

## Using TriQuint's Inductor Simulation Program

11/29/00

This Application Note describes the current, Induct\_fndy1.exe, Spiral Inductor Simulation Program for the PC. This program calculates frequency dependent values for a lumped element equivalent circuit that is used to model the physical Spiral Inductor.

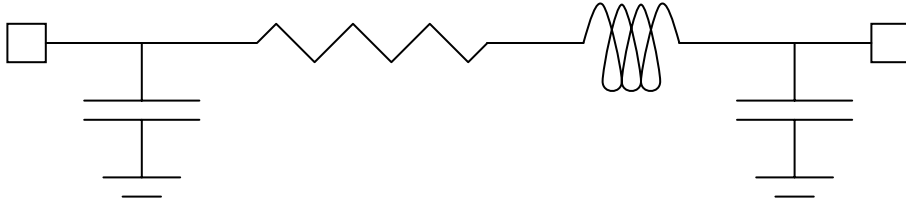
This program executes on the PC in a DOS Window. Open up a DOS Window in the Directory where this Program is stored (or have the Program in a Directory that is in your PATH) and type the name, Induct\_fndy1. Answer a series of questions about the physical dimensions of your Inductor and the Substrate it will be manufactured on. The Substrate (Wafer) thickness will be 100 microns for Wafers with Substrate Vias and 175 microns for Die in standard Plastic Packages. You may have your Wafer ground to a different thickness but these are standard.

This Program is less accurate for frequencies close to the Spiral Inductor self-resonance point. You can find the self-resonant Frequency of the Inductor by finding where the phase of S11, looking into the lumped equivalent circuit, changes from Positive to zero. A safe working range would be up to  $\frac{1}{2}$  of the Resonance Frequency. For more complicated situations such as; operation close to Resonance, where exact values are necessary, or in the presence of coupling to nearby structures, the use of a 2.5 D Electromagnetic Field Solver such as IE-3D (Zeeland Software) is suggested. If a minimum size Inductor is being modeled, where the spacing between turns is less than or equal to the thickness of the Inductor Metal, then a full 3-D simulator, such as Ansoft's HFSS, is needed.

This Application Note will show you how to use the Program and show a comparison of the Program's output to a Spiral Inductor whose S Parameters were measured.

## Equivalent Circuit

The equivalent circuit for the Rectangular Spiral Inductor is a series combination of an Inductance L and a Resistance R, with a shunt C to Ground at each end.



The Program inputs are: (See the following example for a set of default Parameters for the TQTRx Process)

**Number of Segments:** This is the Integer number of quarter turns of the Spiral Inductor. Ex: A 2 and a half turn Spiral Inductor would have 10 Segments.

**L1:** The Side of the Inductor containing the input trace expressed in microns (um).

**L2:** The other side of the Spiral expressed in microns (um).

**W:** The width of the Inductor trace in microns (um).

**G:** The width of the gap between Inductor traces in microns (um).

**T:** The thickness of Metal (Plated Gold) used to build the Inductor in microns (um).

**Er:** The Dielectric Constant of the Substrate.

**H:** The Substrate thickness in microns (um).

**Flow:** The low Frequency limit of the Frequency Band of interest in GHz.

**Fhigh:** The high Frequency limit of the Frequency Band of interest in GHz.

**Fstep:** The Frequency step through the Frequency Band of interest where the Network will be calculated.

### Program OUTPUT Example:

3.000Ghz	Cout=0.0626pf	R=0.760ohms	L=1.181nh	Ccen=0.0277pf
3.200Ghz	Cout=0.0627pf	R=0.779ohms	L=1.181nh	Ccen=0.0277pf
3.400Ghz	Cout=0.0627pf	R=0.798ohms	L=1.180nh	Ccen=0.0277pf
3.600Ghz	Cout=0.0627pf	R=0.816ohms	L=1.180nh	Ccen=0.0277pf
3.800Ghz	Cout=0.0628pf	R=0.834ohms	L=1.179nh	Ccen=0.0277pf
4.000Ghz	Cout=0.0628pf	R=0.852ohms	L=1.178nh	Ccen=0.0278pf

## Comparison between Measured and Modeled for Spiral Inductor

Spiral Inductor Parameters (TQTRx FOUNDRY Process):

1. 8.5 turns = 34 Segments
2. L1 = L2 = 180 microns
3. W = G = 5 microns
4. Thickness = 6 microns
5. Er = 12.9
6. H = 175 microns (Standard Plastic Package Wafer thickness)
7. Flow = 1 (GHz)
8. Fhigh = 3 (GHz)
9. Fstep = 0.5 (GHz)

\*\*\*\*\* DOS PROGRAM OUTPUT FOR IND\_1 \*\*\*\*\*

1.000Ghz Cout=0.0557pf R=2.817ohms L=6.286nh Ccen=0.0147pf  
 2.000Ghz Cout=0.0560pf R=2.978ohms L=6.256nh Ccen=0.0148pf  
 3.000Ghz Cout=0.0565pf R=3.199ohms L=6.205nh Ccen=0.0150pf

\*\*\*\*\*

A quick check of the Phase of S11 from the above equivalent circuit shows that the Phase goes from positive to zero at almost exactly 8GHz. Use of this simulation above 4 to 5GHz should be done with caution.

To compare this against measured 2-Port S Parameters of a Spiral Inductor I first need to extract the S Parameters of the above circuit(s) at the Frequencies of interest. I choose 1 & 3GHz to compare against measured S Parameters, mainly to stay away from the resonance frequency of this inductor.

First I have to add into the above equivalent circuit an inductance of 0.42nH to account for the interconnect in the measured data between the Spiral Inductor and the Coplanar Probe launches. So I am extracting the S Parameters (at 1 & 3 GHz) of the following:

1.000Ghz Cout=0.0557pf R=2.817ohms L=6.706nh Ccen=0.0147pf  
 3.000Ghz Cout=0.0565pf R=3.199ohms L=6.625nh Ccen=0.0150pf

### S Parameters from lumped Equivalent Circuit(s)

**Frequency: 1GHZ**

S11	S12	S21	S22
0.16913+j0.32532	0.83494-j0.34965	0.83494-j0.34965	0.16046+j0.32967

**Frequency: 3GHZ**

S11	S12	S21	S22
0.63530+j0.41335	0.37953-j0.50581	0.37953-j.50581	0.60005+j0.46296

### S Parameters from measured Spiral Inductor on TQTRx Process

**Frequency: 1GHZ**

S11	S12	S21	S22
0.14780+j0.29091	0.84180-j0.34140	0.84268-j0.34070	0.14883+j0.28995

**Frequency: 3GHZ**

S11	S12	S21	S22
0.58456+j0.38141	0.38522-j0.52716	0.38684-j0.52695	0.58737+j0.37408

### Comparison

I compare the two sets of S Parameters by the Magnitude of the Error Vector that links the two. Expressed mathematically and considering the measured S Parameter as  $a1+jb1$  and the simulated S parameter as  $a2+jb2$  then the Magnitude of the Error Vector is:

$$\text{Magnitude of Error Vector for a particular S Parameter} = \text{MAG}[(a2+jb2)-(a1+jb1)]/\text{MAG}(a1+jb1)$$

#### 1GHz

S11 MAG[(a2+jb2)-(a1+jb1)] = A = 0.040487352 MAG(a1+jb1) = B = 0.326300141 A/B = 0.12408 % A/B = <b>12.40801</b>	S12 MAG[(a2+jb2)-(a1+jb1)] = A = 0.010727626 MAG(a1+jb1) = B = 0.908392007 A/B = 0.011809 % A/B = <b>1.180947</b>
S21 MAG[(a2+jb2)-(a1+jb1)] = A = 0.011835304 MAG(a1+jb1) = B = 0.908948872 A/B = 0.013021 % A/B = <b>1.302087</b>	S22 MAG[(a2+jb2)-(a1+jb1)] = A = 0.041382726 MAG(a1+jb1) = B = 0.325915919 A/B = 0.126974 % A/B = <b>12.69736</b>

#### 3GHz

S11 MAG[(a2+jb2)-(a1+jb1)] = A = 0.059951615 MAG(a1+jb1) = B = 0.69798847 A/B = 0.085892 % A/B = <b>8.589199</b>	S12 MAG[(a2+jb2)-(a1+jb1)] = A = 0.022094131 MAG(a1+jb1) = B = 0.652913014 A/B = 0.033839 % A/B = <b>3.383932</b>
S21 MAG[(a2+jb2)-(a1+jb1)] = A = 0.022364054 MAG(a1+jb1) = B = 0.6536964 A/B = 0.034212 % A/B = <b>3.421168</b>	S22 MAG[(a2+jb2)-(a1+jb1)] = A = 0.089775819 MAG(a1+jb1) = B = 0.696379821 A/B = 0.128918 % A/B = <b>12.89179</b>

### CONCLUSIONS

The worst case Magnitude of the Error Vector was in the S22 Parameter at 3GHz and was 12.89%. At this time it is not known how much of the difference can be explained by Probe placement issues.<sup>1</sup>

<sup>1</sup> The Coplanar Probe Launches were perhaps a little too close to the Spiral Inductor and there is some concern that the measured data might have some small errors from that.