A Tool for Measuring High Q Resonators

Introduction

This application communicates with both the HP 3577a and HP 8753 Vector Network Analyzers using HPIB. The application is designed for single port measurements, therefore just S11 is measured and returned to the host PC. The measurements along with user Notes and the VNA's setup parameters can be saved to a standard "s1p" file.

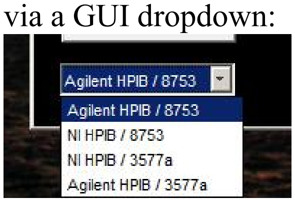
For best results, the VNA should have had an Short Open Load 1-port calibration performed. Both the HP 3577a and HP 8753 have "built in" support for single port corrections.

Prerequisites

MATLAB 2015a or later along with the Instrument Control Toolbox and RF Toolbox are required. You also need "S-Parameter Utilities v1.0.1" from Matlab Central. You can find the S-Parameter Utilities here:
https://www.mathworks.com/matlabcentral/fileexchange/68893-s-parameter-utilities-v1-0-1
Please download this and place in a directory/folder on the Matlab path.

Then you will need an HPIB adapter. This MATLAB application code supports the National Instruments GPIB-USB-B USB to GPIB Interface Adapter as well as the (preferred) Agilent (Keysight) 82357b USB to GPIB Adapter. Of course the requisite driver support software from the respective manufacturers must also be installed for these devices.

The application supports the 4 combinations of the two GPIB Adapters and two VNAa via a GUI dropdown:



The 3577a's GPIB address is set to 11 while the 8753's GPIB address is coded to the default of 16. If these need to be changed, look around line 122 in the vna_QMT.m code.

There are also "Board Index" parameters that may need to be set. The NI adapter is set to 0 while the Agilent is 7. It has been observed that Agilent has also used 8 as a setting. These hardware interface parameters are easy to edit in the source code and can be found around line 203 and 349 in the vna_QMT.m code. The Instrument Control Toolbox "tmtool" can be used to determine which BoardIndex is required for your adapter.

Background

Virtually since the inception of radio, Q (the "**Q**uality" factor) has been an important metric for quantifying RF components. Over the years, this measurement was addressed by a number of techniques and instruments. The first **dedicated** Q measurement instrument appeared in 1934 and this instrument put the Boonton Radio Corporation on the map. (https://en.wikipedia.org/wiki/Boonton_Radio_Corporation).

Since then numerous incremental improvements have been made to the basic Q-Meter design culminating in the Hewlett Packard Model 4342A.
(page 7, http://www.hpl.hp.com/hpjournal/pdfs/IssuePDFs/1970-09.pdf)

As of this writing, this elegant instrument has not been made for over 2 decades, but "pre-owned" instruments can still be purchased. Since its maximum measurement frequency is 70 MHz it does not meet many of the VHF/UHF requirements of today's RF circuits and systems. This does not mean that need to measure component Q has been eliminated, on the contrary. Fortunately, other instruments can be used to make this important measurement.

The Vector Network Analyzer is an essential tool for today's RF design work. Therefore, they are accessible by virtually all RF designers. By post-processing VNA measurements, the functionality of the Q meter can be duplicated, and extended to higher frequencies and improved accuracy as well.

This MATLAB Q Measurement Tool (QMT) to be described is based on the **excellent** paper by professor Darko Kajfez published in the late 1990's:
http://www.engineering.olemiss.edu/~eedarko/experience/rfqmeas2b.pdf

In particular, the QMT implements the "Reflection-type measurement" method in section 4 which is a reincarnation of work Prof. Kajfez did way back in 1984: D. Kajfez and E. J. Hwan, "Q-factor measurement with network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 666-670, July 1984.

And it should be duly noted that all of the above is a descendent of the pioneering work done by E. L. Ginzton back in 1957! (E. L. Ginzton, Microwave Measurements . New York: McGraw-Hill, 1957. See Chapter 9.)

As Professor Kajfez states: "The beauty of this measurement is a perfect circle that the measured reflection coefficient, plotted on a Smith chart, describes as a function of frequency. If you don't see a perfect circle, there is something wrong with your calibration or your reference position!"

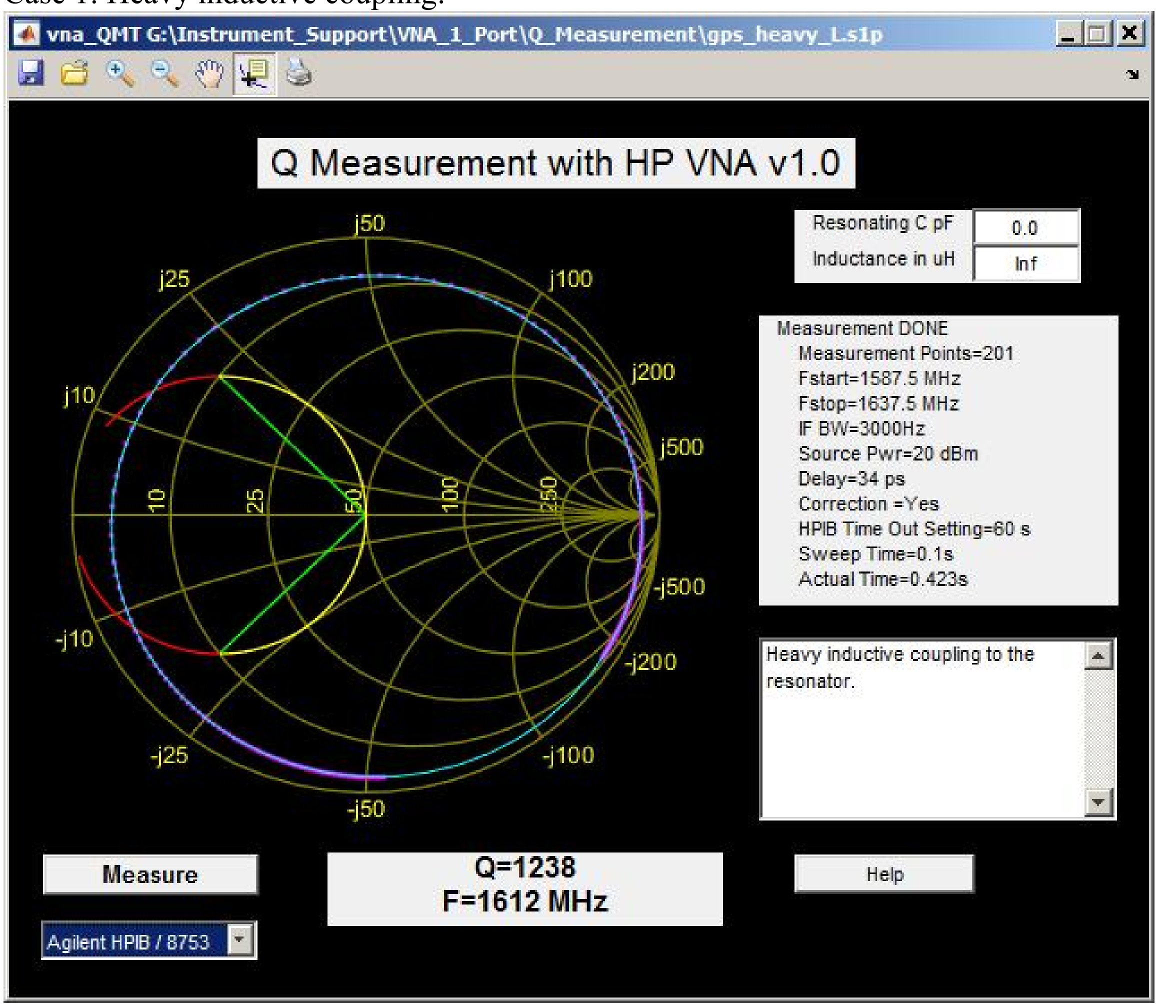
For Q < 100 or so, the component (L or C) can be directly measured with the VNA, Q being simply the ratio of the imaginary to real part of the component's impedance at a given frequency. But when the Q of a component is significantly higher than this, accurate direct measurements become increasingly more difficult.

Example #1

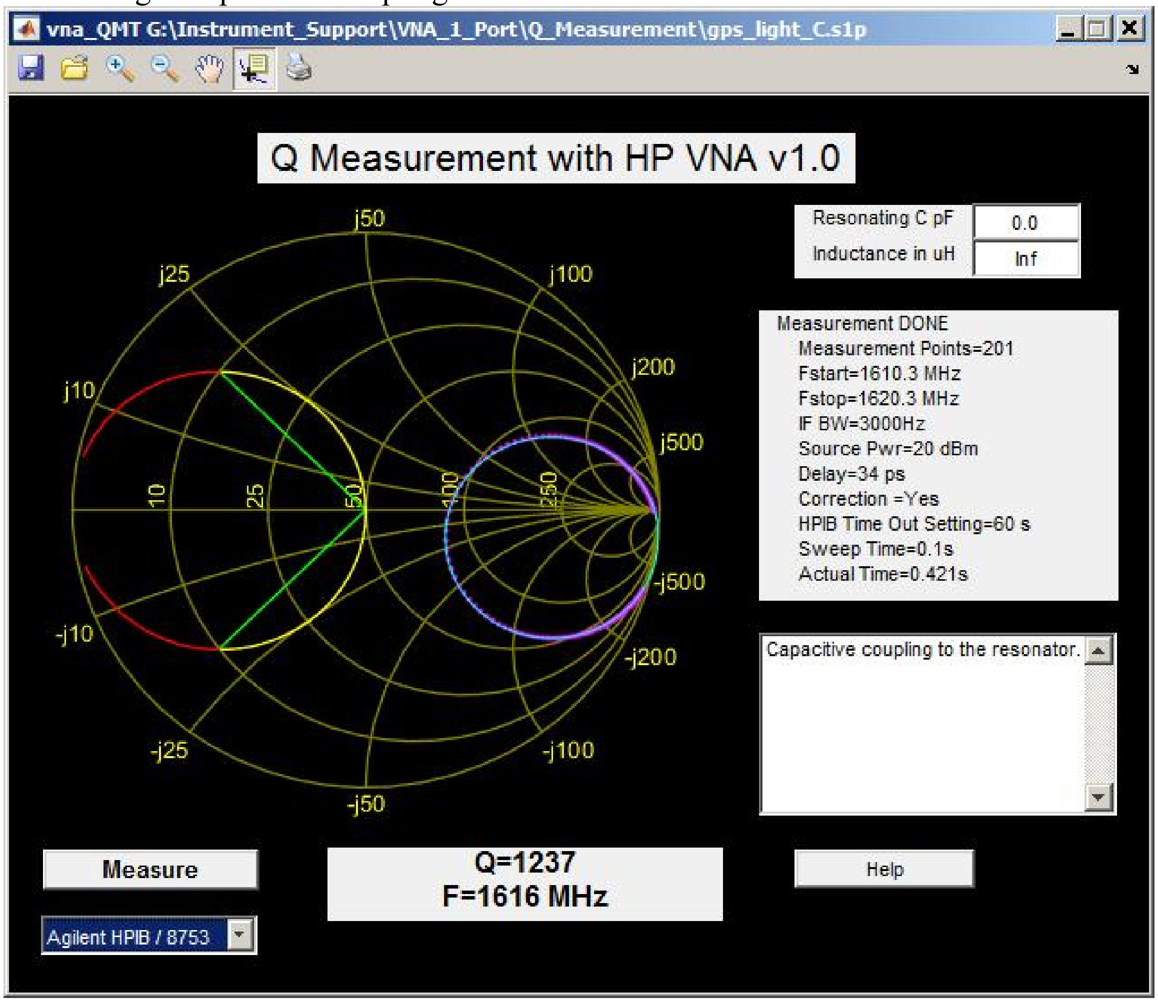
To use this tool, port 1 of the Vector Network Analyzer is coupled either capacitively or inductively to a resonant structure which will be referred to as the "Device Under Test" or DUT. The DUT could be a parallel LC circuit, a cavity resonator, pretty much anything that has a dominant **resonance**. The idea is to measure S11 around the resonant frequency of the DUT and then use the method outlined by Professor Kajfez to process this S11 measurement data.

For this first example, a 1.6 GHz cavity resonator was measured under three very different coupling conditions using the QMT.

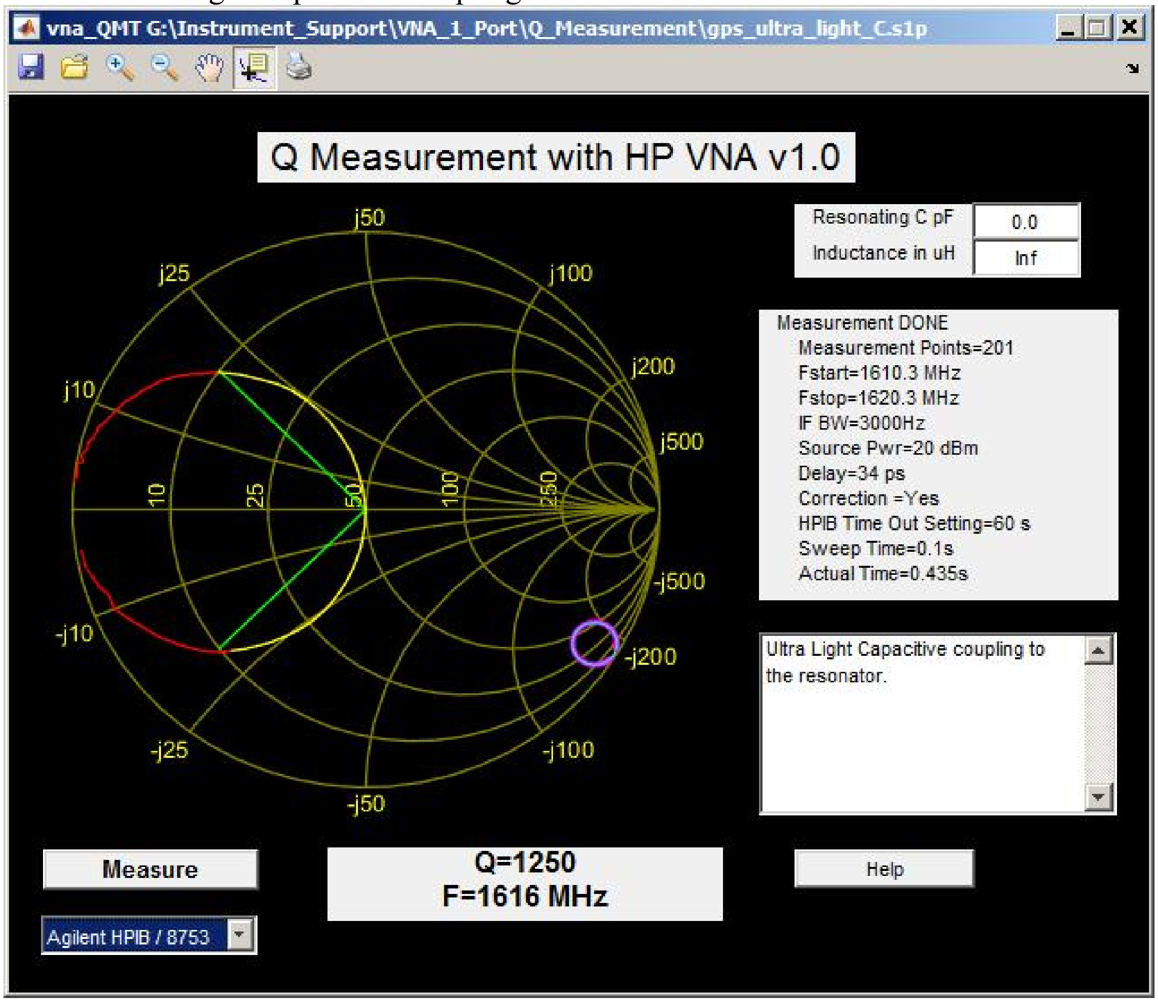
Case 1: Heavy inductive coupling:



Case 2: Light Capacitive Coupling:



Case 3: Ultra Light Capacitive Coupling:



Note the Q and F(requency) values at the center bottom of the window.
The important points are:

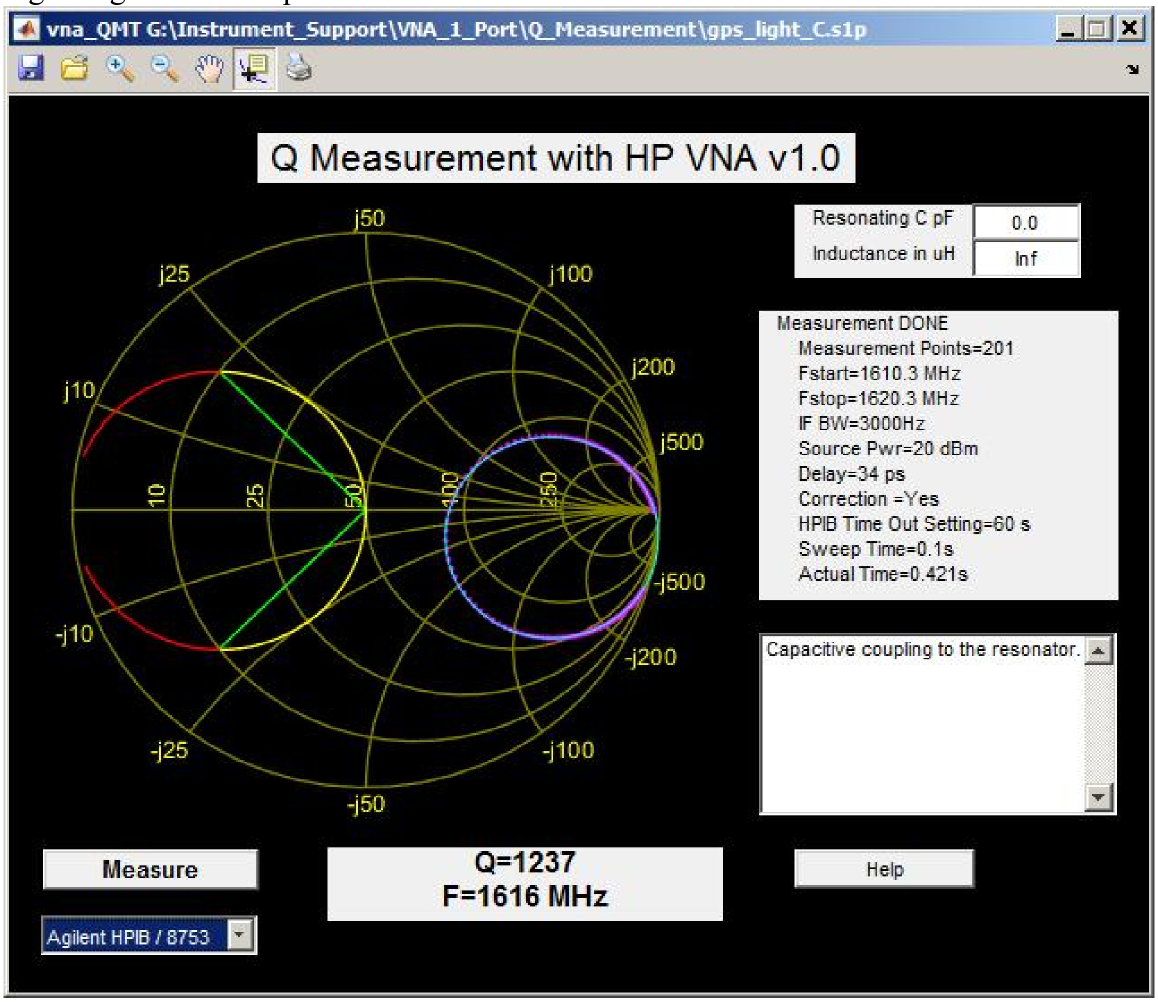
1) There were two very different ways of coupling to the DUT (inductive and capacitive)
2) There was a **huge** difference in the three coupling coefficients.

But these three different measurement conditions had **very little influence** on the resonator's **measured Q and frequency.** The Q varied from a max of 1250 to a min of 1237 which is about 1%. The resonant frequency went from 1612 to 1616 MHz, which is a 0.24% change.

Measuring the same device several ways is ***one way*** of verifying the robustness of this measurement technique. It also is confirms that the measurement of the DUT Q is accurate.

Or does it?
More on that in Example 2.

Here is another view of the vna_QMT application window to provide more detail regarding the various plot lines and controls:



The Smith Chart displays the following:

1) The measured S11 data are the violet dots
2) A circle is fit to this data and then plotted in green (hard to see since it fits so well)
3) The fit circle is rotated, translated, and scaled to create the yellow and red arcs
4) The frequencies where the 45 degree lines intersect the circle and the amount of scaling that was required to create the new circle provide the resonant frequency and Q results. Please see the Kajfez pdf for more details.

The popup (drop down) in the lower left selects from 1 of 4 hardware configurations.

Agilent 82357B USB/GPIB Interface with HP 8753x VNA
NI GPIB-USB A or B with HP 8753x VNA
NI GPIB-USB A or B with HP 3577a VNA
Agilent 82357B USB/GPIB Interface with HP 3577a VNA

The Measure button commands the VNA to make a measurement of S11, and the results retrieved, plotted, and post processed.

The user can enter notes in the lower right text edit box, and the measurement data, instrument status (above notes).

The S11 measurement will be saved to a file by clicking the Write Icon in the Toolbar.

Any S1P format file can be read by clicking the Open File icon,

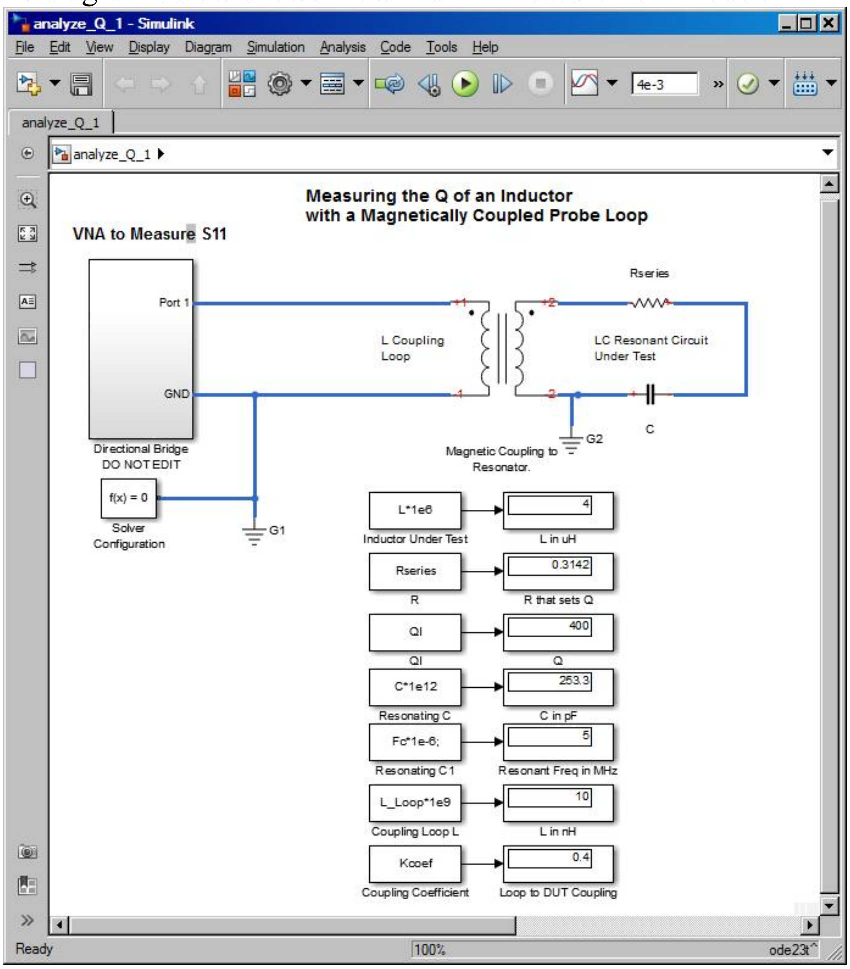
and the s1p file need not be generated by QMT.

However, unless a resonant circuit was measured, the results are likely to be useless.

Example #2

The first example was purely experimental. Indeed the results (Q and resonant frequency) were consistent, but that does not guarantee them to be correct! They could very well be consistent, but consistently wrong. This next example is "analytic" in that the DUT Q is specified and forced to be 400 with a resonant frequency 5.0 MHz. The analysis uses a little known fact is Simulink can be used to perform not only time domain simulation, but frequency domain analysis as well.

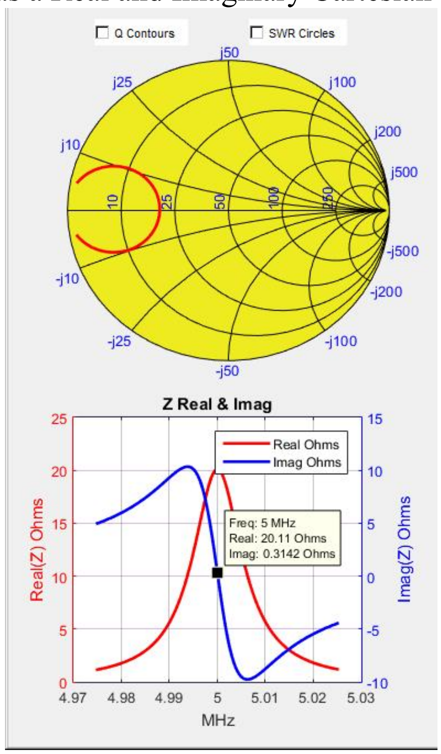
The schematic diagram below shows the Simulink measurement model:



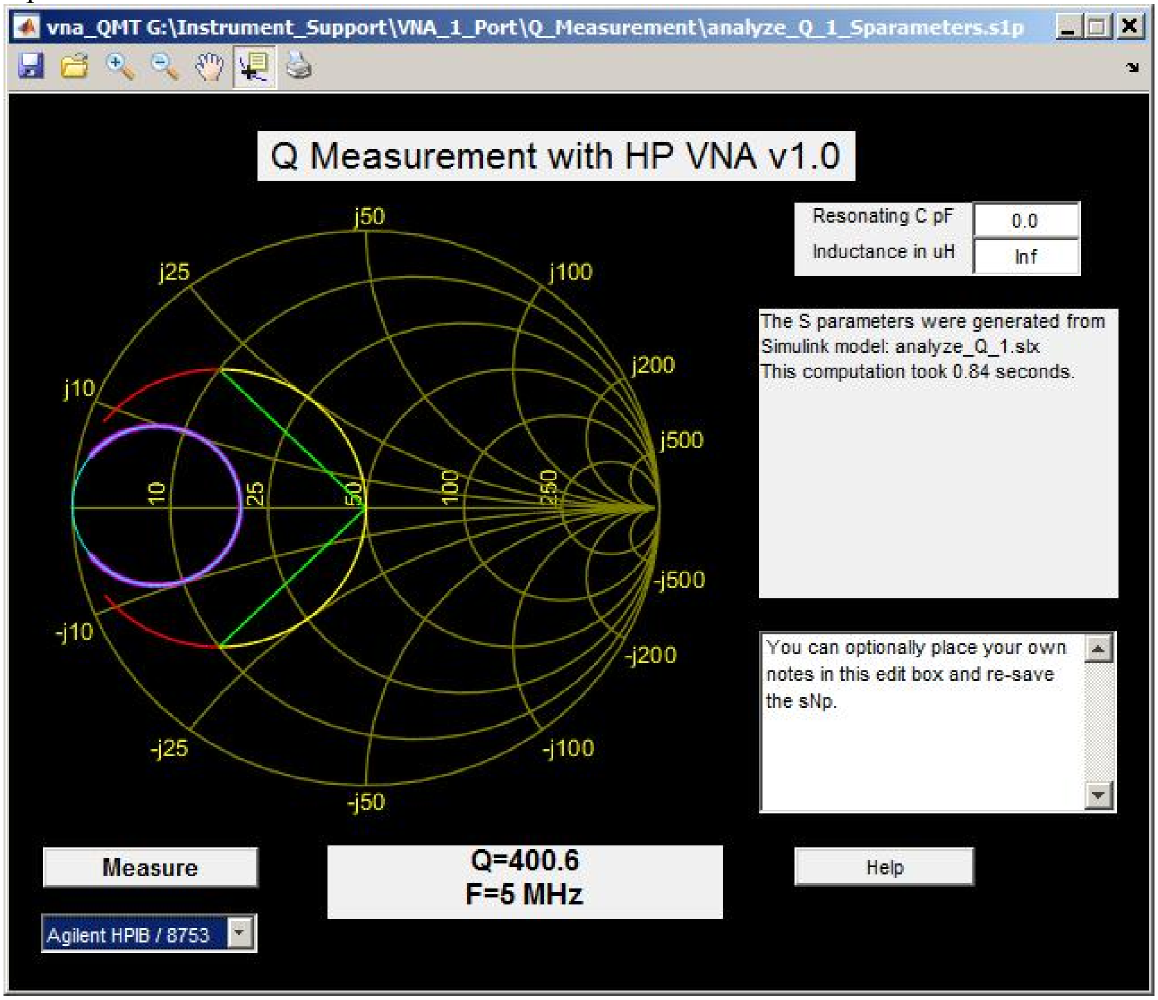
The mutually coupled inductors model a "probe" or coupling loop on the left (primary), and the DUT resonant circuit on the right (secondary).

For this example, the coupling loop is a 10 nH inductor and the secondary has 4 uH of inductance. A capacitor of 253.3 pF sets the resonant frequency to 5.0 MHz, and the series resistor in the secondary sets the Q to be 400. The coupling coefficient between the primary probe loop and the secondary DUT is set by a variable Kcoef.

This model and a bit of MATLAB code generate an S1P file that contains the analytic "measured" S11 looking into the primary coupling loop. Here is S11 (or Gamma) plotted on the Smith Chart as well as a Real and Imaginary Cartesian axis:

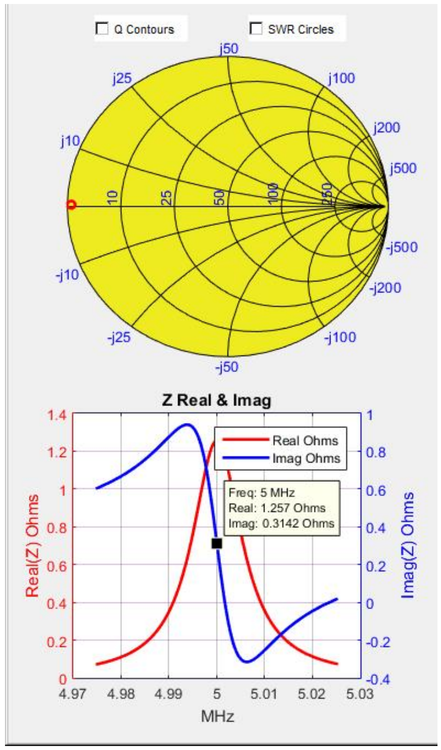


This S11 measurement data can then be analyzed by the QMT application, using the Open File icon:

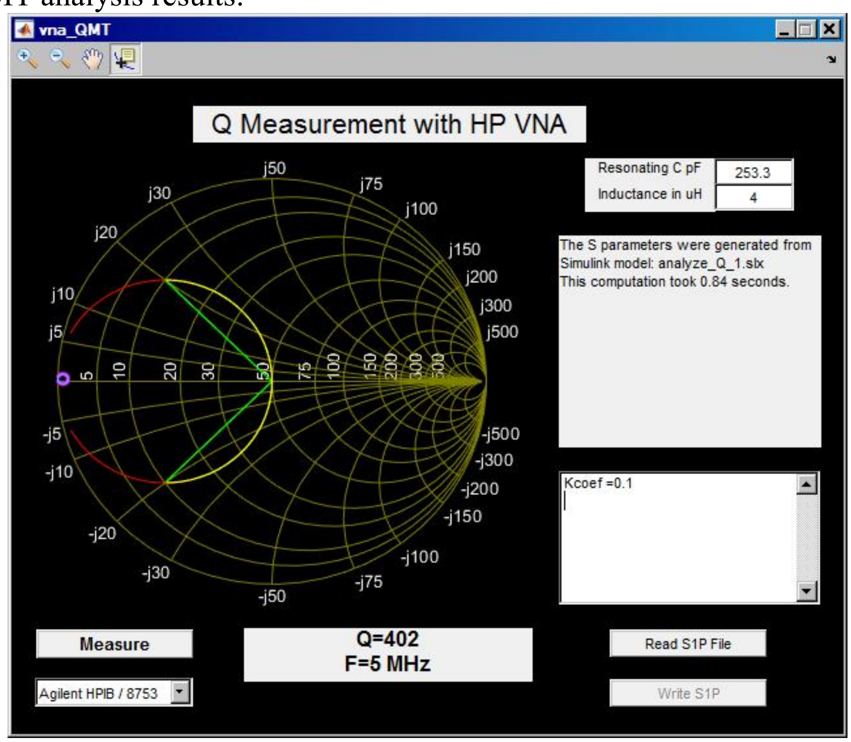


The results (Q=400.6, F=5.0 MHz) are essentially perfect.

Next, the coupling coefficient (Kcoef) between the primary loop and the secondary (DUT) is reduced from 0.4 to 0.1. This is now **very light** magnetic coupling, so the diameter of the resonance circle is reduced considerably (tiny red circle on left of the Smith Chart):



And the QMT analysis results:

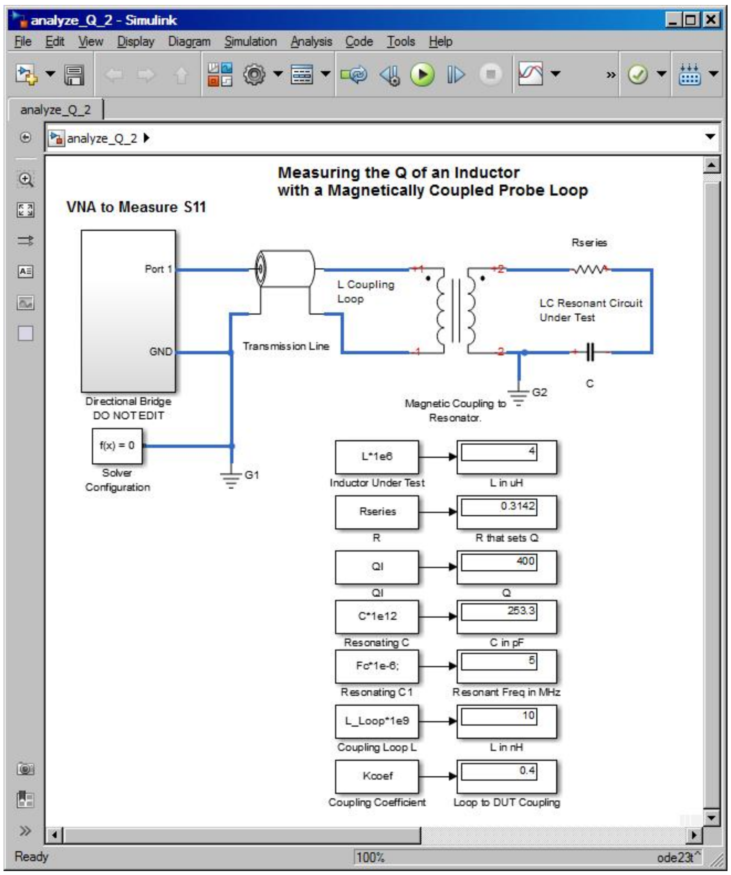


The agreement with the Q of 400 and 5 MHz resonance are still excellent, proving the technique's invariance with respect to the amount of coupling between the loop and the resonator, AND that it produces the correct results.

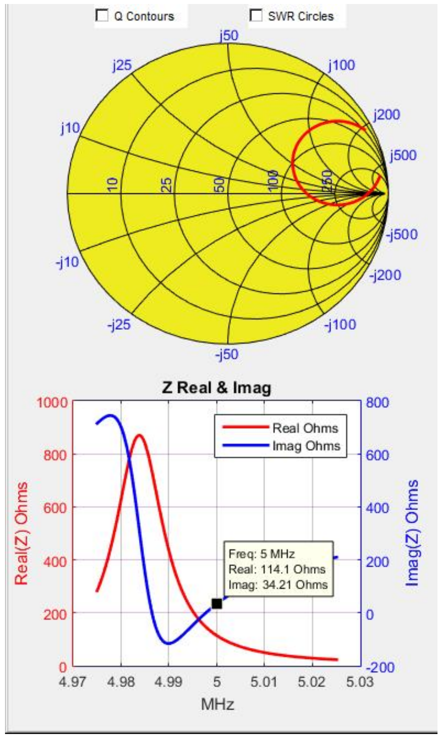
Example #3

There is one more sanity check to be done and that is to rotate S11 in the Smith Chart by introducing a lossless transmission line before the coupling loop. Adding a lossless transmission line before the coupling loop should not change the measured Q or resonant frequency of the DUT.

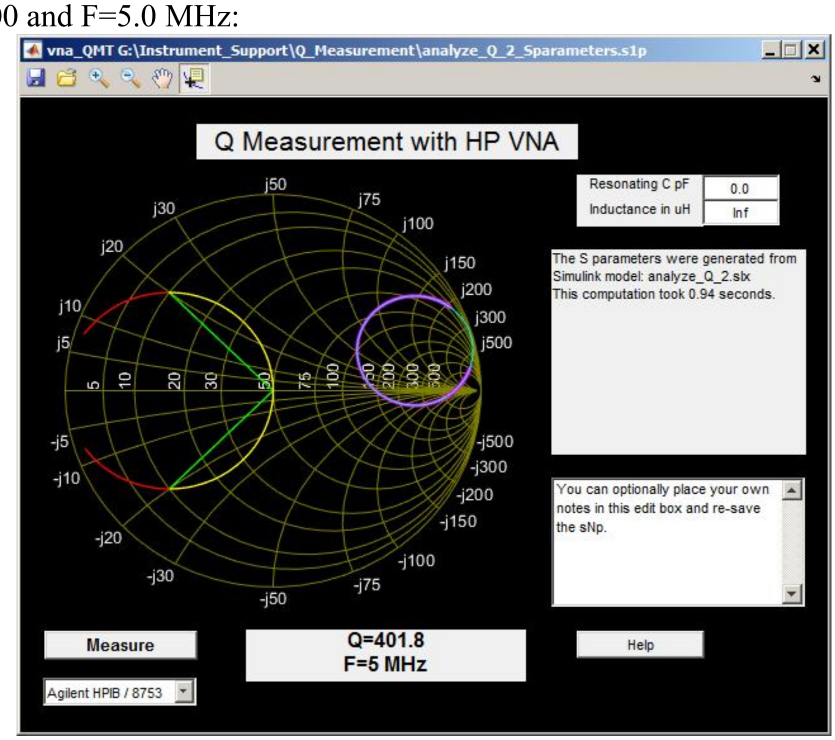
Here is the Simulink model with the transmission line:



The S11 data are clearly quite different:



However, the Q and resonant frequency results are again in essentially perfect agreement of the Q=400 and F=5.0 MHz:

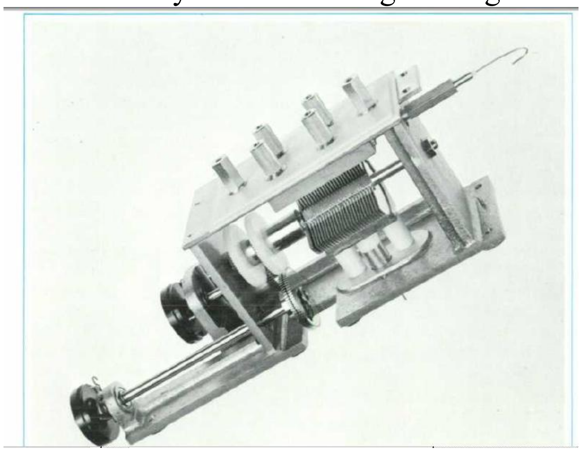


Physical Measurement Requirements

First and foremost, the measurement technique requires a **resonant** Device Under Test. This could be a lumped LC circuit, or as in Example #1, a cavity resonator.

In the case of an LC circuit, often a C is used as a reference standard and the L is the unknown. The accuracy of the results will therefore depend on the accuracy of the standard C being used. The Q of the standard C naturally impacts the measured Q of the L. For example, if the L had an actual Ql of 500, and the resonating standard C had a Qc of 3000, the measured Qi (Q indicated) will be: $Qi = 1/(1/Ql+1/Qc) = 428$ or a 14% error.

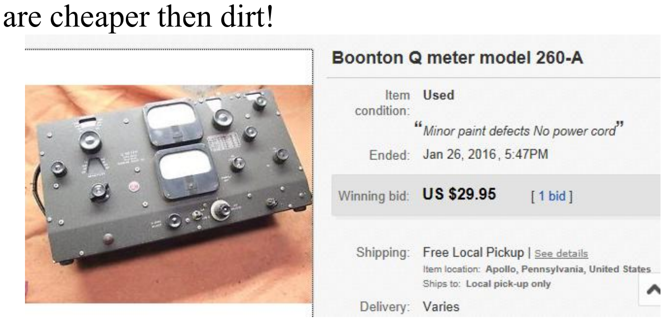
Arguably the best variable capacitor ever made for the job of the standard C can be found in the HP 4342A Q Meter. It is truly a marvel of engineering:



http://hpmemoryproject.org/pict/wall_b/anim/4342a_q90/viewer.htm

I have seen (but can't recall or verify where ☹) claims that this capacitor has a Q > 20,000. I am fortunate enough to have an HP 4342a and after examining the capacitor, the 20,000 seems to be a credible claim. It is hard for me to imagine how a better variable capacitor could be built.

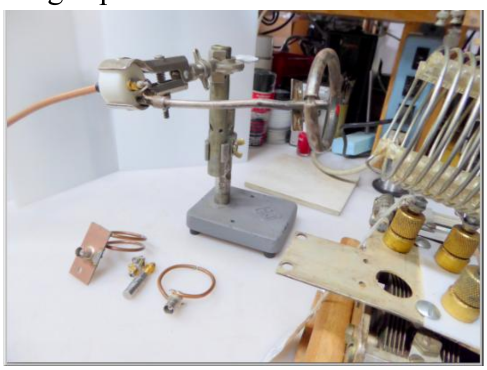
The next best version of a capacitor can be found in Boonton Radio Corp Q meters. The Boonton 260a was ***THE*** Q meter until the introduction of the HP 4342a. My guess is that its capacitor has a Q of >10000. But this likely varies with capacitance, frequency and condition so the number cannot be taken as gospel. This very good capacitor can be scavenged from a 260a which are common. If you get lucky, and if the seller is "motivated", they are cheaper then dirt!



Next, a suitable coupling mechanism to the DUT must be found. For LC circuits with air wound inductors, this is typically a small loop.

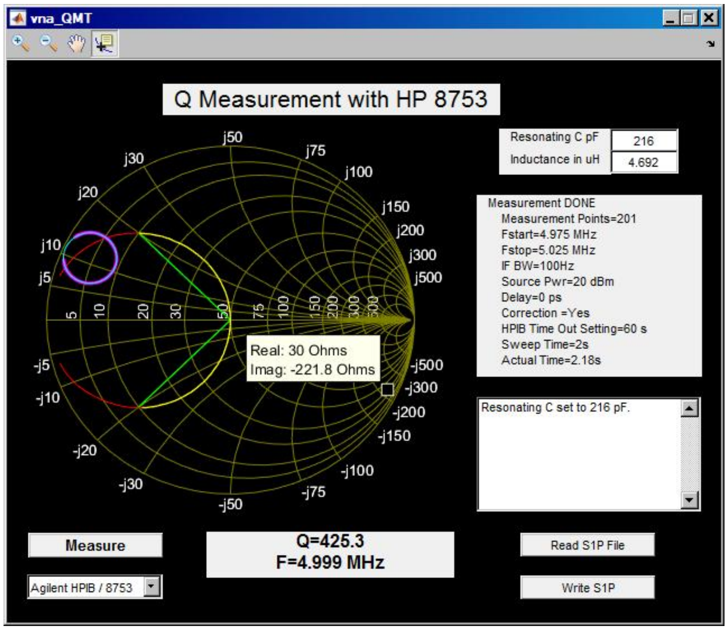
Example #4

Here are a couple of photos showing some typical loops and an air-core inductor resonated by a Boonton 260A capacitor. The primary objective being to measure the Ql of the L (assuming the Qc of the resonating C Qc >> Ql) and secondarily the inductance by knowing capacitance value of the resonating capacitor.




Note that the loop being used is displaced by a length of cable from the VNA Short Open Load calibration plane which is located back at the white Delrin seen in test tube clamp. This cable induces the rotation of the measurement as show in Example 3.

Here is measurement result:

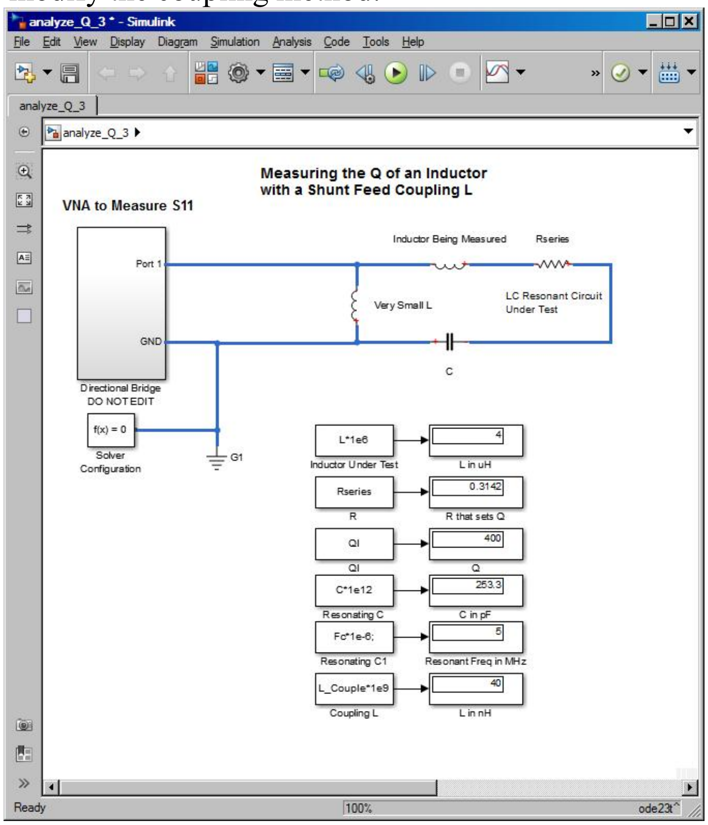


The Q=425 is in excellent agreement with the HP 4342A Q measurement of 430. The 260A resonating C was set to 216 pF to tune the resonant frequency to 5 MHz. The inductance is then computed to be 4.69uH. The HP 4342A measures 4.7 uH. It does not get much better than that.

Example #5

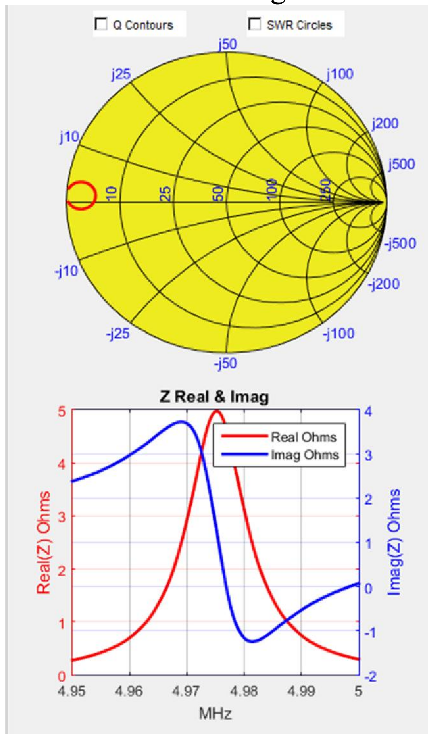
We have assumed that inductive coupling to the DUT would be done by way of a loop probe. But what if the resonant circuit cannot be coupled to by using a loop? This problem does NOT arise with an inductor on a torroidial core since all one has to do is pass a wire through the core! But it would happen with a “pot core” inductor.

The solution is to modify the coupling method:

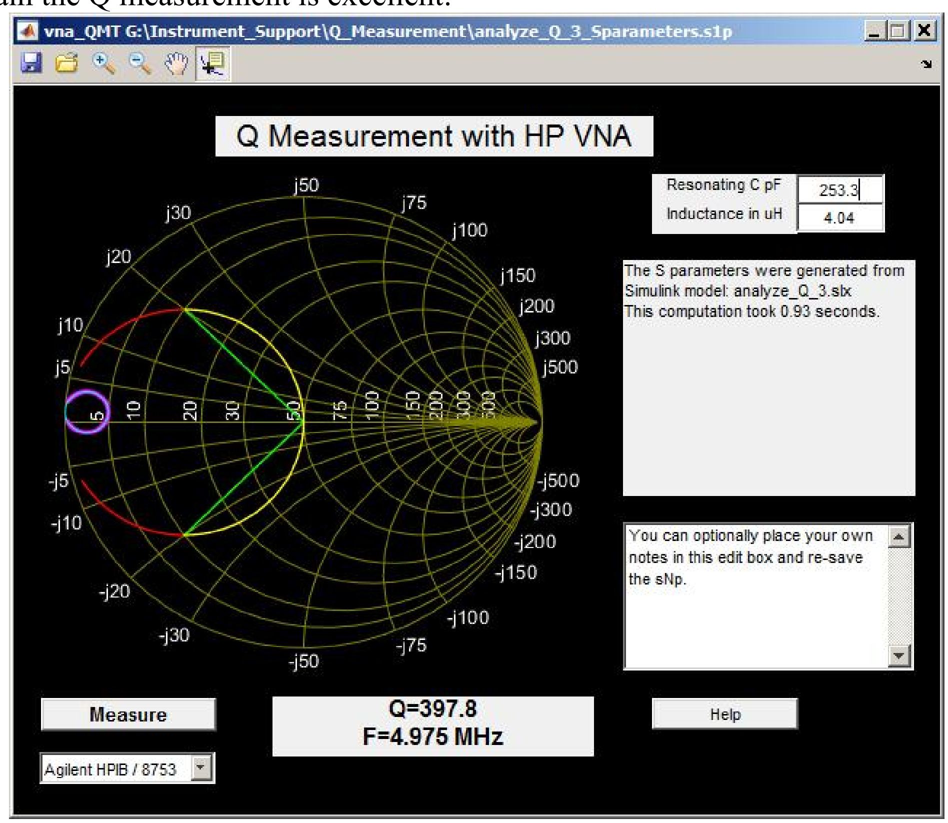


Rather than a loop, a small inductance can be inserted in series with the inductor being measured as shown above. In this analytical example it was chosen to be 40 nH.

The S11 measurement looks similar to what one gets with the loop:



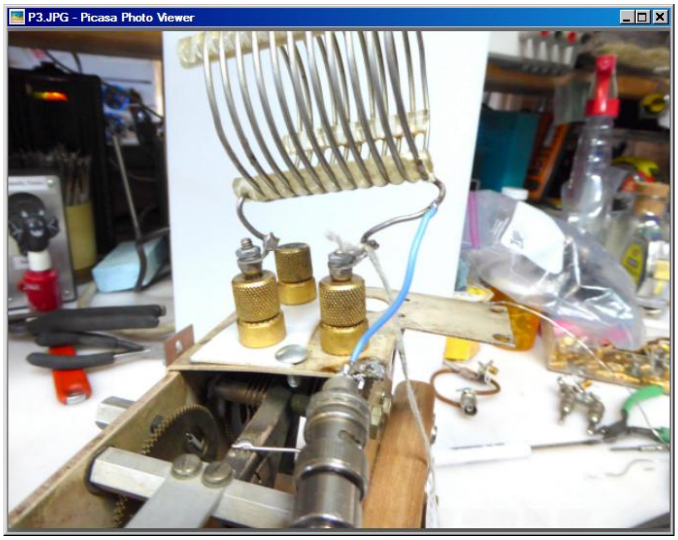
And again the Q measurement is excellent:



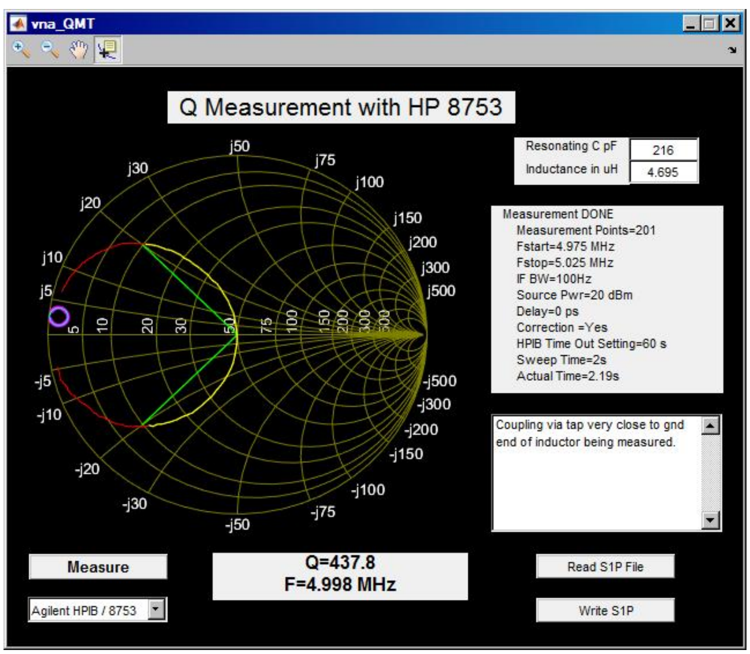
Note that the measured L is 40 nH higher (4.04 uH) since the resonant frequency is 25 kHz lower. This is due to the addition of the 40 nh coupling inductor in series with the DUT L.

Rather than explicitly adding an inductor, in some cases it may be possible to simply place a tap very close to the “cold” end of the inductor being measured. This way the measured value of L is not disturbed.

For a physical example of this, a tap close to the “cold” end of the 4.7 uH inductor is made with the blue wire which goes to the center conductor of the coaxial cable that connects to port 1 of the VNA.



The results:



Perfect? No. But again, the 4342a Q meter reads 430, and 438, is pretty darn close.

Measurement Quality Sanity Tests

The sanity test for measurement quality tests are relativity simple:

1) The VNA should have a Short-Open-Load calibration, but sections of low loss line can be between the calibration reference plane and the DUT. You can set the center frequency and span before doing the calibration and make a rough cut at the Q measurement. But for the final result, a calibration should be done.

2) If there is not a good match between the measurement points (violet dots) and the fitted (green) circle, the basic assumption of the Q measurement technique are not being met and the results will be questionable.

3) The red arcs on the Smith Chart should be greater then zero length, and preferably **about** equal in length. This indicates that the center of the VNA sweep is well aligned with the center frequency of the resonance and the VNA Span is set appropriately. All the examples shown satisfy this.

4) The circle formed from the raw S11 measurement should have a gap for best results. If there is no gap, reduce the frequency Span of the VNA until there is one. If the span is reduced too much, 3) above will not be satisfied.

This document covers the measurement of a resonator's Q with an HP VNA and the vna_QMT.m application. It does not even begin to cover the many possible variations on this theme.

A **great** reference on Q measurement is the HP (Agilent/Keysight) 4342a Q-Meter manual. It seems to move around a lot on the WWW so just Google up:
"hp 4342a manual"
and you will likely find several sources.

Example s21p files can be found in the s1p_Files folder.

Dick Benson
September 2018