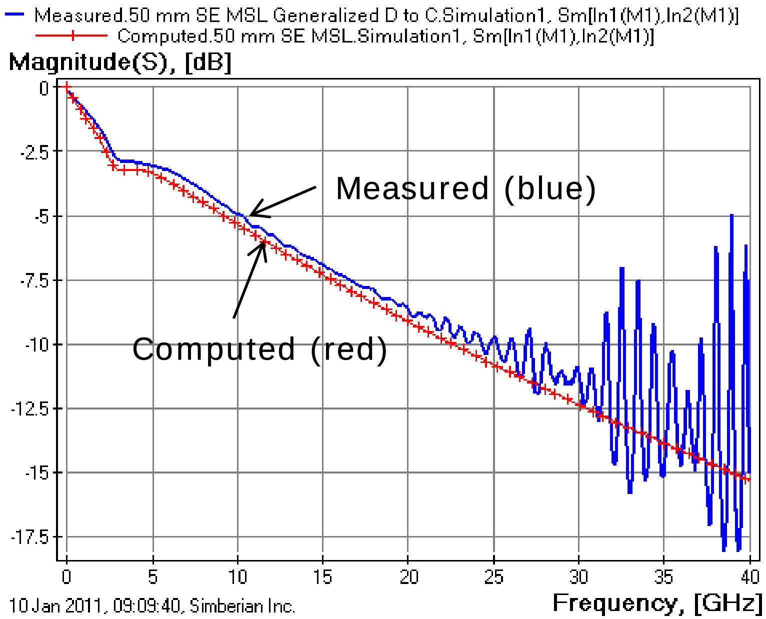
- Simulated – rectangular shape with 0.05 um of Au/6 um of Ni/9 um of Cu
- Actual structure has irregular shape – not even trapezoidal

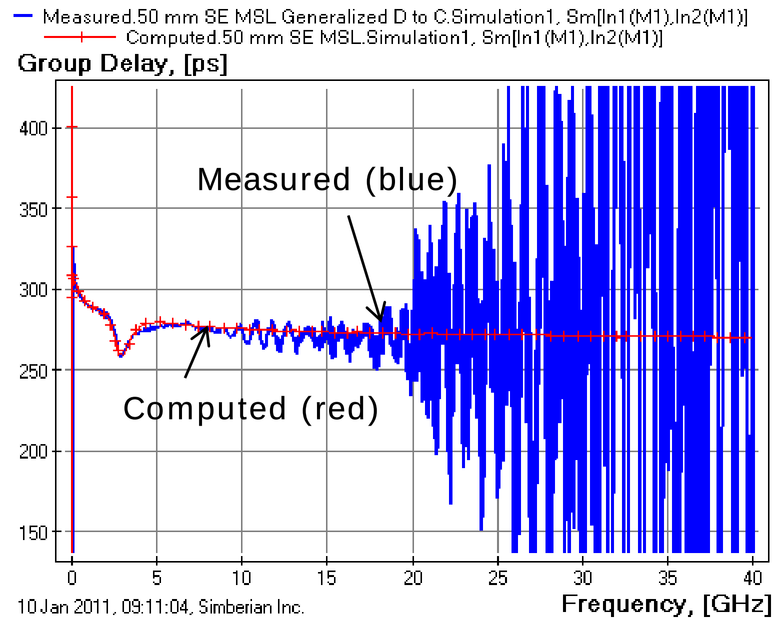


Strip bottom: RMS roughness 0.6-1.2, Roughness factor 2.5 – should be defined formally with profilometer measurements

Plated Nickel Model Identification (2)

- Adjust Ni model parameters to match measured and computed GMS-parameters for 50 mm segment of microstrip line, strip width 69 um, thickness 12 um

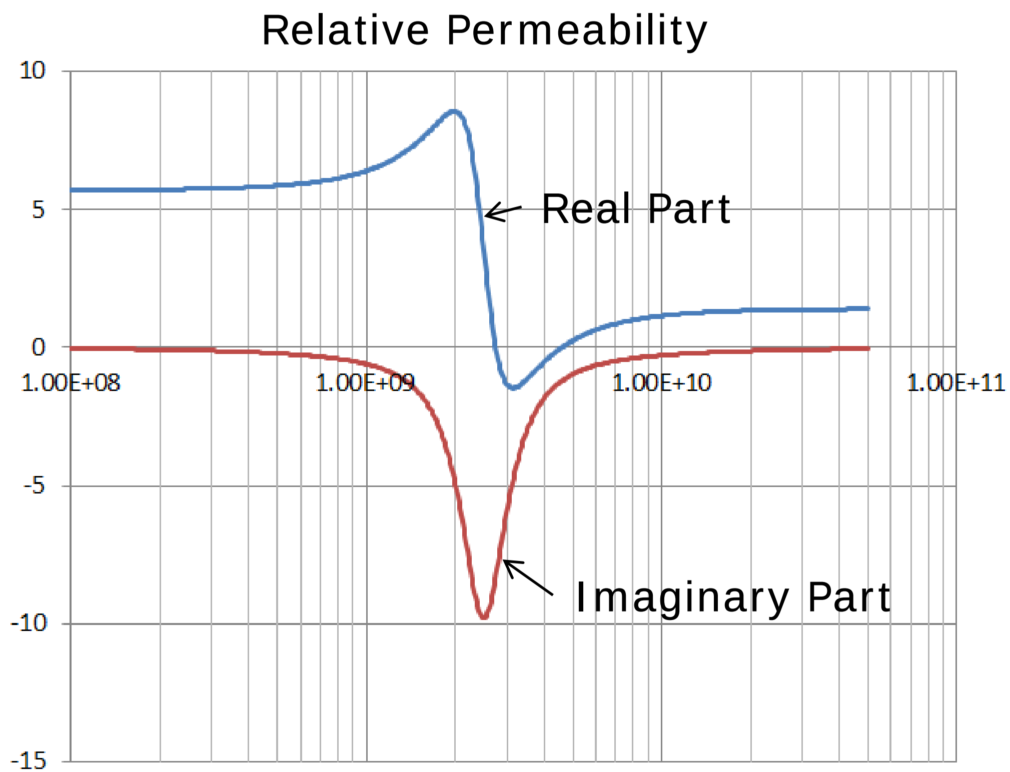




ENIG finish with about 1 um of Ni over the copper
Substrate dielectric DK=3.x and LT=0.01x at 1 GHz, wideband Debye model
Landau-Lifshits model for Nickel: Mul=5.7, Muh=1.4, f0=2.5, dc/f0=0.22, relative resistivity 3.75

Identified Model for Plated Nickel (2)

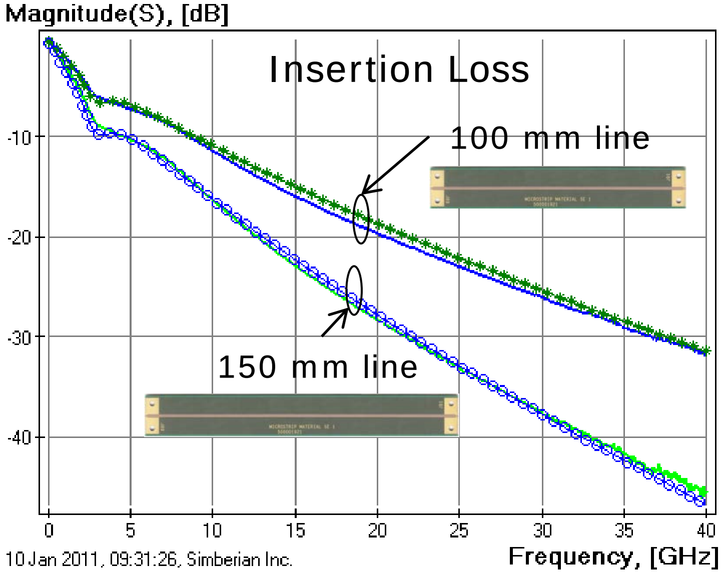
- Resistivity 6.46e-8 Ohm*meter (conductivity 1.55e7 S/m)
- Landau-Lifshits Permeability Model: Mul=5.7, Muh=1.4, f0=2.5, dc/f0=0.22

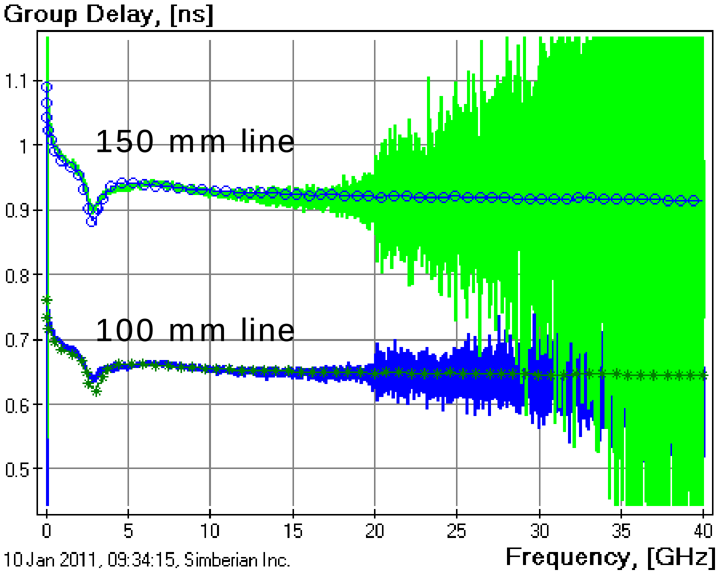


May be further refined with a dedicated experiment with more defined geometry

S-parameters of test fixtures

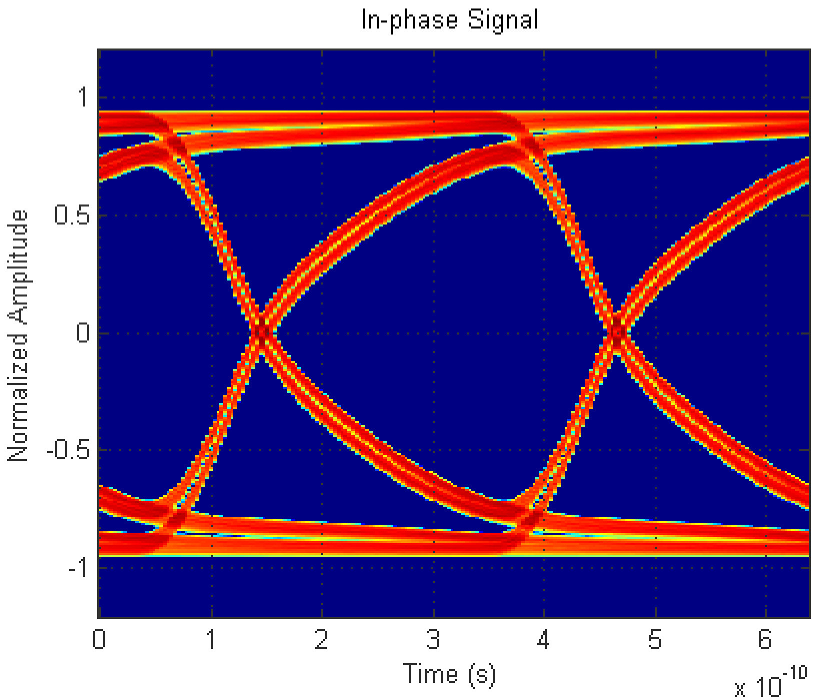
- Nickel: resistivity 6.46e-8 Ohm*meter, Landau-Lifshits Permeability Model: : Mul=5.7, Muh=1.4, f0=2.5, dc/f0=0.22



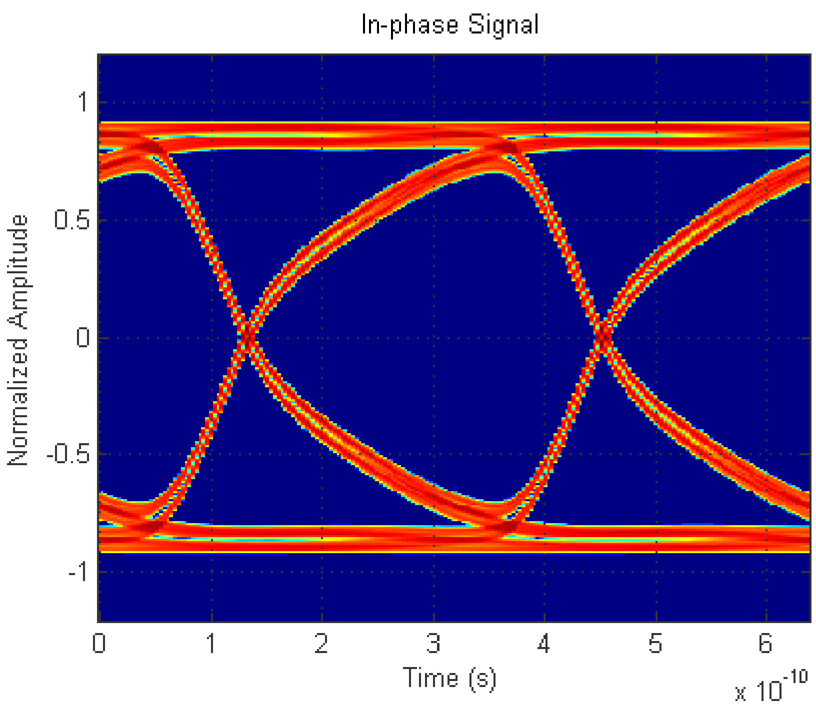


3.125 Gbps signal in structure with 150 mm line

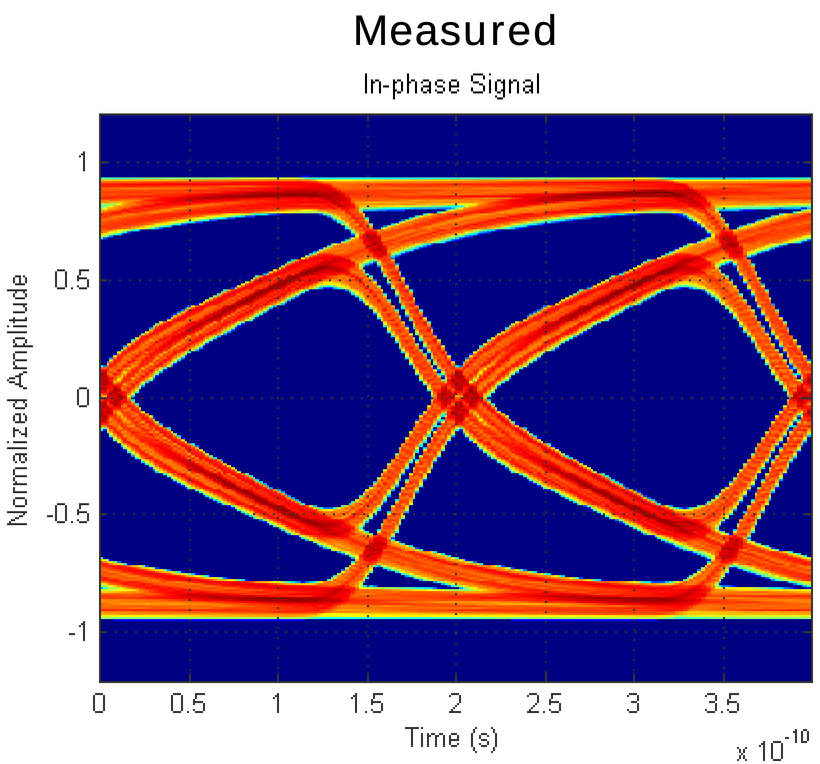
Measured

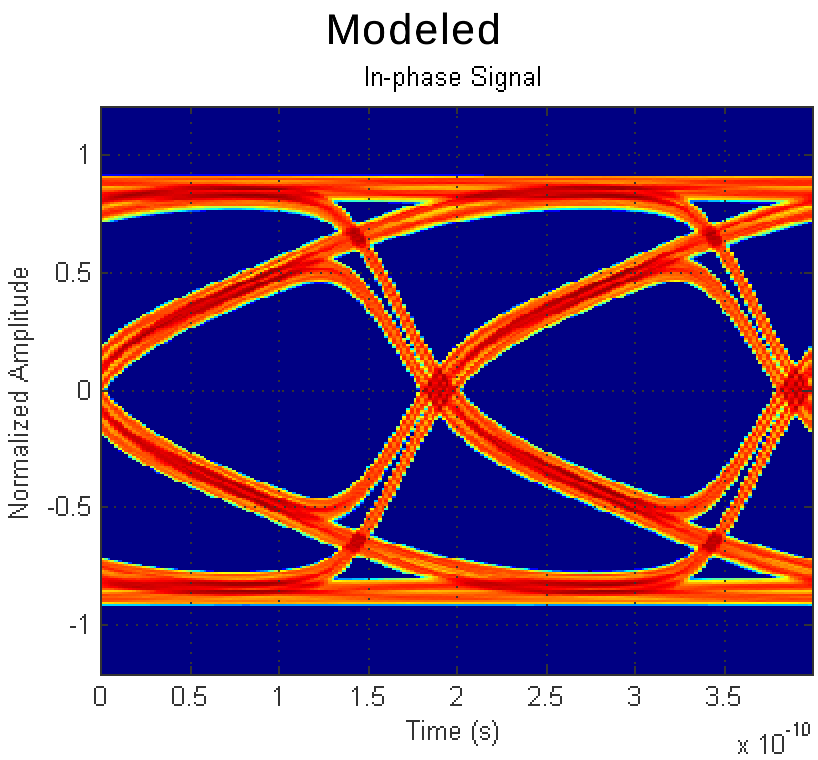


Modeled



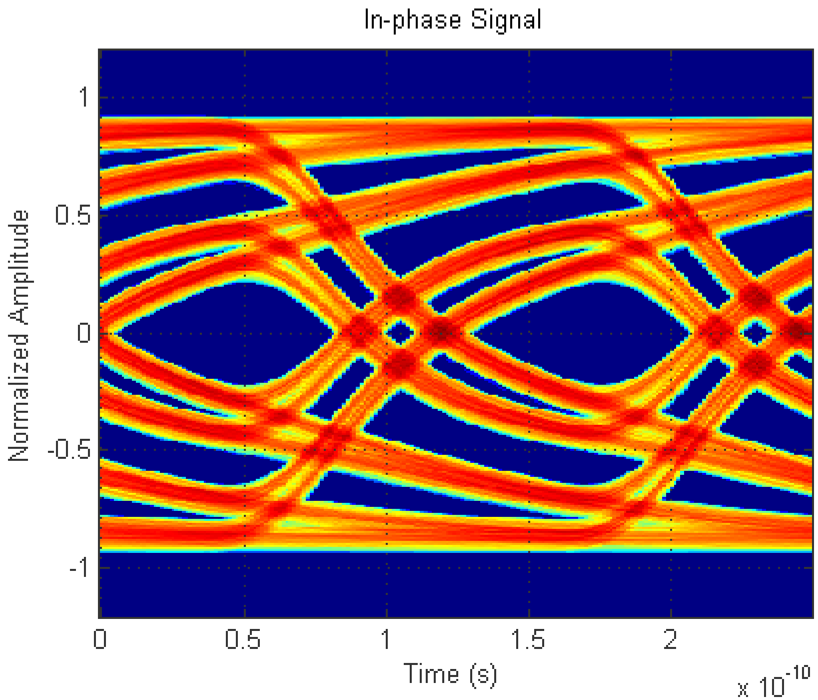
5 Gbps signal in structure with 150 mm line



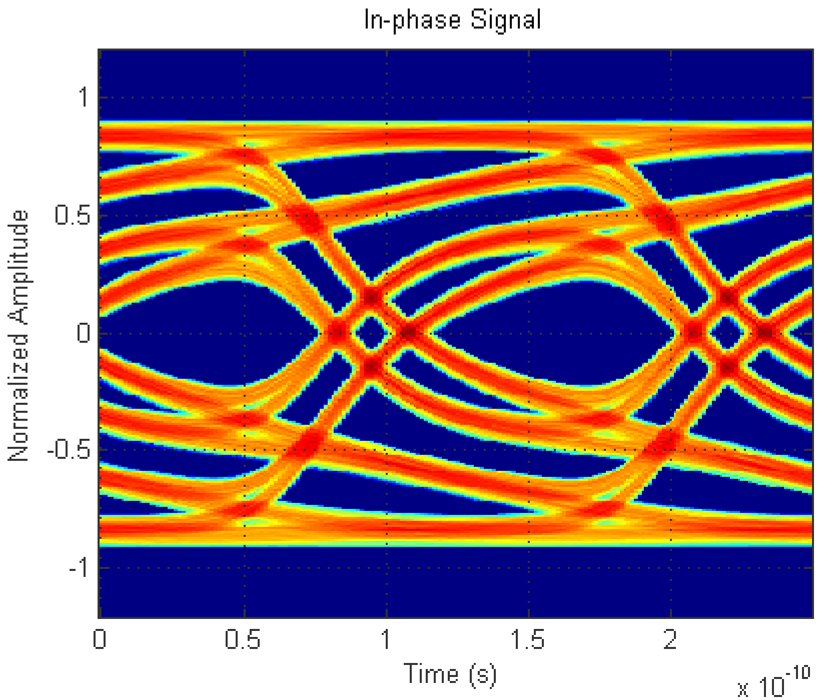


8 Gbps signal in structure with 150 mm line

Measured

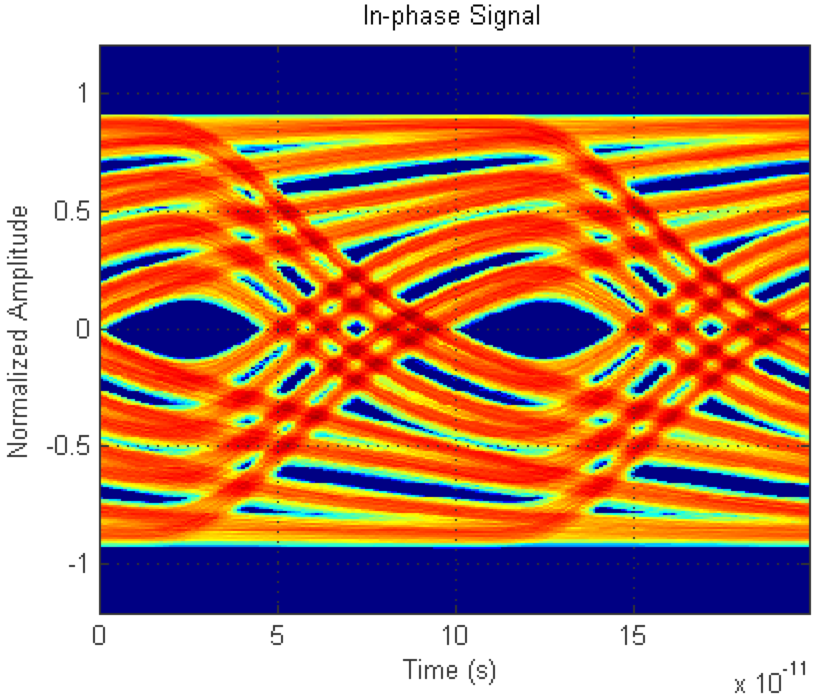


Modeled

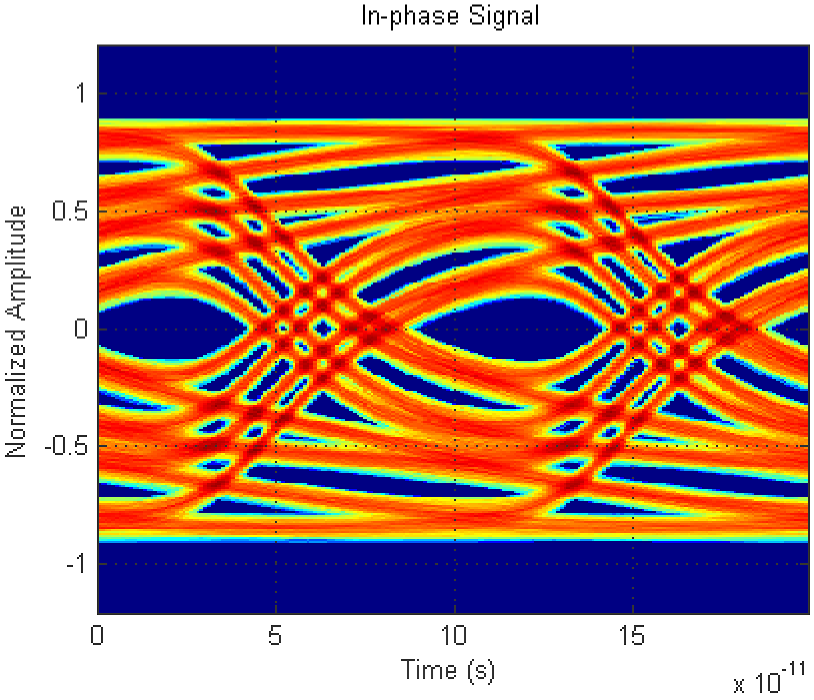


10 Gbps signal in structure with 150 mm line

Measured

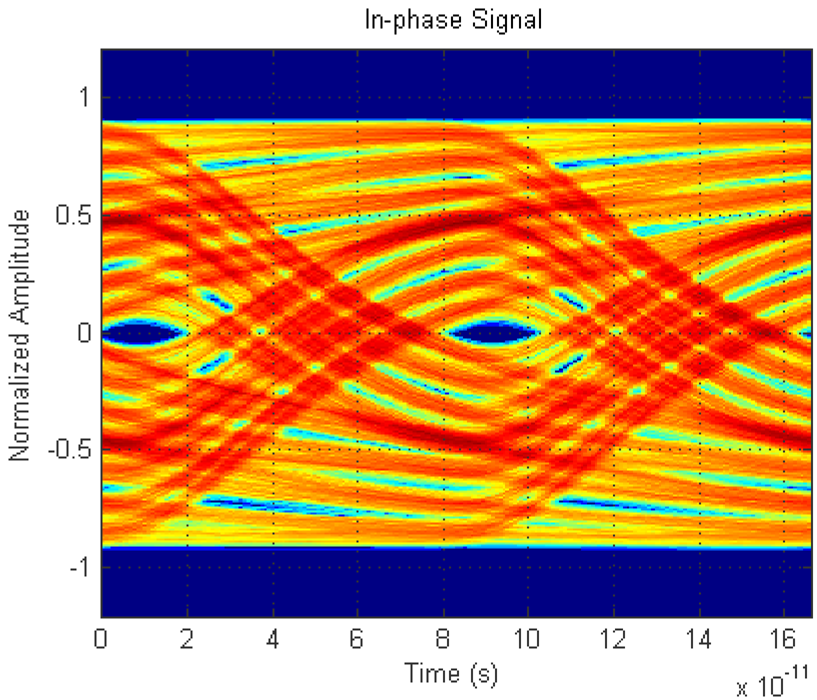


Modeled

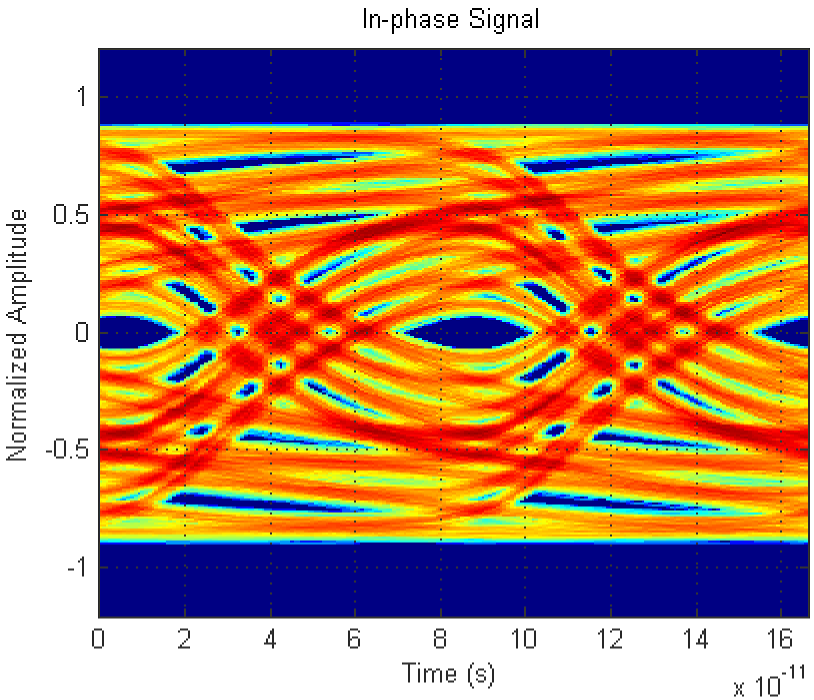


12 Gbps signal in structure with 150 mm line

Measured



Modeled



Conclusion

- Resonant behavior of interconnects made of copper plated with nickel and gold (ENIG finish) has been reported
  - Resonance at about 2.7 GHz shows up on insertion loss as well as on group delay graphs and cannot be simply explained
  - The resonance is attributed to ferromagnetic properties of nickel layer
- Electromagnetic model of copper microstrip line segment plated with Ni and Au has been constructed
- Landau-Lifshits (L-L) ferromagnetic metal model is used to simulate nickel in the multi-layered conductor
- Parameters of the L-L model are identified by matching measured and computed GMS-parameters of line segment
- Use of accurate Nickel models increases confidence in modeling of ENIG-finished interconnects

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