Spiral inductor modeling on RFICs

By John Dunn, Engineering Consultant, Applied Wave Research, Inc.

Simulation and modeling of radio-frequency integrated circuit (RFIC) inductors is a difficult task, where several common problems and pitfalls are possible. This article examines a number of issues that must be considered when modeling inductors, selecting a simulation tool, and measuring test inductors for verification.

Spiral inductors on RFIC circuits (Figure 1) are critical for filtering and tuning purposes. However, correct modeling of the inductor is far from trivial. It is important that the inductor model predict the Q of the inductor, and the resonance accurately (Figure 2). This is contrasted to broadband amplifier design, where an inductor might be used to compensate for capacitance, and an extremely accurate model is not necessary. Developing an accurate model is however a nontrivial task. In this paper, the principal issues in accurate modeling are discussed, including conductor losses, inductance effects, substrate effects, unknown ground return, capacitance issues, and SPICE compatibility issues.

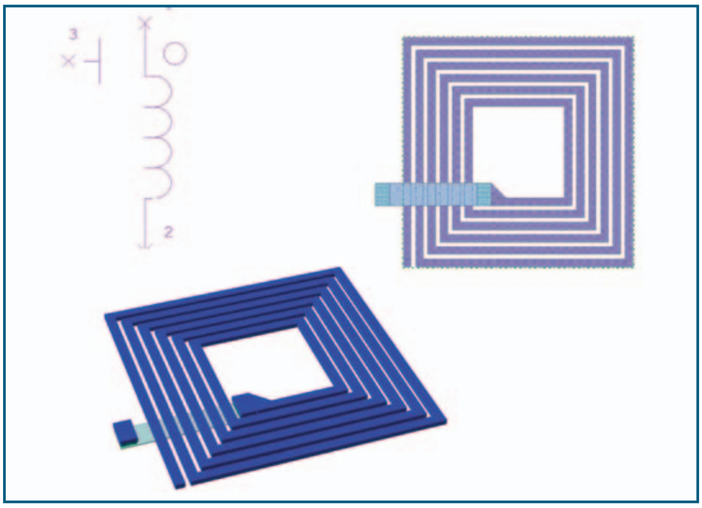
This paper examines a number of issues to keep in mind when using simulation software, including substrate effects, 3D conductors, conductor losses, frequency effects, current return, extraction of model parameters, and convergence of simulation.

Many companies build and measure inductors to test models, check simulations, and develop model libraries. This article discusses common problems to be avoided, including calibration, current return, and parameter sensitivity.

Modeling issues

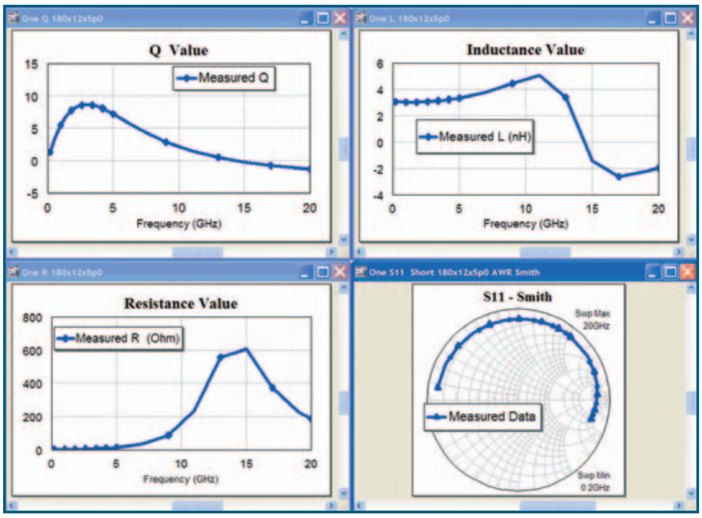
Spiral inductors on RFIC circuits are critical for filtering and tuning purposes. However, correct modeling of the inductor is far from trivial. It is important that the inductor model predict the Q of the inductor, and the resonance accurately. This is contrasted to broadband amplifier design, where an inductor might be used to compensate for capacitance, and an extremely accurate model is not necessary. Developing an accurate model is, however, a complicated task (Figure 3). The principal reasons are:

Figure 1: Spiral filters are complicated structures, with non-zero thickness lines, underpasses, and more than one spiral metal layer possible.



- ***Conductor losses:* —** Normally, spiral inductors are placed on top layer metal, in order to reduce conductor loss (because of the larger line cross sections possible), and to minimize the coupling to the substrate (see below). The metal thickness and width are typically on the order of a few microns in each dimension. At the frequency of a few GHz, these dimensions are on the order of a skin depth for aluminum or copper. This means the current distribution in the conductors will start to change – crowding toward the surface of the line. This current crowding increases the resistance in the inductor, and therefore decreases the Q. The model must therefore have some form of frequency dependent resistance. In aluminum lines on top layer metal, it is possible for resistance to increase ten fold or more as one goes up to 20 GHz.
- ***Inductance effects:* —** The current crowding will also affect the inductance as a function of frequency. Inductance is composed of two terms – the external inductance and the internal inductance. Internal inductance is due to magnetic flux internal to the metal conductor; similarly, external inductance is due to the flux external to the conductors. Normally, external inductance dominates

Figure 2: Designers are concerned about the spiral's inductance, resistance, and Q value, all as a function of frequency.



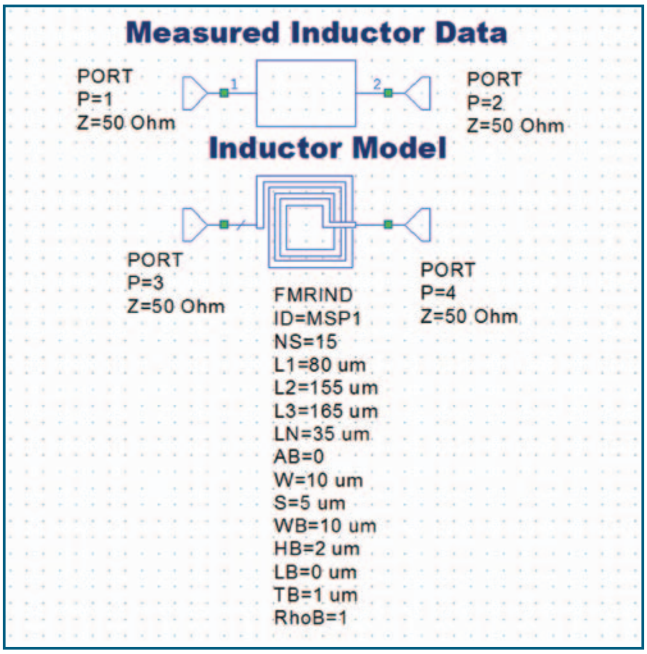


Figure 3: Inductor models can be quite sophisticated. This model for a single layer spiral has thirteen physical parameters in order to match the experimental data accurately.

internal inductance for electrical lines. However, for a spiral inductor with tightly spaced lines, the width of the lines can be larger than the spacing, and internal inductance can be an important contributor. As the current crowding occurs at higher frequencies, the internal inductance will go down, as the current and flux are being excluded from the interior of the lines. Therefore, there is a frequency dependent inductance effect, which also affects the Q.

- ***Substrate effects: —*** The lossy substrate can contribute substantially to reduction of the Q by providing a resistive loss mechanism. Specifically, through capacitive coupling to the substrate, it is possible to excite eddy currents in the substrate. These currents then dissipate energy as the substrate is lossy. Notice that the magnetic field does not normally couple to the substrate as much, as the silicon is a relatively poor conductor which the magnetic field will go right through. The problem of including the substrate coupling is compounded by having to ask how the substrate is connected to the rest of the circuit. For example, the current generated will typically go out of the substrate through substrate contacts attached to a power plane. It therefore becomes difficult to determine the entire current path, and the resulting loop inductance. For these reasons, more and more designers are deliberately placing some kind of shielding below the inductor to isolate it from the substrate. The advantages of doing this are two fold. First, the substrate losses are replaced by metal losses in the intervening shielding layer, which is typically a better conductor. Second, it is easier to model the intervening layer and the return currents, thereby following the philosophy of “only use what you can accurately model in layout”.
- ***Unknown ground return: —*** Inductance is only uniquely defined when there is a loop of current. Unfortunately, the modeler rarely has the luxury of knowing exactly where the return current is going to be. Therefore, certain assumptions have to be made. Perhaps the return current is assumed to be on the substrate? Perhaps an intervening power plane? Or a ground return ring? A circuit simulator implicitly has a “node 0” current return – which often does not fit reality well.
- ***Capacitance issues: —*** A multi-turn spiral has a large amount of capacitive coupling to itself. The capacitance normally does not change much with frequency, as it is a result of charge-to-charge coupling. Charge will stay on the surface of a “good” conductor, and aluminum is a good conductor well past 100 GHz. However, it is often difficult to predict the capacitance, as the lines are very three dimensional structures. See below with regard to simulation.
- ***Spice compatibility issues: —*** As mentioned earlier, the resistance and inductance will change with frequency. Therefore, it is tempting to make a model with frequency dependent resistance and inductance. This is, however, a dangerous practice in that when the model is exported to Spice, undesirable behavior can occur. The response can become completely non-physical. Therefore, care must be used when using the model in Spice.
- ***Underpass effects: —*** The signal must be brought out from the center port of the spiral inductor. Typically this is accomplished by connecting to a line on a lower metal layer, creating an underpass. It is important that the effect of the underpass be included in the model. Notice that the electrical properties of the underpass will be different in the central region of the spiral, and when the line is running under the spiral conductors.

Simulation issues

Electromagnetic simulation software is often used to obtain simulated data for inductor modeling and design. Several products are available using a variety of methods. Many of these products are general purpose simulators. Some of them, such as EMSight from Applied Wave Research (AWR) are specifically designed for spiral inductor modeling in RFICs. Simulation of inductors is difficult, and care must be taken. Indeed, the fact that there are specialized products available is some indication of the complexity of the problem. Here are a number of issues to keep in mind when using simulation software:

- ***Substrate effects: —*** The substrate must be included somehow. There are two possible ways to do this. First, it can be included as an extra layer. The problem with this approach is that one is placing a very thick layer under thin SiO2 layers. This leads to complications for finite element codes that mesh volumes, and possible numerical concerns for moment method codes which use a Green’s function that includes all the layers’ information. The second possibility is to use an impedance boundary condition on the surface of the silicon. The problem is that the silicon isn’t all that good a conductor.
- ***3D conductors: —*** The conductors’ thicknesses cannot be ignored. In modern RFIC technologies, the inductor lines can be as thick as they are wide, with small gaps between loops of the spirals. Therefore, the software must have some way of accounting for non-zero metal thickness. 3D simulation software can, in principal, model this effect. It is possible

to give lines a thickness in a 2 ½ D simulator if one stacks two lines on top of one another and meshes them together judiciously with vias. It is important to experiment with this approach on simple straight line geometries, to make sure one has the right separation and via count.

- ***Passivation layers:* —** The circuit is usually passivated by placing a thin layer of passivating material on top of the chip. The inductor's self resonance can be affected by this layer; it is therefore important to include its effects in the model.
- ***Conductor losses:* —** These are important for correct calculation of the Q. Simulation software will corporate conductor loss in one of two ways. Either it will use impedance boundary conditions on the surfaces of the conductors, or it will mesh the interior of the conductors in a 3D fashion. Both ways have reported to have been successful if carefully used.
- ***Frequency effects:* —** The software should include frequency effects for RFIC applications. There is software available that gives DC inductance and resistance values, but this is of limited use because of the frequency dependent nature of the inductance and the capacitance.
- ***Current return:* —** It is important to understand how the software is setting up sources that excite the inductor and where the return current is. For example, many software packages excite the structure with wave ports, sometimes called edge ports. These ports exist at the edge of the simulation boundary, and are excited with an electromagnetic wave. Let's assume one is using an impedance boundary condition ground which is set to that of the substrate. How does one know that the return current is coming back on this plane? For example, it may really be going on the sidewalls of the box – if there is one. Also, even if the current is in the substrate, it will in reality not be as simulated because it will actually flow between two substrate contacts. Therefore, care must be taken in setting up the excitation.
- ***Extraction of model parameters:* —** S parameters are the normal output of the software. The modeler is then faced with fitting the model parameters to the data. (Of course, he or she also has the option of inserting the S parameter block into the circuit simulation software directly.) This can be an error prone process. The two most common problems are a lack of model sensitivity to a given parameter, and a large number of parameters to fit. If the model is not sensitive to a parameter, it is possible to have wide swings in the parameter's value. As a simple, contrived example, imagine one simulates an inductor with only one port – the other port being open. It will be virtually impossible to see the inductance as no current will be going through it (although it might be a good way to look at capacitance). As another more realistic example, when one excites the inductor with a wave, there is an impedance to the two ports. Make sure that the parameters you are trying to extract give impedances that are the same order of magnitude of the port impedances. Otherwise, you will not be able to get an accurate answer. For example, if you use ports that have impedances of 100 Ohms, and the capacitance has an effective impedance of 10,000 Ohms, it will look like an open, and be very difficult to get an accurate answer.
- ***Convergence of simulation:* —** How does one know the simulation has converged? The simplest answer is – experience and intuition. For simulators with iterative meshers, one must always ask what the convergence criteria are. It is very common to have the simulator converge on the S parameter changes. The problem is that the S parameter could be totally dominated by the inductance. The mesh may not yet be adequate for an accurate resistance value. Therefore, care must be taken when specifying an error criterion.

Measurement issues

Many companies build and measure inductors to test models, check simulations, and develop model libraries. Common problems to be avoided are:

- ***Calibration:* —** Make sure that the system has been properly calibrated. The probes, and test structures have inherent inductance, capacitance, and resistance. It is important that these effects be understood, and removed if the final model parameter values are to be accurate.
- ***Current Return:* —** Understand where the return current is. The inductance value measured is the loop inductance, which includes the return current.
- ***Parameter Sensitivity:* —** Make sure that the measurements are sensitive to the parameters you are interested in. For example, if the inductance is completely dominating the resistance, it is unlikely a good resistive value can be determined.

Software available

Several excellent EM software tools are available through the AWR EM Socket™ interface, and AWR continues to work with other emerging EM and spiral inductor modeling tool vendors to integrate their solutions into the AWR design platform through its EM Socket technology Links to the vendors' web sites can be found at: http://www.appwave.com/sales/alliance/partners/EM.

- AWR – EMSight – Method of moments simulator.
- Sonnet – Method of moments software.
- IE3D – Method of moments software. There is a discussion of inductor modeling on their Technical Notes page.
- EM3DS – MEM Research – Method of moments software. Uses volume currents or surface currents.
- OEA Spiral — the product is specifically tailored for spiral inductor analysis. It also has synthesis capability, wherein the designer inputs the inductance value, and the layout is created.
- Optimal – SI applications, including O-Wave, a 3D full-wave extraction tool.

Author biography

Dr. John Dunn is a senior engineering consultant at Applied Wave Research, Inc., specializing in signal integrity issues. His areas of expertise include electromagnetic modeling and simulation for high-speed circuit applications. Before joining AWR, he was a professor of electrical engineering at the University of Colorado for 15 years.

Dr. Dunn is the author of twenty papers in technical journals, as well as numerous conference publications, and several invited talks. He received his Ph.D. in applied physics from Harvard University in 1984 and is a senior member of IEEE.

Company Information

Applied Wave Research
www.appwave.com