

Characterizing Inductors at HF and VHF

Inductors are a key component in RF circuits. Their performance makes a great difference in the operation of amplifiers, oscillators, and other circuit blocks -- yet many designers have no way of determine the real-world performance of these devices at radio frequencies. This paper describes one method of measuring inductance and quality factor (Q) using an RF spectrum analyzer with a tracking signal generator. The method can be adapted if the experimenter does not have access to this equipment.

Inductor Assumed Model

Figure 1 shows the model of the inductor that will be used during the discussion. It is a second approximation with all loss resistance lumped into one series equivalent resistance. No stray capacitance is accounted for in the model. This approximation will be valid as long as the test frequency is kept at least an octave below the self-resonant frequency of the inductor being tested.



Figure 1: Assumed inductor model

Test Fixture

Figure 2 shows the test setup in schematic form and Figure 3 shows the actual fixture, which is constructed by soldering a pair of 50-ohm BNC connectors directly to a section of copper-clad printed circuit board. The connectors must be placed close together to minimize stray inductance. In addition, the parts being used for the test should be kept away from the ground plane to minimize stray capacitance.

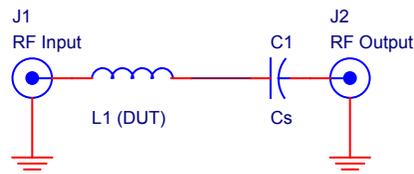


Figure 2: Test fixture schematic

Please note that the test fixture *must* be built on a metal chassis or ground plane; "prototyping boards" will not work at radio frequencies!

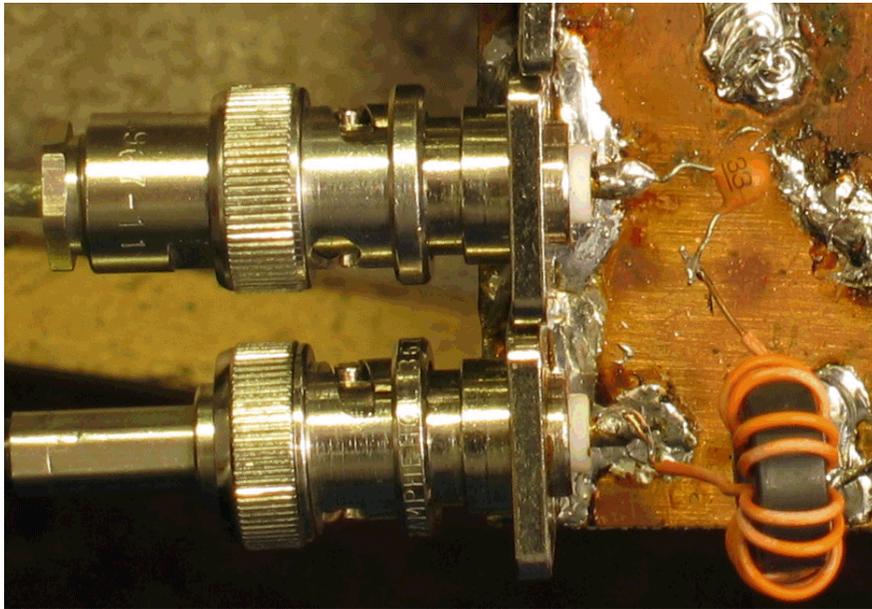


Figure 3: Test fixture construction

Test Procedure

1. A series capacitor is chosen and accurately measured using an LCR bridge. (The author uses a B&K Instruments digital LCR bridge with 0.1 pF resolution, auto-calibrated to 0.0 pF using 3 cm test leads in an open-circuit configuration).

TIP: Choose a series capacitance that will bring the circuit into series resonance at or near the desired frequency of operation for the inductor.

2. Connect the inductor being tested in series with the capacitor from Step 1, keeping leads as short as possible. Solder all connections.

WARNING: Do not solder connections in the circuit while it is connected to any of the test equipment.

3. Connect the tracking generator and spectrum analyzer to the RF input and RF output of the test fixture. Set the generator level to 0 dBm and the analyzer reference level to 0 dBm.

TIP: You may want to temporarily connect a BNC-to-BNC adapter in between the two RF cable ends to verify and calibrate the 0 dB level of the analyzer, and compensate for any signal loss in the cables.

4. Adjust the spectrum analyzer until you locate the resonant frequency of the circuit, which will appear as a more or less distinct peak on the display. Accurately measure this frequency and apply Equation 1 to find the inductance.

$$(1) L = \frac{1}{4\pi^2 f^2 C}$$

5. Measure the circuit loss in dB at resonance (the peak) and use Equation 2 to find the equivalent series resistance (ESR) of the circuit.

$$(2) R_s = Z_0 \left(10^{(dB/20)} - 1 \right) \quad \text{Where } Z_0 \text{ is 50 ohms in the author's setup, dB is the loss.}$$

TIP: Set the spectrum analyzer to 1 or 2 dB per vertical division to increase the accuracy of this measurement.

TIP: This value includes the ESR of the capacitor you've chosen to series-resonate the coil. To eliminate the ESR of the capacitor, short the inductor and measure the loss (preferably at a frequency high enough for stiff coupling between tracking generator and load, where $X_c \ll Z_0$).

6. With the series resistance in hand, calculate the Q of the inductor using Equation 3.

$$(3) Q = \frac{X_s}{R_s} = \frac{2\pi fL}{R_s}$$

Examples and Results

Three different inductor - frequency combinations were measured to help confirm the properties of inductor *material 67* procured from Amidon associates. This material is rated for operation up to 80 MHz for resonant circuit applications. A toroidal core of size 37 (Amidon part number FT 37-67) was used for the inductors.

Trial 1:

C = 33.1 pF, L = 10 T on FT 37-67 core. Sweep shown in Figure 4.

Frequency of Resonance: 18.332 MHz

Inductor Measured Value: 2.28 μ H

Loss: 0.4 dB @ resonance

R_s: 2.36 Ω

Q: 111 J/J

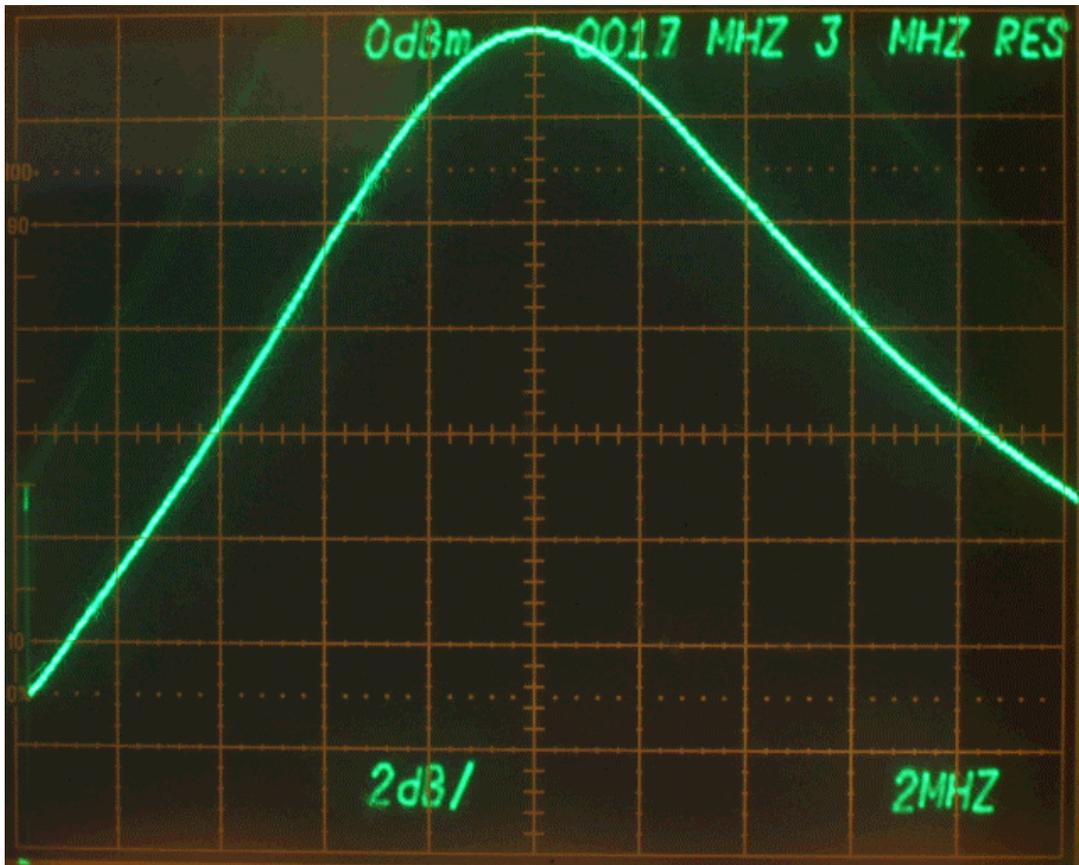


Figure 4: Trial #1 sweep. 2 dB/vertical division.

Trial 1 narrative: The inductor is performing well at this frequency. The Q may actually be slightly higher since the capacitor ESR was not measured.

Trial 2:

$C = 5.2 \text{ pF}$, $L = 10 \text{ T}$ on FT 37-67 core. Sweep shown in Figure 5.

Frequency of Resonance: 82.662 MHz

Inductor Measured Value: $0.712 \text{ } \mu\text{H}$

Loss: 3 dB @ resonance

$R_s: 20.6 \text{ } \Omega$

$Q: 18.0 \text{ J/J}$

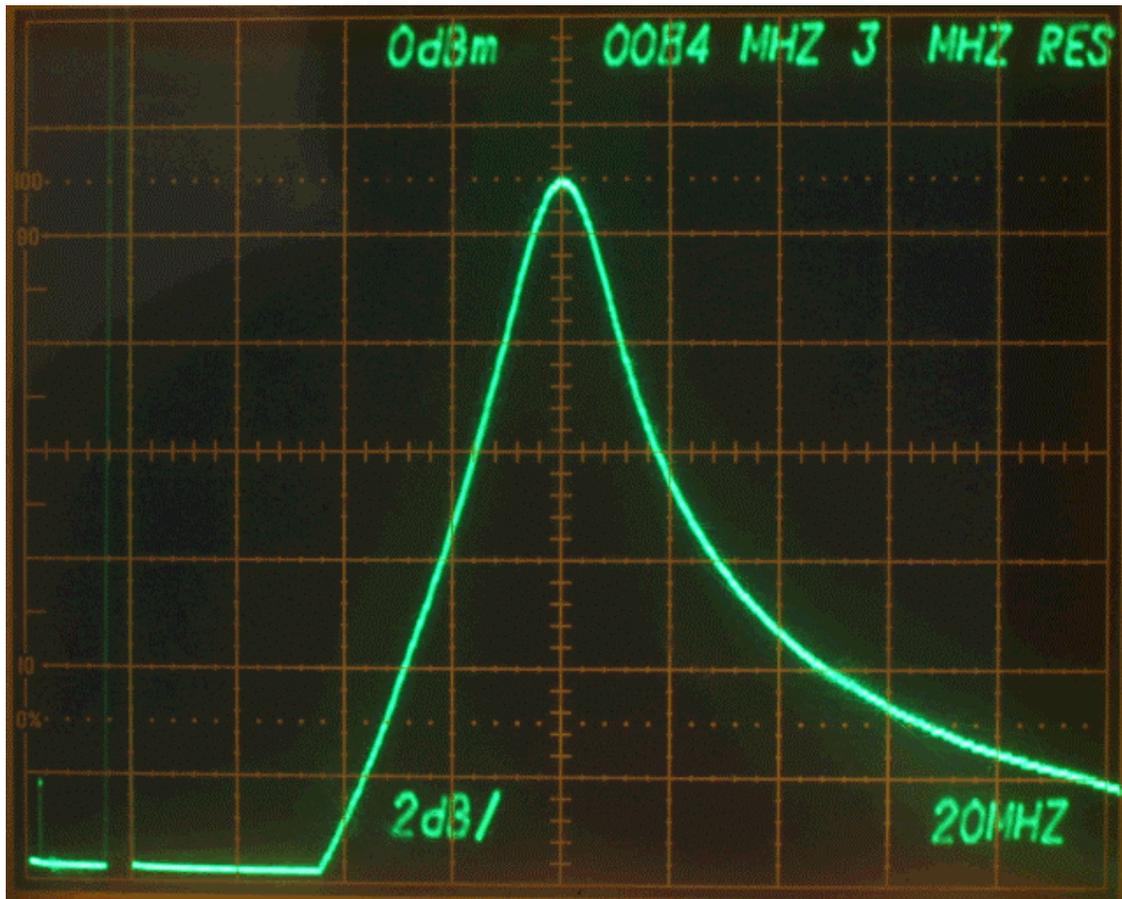


Figure 5: Trial #2 sweep. 2 dB/vertical division.

Trial 2 narrative: The inductance has fallen considerably (the is the *same* part as used in trial 1; it measured four times larger at the lower frequency!) Also, the Q of the part has fallen drastically; the ESR has risen by a factor of ten even though the frequency was only increased by a factor of about 4.5.

The permeability of core materials is frequency dependent (a fact not often explained in textbooks), and this is highly evident from this example. Amidon does not recommend this core material for operation over 80 MHz, and with good reason!

Also, this particular test may be violating the rule about staying at least an octave below the self-resonant frequency of the device being tested. The coil consists of 10 turns on the core; the distributed capacitance of this part is highly important at this frequency.

Trial 3:

C = 2.0 pF, L = 4 T on FT 37-67 core. Sweep shown in Figure 6.

Frequency of Resonance: 121.000 MHz

Inductor Measured Value: 0.865 μ H

Loss: 11.6 dB @ resonance

R_s: 140 Ω

Q: 4.7 J/J

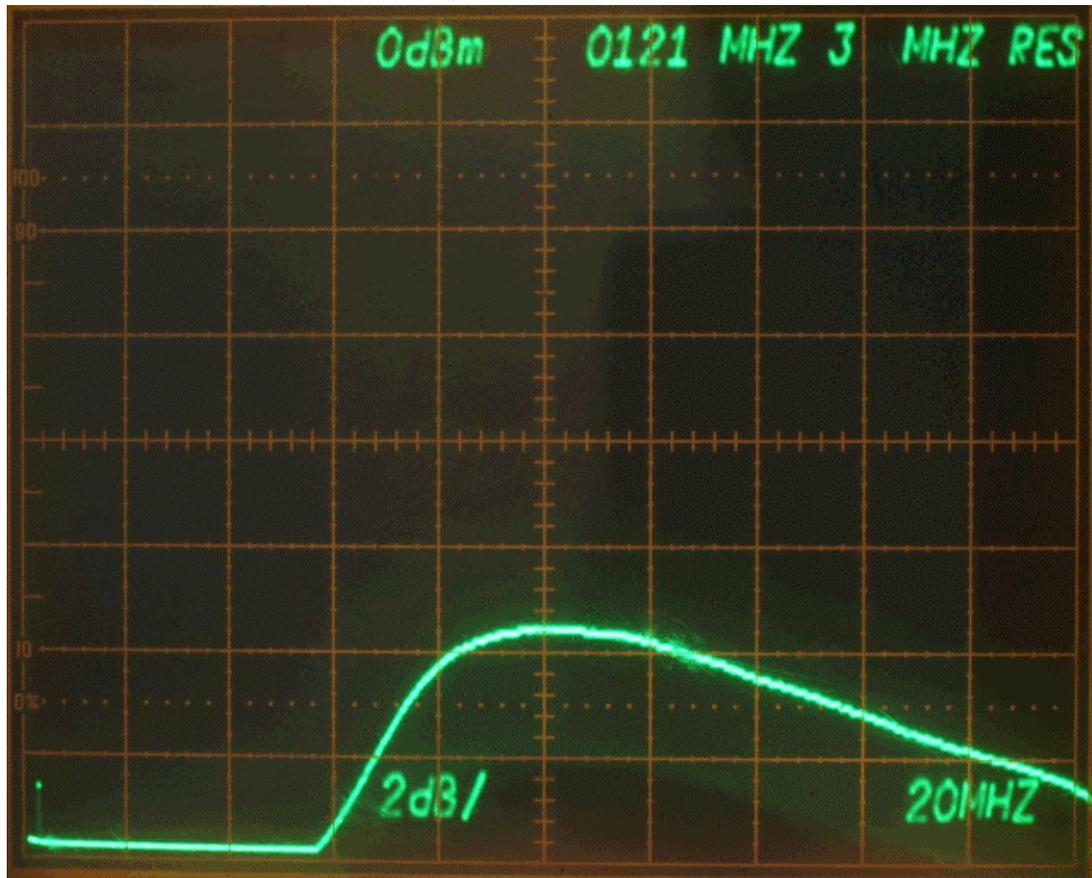


Figure 6: Trial #3 sweep. 2 dB/vertical division.

Trial 3 narrative: The inductor was reduced to four turns on the same core material, and the capacitance was reduced to increase the resonant frequency even higher. The core material performs horribly at this frequency; the Q is a measly 4.7 J/J.

The calculated inductance is actually higher than that obtained in Trial 2, even though the number of turns on the inductor was reduced by a factor of five. This raises suspicion about the actual inductance measured in Trial 2. Variations of this type are to be expected when performing dynamic measurements on real-world components.

Conclusion

Using the procedure described in this document, a designer can begin to measure the real-world characteristics of the inductors he or she is working with. This is invaluable in high frequency design work. The procedure also demonstrates the non-linear characteristics of core materials and can be used to compare the effects of various core compositions.

The technique has a couple of important limitations. First, it can't compensate for stray capacitance inherent in an inductor's design. At higher measurement frequencies this will be an issue. Also, with increasing loss, the load on the tracking signal generator becomes increasingly mismatched, raising the issue of reflected signals on the line leading to the tracking generator. This second limitation could be resolved by inserting a 20 dB attenuator at the test fixture RF input.