RF-PASS™

RF Passive Component Analysis Tool

OEA International, Inc.

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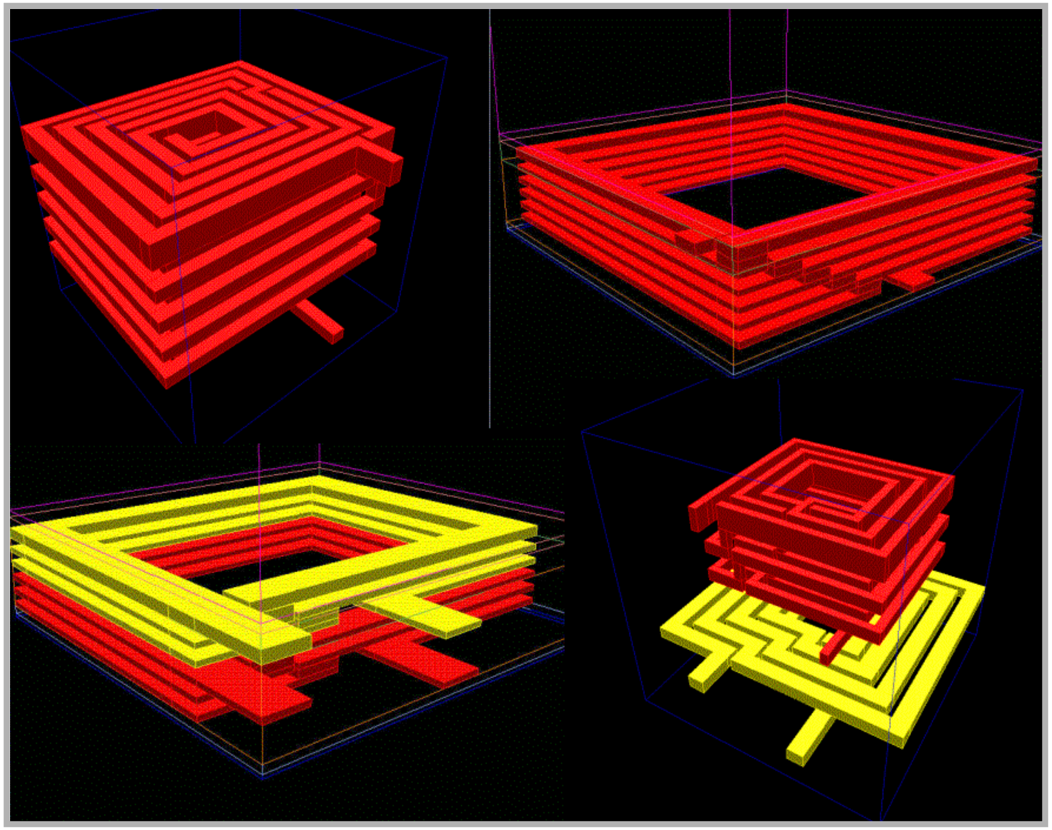
The Need for RF-PASS

- **RFIC Passive Integration Continuously Increasing**
  - A challenge for radio IC development
  - Smaller, more features, time-to-market demands
- **New RFIC Technologies**
  - Six or more metal layers means many more options available
  - Enables new approaches to passive component design
- **Libraries of Pre-Characterized Parts are Inadequate**
  - Large lag time for developing and characterization
  - Exact component desired often not found in library
  - No guarantee of any optimized components in library

RF-PASS Features

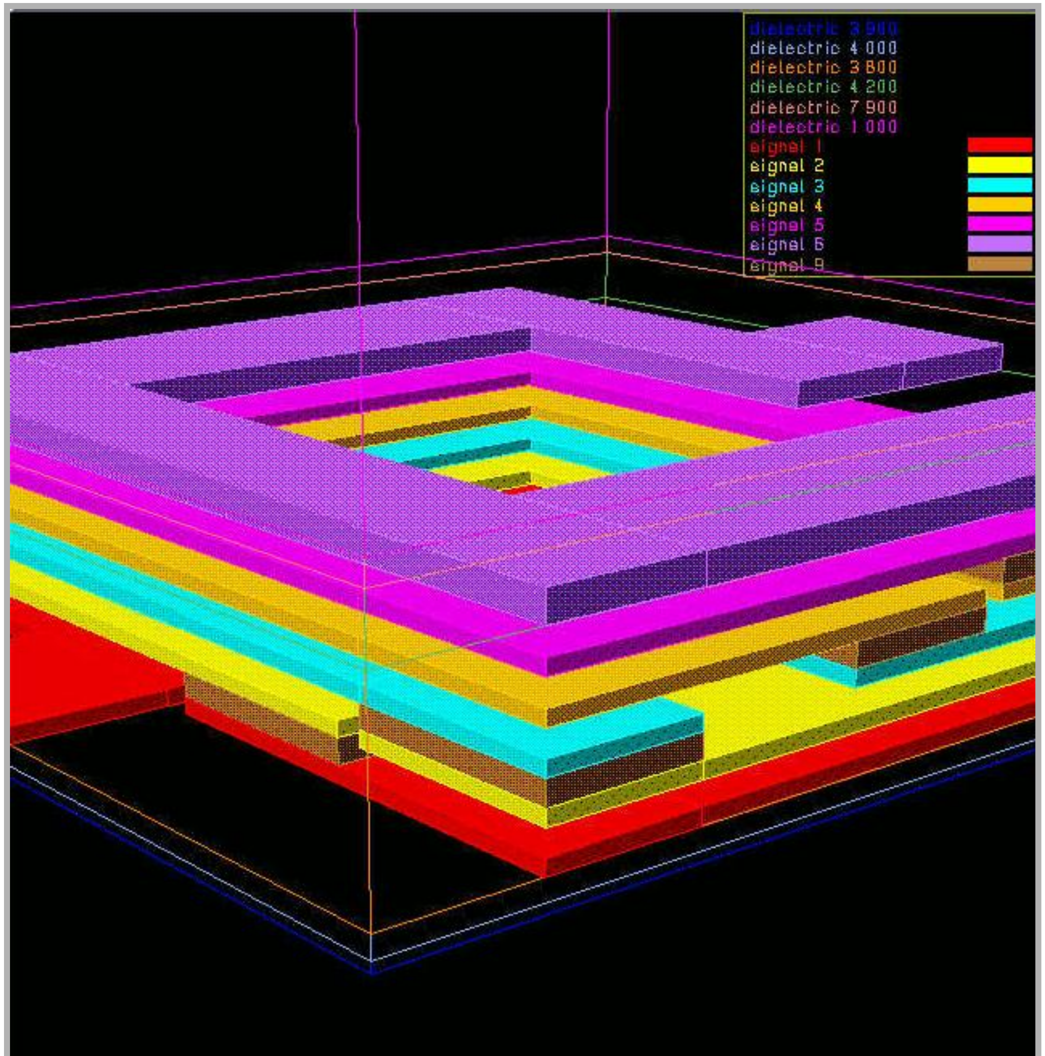
- **Design Aids Generates Complex Inductors, Transformers, Baluns, Capacitors and Resistors**
- **Full 3D seamless field solution for the highest accuracy-yet runs in seconds**
- **Includes non-uniform current distribution due to skin and proximity effects**
- **Detailed model of substrate includes losses due to eddy currents and displacement current**
- **Generates S, Y, or Z-Parameters**



- **Generates fully coupled and distributed RCLK Spice sub-circuits**
- **Generates equivalent circuit model**

Using the RF IC Passive Component Builder

- **Design**
  - Using a few parameters
- **Extract**
  - Complex frequency dependent RCLK
- **Model**
  - Create S, Y, Z Parameters and Compact Model
- **Optimize**
  - Through iteration



Additional RF-PASS Features

- Fast Run time (*typically seconds*)
- Input is GDSII layout for layout tools or simple ASCII control file for automated builders
- Automated builders generate cells for layout in GDSII format
  - Choices include Spirals, Helices, Transformers, Symmetrics, Baluns or Any Combination of Above Structures
  - Add to or Modify Layouts Before Modeling
    - Model various substrate shielding techniques
    - Model location, shape and size of ground contacts
    - Model pad parasitics (alternative for de-embedding)
  - Arrays of minimum sized vias
  - Snaps vertices to selected grid size
- OEA Optimizer included for max, min or best fit of user defined compact model
- Compatible with SpectreRF, HSPICE, SmartSPICE, ADS, etc. through industry standard output formats

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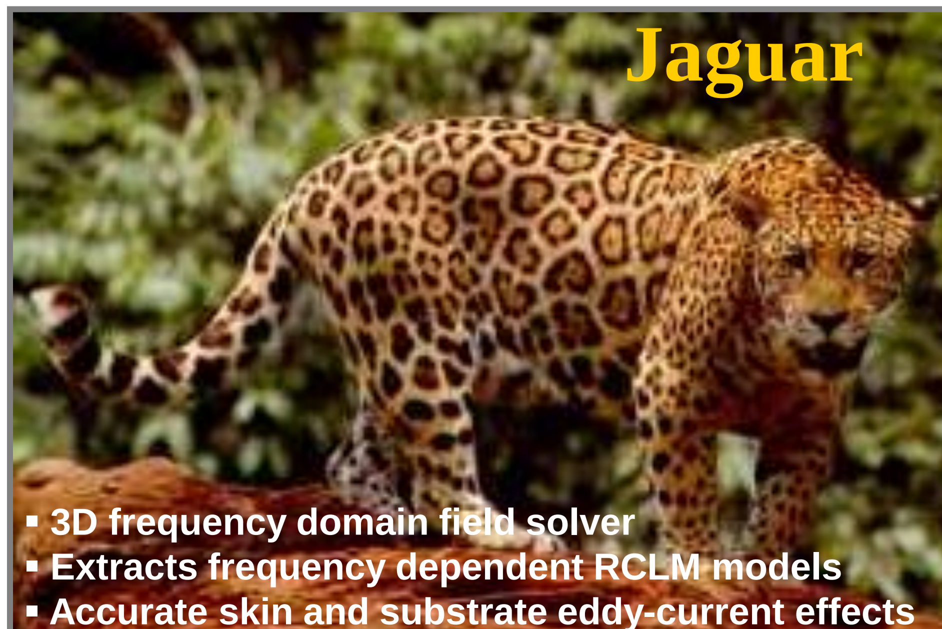
RF-PASS Solver Technologies



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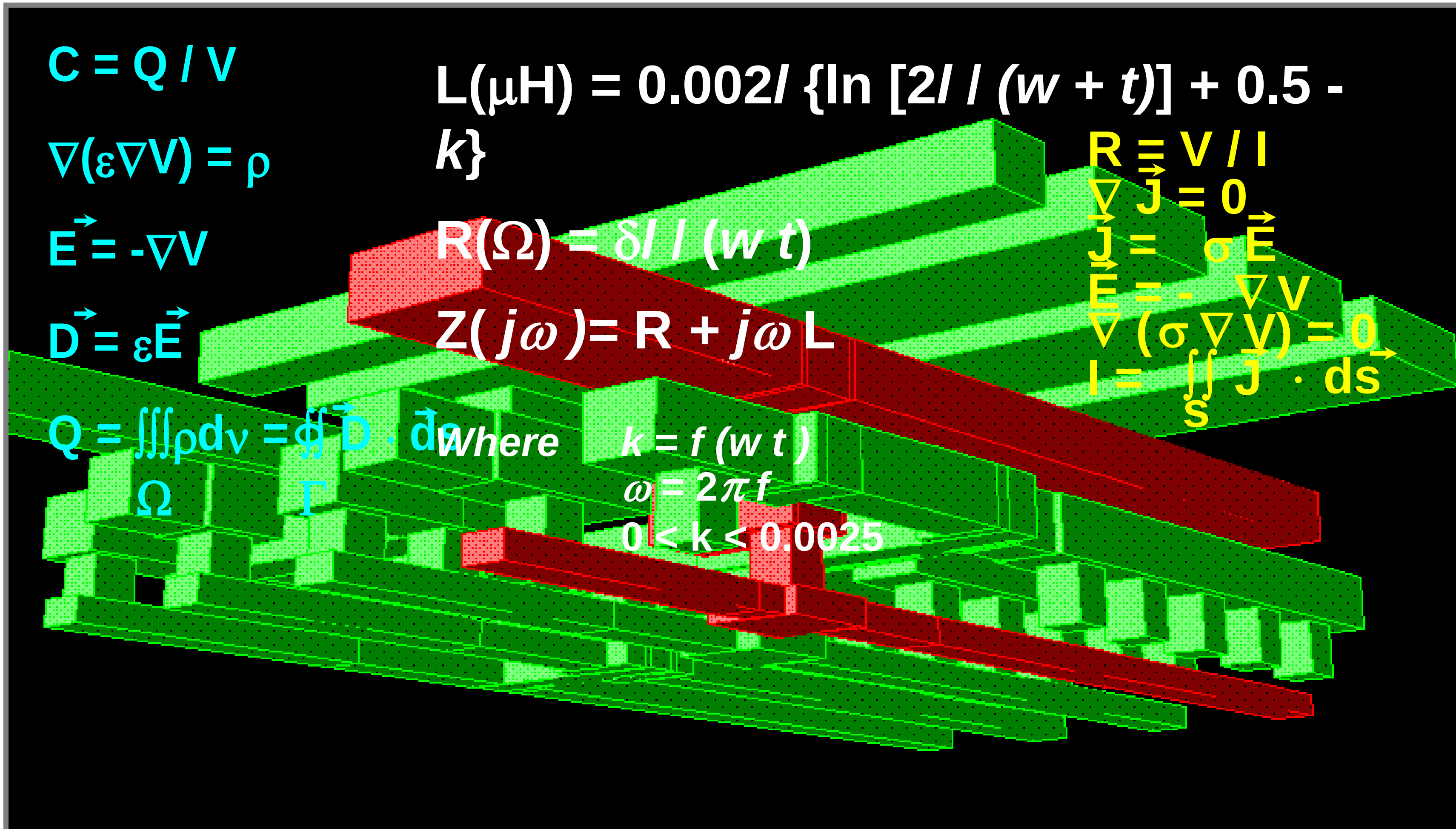
Full 3D Field Solutions

Industry's defacto Accuracy Standard



Inductance Modeling Approach
Partial Equivalent Element Method (PEEM)

Six Self Inductances: ***L_1, L_2, L_3, L_4, L_5, L_6***

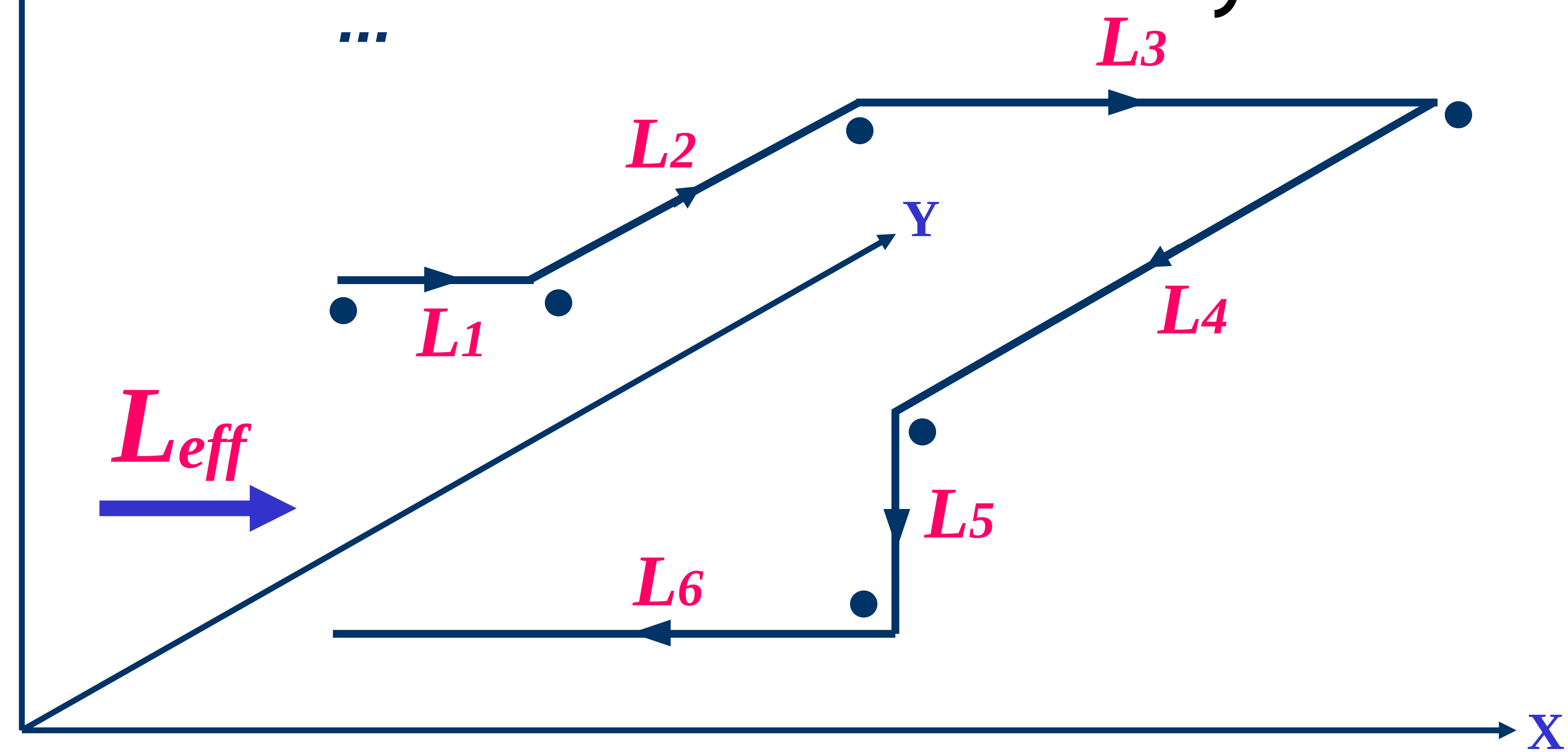
Thirty Mutual Inductances:

L_1 is coupled to ***L_2, L_3, L_4, L_5, L_6***

L_2 is coupled to ***L_1, L_3, L_4, L_5, L_6***

...

$\Big\}$ ***L_{eff}***



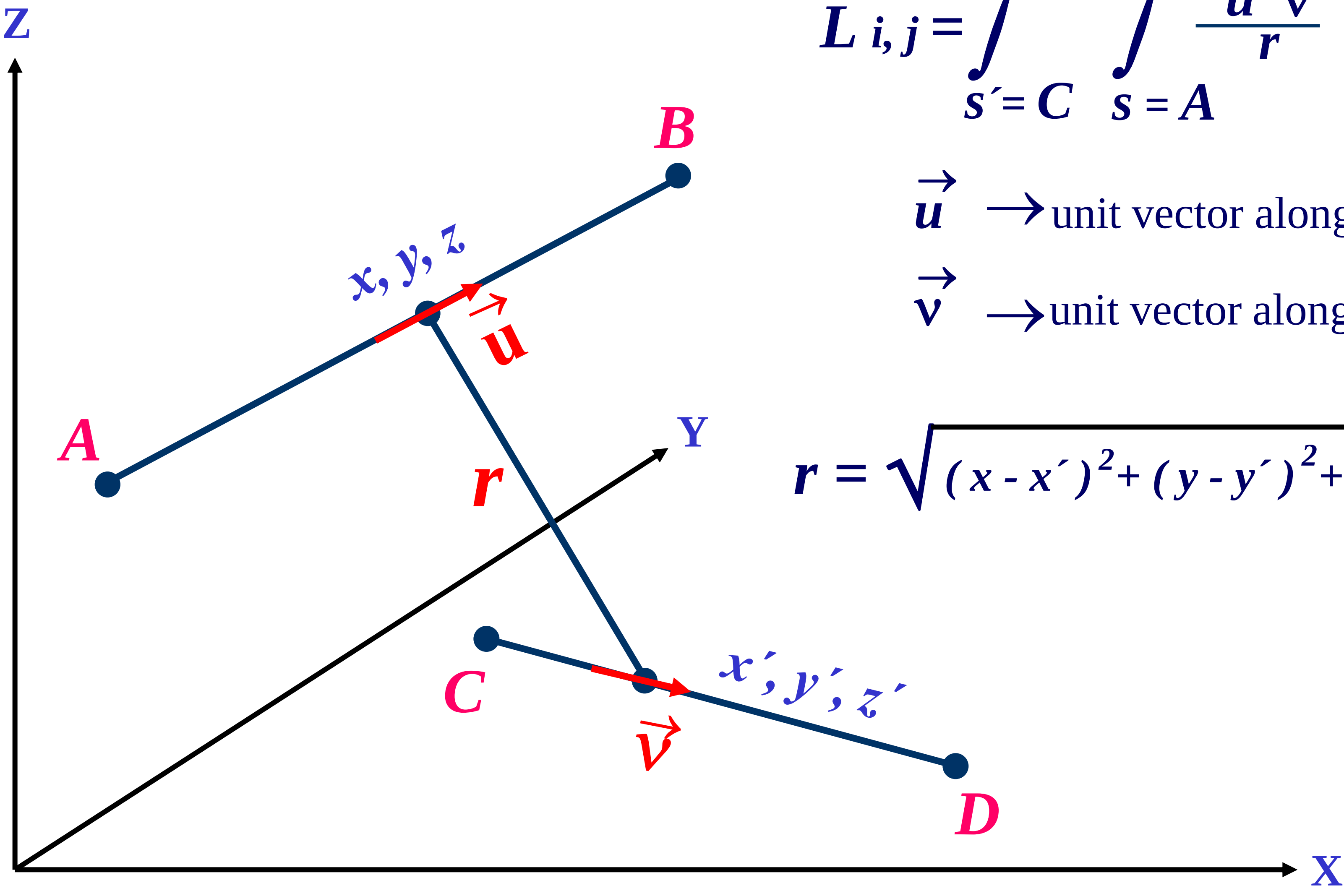
Neumann Formulation of Mutual Inductance

$$L_{i,j} = \int_{s'=C}^{D} \int_{s=A}^{B} \frac{\vec{u}\ \vec{v}}{r}\, ds\, ds'$$

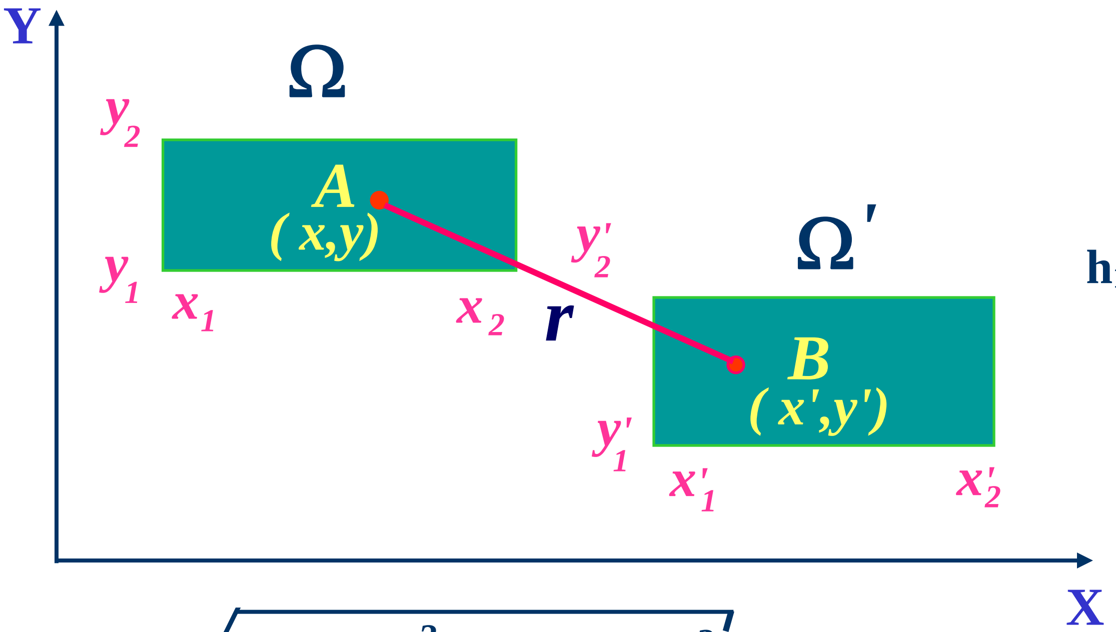
$\vec{u} \longrightarrow$ unit vector along ***AB***

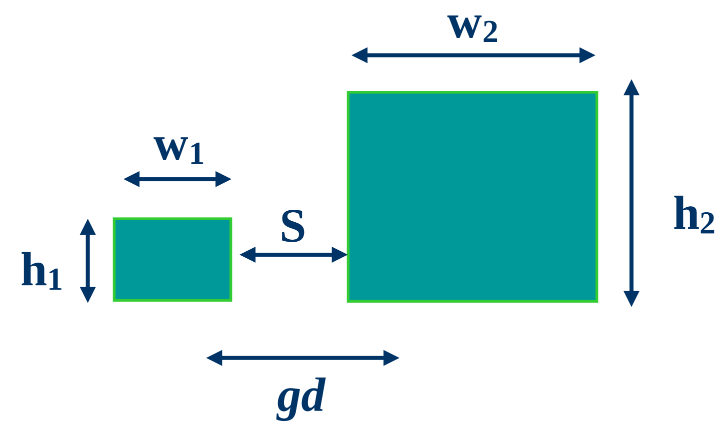
$\vec{v} \longrightarrow$ unit vector along ***CD***

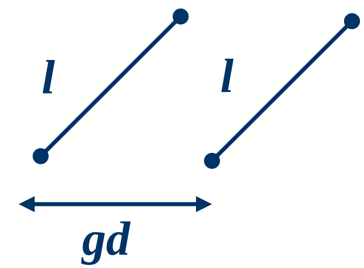
$$r = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$$



Geometric Distance Between Objects







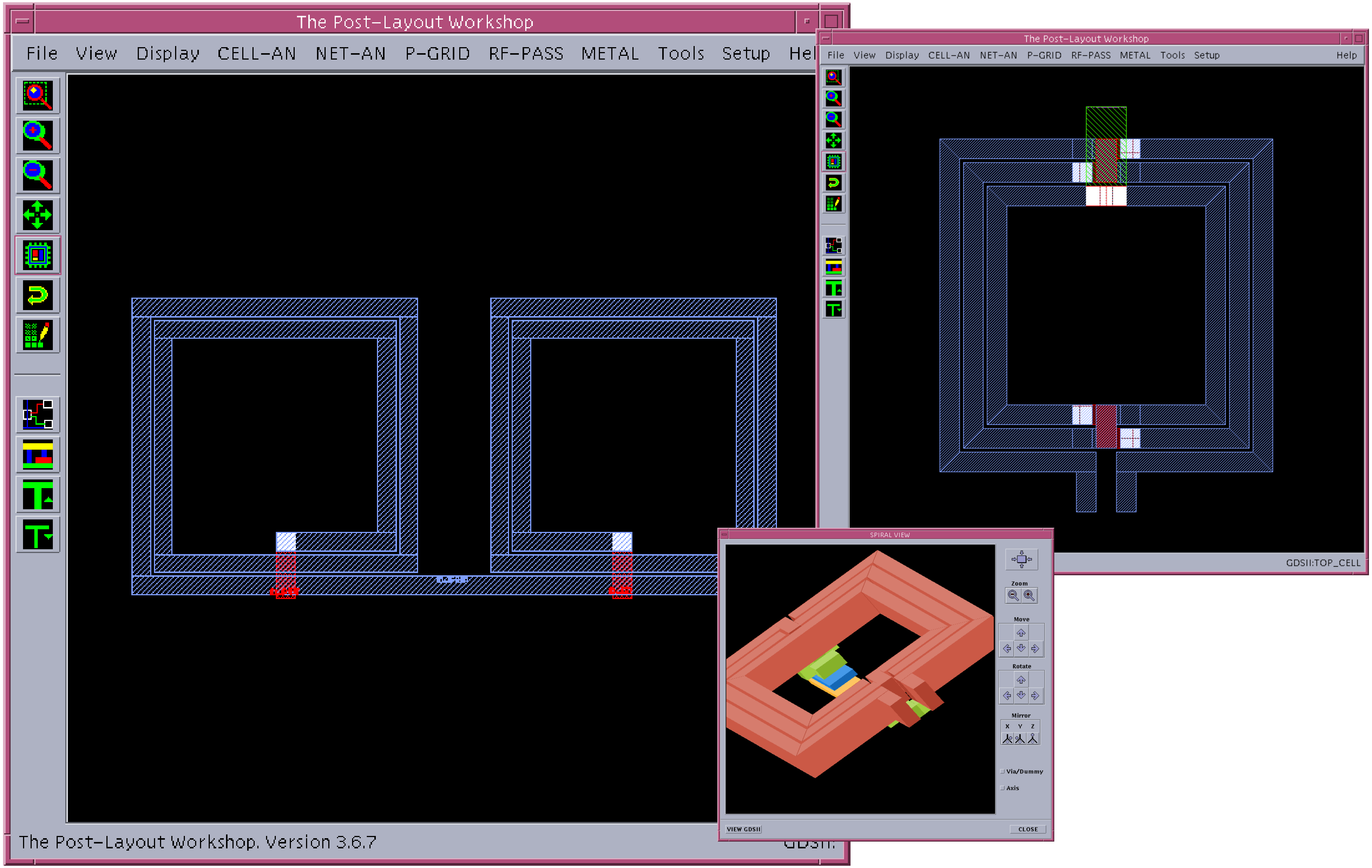
$$r = \sqrt{(x - x')^2 + (y - y')^2}$$

$$gd = \int_{\Omega'}\int_{\Omega} \ln(r)\, d\Omega\, d\Omega'$$

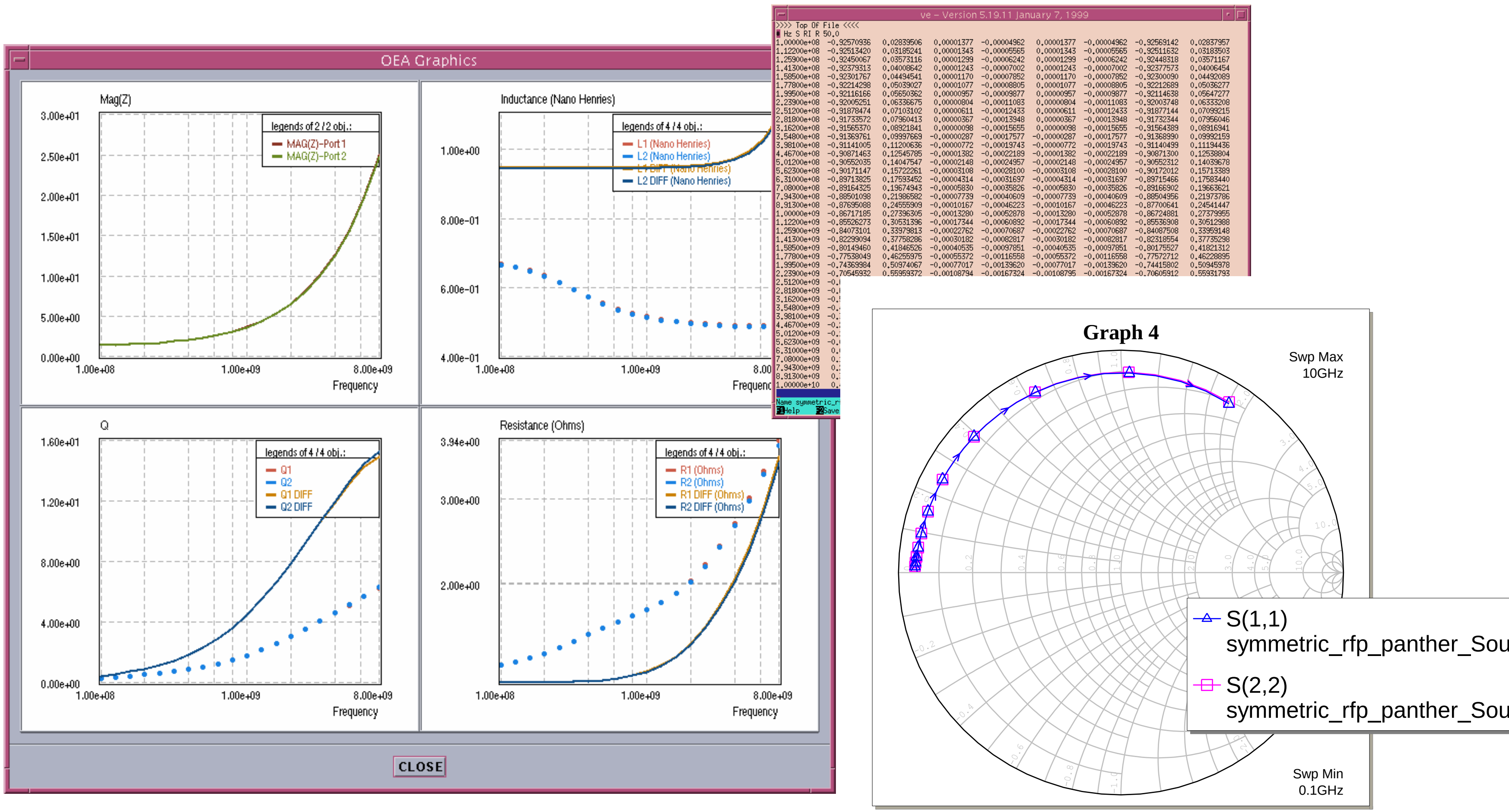
$$gd = \int_{y'=y_1'}^{y_2'}\int_{y=y_1}^{y_2}\int_{x'=x_1'}^{x_2'}\int_{x=x_1}^{x_2} \ln\sqrt{(x - x')^2 + (y - y')^2}\; dx\, dx'\, dy\, dy'$$

Examples of Inductive Components

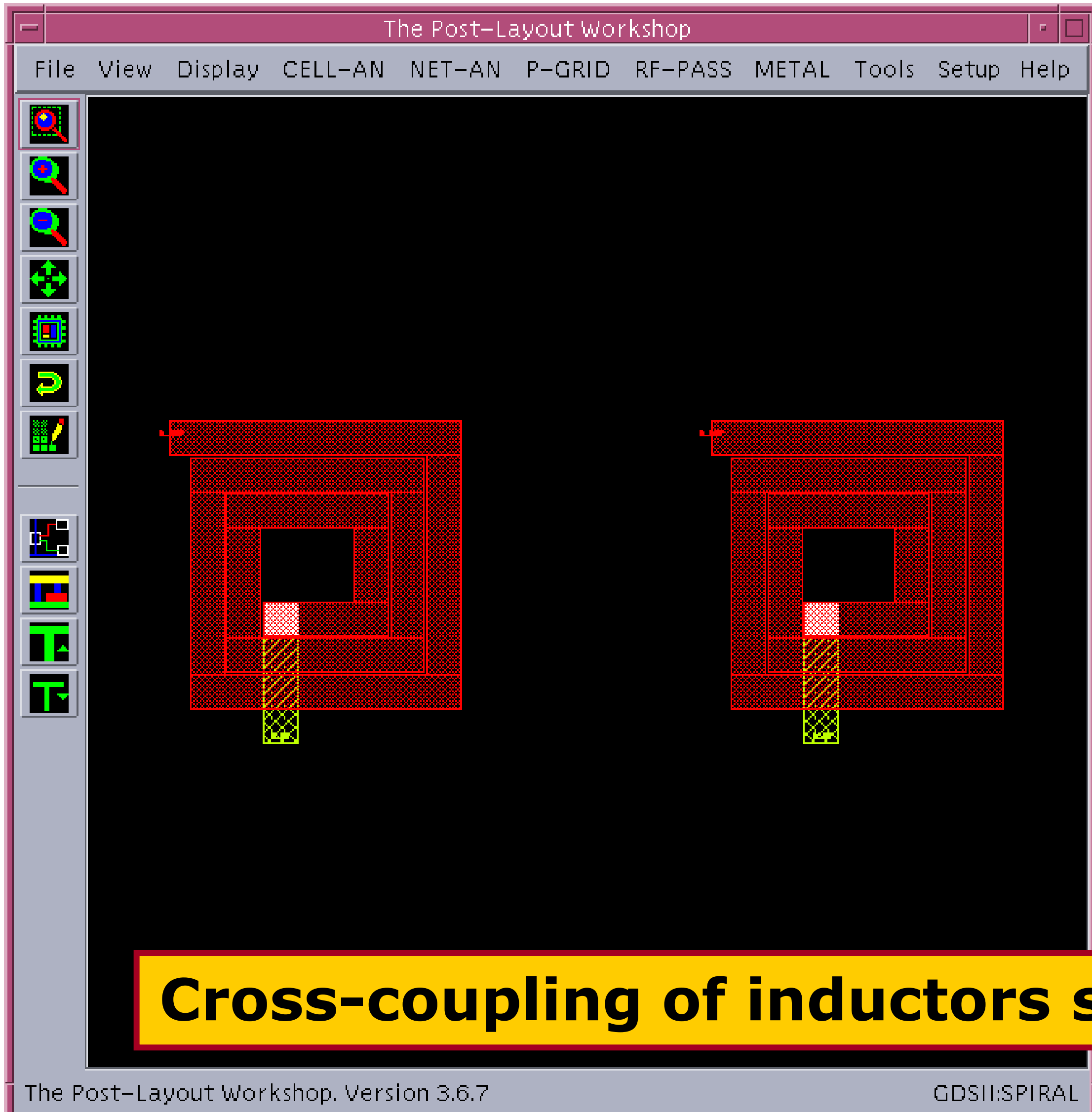
Symmetric Inductors

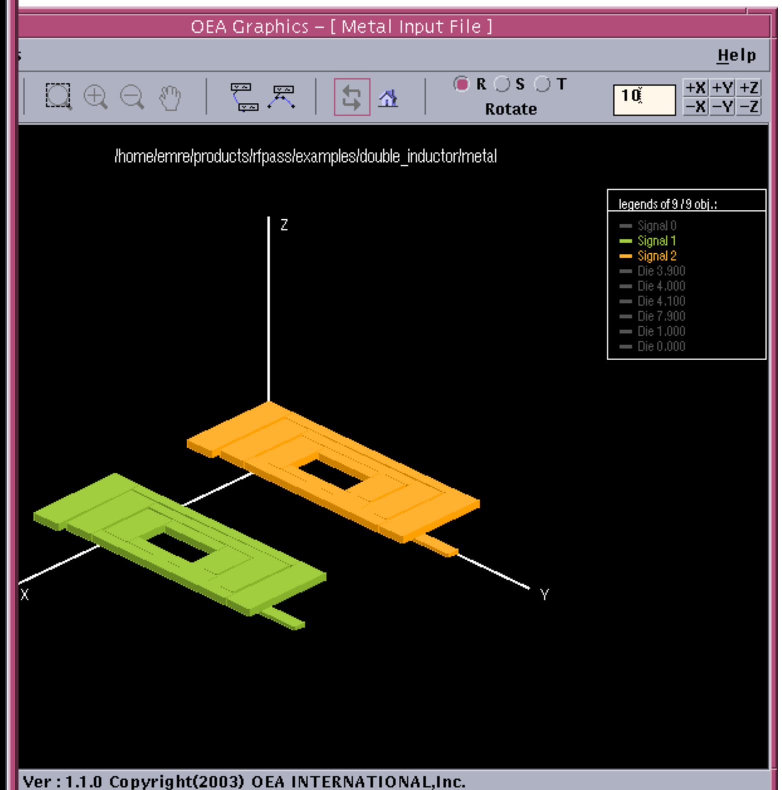


Differential and Single Ended Example LRQ – Mag(Z) Plots



Paired Inductors





Cross-coupling of inductors should be analyzed!

Example Report File

Terminal

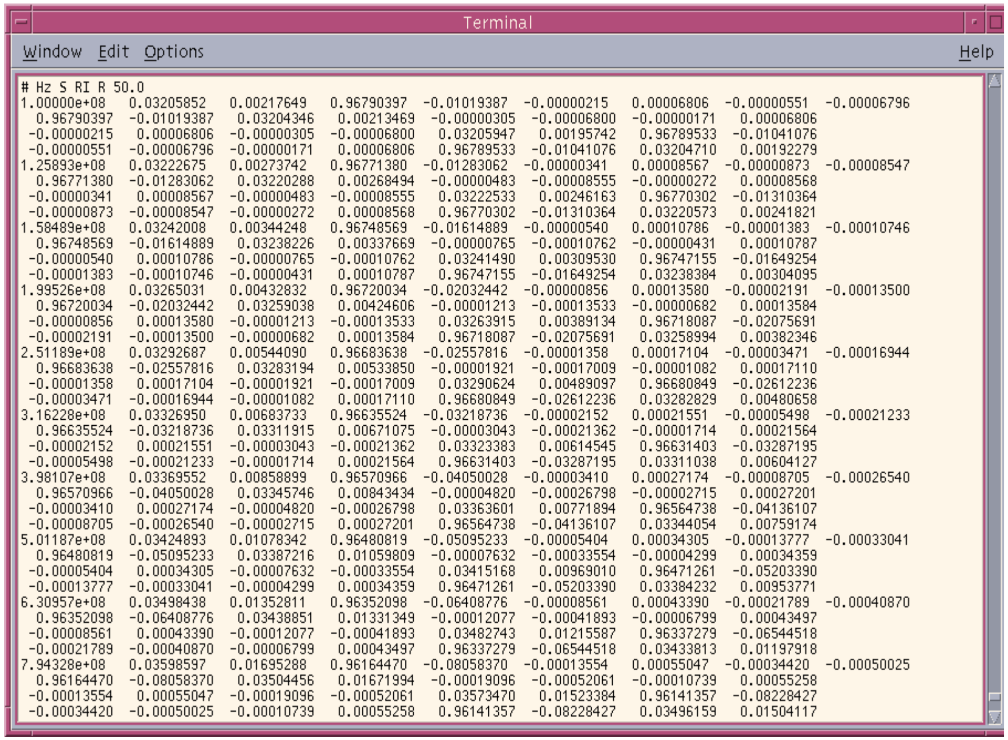
Window Edit Options Help

```
1       A_IN
2       B_IN
RF-PASS Capacitance Report


Net to SUBSTRATE Capacitance:
NET A_IN        ->      SUBSTRATE       2.5587e-13
NET B_IN        ->      SUBSTRATE       2.6964e-13

Net to Net Coupling Capacitance:
NET A_IN        ->      NET A_IN        2.3872e-14
NET B_IN        ->      NET B_IN        7.7297e-15

Net Layer Capacitance:
NET A_IN total cap 2.7974e-13
Layer31 2.2253e-14      7.95%
Layer33 2.5749e-13      92.05%
NET B_IN total cap 2.7737e-13
Layer31 2.2253e-14      8.02%
Layer33 2.5512e-13      91.98%

Effective Inductance A (A_IN to A_OUT): 1.0491e-09
        (With All Other Ports Open, substrate omitted)
Series DC resistance A (A_IN to A_OUT): 3.1792e+00

Effective Inductance B (B_IN to B_OUT): 1.0492e-09
        (With All Other Ports Open, substrate omitted)
Series DC resistance B (B_IN to B_OUT): 3.1797e+00

Mutual inductance between inductor A and B is : 1.0106e-11

Inductive Coupling Coefficient (K) between inductor A and B is : 9.6330e-03

Device A on Net Number 1 has an effective area of 5.113e+04 square microns

Device B on Net Number 2 has an effective area of 1.299e+05 square microns

4 Ports found. Results are in Yout,
Port 1 = A_IN
Port 2 = A_OUT
Port 3 = B_IN
Port 4 = B_OUT
```

Effective inductance given for each DC path node pair

Coupling between the inductors is also computed

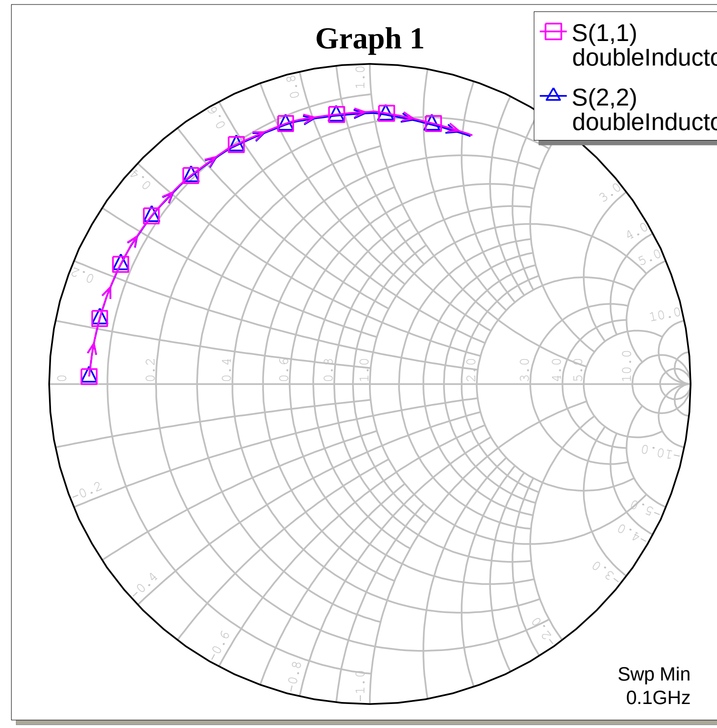
Example of Touchstone 4-port S-Parameters



Terminal

Window Edit Options Help

```
# Hz S RI R 50.0
1.00000e+08   0.03205852   0.00217649   0.96790397  -0.01019387  -0.00000215   0.00006806  -0.00000551  -0.00006796
  0.96790397  -0.01019387   0.03204346   0.00213469  -0.00000305  -0.00006800  -0.00000171   0.00006806
 -0.00000215   0.00006806  -0.00000305  -0.00006800   0.03205947   0.00195742   0.96789533  -0.01041076
 -0.00000551  -0.00006796  -0.00000171   0.00006806   0.96789533  -0.01041076   0.03204710   0.00192279
1.25893e+08   0.03222675   0.00273742   0.96771380  -0.01283062  -0.00000341   0.00008567  -0.00000873  -0.00008547
  0.96771380  -0.01283062   0.03220288   0.00268494  -0.00000483  -0.00008555  -0.00000272   0.00008568
 -0.00000341   0.00008567  -0.00000483  -0.00008555   0.03222533   0.00246163   0.96770302  -0.01310364
 -0.00000873  -0.00008547  -0.00000272   0.00008568   0.96770302  -0.01310364   0.03220573   0.00241821
1.58489e+08   0.03242008   0.00344248   0.96748569  -0.01614889  -0.00000540   0.00010786  -0.00001383  -0.00010746
  0.96748569  -0.01614889   0.03238226   0.00337669  -0.00000765  -0.00010762  -0.00000431   0.00010787
 -0.00000540   0.00010786  -0.00000765  -0.00010762   0.03241490   0.00309530   0.96747155  -0.01649254
 -0.00001383  -0.00010746  -0.00000431   0.00010787   0.96747155  -0.01649254   0.03238384   0.00304095
1.99526e+08   0.03265031   0.00432832   0.96720034  -0.02032442  -0.00000856   0.00013580  -0.00002191  -0.00013500
  0.96720034  -0.02032442   0.03259038   0.00424606  -0.00001213  -0.00013533  -0.00000682   0.00013584
 -0.00000856   0.00013580  -0.00001213  -0.00013533   0.03263915   0.00389134   0.96718087  -0.02075691
 -0.00002191  -0.00013500  -0.00000682   0.00013584   0.96718087  -0.02075691   0.03258994   0.00382346
2.51189e+08   0.03292687   0.00544090   0.96683638  -0.02557816  -0.00001358   0.00017104  -0.00003471  -0.00016944
  0.96683638  -0.02557816   0.03283194   0.00533850  -0.00001921  -0.00017009  -0.00001082   0.00017110
 -0.00001358   0.00017104  -0.00001921  -0.00017009   0.03290624   0.00489097   0.96680849  -0.02612236
 -0.00003471  -0.00016944  -0.00001082   0.00017110   0.96680849  -0.02612236   0.03282829   0.00480658
3.16228e+08   0.03326950   0.00683733   0.96635524  -0.03218736  -0.00002152   0.00021551  -0.00005498  -0.00021233
  0.96635524  -0.03218736   0.03311915   0.00671075  -0.00003043  -0.00021362  -0.00001714   0.00021564
 -0.00002152   0.00021551  -0.00003043  -0.00021362   0.03323383   0.00614545   0.96631403  -0.03287195
 -0.00005498  -0.00021233  -0.00001714   0.00021564   0.96631403  -0.03287195   0.03311038   0.00604127
3.98107e+08   0.03369552   0.00858899   0.96570966  -0.04050028  -0.00003410   0.00027174  -0.00008705  -0.00026540
  0.96570966  -0.04050028   0.03345746   0.00843434  -0.00004820  -0.00026798  -0.00002715   0.00027201
 -0.00003410   0.00027174  -0.00004820  -0.00026798   0.03363601   0.00771894   0.96564738  -0.04136107
 -0.00008705  -0.00026540  -0.00002715   0.00027201   0.96564738  -0.04136107   0.03344054   0.00759174
5.01187e+08   0.03424893   0.01078342   0.96480819  -0.05095233  -0.00005404   0.00034305  -0.00013777  -0.00033041
  0.96480819  -0.05095233   0.03387216   0.01059809  -0.00007632  -0.00033554  -0.00004299   0.00034359
 -0.00005404   0.00034305  -0.00007632  -0.00033554   0.03415168   0.00969010   0.96471261  -0.05203390
 -0.00013777  -0.00033041  -0.00004299   0.00034359   0.96471261  -0.05203390   0.03384232   0.00953771
6.30957e+08   0.03498438   0.01352811   0.96352098  -0.06408776  -0.00008561   0.00043390  -0.00021789  -0.00040870
  0.96352098  -0.06408776   0.03438851   0.01331349  -0.00012077  -0.00041893  -0.00006799   0.00043497
 -0.00008561   0.00043390  -0.00012077  -0.00041893   0.03482743   0.01215587   0.96337279  -0.06544518
 -0.00021789  -0.00040870  -0.00006799   0.00043497   0.96337279  -0.06544518   0.03433813   0.01197918
7.94328e+08   0.03598597   0.01695288   0.96164470  -0.08058370  -0.00013554   0.00055047  -0.00034420  -0.00050025
  0.96164470  -0.08058370   0.03504456   0.01671994  -0.00019096  -0.00052061  -0.00010739   0.00055258
 -0.00013554   0.00055047  -0.00019096  -0.00052061   0.03573470   0.01523384   0.96141357  -0.08228427
 -0.00034420  -0.00050025  -0.00010739   0.00055258   0.96141357  -0.08228427   0.03496159   0.01504117
```



4-port S-parameters in Touchstone format

Input impedance over frequency of both inductors plotted on a Smith Chart

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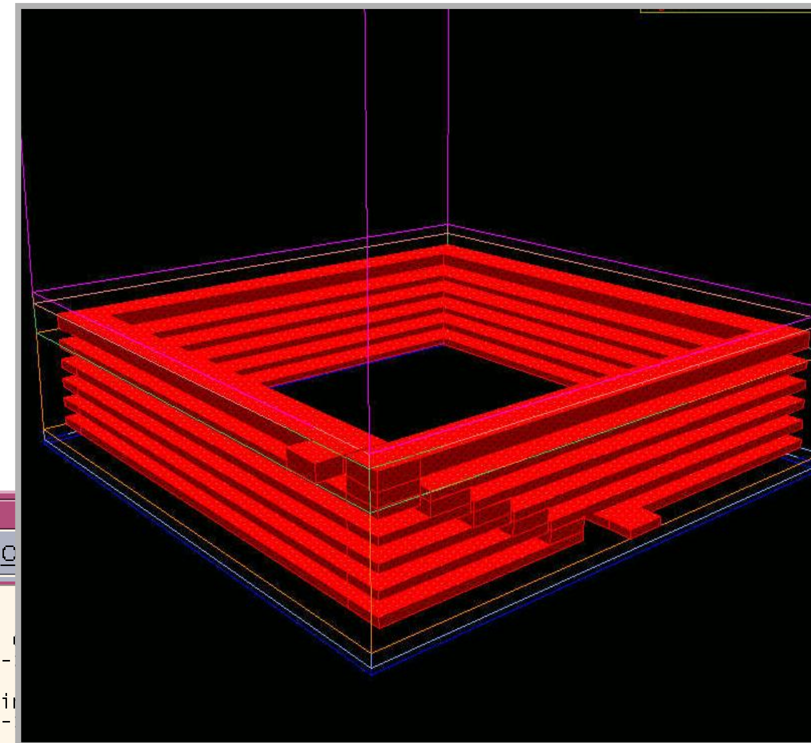
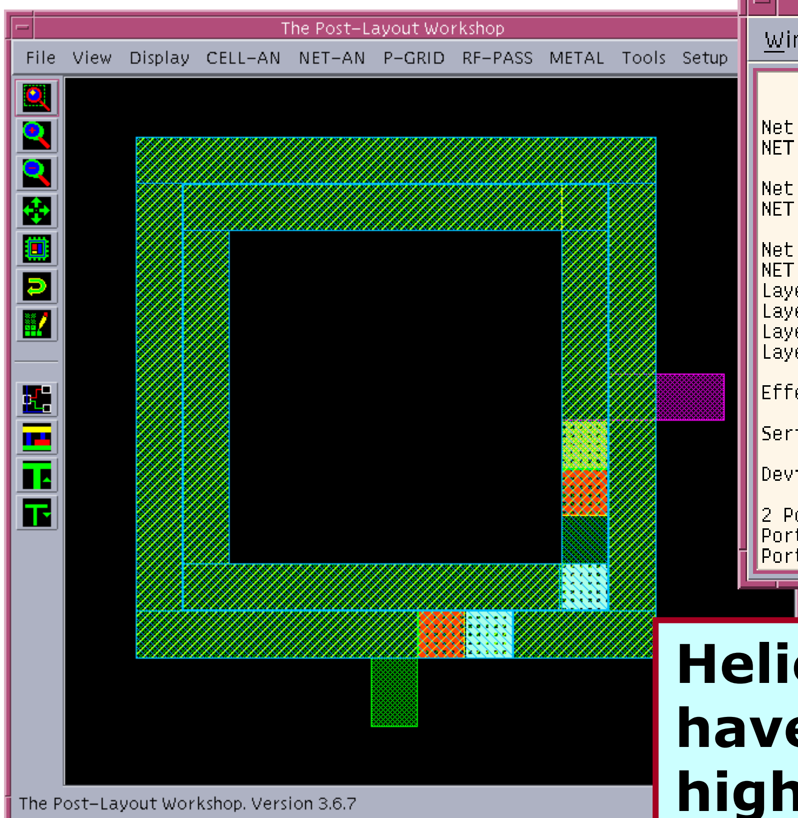
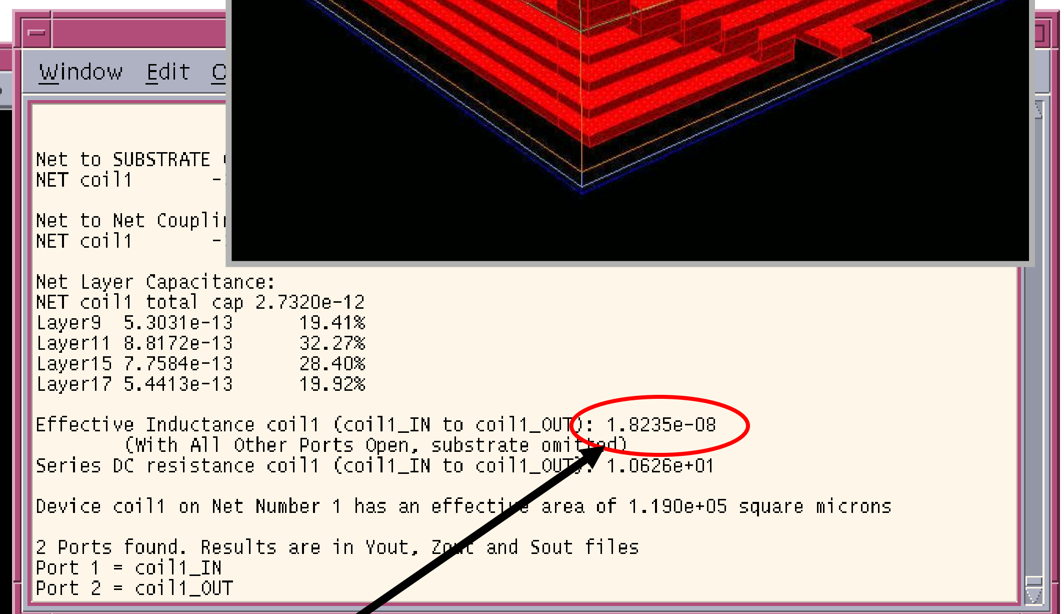
Helical Inductors

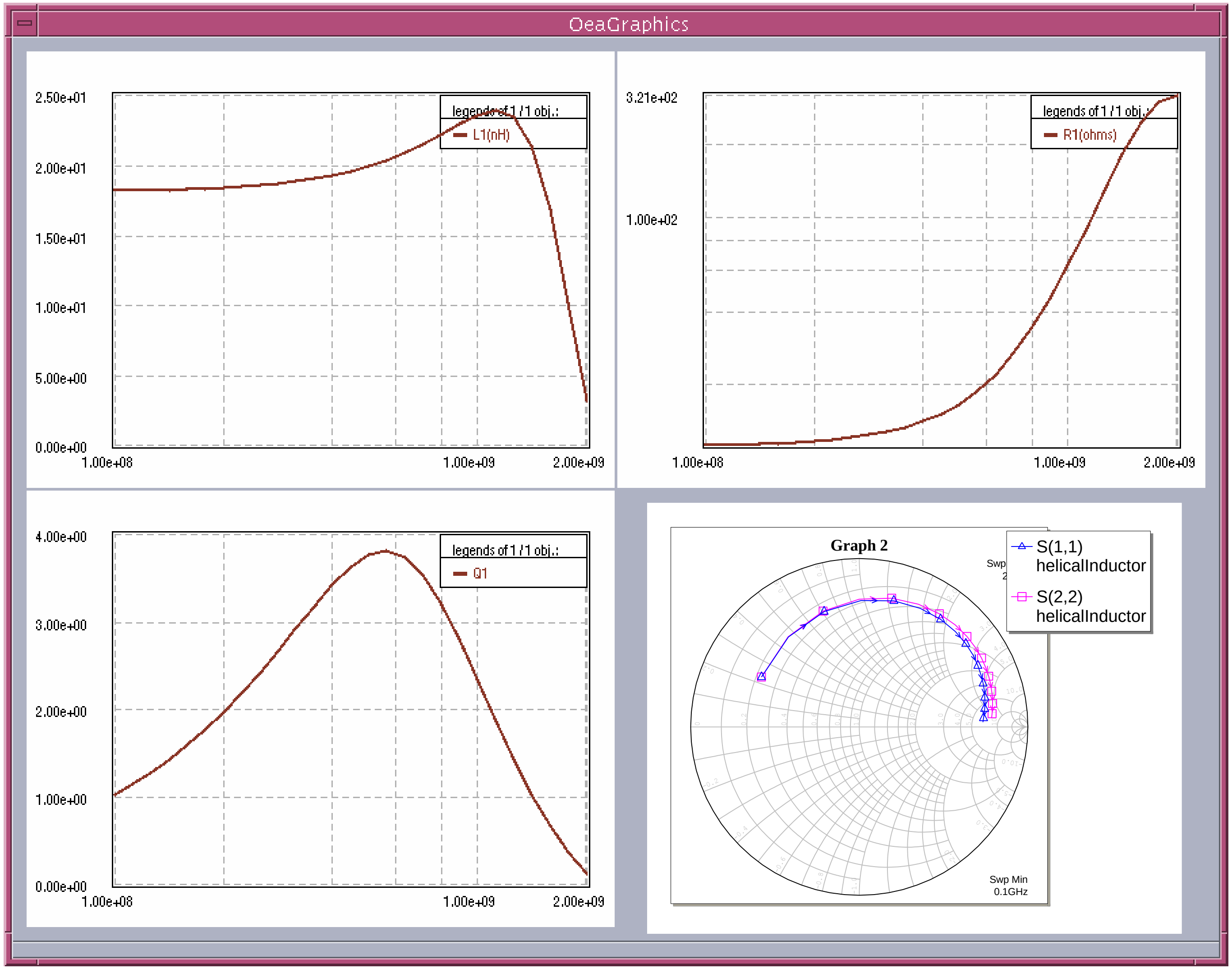




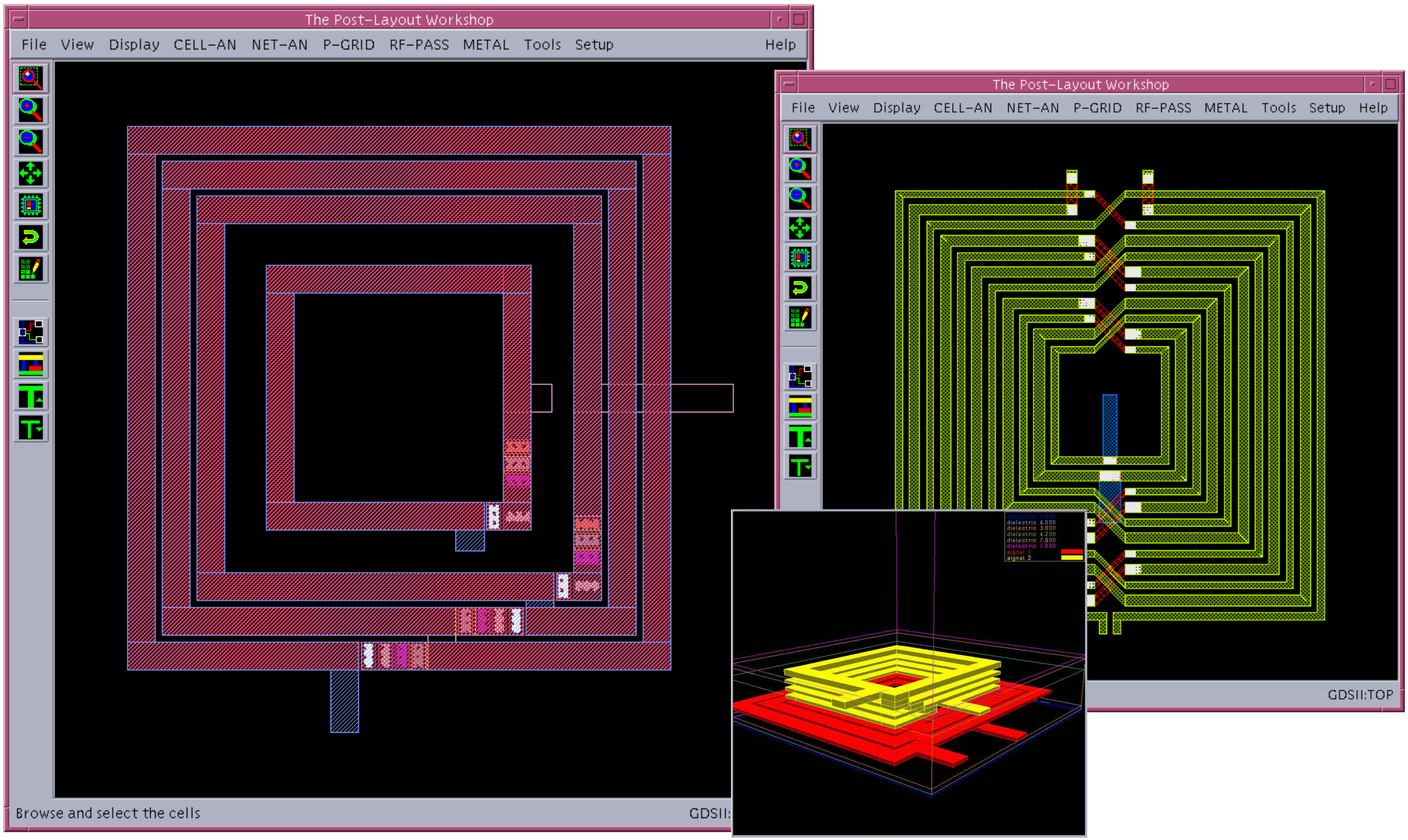


Helical series inductors have the advantage of having higher inductance per unit area.

Example of LRQ Plots – Smith Chart Output



Transformers and Baluns



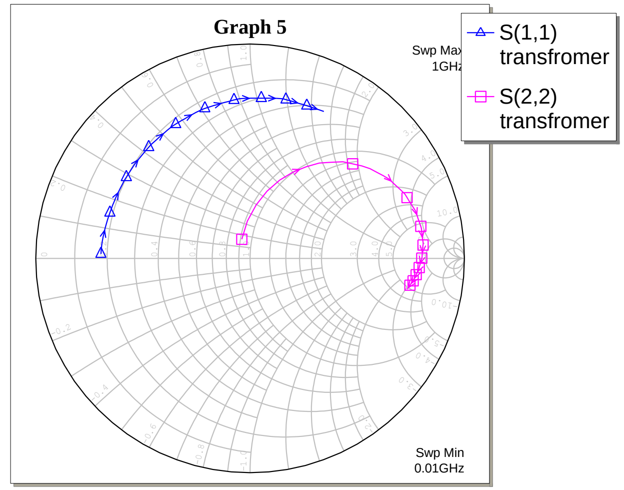
Example of Report File Showing Insertion Loss

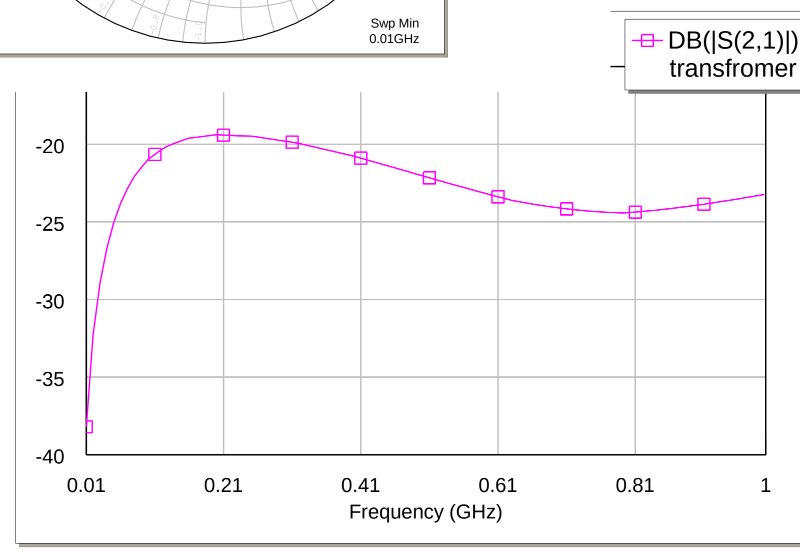
Terminal

Window Edit Options

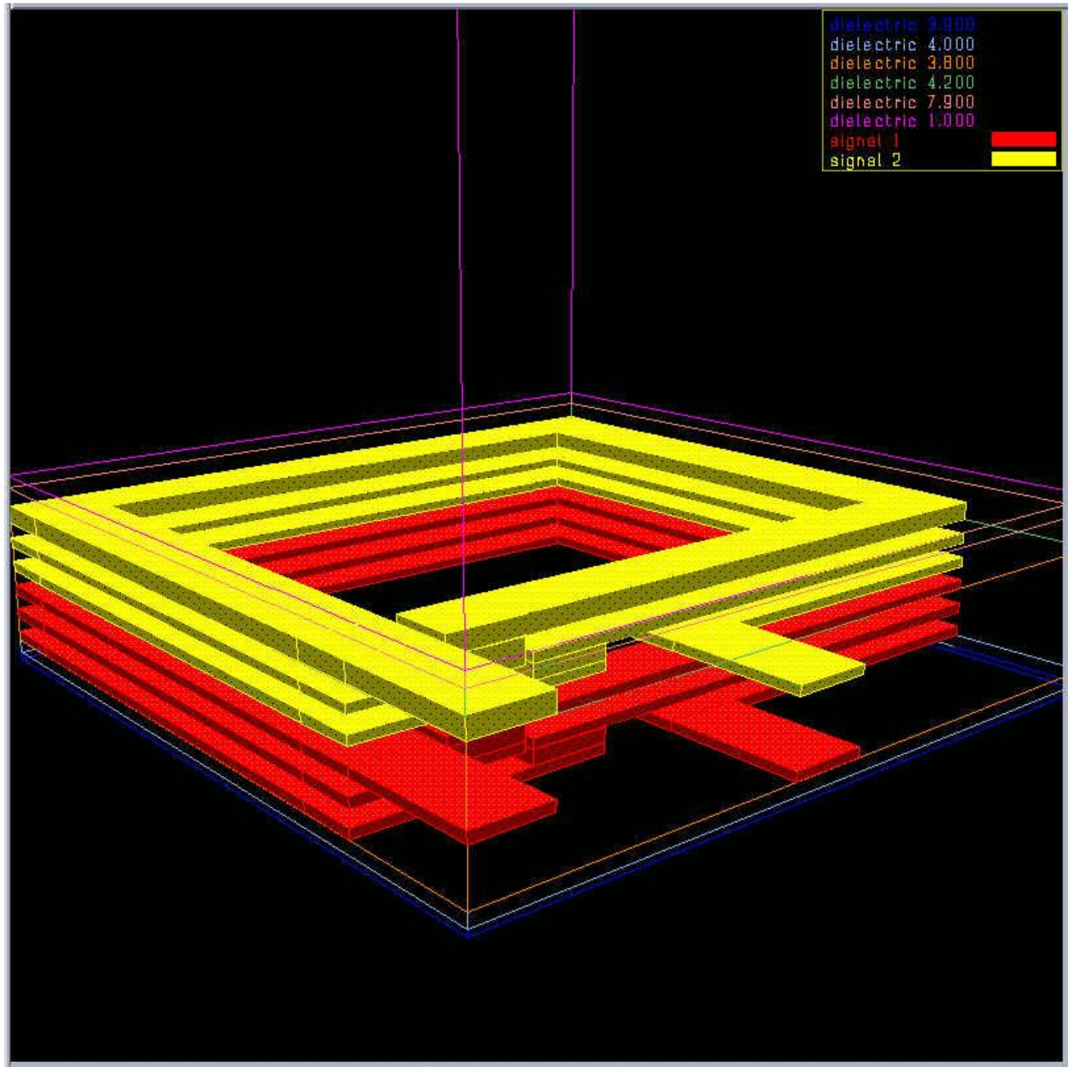
```
2 Nets
1        primary
2        secondary
RF-PASS Capacitance Report


Net to SUBSTRATE Capacitance:
NET primary    ->      SUBSTRATE      1.1963e-12
NET secondary  ->      SUBSTRATE      5.0993e-12

Net to Net Coupling Capacitance:
NET primary    ->      NET primary    7.5062e-13
NET secondary  ->      NET secondary  2.2150e-12

Net Layer Capacitance:
NET primary total cap 1.9470e-12
Layer8   5.6698e-13      29.12%
Layer10  3.7503e-13      19.26%
Layer12  3.0671e-13      15.75%
Layer19  2.5371e-13      13.03%
Layer21  2.3013e-13      11.82%
Layer23  2.1439e-13      11.01%
NET secondary total cap 7.3143e-12
Layer8   8.8810e-13      12.14%
Layer10  1.8031e-12      24.65%
Layer12  1.4311e-12      19.57%
Layer19  1.1992e-12      16.40%
Layer21  1.0674e-12      14.59%
Layer23  9.2540e-13      12.65%

Effective Inductance primary (primary_IN to primary_OUT): 1.1566e-08
        (With All Other Ports Open, substrate omitted)
Series DC resistance primary (primary_IN to primary_OUT): 8.7574e+00

Effective Inductance secondary (secondary_IN to secondary_OUT): 1.3496e-07
        (With All Other Ports Open, substrate omitted)
Series DC resistance secondary (secondary_IN to secondary_OUT): 4.4522e+01

Mutual inductance between inductor primary and secondary is : 1.1065e-08

Inductive Coupling Coefficient (K) between inductor primary and secondary is : 2.8007e-01

Device primary on Net Number 1 has an effective area of 4.202e+04 square microns

Device secondary on Net Number 2 has an effective area of 1.892e+05 square microns

4 Ports found. Results are in Yout, Zout and Sout files
Port 1 = primary_IN
Port 2 = primary_OUT
Port 3 = secondary_IN
Port 4 = secondary_OUT
```

Effective inductance of the primary and the secondary with coupling coefficient (K).

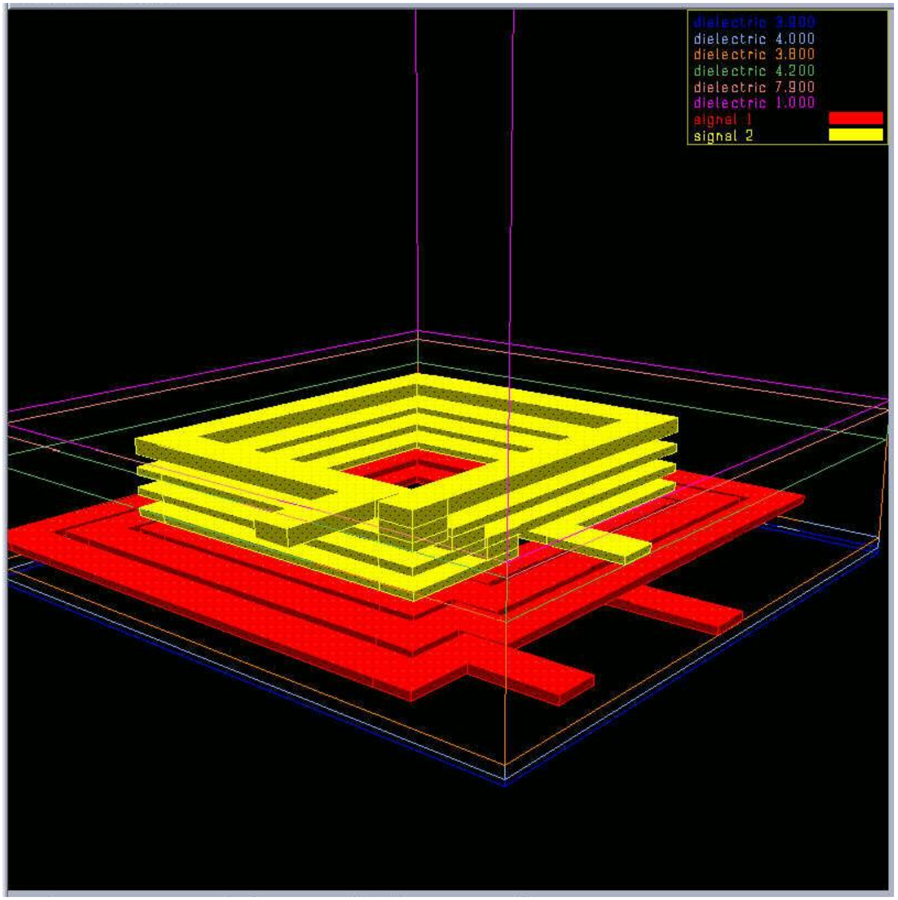




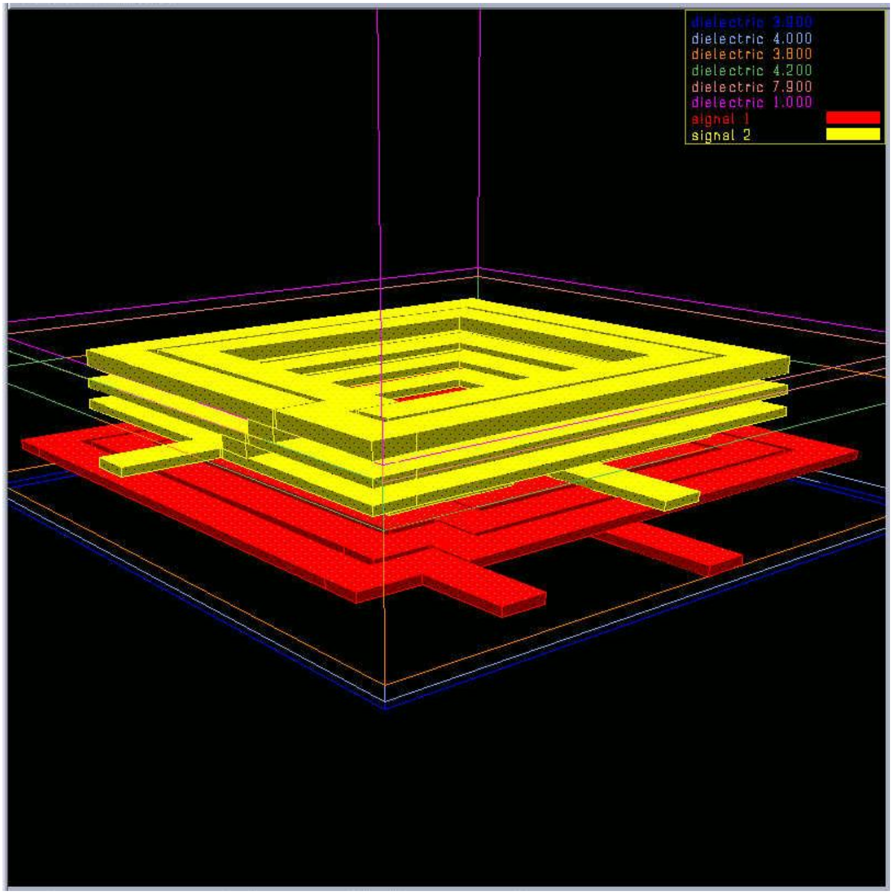
Transformer from Two Concentric Helices



Transformer with Helix on Spiral

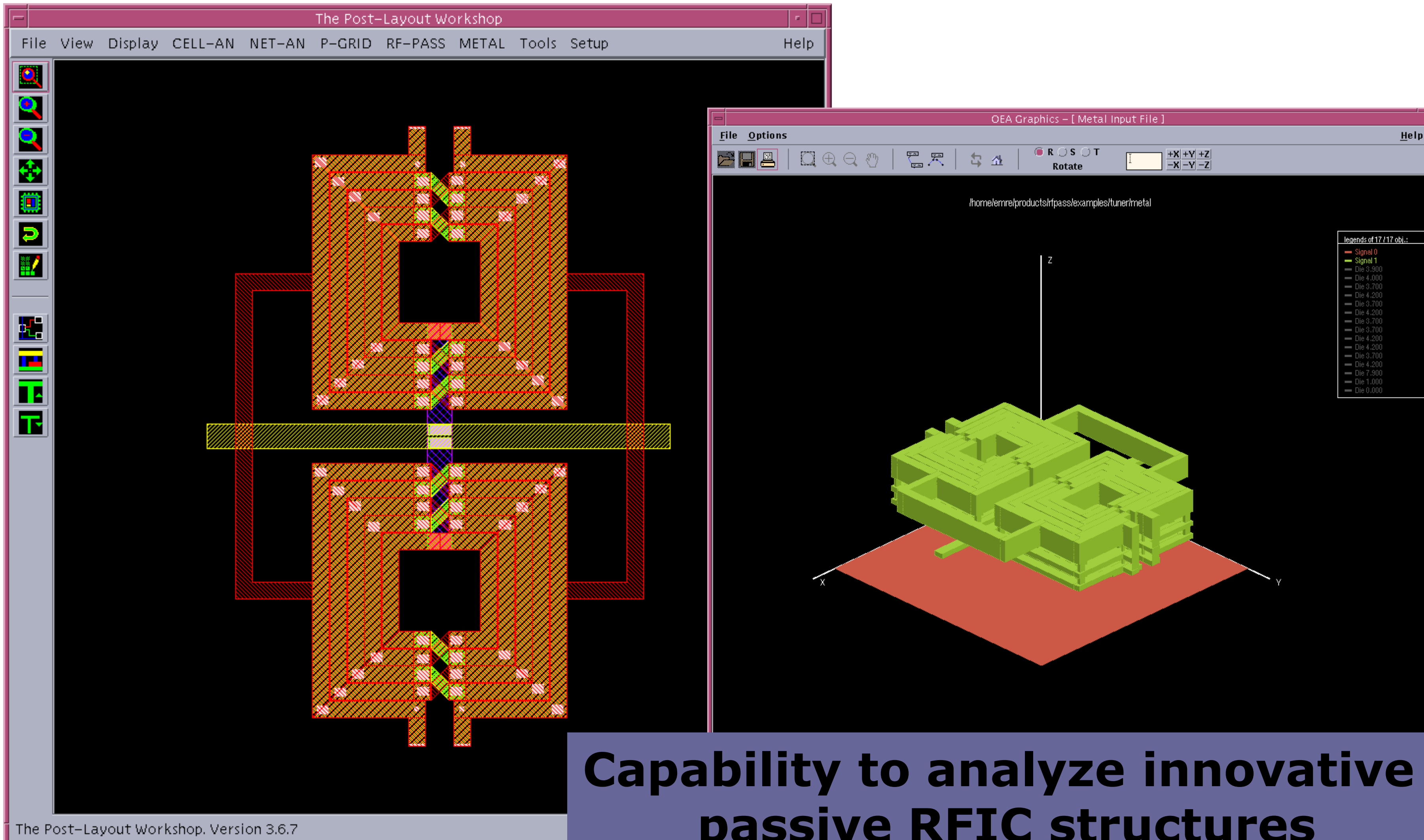


Single Helix



Double Helix

Coupled Resonant Circuits



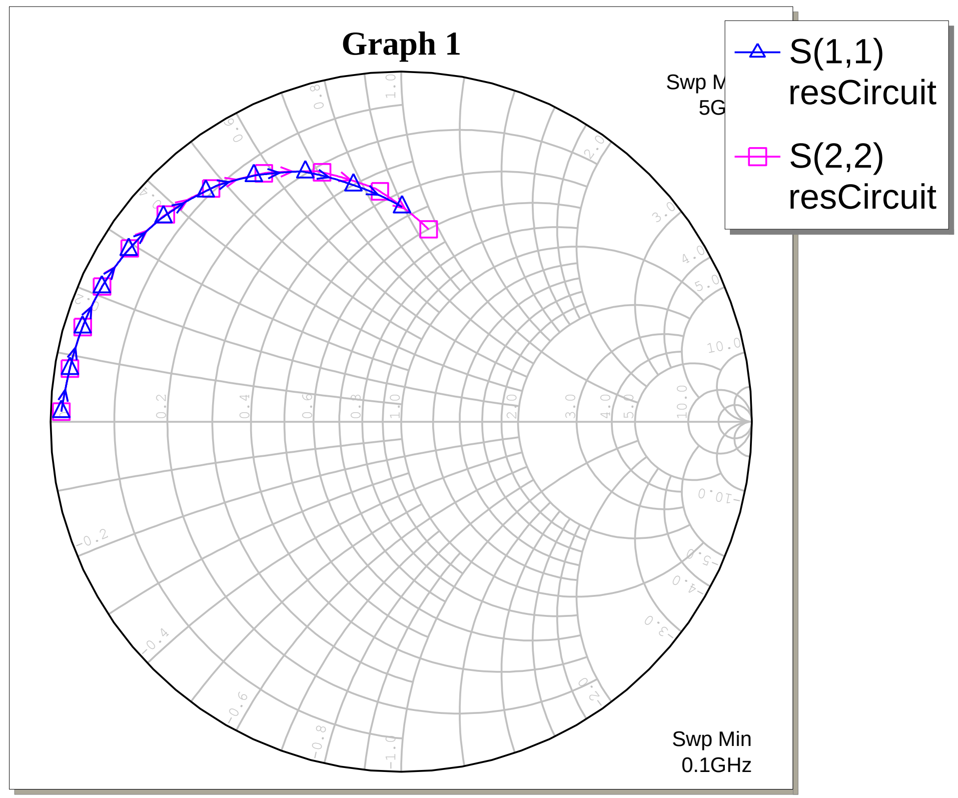
Capability to analyze innovative passive RFIC structures

Example of Report File and Smith Chart

Terminal

Window Edit Options

```
1        // total nets
1        1
RF-PASS Capacitance Report


Net to SUBSTRATE Capacitance:
NET 1    ->       SUBSTRATE       1.0038e-11

Net to Net Coupling Capacitance:
NET 1    ->       NET 1    9.4149e-12

Net Layer Capacitance:
NET 1 total cap 1.9453e-11
Layer16 8.2566e-13       4.24%
Layer18 4.0218e-13       2.07%
Layer28 8.6744e-13       4.46%
Layer31 6.3025e-12       32.40%
Layer33 6.4955e-12       33.39%
Layer38 4.5596e-12       23.44%

Effective Inductance a (a_IN to a_OUT)  4.6896e-09
        (With All Other Ports Open, substrate omitted)
Series DC resistance a (a_IN to a_OUT)  2.1721e+00

Effective Inductance b (b_IN to b_OUT)  4.6923e-09
        (With All Other Ports Open, substrate omitted)
Series DC resistance b (b_IN to b_OUT)  2.1755e+00

Mutual inductance between inductor a and b is : 3.2073e-08

Inductive Coupling Coefficient (K) between inductor a and b is : 6.8372e

Device a on Net Number 1 has an effective area of 1.252e+06 square micro

Device b on Net Number 1 has an effective area of 1.252e+06 square micro

4 Ports found. Results are in Yout, Zout and Sout files
Port 1 = a_in
Port 2 = a_out
Port 3 = b_in
Port 4 = b_out
```



Effective DC Inductance And Series DC resistance Given for both Devices

Verifying the symmetry by Overlaying the input impedance Of the two inductors

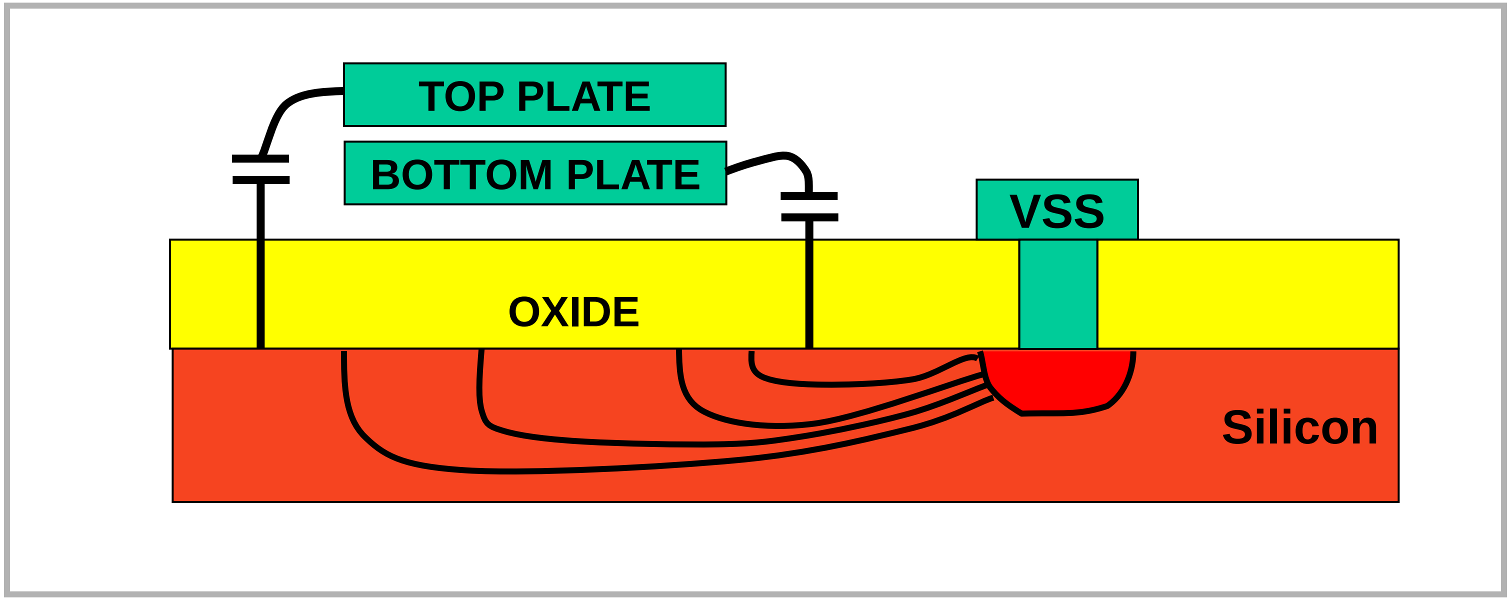
Lets talk

Capacitive Components

Capacitive Components

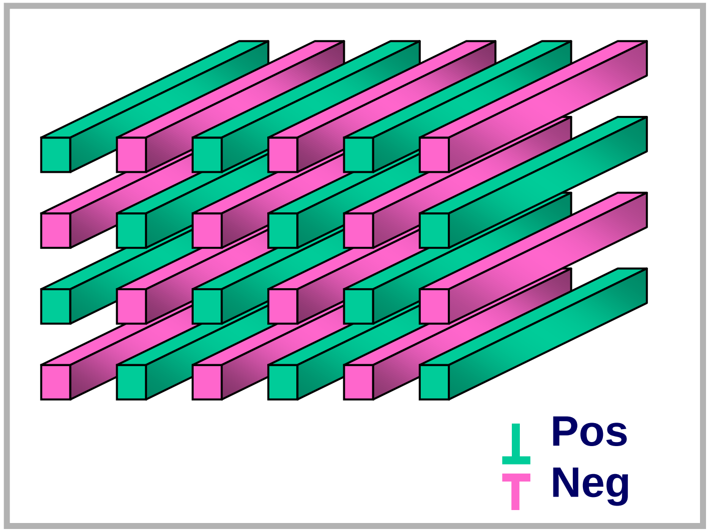
MIM Capacitors *(Not as Simple as they Look)*

- Large Devices with Distributed Resistance and Capacitance
- Could Include Significant Substrate Effects
- Asymmetry Could Cause Noise Pickup from Substrate

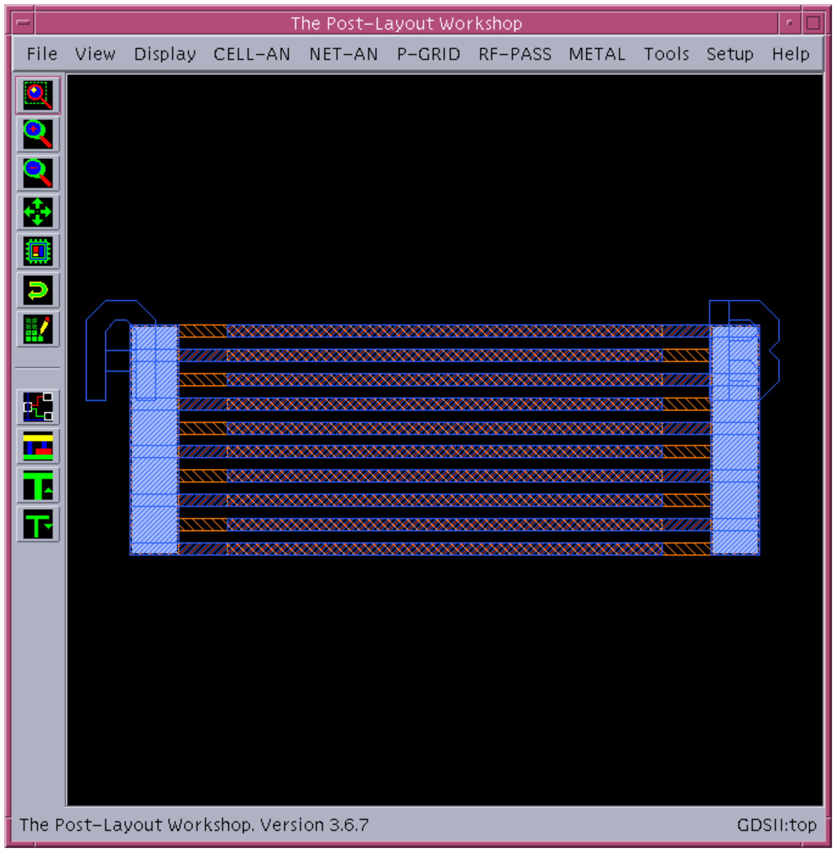


Capacitive Components

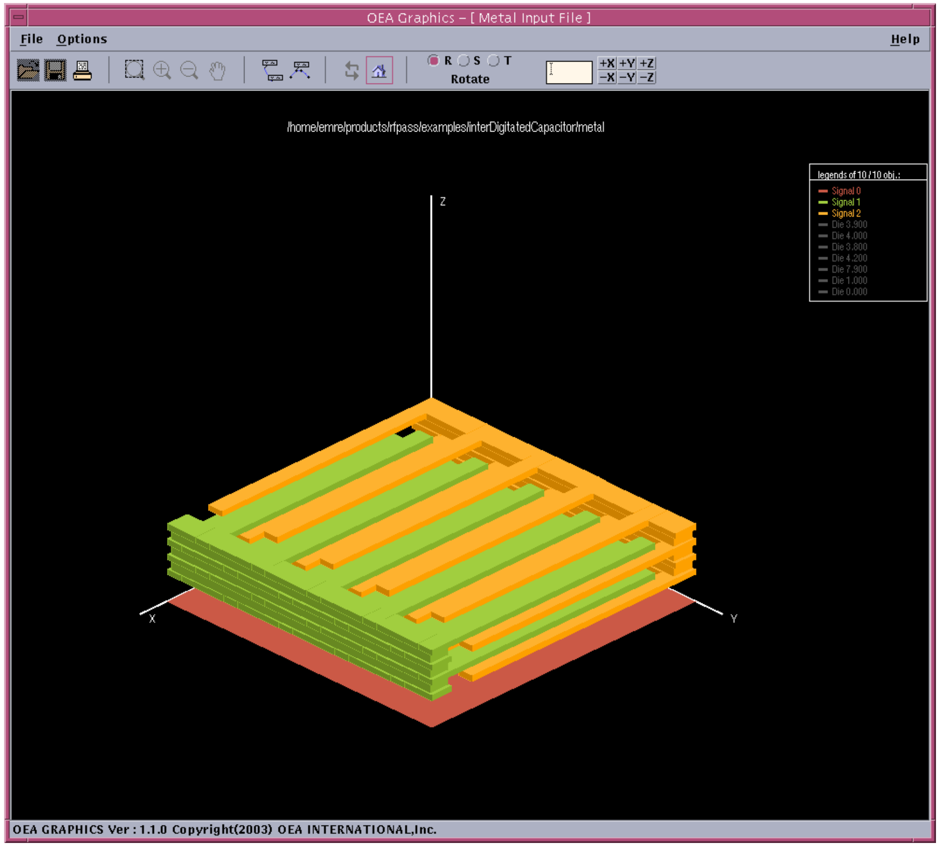
- **Multi-layer Interdigitated Structures**
  - Patented structure (owned by LoneStar Inventions)
  - Maximize Capacitance per unit area (4X standard parallel plate)
  - Symmetric relative to substrate (minimize noise pickup from substrate)
  - RF-PASS Modeling will include skin and proximity effects
- **RF-PASS can help optimize this type of design**
  - Control undesired RL effects
  - Helps easily customize to fits in oddly shaped regions
  - Optimize selection and usage of metals
  - Optimize finger width and spacing
  - Optimize placement of metal straps
  - Optimize Q



Example of Interdigitated Capacitor*



GDS2 View



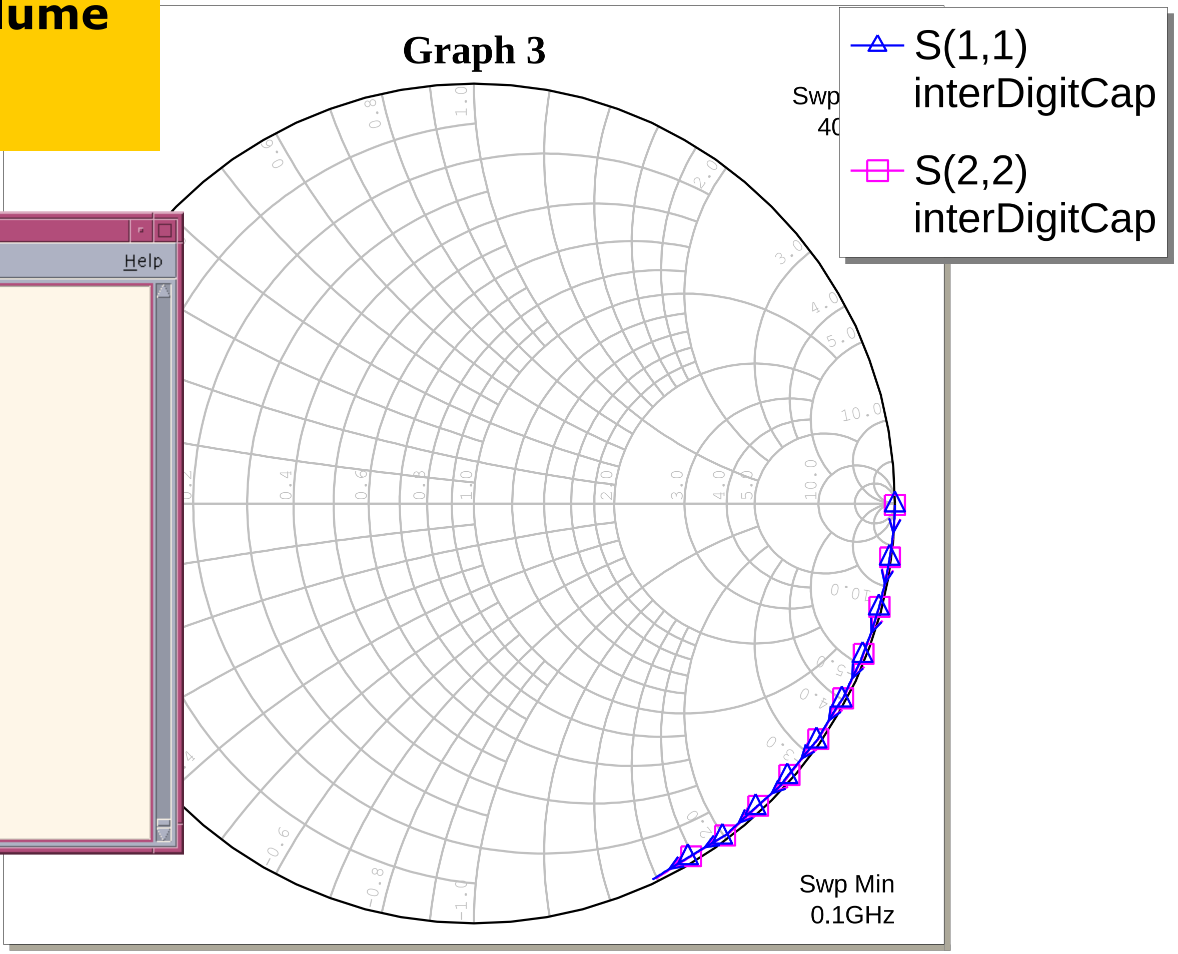
3-D Image

*** Patent: LoneStar Inventions**

Example Capacitor Report File and Plots

Inter-digitated caps provide more capacitance per volume by taking advantage of fringing effects.

```
Terminal
Window  Edit  Options                                    Help
2       // total nets
1       A
2       B
RF-PASS Capacitance Report


Net to SUBSTRATE Capacitance:
NET A   ->      SUBSTRATE       7.4359e-15
NET B   ->      SUBSTRATE       6.4629e-15

Net to Net Coupling Capacitance:
NET A   ->      NET A   4.5948e-15
NET A   ->      NET B   4.4931e-14
NET B   ->      NET B   2.8781e-15

Net Layer Capacitance:
NET A total cap 5.6962e-14
Layer5  1.4678e-14      25.77%
Layer7  1.4322e-14      25.14%
Layer45 1.3879e-14      24.37%
Layer50 1.4083e-14      24.72%
NET B total cap 5.4272e-14
Layer5  1.3769e-14      25.37%
Layer7  1.3856e-14      25.53%
Layer45 1.3058e-14      24.06%
Layer50 1.3589e-14      25.04%

WARNING : _IN / _OUT node pair not defined for A

WARNING : _IN / _OUT node pair not defined for B

2 Ports found. Results are in Yout, Zout and Sout files
Port 1 = A
Port 2 = B
```



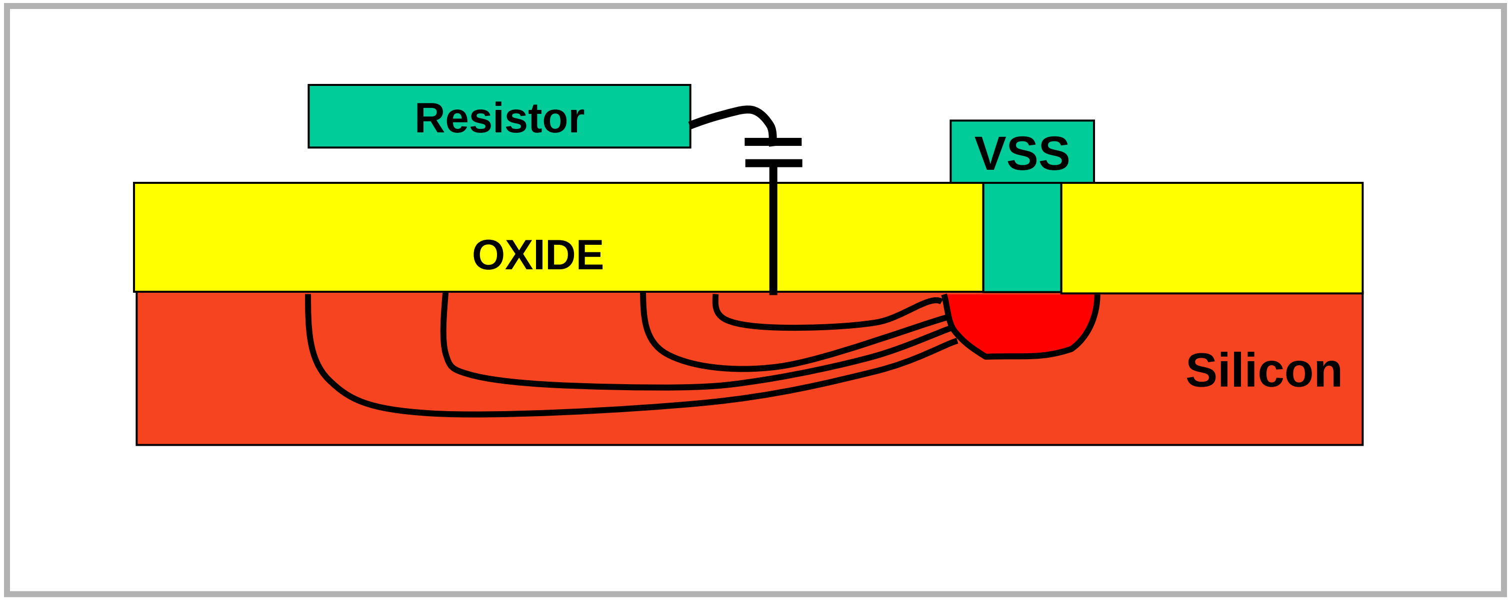
Lets Talk

Resistive Components

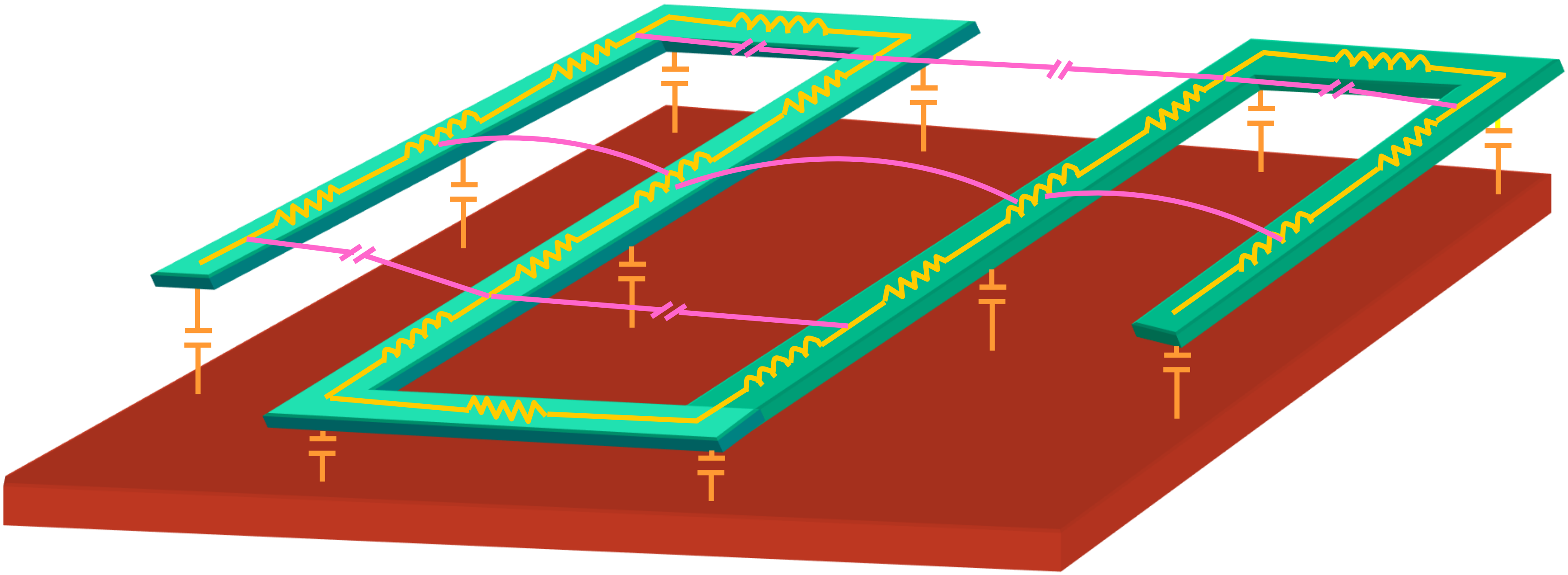
Resistive Components

Thin Film Resistors *(Not as Simple as they Look)*

- Large Devices with Distributed Resistance and Capacitance
- Could Include Significant Substrate Effects
- Asymmetry Could Cause Noise Pickup from Substrate

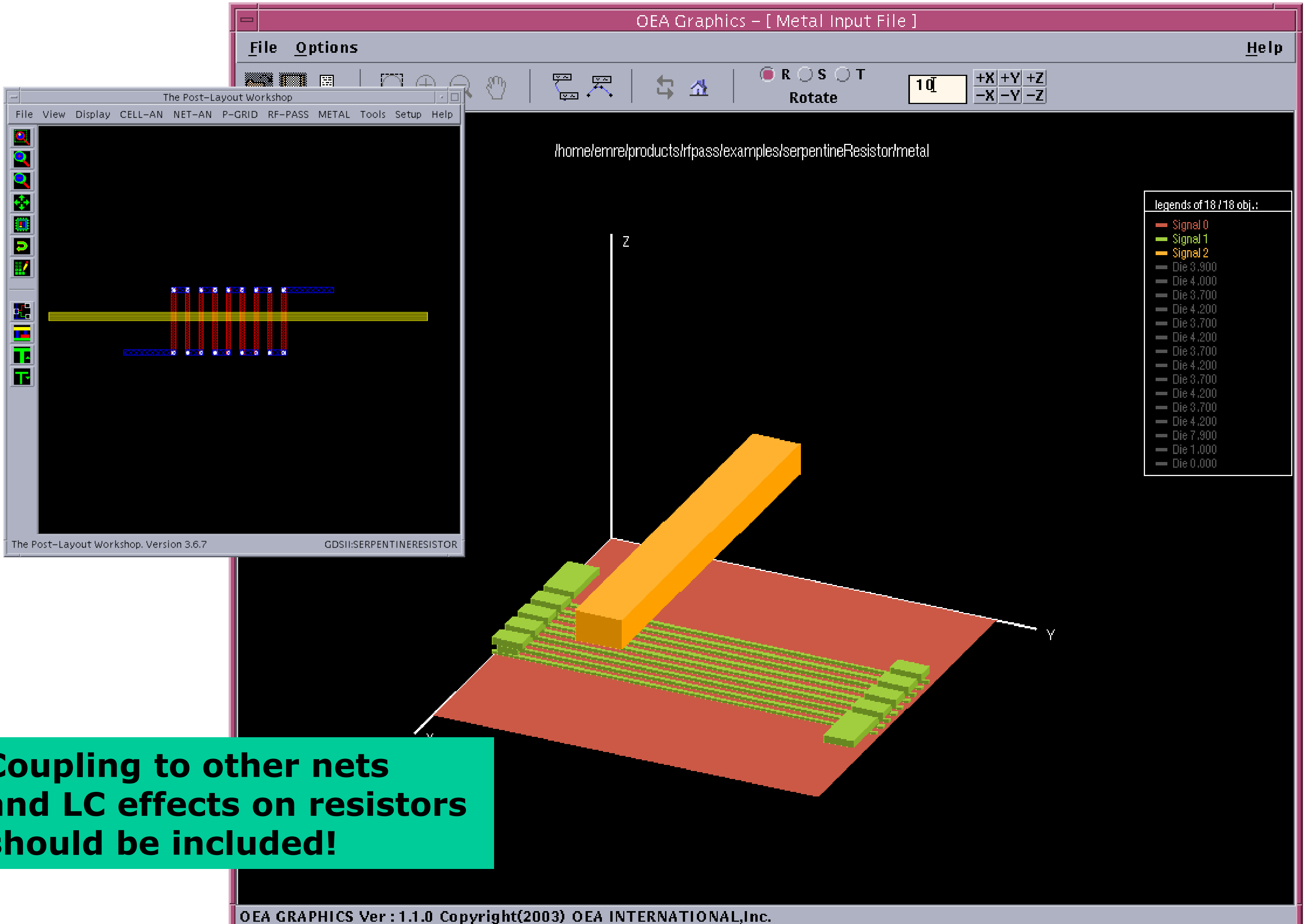


Thin Film Serpentine Resistor



- What is the coupling across segments?
- What is the coupling through the substrate?

Serpentine Resistor



Coupling to other nets and LC effects on resistors should be included!

Example Resistor Report File

Capacitance to GND

Coupling coefficient (K) Between the resistor and the net

Terminal

Window Edit Options Help

```
2       // total nets
1       1
2       2
RF-PASS Capacitance Report


Net to SUBSTRATE Capacitance:
NET 1   ->      SUBSTRATE       1.1255e-12
NET 2   ->      SUBSTRATE       8.4888e-14

Net to Net Coupling Capacitance:
NET 1   ->      NET 1   5.1803e-14

Net Layer Capacitance:
NET 1 total cap 1.1773e-12
Layer13 1.0260e-12      87.15%
Layer16 1.5126e-13      12.85%
NET 2 total cap 8.4888e-14
Layer38 8.4888e-14      100.00%

Effective Inductance res (res_IN to res_OUT): 6.4960e-10
        (With All Other Ports Open, substrate omitted)
Series DC resistance res (res_IN to res_OUT): 8.4635e+02

Effective Inductance net (net_IN to net_OUT): 6.8154e-10
        (With All Other Ports Open, substrate omitted)
Series DC resistance net (net_IN to net_OUT): 8.1010e-01

Mutual inductance between inductor res and net is : 5.8768e-11

Inductive Coupling Coefficient (K) between inductor res and net is : 8.8323e-02

Device res on Net Number 1 has an effective area of 4.713e+04 square microns

Device net on Net Number 2 has an effective area of 1.613e+04 square microns

4 Ports found. Results are in Yout, Zout and Sout files
Port 1 = res_in
Port 2 = res_out
Port 3 = net_in
Port 4 = net_out
```

Summary

Full 3D Field Solver with Frequency Effects with Fast Run Times

- S, Y, Z-Parameter and Compact Model Output
- GDSII Input or Automatic Creation of Structures.
- Useful for all RF Passive structures