Measuring Self Resonant Frequency

Introduction

When comparing published electrical values, engineers require a common basis for comparison. Ideally, a 100 nH inductor with a self resonant frequency (SRF) of 1 GHz from one manufacturer is equivalent to inductors with the same published values from every other manufacturer. Realistically, however, the test instrument and fixture affect the SRF measurement. Since all manufacturers do not use the same instruments and fixtures, not all published SRF specifications are equivalent, which makes inductor comparisons difficult. The following discussion is intended to provide insight into practical SRF determinations and comparisons.

Self Resonance of Inductors

Ideal inductors would have zero resistance and zero capacitance. But, real inductors have “parasitic” resistance and capacitance. The first self resonant frequency of an inductor is the lowest frequency at which an inductor resonates with its self-capacitance. The first resonance can be modeled by a parallel combination of inductance and capacitance, shown in Figure 1. Resistor “R1” limits impedance near the resonant frequency.

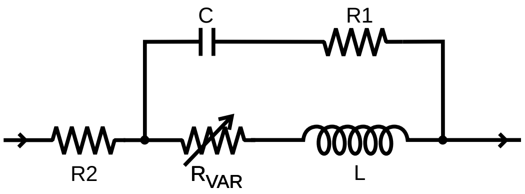

Figure 1. Inductor Model

At the SRF of an inductor, all of the following conditions are met:

- The input impedance is at its peak.
- The phase angle of the input impedance is zero, crossing from positive (inductive) to negative (capacitive).
- Since the phase angle is zero, the Q is zero.
- The effective inductance is zero, since the negative capacitive reactance ($X_c = 1 / j\omega C$) just cancels the positive inductive reactance ($X_L = j\omega L$).
- The 2-port insertion loss (e.g. S21 dB) is a maximum, which corresponds to the minimum in the plot of frequency vs. S21 dB.
- The 2-port phase (e.g. S21) angle is zero, crossing from negative at lower frequencies to positive at higher frequencies.

A measurement of any of these conditions can be used to determine the SRF of an inductor.

How Capacitance Affects SRF

Historically, inductor capacitance is called “inter-winding capacitance” based on the assumption that it is the result of charge separation between insulated coil windings. However, if the inductor is measured over a conducting ground plane, capacitance between the coil and the ground plane is also part of the measurement. The distance of the coil from the measurement ground plane and the effective dielectric constant of the measurement substrate affects the capacitance to ground. This partially explains how the test fixture affects the SRF measurement. The following equation shows how the SRF is related to inductance and capacitance in an LC circuit.

$$\text{SRF} = \frac{1}{2\pi\sqrt{(LC)}} \text{ in Hz}$$

where :
L is the inductance in Henries
C is the capacitance in Farads

From this equation, it is clear that increasing inductance or capacitance lowers the measured SRF. Reducing inductance or capacitance raises the SRF.

Fixture Effects on SRF Measurements

A fixture is required to connect an inductor to the terminals of a test instrument. After calibration and fixture compensation are performed, it is assumed that all fixture effects have been de-embedded (removed) from the measurement.

Fixture compensation uses open and short standards, but it cannot predict the interaction of a specific inductor with the test fixture. Therefore, some residual capacitance between the measured inductor and the fixture may exist after calibration and fixture compensation. The result is that SRF measurements of the same inductor can change with each different combination of instrument and fixture. Coilcraft states the specific instrument and fixture used to measure the SRF of its inductors.

To illustrate the effect of residual fixture capacitance on SRF, Figure 2 plots the effective series inductance of a 100 nH chip inductor using AWR Microwave Office / Visual System Simulator 2002. The modified SPICE model simulation shows the effect of an additional 0.01 pF of capacitance to ground at the input terminal. The term “effective inductance” is used, because the low-frequency inductance is the same (100 nH) for both models, but the induc-

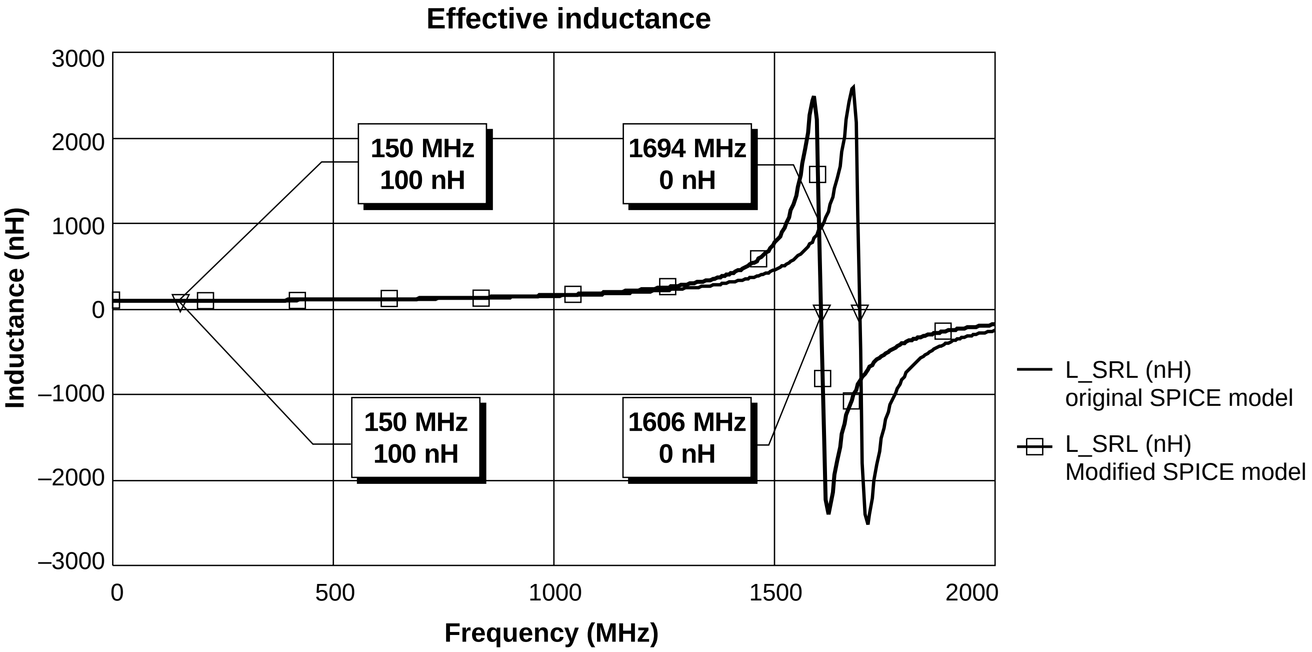

Figure 2. Effective Inductance With Residual Capacitance Effects

tance near the SRF is affected by capacitance between the inductor and the fixture.

The effect of residual fixture capacitance is more pronounced on lower value inductors. The effect of residual fixture capacitance on larger power inductors is often negligible.

Several important conclusions can be made from Figure 2:

- A slight difference in fixture design and calibration can have a large effect on the measured SRF.
- In the region of the measured SRF, a small difference in fixture design and calibration can mean the difference between reading a large positive inductance or a large negative capacitance.
- If the parasitic capacitance (and inductance) of the circuit board to which an inductor is attached is different from the test fixture, the SRF measurement of the board-mounted inductor will be different.
- Since SRF measurements are fixture/substrate-dependent, a “typical” SRF cannot be defined when the fixture effect is significant.

How Small Differences in Capacitance Affect Q

Figure 3 illustrates the effect of residual fixture capacitance on Q values. The values represent the Q for the original inductor model plotted in Figure 2 compared to the Q of the same inductor with an additional 0.01 pF of capacitance to ground at the input terminal. At lower frequencies, the residual fixture capacitance has little effect on the Q value. At higher frequencies, the effect on Q becomes significant. In this example, the small residual capacitance to ground causes the peak Q value to shift by 132 MHz and to decrease in magnitude by 23% of the original value.

How Coilcraft Measures Inductor SRF

When compiling data for publication, Coilcraft normally uses the same instrument and fixture to measure the SRF of all our chip inductors and power inductors: an Agilent/HP Vector Network Analyzer and a Coilcraft SMD-D (2-port) test fixture. The SRF is determined to be the frequency at which the insertion (S21) phase changes from negative through zero to positive.

Because SRF measurements are so sensitive to fixture effects, we specify the SRF for our low inductance RF chip inductors as a “minimum” value, approximately 15% to 20% below the actual average measurement of a representative sample. Since fixture effects become negligible for higher inductance values, SRF for our power inductors is specified as “typical.”

Comparing Coilcraft Inductor SRF to Other Inductors

When comparing the SRF of Coilcraft chip inductors to other inductors, the same instrument, fixture, calibration, and fixture compensation standards should be used. If not, any differences in SRF specifications may be masked by instrument and fixture effects, possibly causing incorrect conclusions.

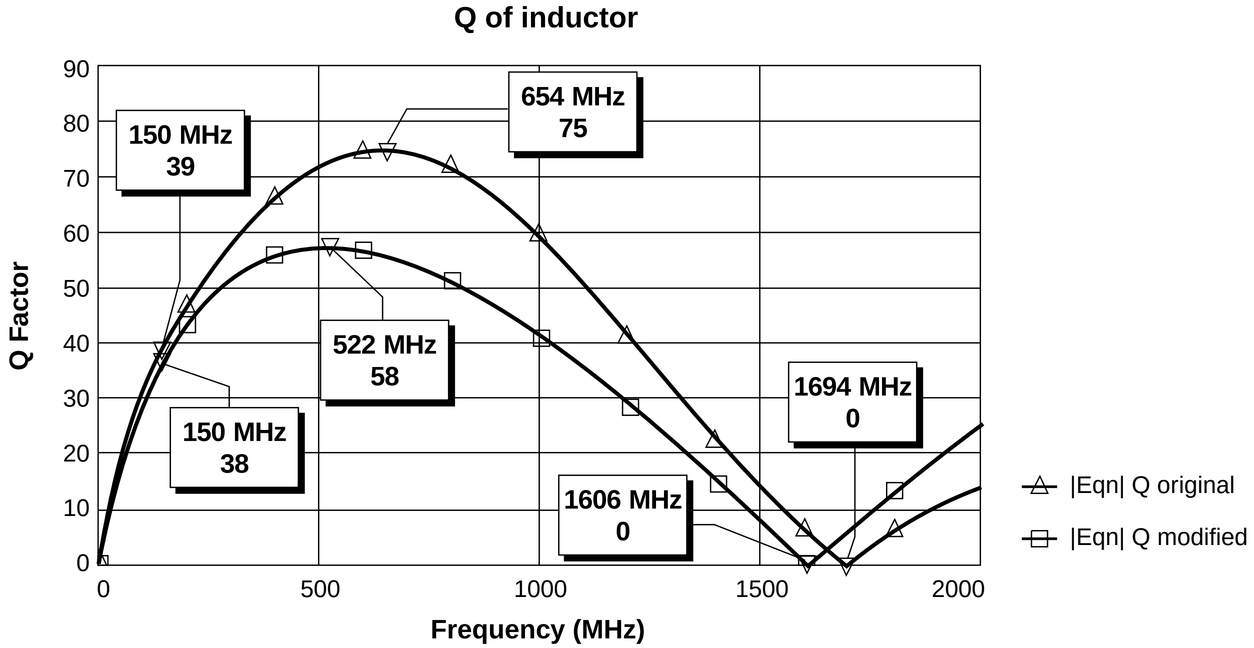

Figure 3. Effect of Capacitance on Measured Q

Simulating Substrate-Dependent SRF

Remeasuring the SRF of inductors for each new application circuit board is clearly not convenient or timely for circuit designers. There is an easier way to determine the SRF of an inductor in a specific application: circuit simulation.

To the best extent possible, fixture effects are removed from our measurements before we create our SPICE models and S-parameters. As a result, the SRF of the de-embedded measurement is higher than the measured value.

And yet, the de-embedded SRF is not the true SRF. The true SRF of any inductor always depends on the specific characteristics of the circuit board to which it is mounted. In other words, the SRF is substrate-dependent.

By simulating the Coilcraft model over a specific circuit board substrate, you can determine the SRF of an inductor for your application. The circuit board substrate dielectric constant and thickness, and the size and layout of the conductor traces in the vicinity of the inductor determine the SRF of the inductor.

Eagleware's RF and microwave design software offers high-accuracy libraries of many of our chip inductor series. The models are substrate-scalable, based on measurements of our inductors over various thicknesses of FR4 and alumina.

By applying the circuit board characteristics and tolerances to the simulation, circuit designers can see the effects they have on the SRF and all other electrical characteristics, such as inductance, Q, input impedance, phase, insertion loss and return loss. This knowledge gives the designer a practical basis to apply when comparing inductors, and ultimately can answer the question of whether an inductor is appropriate for the application.