Lumped Skin Effect Model for Package Leads

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Outline

- Brief overview of previous works on the modeling of skin effect
- Proposed modeling methodology
- Application examples
- IBIS issues
- Conclusion

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PEEC Based Methods (Ref [1])

Advantages	Disadvantages
Accuracy	Complexity (curve fitting is an alternative)
	Assumption of known geometry

FIG. 1

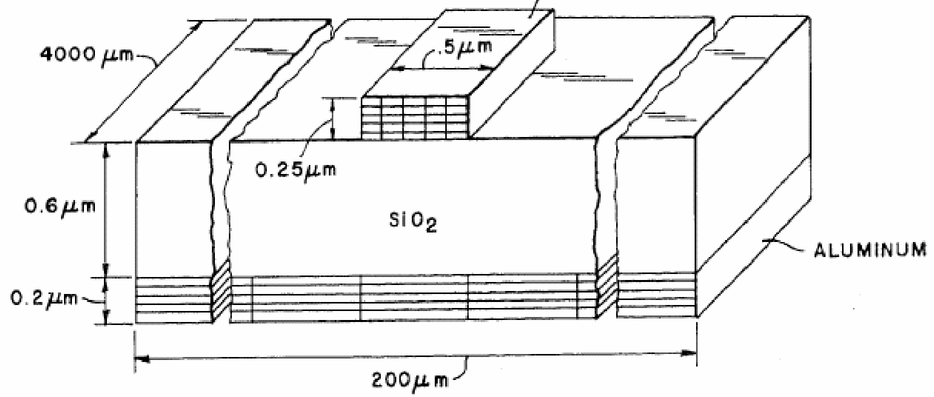
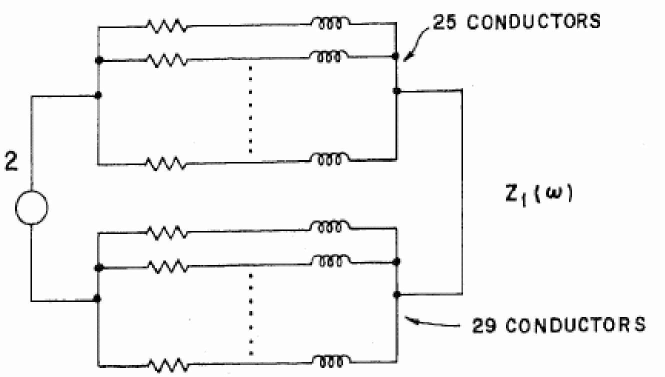


FIG. 2



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Coaxial Line Based Models (Ref [2])

Advantages	Disadvantages
Physics-based	Requires curve-fitting for arbitrary cross-sections
	Computationally inefficient

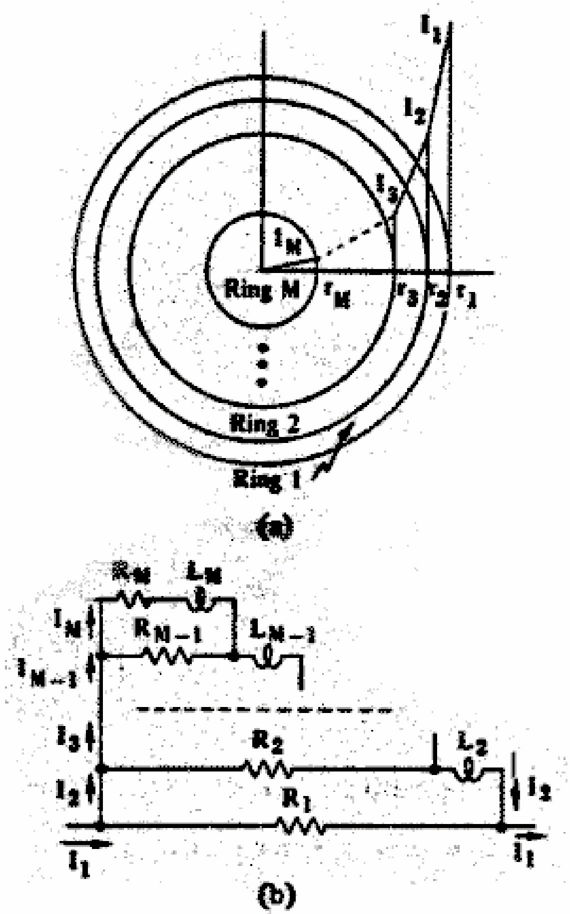
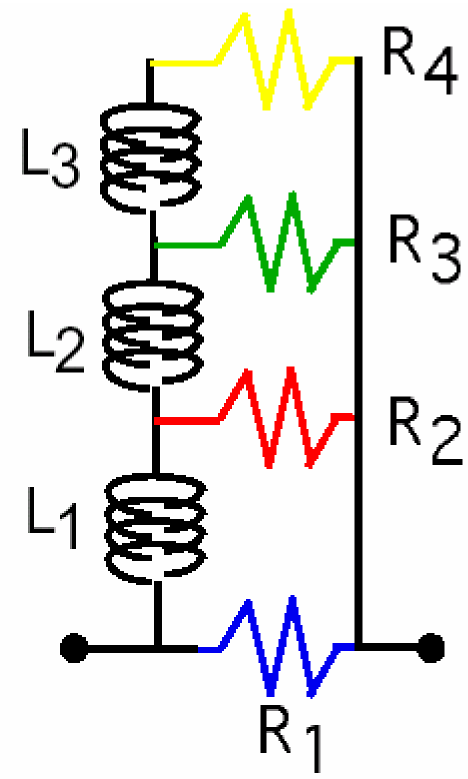


Fig. 1. (a) Center conductor ring definition and current distribution. (b) Equivalent circuit for skin-effect loss.

Ladder Network Based Model (Ref [3])

Advantages	Disadvantages
L_{dc}, R_{dc}, and R_{ac} are considered	Requires fitting of a parameter
	Bandwidth is limited

- $R_i / R_{i+1} = RR$, a constant (> 1)
  - $R_2 = RR\ R_1$, $R_3 = RR^2 R_1$, $R_4 = RR^3 R_1$
- $L_i / L_{i+1} = LL$, a constant (< 1)
  - $L_2 = LL\ L_1$, $L_3 = LL^2 L_1$



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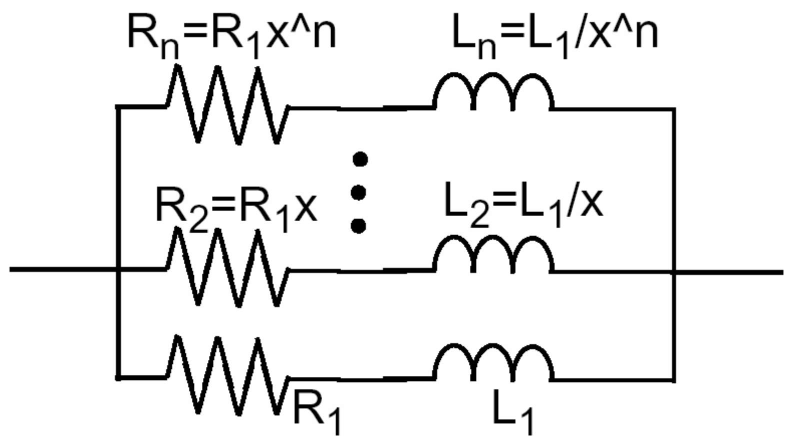
Foster-Type Model (Ref [4])

Advantages	Disadvantages
Bandwidth can be increased easily	Not very accurate (does not consider Rac)
No curve fitting is necessary	



Ideal Skin-Effect Model

Advantages	Disadvantages
Accuracy	
Physics-based	
L_{dc}, R_{dc}, and R_{ac} are considered	
Bandwidth can be increased easily	
No curve fitting is necessary	

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Skin-Effect in a Conducting Half-Plane (Ref[5])

- ❑ Inductance

$$\Delta L = \frac{\mu l \Delta z}{w}$$

- ❑ Admittance

$$\Delta G = \frac{\sigma w \Delta z}{l} = \frac{w \Delta z}{\rho l}$$

- ❑ Characteristic Impedance

$$Z = \sqrt{j\omega \Delta L / \Delta G} = \frac{l}{w}\sqrt{j\omega\mu\rho}$$

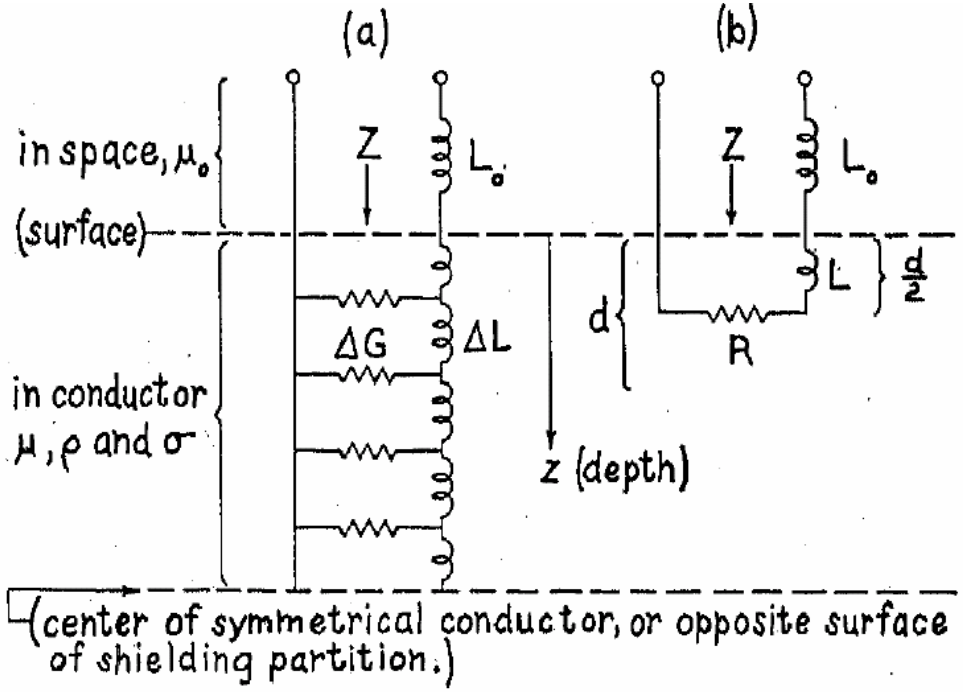

Fig. 3—The internal impedance of a conductor, in terms of distributed circuit parameters (a) and equivalent lumped parameters (b).

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Driving-Point Impedance of an Open-Circuited ULG Line

- Driving-point impedance of an open-circuited uniform LG Line (L and G are the total inductance and admittance)

$$Z_{oc} = \sqrt{\frac{sL}{G}} coth(\sqrt{sLG})$$

- For given R_{DC}, $R(f_0)$ and f_0

$$G = 1/R_{DC}$$

$$R(f_0) = \sqrt{(}\pi f_0 \frac{L}{G})$$

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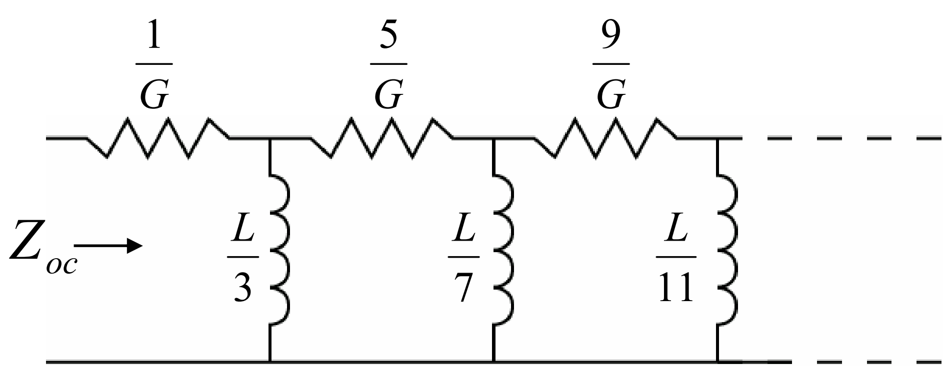
Approximation of the Input Impedance (Ref [6][7])

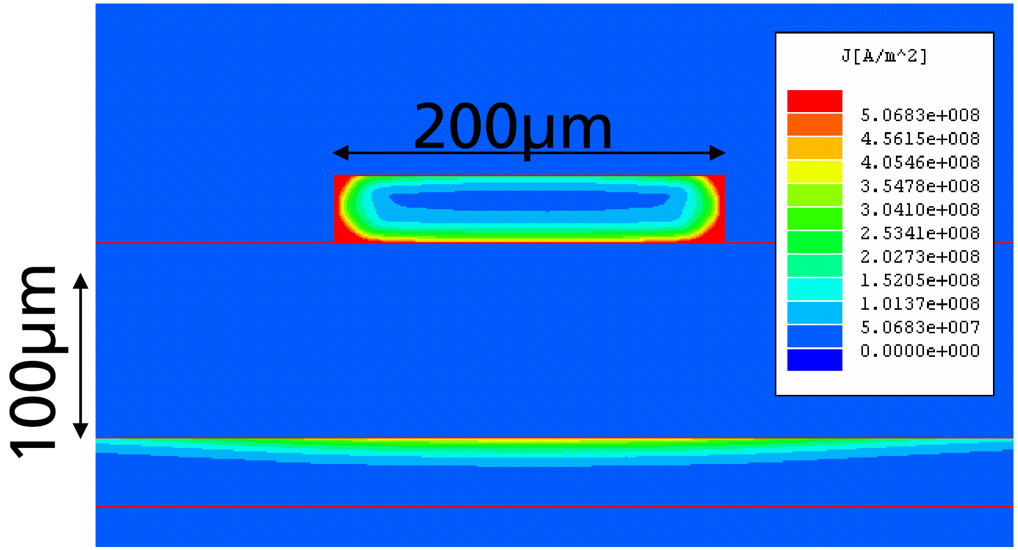
- Continued Fraction Expansion:

$$Z_{oc} = \frac{1}{G} + \cfrac{1}{\cfrac{3}{sL} + \cfrac{1}{\cfrac{5}{G} + \cfrac{1}{\cfrac{7}{sL} + \cdots}}}$$

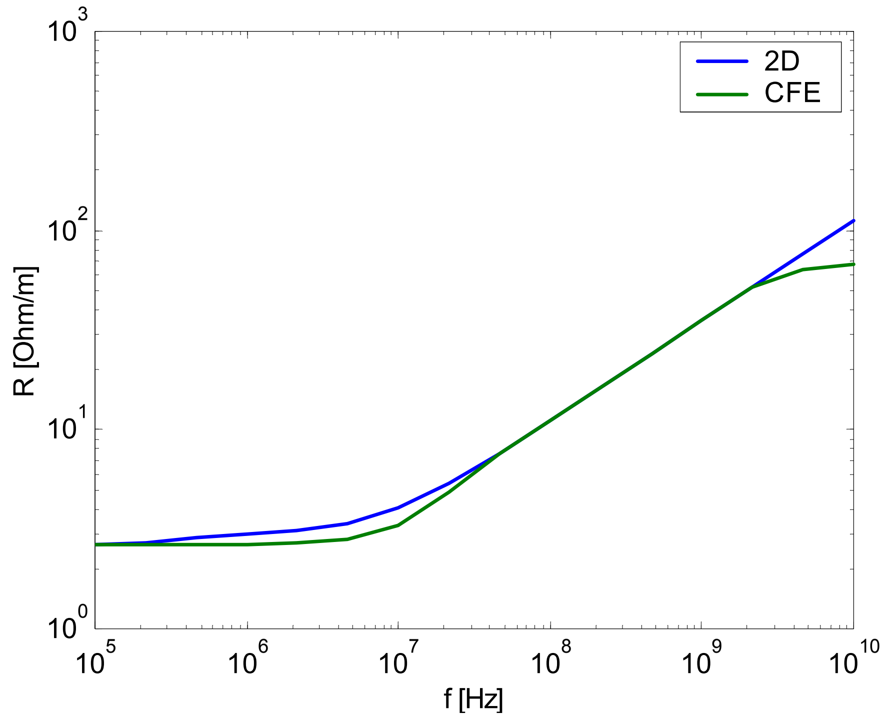


2D Simulation of a Microstripline

- 2D Simulation, CFE (n=6, L=1.57e-7, G=0.4)
- R_{DC}=2.5 Ohm, $R(f_0)$=35.6 Ohm, f_0=1GHz



Current Distribution at 100 MHz



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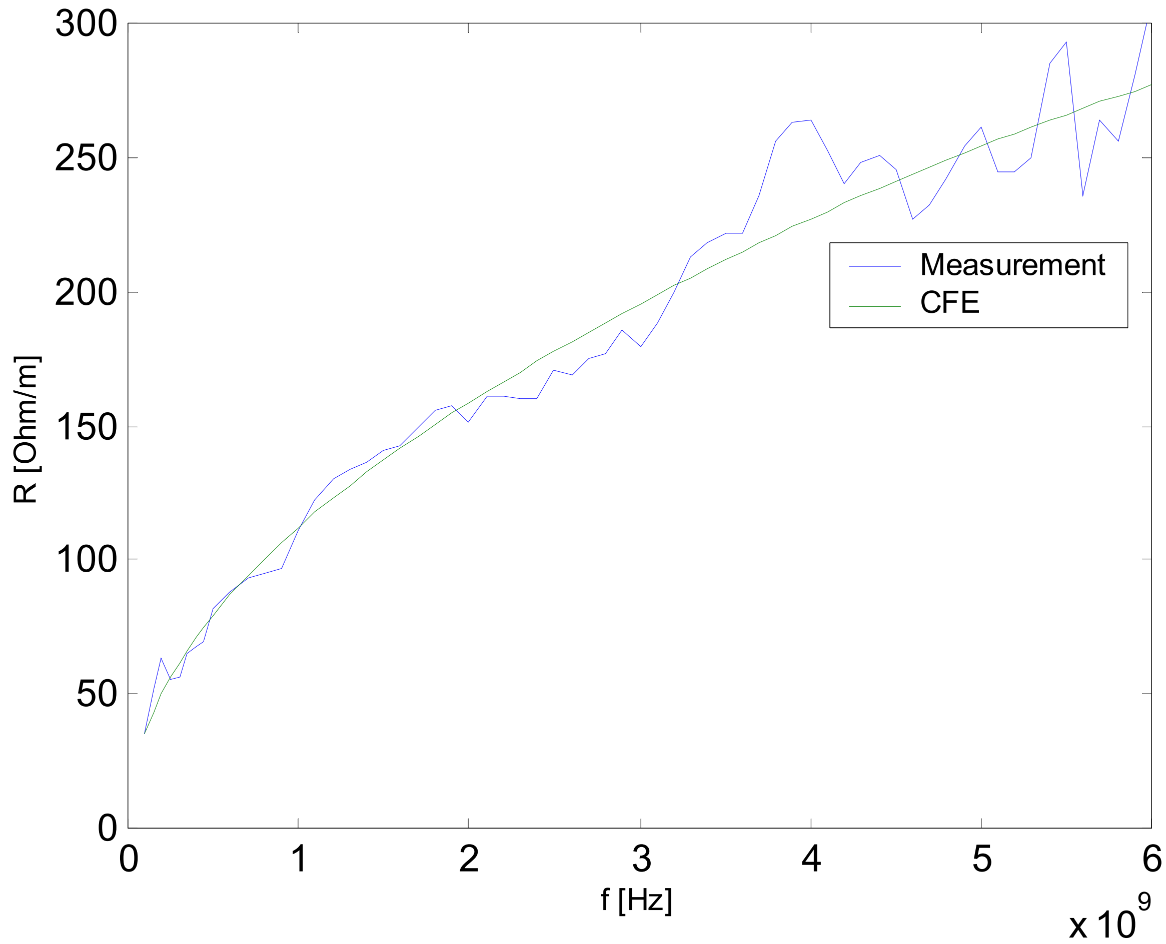
Measurement of a Stripline

- Measurement,
  CFE (n=6, L=2.41e-7, G=0.0625),

- R_{DC}=15 Ohm, $R(f_0)$=110 Ohm,
  f_0=1GHz



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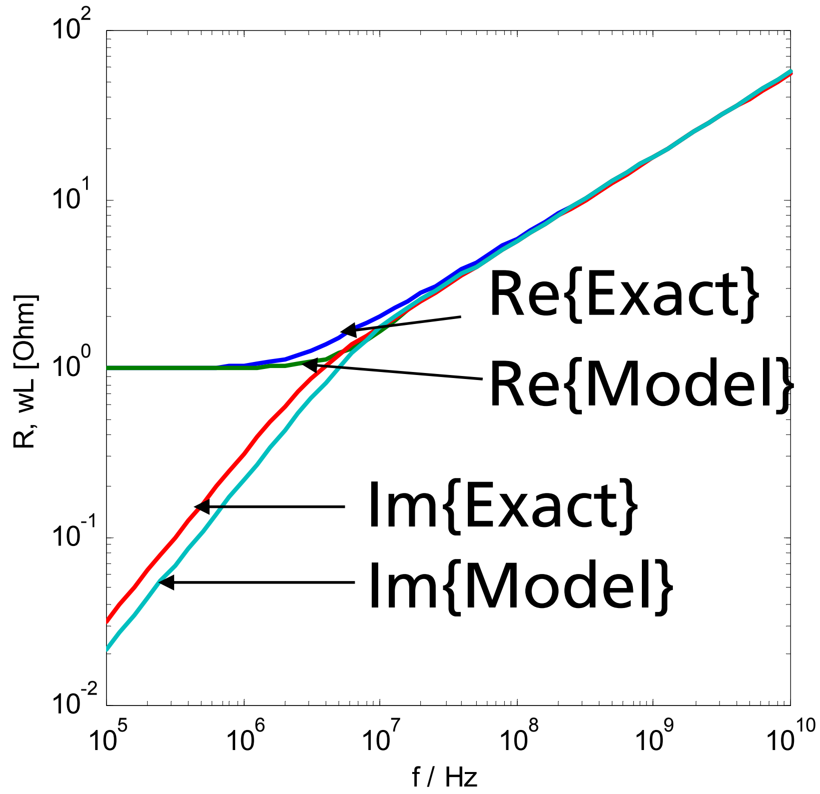
Comparison with a Round Wire

- Internal impedance of a round wire

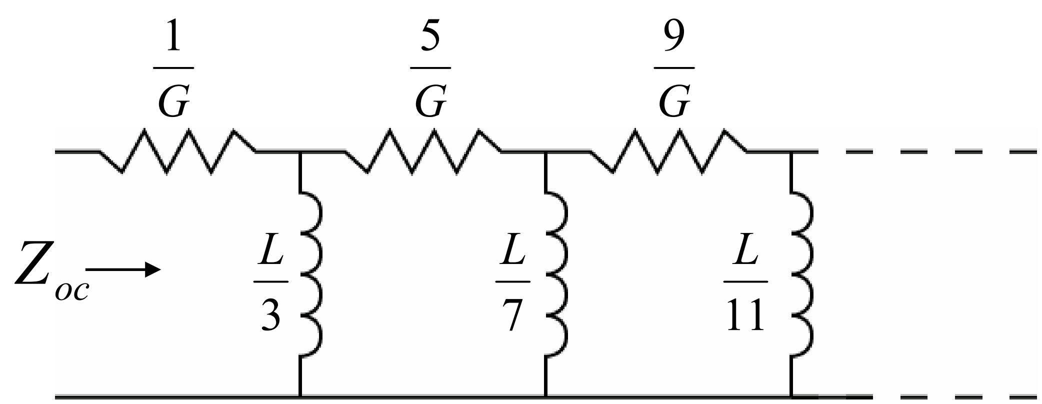
$$Z = \frac{\sqrt{jw\mu/\sigma}}{2\pi r}\frac{I_0(r\sqrt{jw\mu\sigma})}{I_1(r\sqrt{jw\mu\sigma})} \quad \mathrm{Ohm/m}$$

- Very good correlation for high frequencies, small deviation at the transition region and the internal inductance term



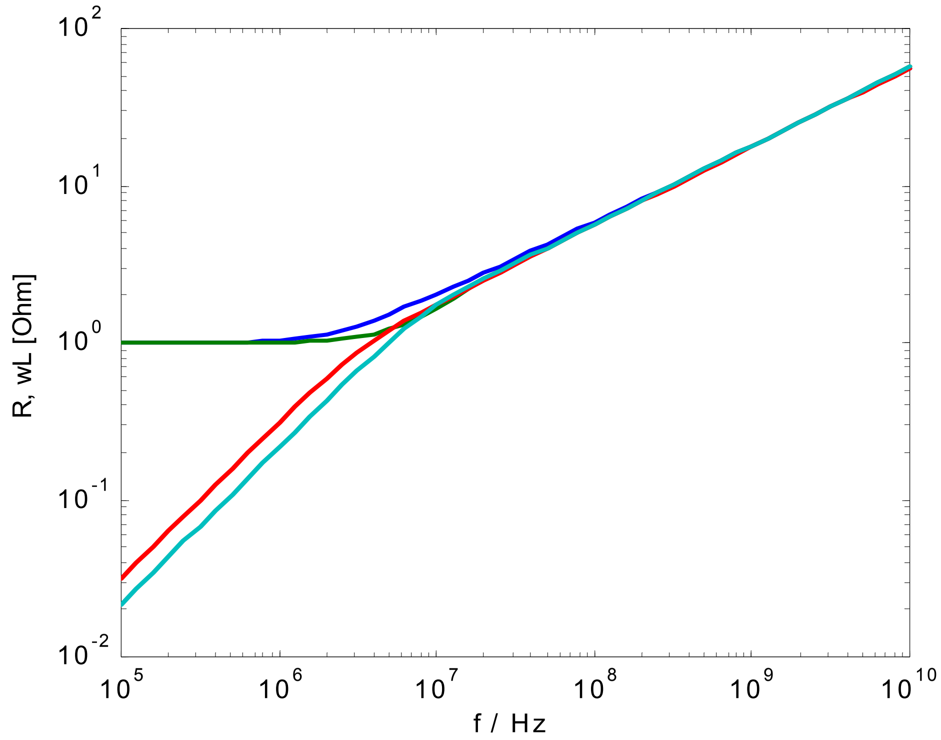
Inclusion of the Correct Internal Inductance Term in CFE

- L can be obtained as $L=3*L_{DC}$
- G can be obtained from the AC resistance
- The first resistance should be R_{DC}

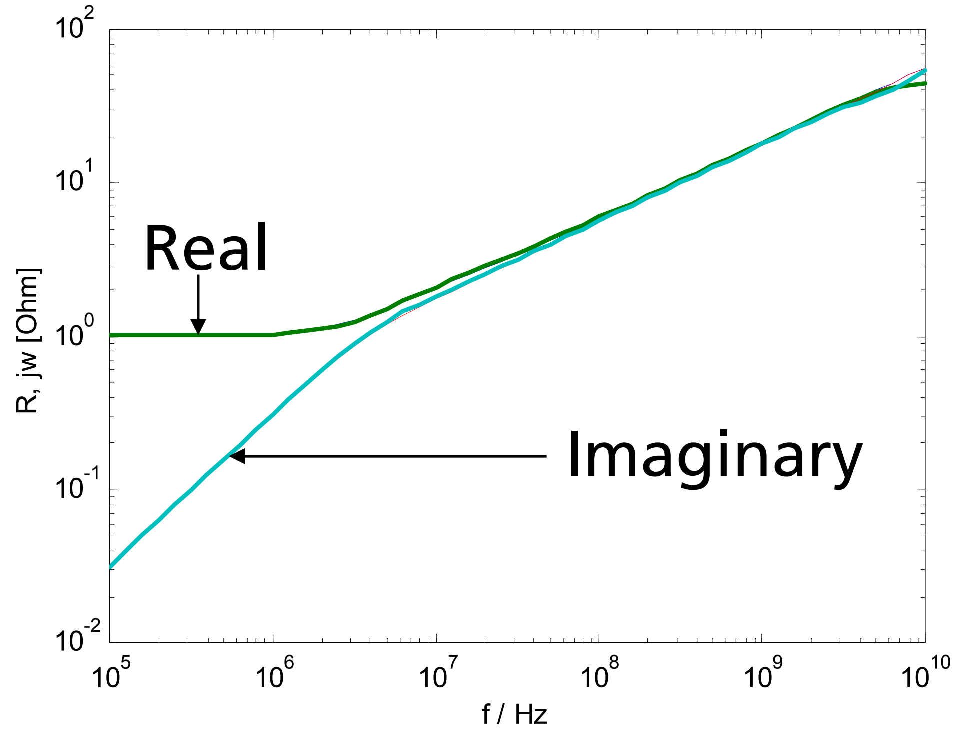



```
.SUBCKT cfe na nb rdc=1 ldc=5e-8 rac=100 fac=1e4
.PARAM l='ldc*3' g='pi*fac*l/(rac*rac)'
R1 na 2 'rdc'
L1 2 nb 'l/3'
R2 2 3 '5/g'
L2 3 nb 'l/7'
R3 3 4 '9/g'
L3 4 nb 'l/11'
R4 4 5 '13/g'
L4 5 nb 'l/15'
R5 5 6 '17/g'
L5 6 nb 'l/19'
R6 6 7 '21/g'
...
.ENDS
```

Inclusion of the Correct Internal Inductance Term in CFE



Before correcting the L_{DC} term



After correcting the L_{DC} term

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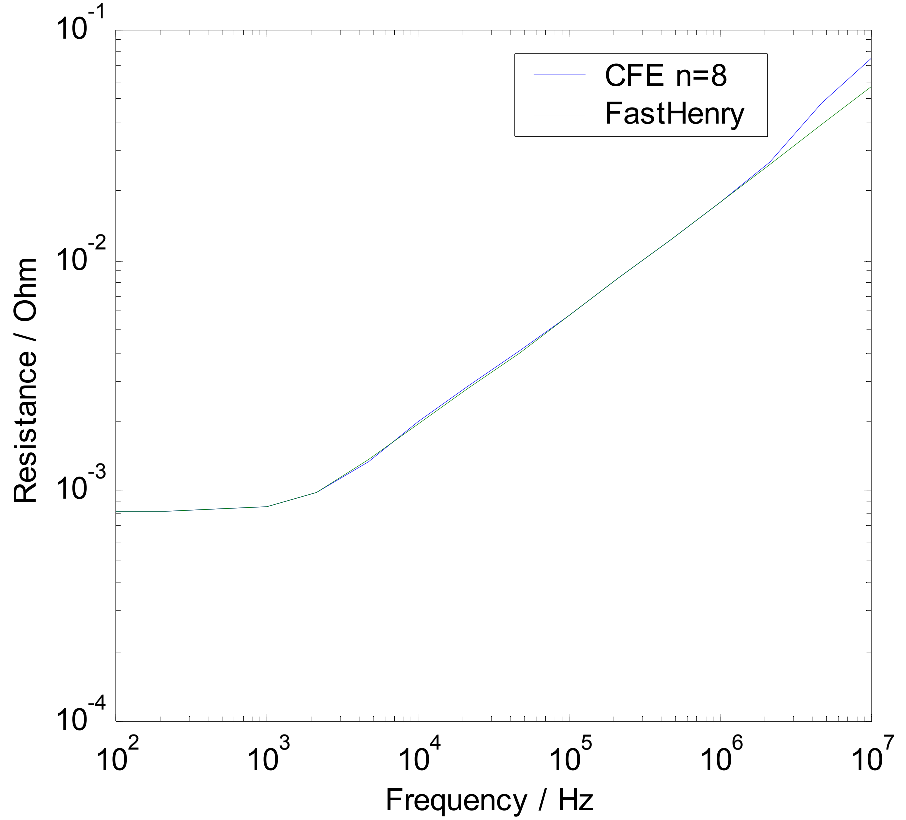
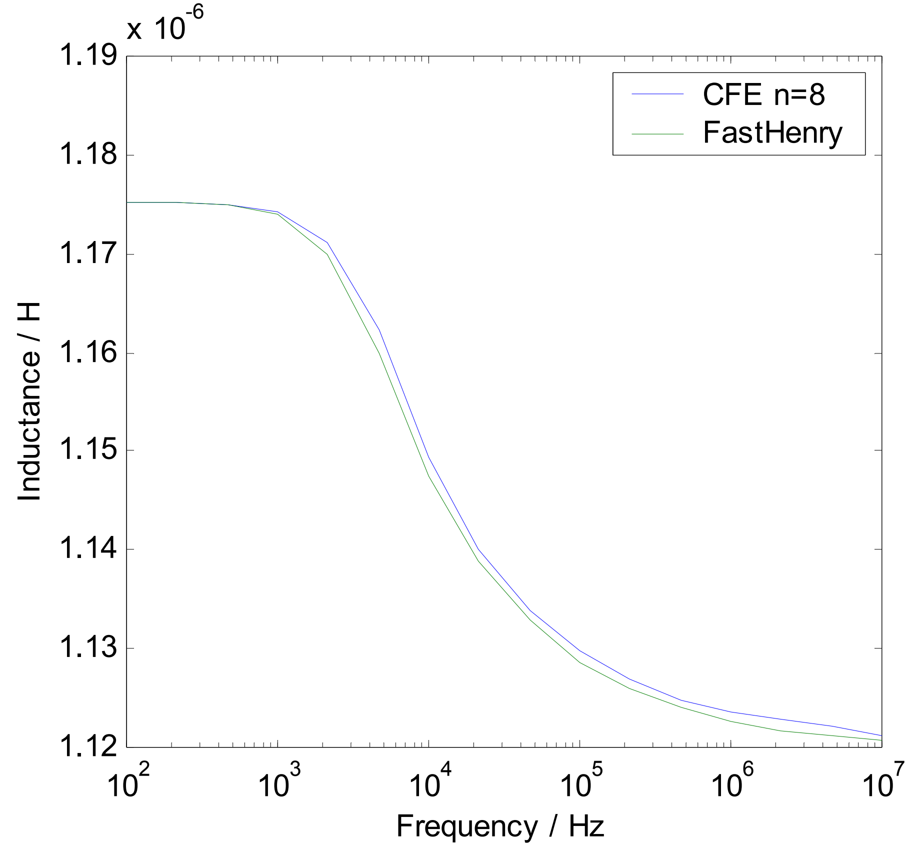
Isolated Square Wire (n=8)

- For n=8 the bandwidth is appr. 3 decades. (cross-section of the wire: 4.6mm x 4.6mm)





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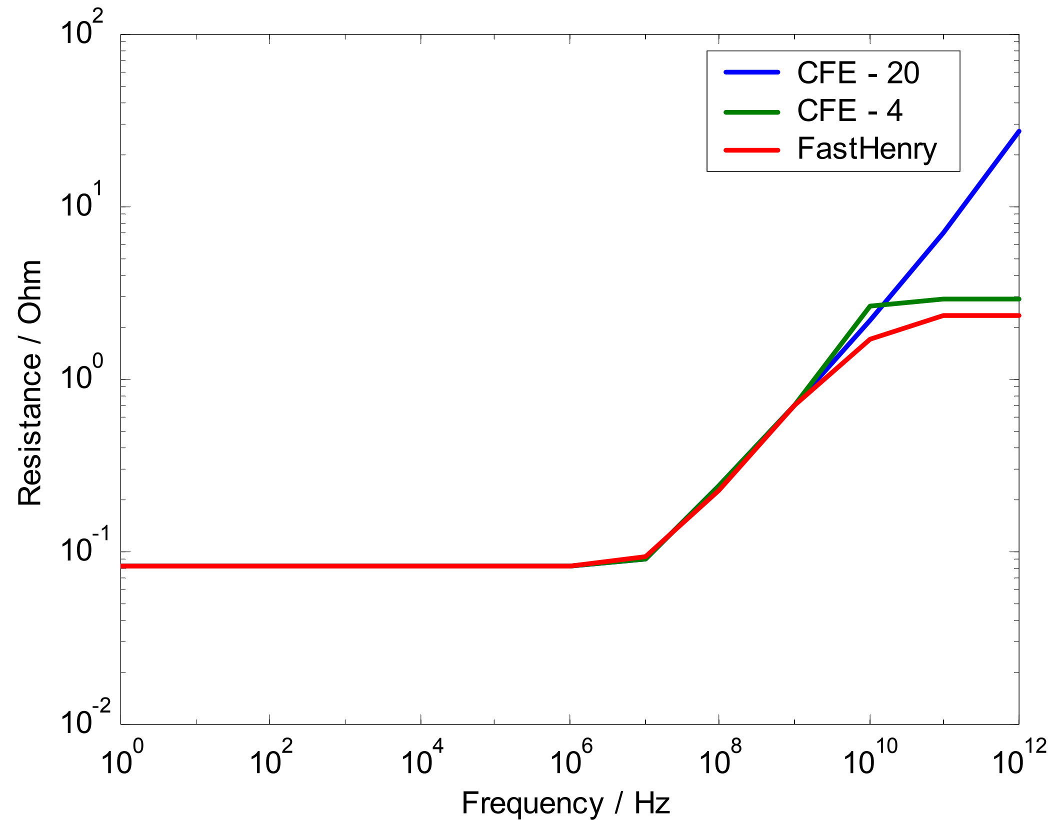
Simulation of a Package Pin (FastHenry Manual p. 22)

- ❑ The bandwidth of the CFE can be so wide, such that a field simulation is impracticable

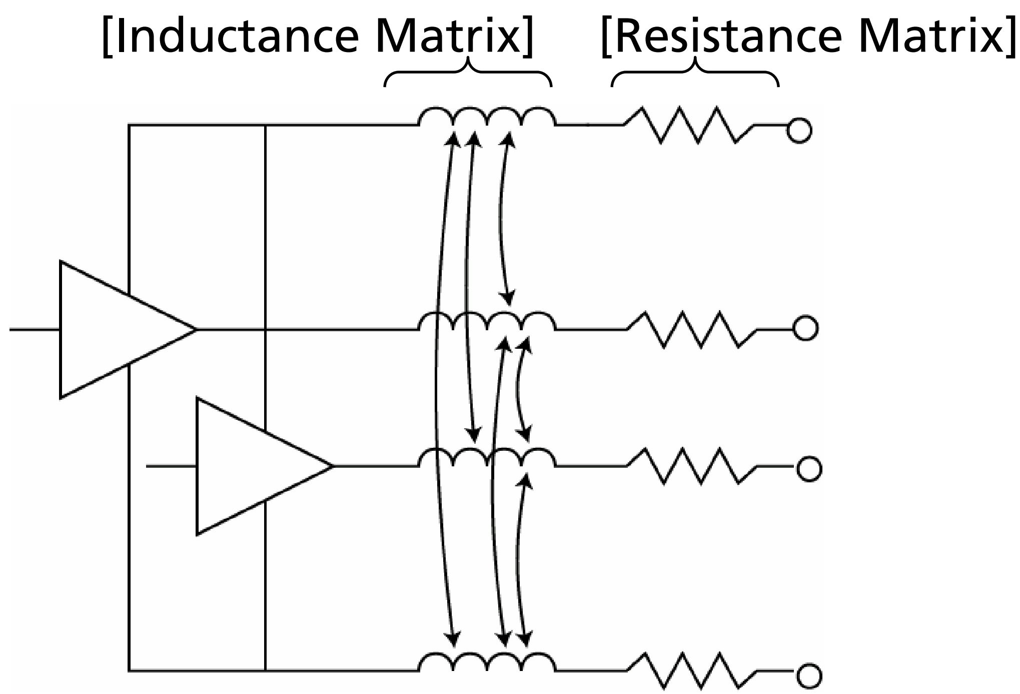


Accuracy Considerations

- n=4 (4 Inductors + 5 Resistors)
  - Relative Error < %2 (not considering the transition region) for 2 decades beginning from the transition frequency (i.e., when Rdc=Rac)
- n=8 (8 Inductors + 9 Resistors)
  - Relative Error < %2 (not considering the transition region) for 3 decades beginning from the transition frequency (i.e., when Rdc=Rac)
- Doubling the number of elements adds appr. 1 decade to the model

IBIS Issues

- The partial inductances/resistances can be provided in an IBIS model using the [Inductance/Resistance Matrix] keyword
- [Resistance Matrix]
  - only the dc resistances can be provided
- [Inductance Matrix]
  - IBIS doesn't specify any frequency (external inductance?)
- [ICM S-Parameter]
  - Too complex for coupled leads
- [External Circuit]
  - Network topology, bandwidth, etc. are fixed



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IBIS Issues cont.

- At present, skin effect cannot be conveniently represented within the IBIS format
- Possible modifications to consider skin effect
  - Provide a keyword for the extraction frequency of the resistance and inductance matrices
    - R_{ac} is correctly modeled
  - In addition, provide the dc resistance matrix
    - R_{ac} and R_{dc} are correctly modeled
  - In addition, provide the dc inductance matrix
    - R_{ac}, R_{dc}, and L_{dc} are correctly modeled
  - Additional matrices are not required by the proposed approach, but could be of interest for macro modeling methodologies
  - Another possibility is the HSPICE W-element format: $\mathbf{R}(f) \cong \mathbf{R}_0 + \sqrt{f}(1+j)\mathbf{R}_s$
    - R_{ac} and R_{dc} are correctly modeled

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Conclusion

- A lumped skin effect model for any kind of cross-section with analytically determined element values is presented
  - Input: Resistance and inductance matrices at dc and at a high frequency point
  - Output: SPICE subcircuit considering the skin effect
- An additional inductance/resistance matrix in addition to the already available dc matrices in the IBIS specification provides necessary information for accurate skin effect modeling

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[4] Bidyut K. Sen and Richard L. Wheeler. "Skin Effects Models for Transmission Line Structures using Generic SPICE Circuit Simulators". *IEEE 7th Topical Meeting on Electrical Performance of Electronic Packaging*, pages 128–31, 1998.

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[7] Suhash C. Dutta Roy. "On the Realization of a Constant-Argument Immittance or Fractional Operator". *IEEE Transactions on Circuit Theory*, 14(3):264–274, September 1967.

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