Resonator Measurements with Non-contact Probes

Introduction

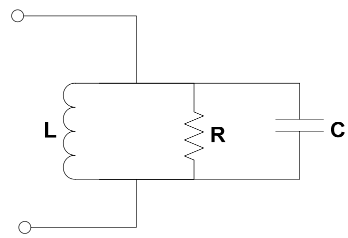
The measurement of resonator center frequency and Q-factor is an essential part of the design of RF and microwave filters and oscillators. Typically, this is a time-consuming process, involving the construction of custom coupling networks to connect the resonator to a network analyzer.

The measurement of Q is particularly difficult, because an improperly-designed coupling network can load the resonator under test, degrading the measured Q.

A resonator measurement method is described in this article that avoids these limitations. Using the Beehive Electronics 100 Series non-contact E-field and H-field probes, the user can rapidly make resonator measurements with no special fixturing. Since the coupling can be varied by simply changing the probe position, it is easy and quick to adjust the coupling so that measurements of Q are accurate.

The Basics

A simple model of a parallel resonator is shown below.



Parallel
Resonator

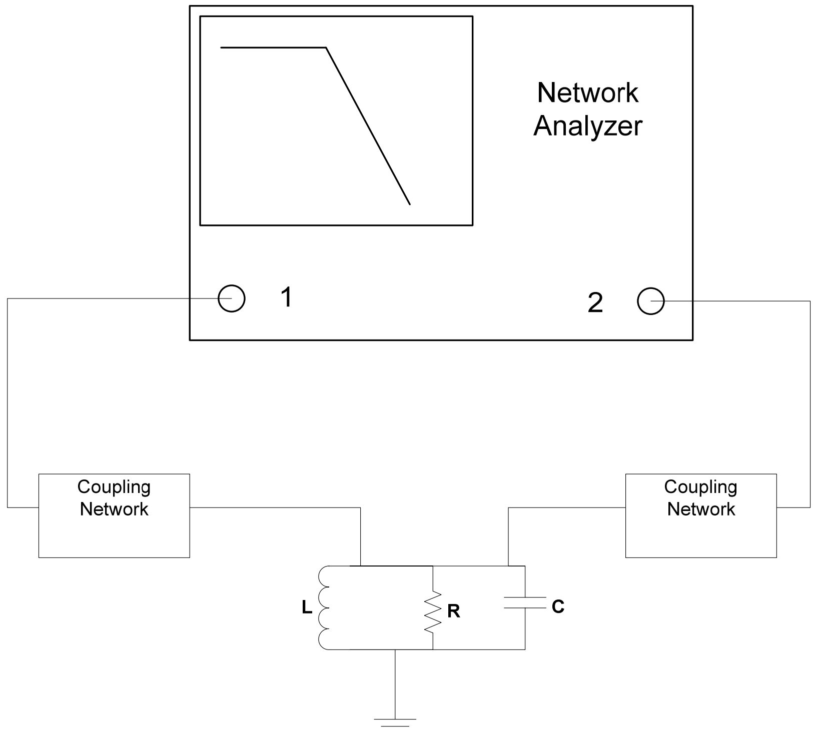
The resonant frequency, ω_0, and the quality factor, are determined from the following formulas:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \omega_0 RC$$

There are two basic methods for measuring the resonant frequency and Q: the one-port method and the two-port method. Non-contact probes can be used for either method. The one-port method has limitations that render it difficult or impossible to use in many cases, so only the two-port method will be discussed here.

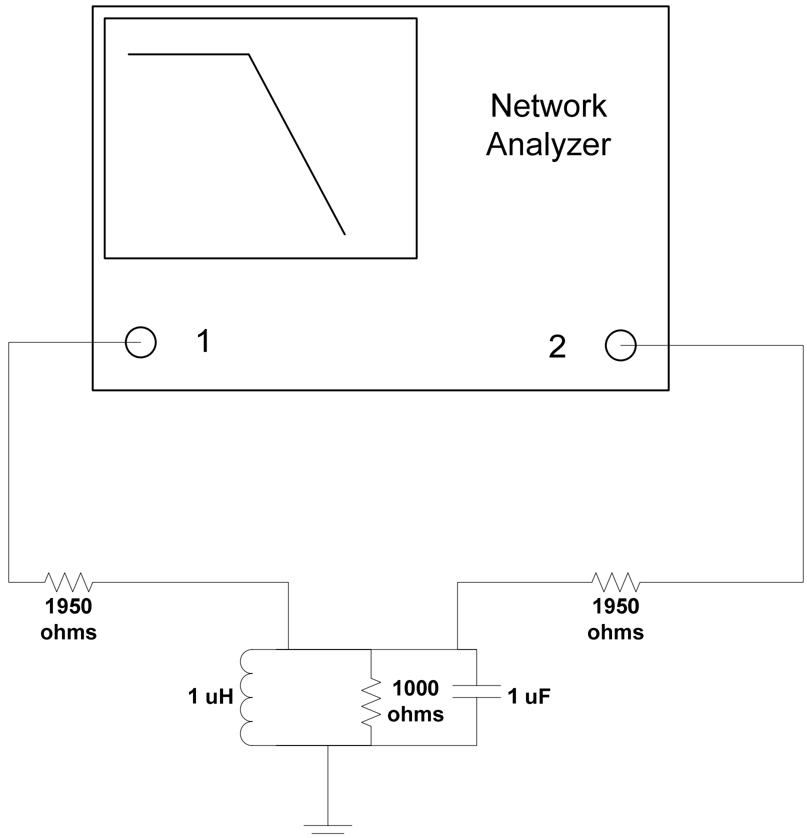
In the two-port method, there are two connections to the resonator under test. A stimulus and a receiver are both connected to the resonator under test. This is most conveniently done with a network analyzer, but it could also be done with a signal generator and a receiver such as a spectrum analyzer or power meter. Using a network analyzer, the connections are as shown below.



The purpose of the coupling networks is to isolate the resonator from the 50 ohm impedance of the network analyzer ports, so that the effective resistance seen by the inductor and capacitor is still equal to R, the resistance of the resonator itself.

The Coupling Network Problem

At low frequencies, the coupling networks can simply be a large value resistor. Using a simple example can help demonstrate the importance of proper coupling networks. The drawing below shows the resonator connected to a network analyzer, using 1950 Ω resistors as the coupling networks.

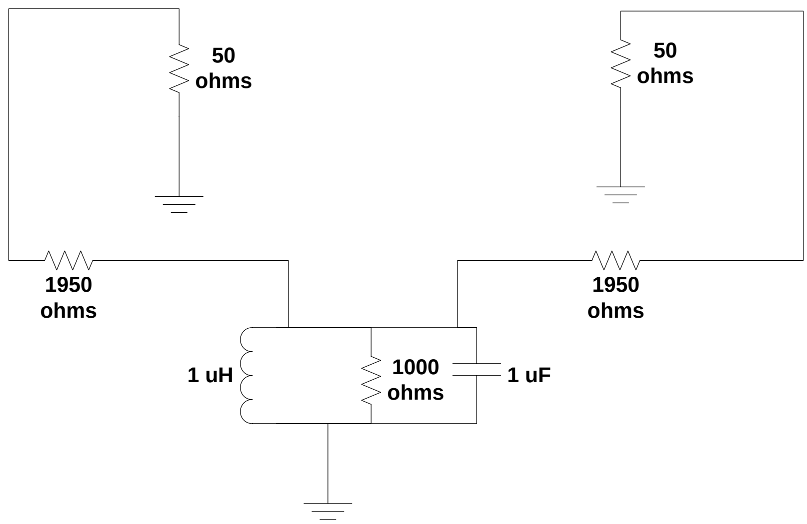


Using the equations presented earlier, we can calculate the resonant frequency and Q of the resonator:

$$\omega_0 = \frac{1}{\sqrt{(1*10^{-6})*(1*10^{-6})}} = 1*10^6 \ rad/s$$

$$Q = \omega_0 RC = 1e6*1000*(1*10^{-6}) = 1000$$

However, in our measurement, the resonator is also loaded by the impedance of the coupling networks. An equivalent circuit of the resonator and test setup, accounting for the effects of the loading of the coupling networks, is shown below.



The resonator sees, in addition to its 1000 Ω internal resistance, two resistances of 2000 Ω each across the resonator. The parallel combination of the 1000 Ω internal resistance and the two 2000 Ω loads yields an effective resonator resistance of 500 Ω. Since the effective resonator resistance has dropped by a factor of two, the measured Q will drop by a factor of two as well, resulting in a measured Q of 500 instead of the correct value of 1000. The true Q of the resonator is known as the *unloaded Q*. What we actually measure is the Q of the resonator degraded by the coupling networks, known as the *loaded Q*.

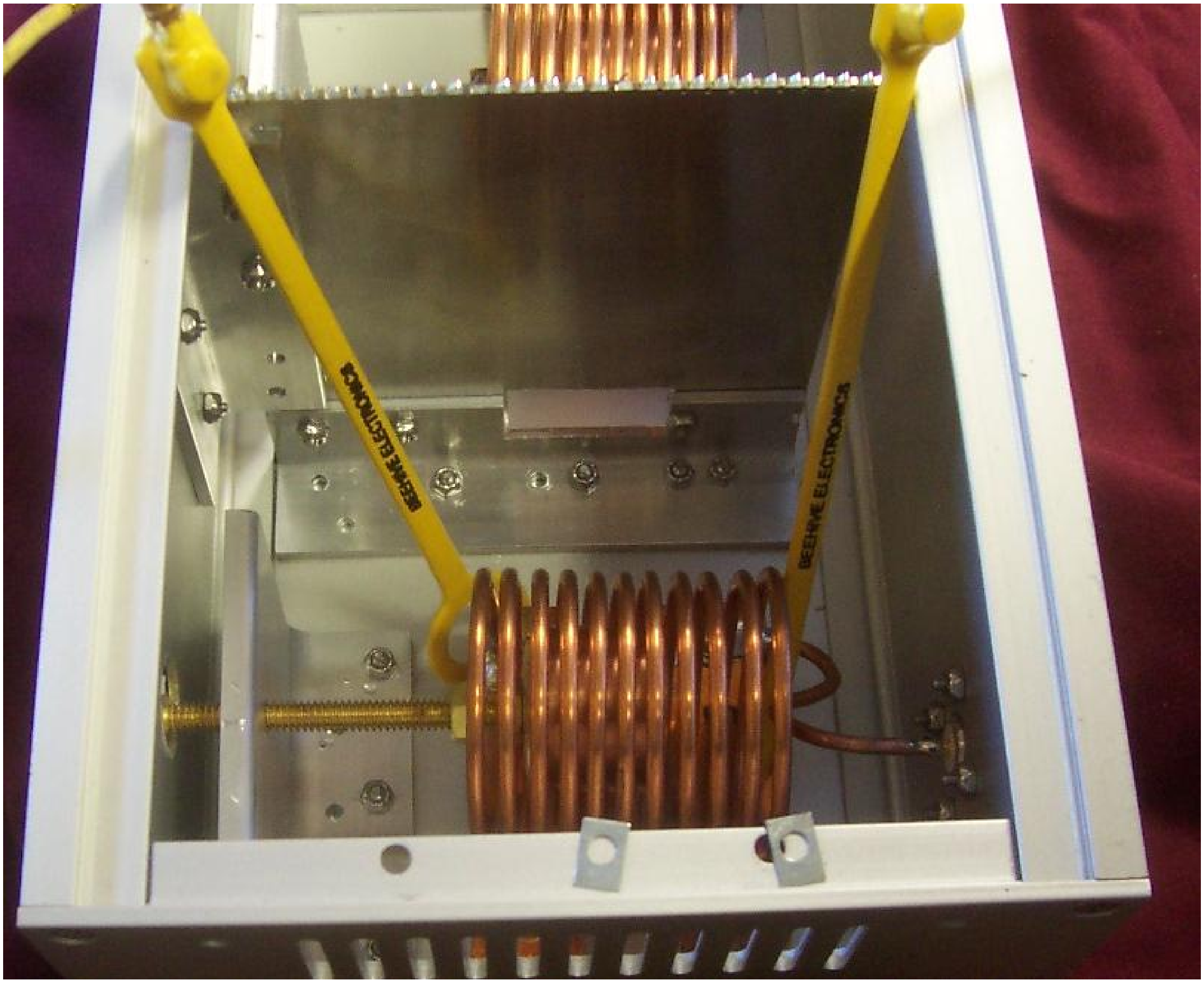
At low frequencies, this problem is easily solved by increasing the value of the coupling resistors so that the effective resonator resistance is not degraded. At RF and microwave frequencies, this solution does not work because it is not possible to fabricate a resistor that looks like a pure resistance of, say, 10 kΩ. For this reason, coupling networks at RF are typically realized with reactive elements such as capacitors or using some form of magnetic coupling. The problem still remains, however, of how to isolate the resonator sufficiently from the test equipment so that the Q of the resonator is not degraded.

Coupling with Probes

The easiest way to construct these coupling networks at RF is to use electric or magnetic field probes to couple the resonator to the test equipment. For example, a magnetic field probe can be used to couple a small amount of energy from the network analyzer source into the resonator inductor, inducing a current in the inductor. An electric field probe can be used to sense the electric field generated by the voltage across the resonator.

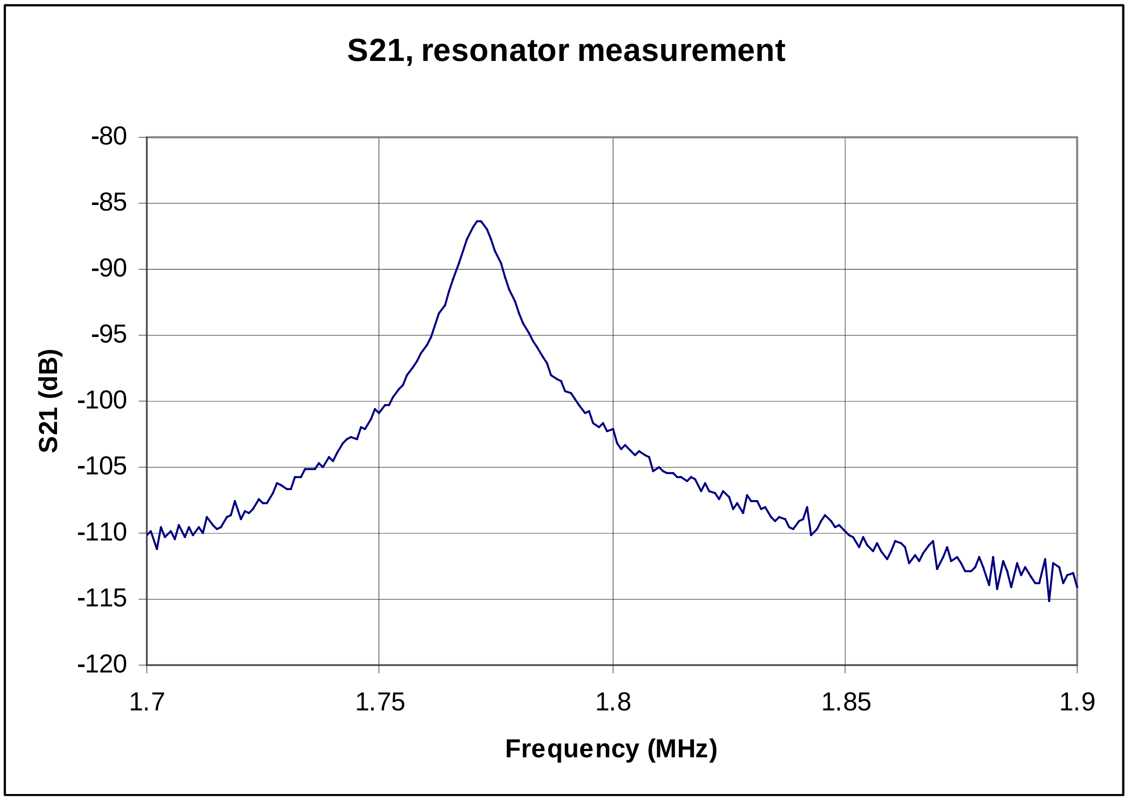
This approach has two advantages. The first is simplicity. Since the probes do not require a direct connection to the resonator under test, no coupling networks need to be built. Secondly, the degree of coupling between the probes and the resonator can be adjusted simply by moving the probes closer to, or farther away, from the resonator. It then becomes a trivial matter to adjust the coupling low enough so that Q is not degraded, but high enough that the measurement has sufficient sensitivity.

As an example, a parallel L-C resonator was measured using a Beehive Electronics 100C magnetic field probe and 100D electric field probe. A photo of the measurement setup is shown below.



This particular resonator was designed as part of a 10 kilowatt 2 MHz notch filter. Given the high power levels involved, it's important that the resonator Q be as high as possible to minimize loss in the filter passband. In this setup, the 100C magnetic field probe was connected to port 1 of the network analyzer, and the 100D electric field probe was connected to port 2. These connections could be reversed; it doesn't matter which probe is connected to the stimulus and which is connected to the receiver.

Using the network analyzer, S21 was measured. Energy was coupled from the network analyzer source into the resonator with one probe, and coupled out of the resonator and into the network analyzer receiver through the second probe. The results of the measurement are shown below.



The center frequency of the resonator can be read directly from the graph; it is approximately 1.77 MHz. The Q of the resonator can be calculated from the relationship

$$Q=F_0/BW,$$

where F_0 is the center frequency of the resonator, and BW is the 3 dB bandwidth of the peak in the S21 measurement. In this case, the measured Q was 215. It was simple to verify that the loading of the test setup was not degrading the Q of the resonator, using the following procedure:

1. Measure the Q of the resonator with the probes in their starting locations.

2. Move the probes farther away. This will decrease the coupling and decrease the magnitude of the peak in the S21 measurement.

3. Recalculate the Q with the new measurement. If the resonator is being loaded excessively by the measurement setup, the Q will have increased over the original value as the probes were moved farther away.

4. If the Q increased in steps 2 and 3, move the probes farther from the resonator and repeat steps 2 and 3 until the Q value is stable.

Once a stable Q measurement has been reached, we can be sure that the Q of the resonator is not being degraded by the test setup and that the measurement is accurate.

Advantages of Dual-Mode Coupling

In the above example, one probe was an electric field probe, while the other was a magnetic field probe. These measurements could also be made using two magnetic field probes, or two electric field probes.

However, there are performance advantages to using a single magnetic field probe and a single electric field probe. These become most apparent when measuring the very high-Q resonators.

When measuring high-Q resonators, as in the example above, the coupling between the test equipment and the resonator must be very loose so that the resonator Q will not be degraded. As a result of this, the peak magnitude of the S21 measurement will be low; in the example above the peak was approximately -87 dB.

In the two-port resonator measurement technique, there will always be a certain amount of coupling directly from the input coupling network to the output coupling network, around the resonator itself. For example, if two magnetic field probes were used, the coupling directly between the resonators might be on the order of, say, -80 dB, even if the resonator were not present. This extraneous coupling can make it difficult to see the resonance peak and can degrade the accuracy of the Q measurement. For this reason, it is important that the coupling between the input and output coupling networks be significantly less than the coupling through the resonator. Please note that these comments apply to traditional coupling networks as well as non-contact probes.

The coupling between a magnetic field probe and an electric field probe will be lower than the coupling between two probes of the same type. For this reason, dual-mode coupling should be considered when making measurements of very high-Q resonators. In particular, Beehive Electronics' magnetic field probes are shielded against electric fields, resulting in very low coupling between the magnetic field and electric field probes, allowing the measurement of very high-Q devices.

Microwave Resonator Measurements

The same principles can be used to measure the Q of microwave resonators, such as cavity or microstrip resonators. For example, consider a simple microstrip quarter-wave resonator, as shown below.

To couple the probes to the resonator, all that is required is to place them near the resonator itself. As always with microwave measurements, it is worthwhile to consider where the current and voltage maxima occur when coupling into the resonator. At the grounded end of the resonator, the current flowing through it will be high and the peak voltage present will be low. Since currents cause magnetic fields, the magnetic fields will be highest at the grounded end. Conversely, at the open-circuited end, current will be low and voltage will be high, resulting in a high electric field. It will be easiest to achieve appropriate coupling levels by placing the magnetic field probe close to the grounded end, and placing the electric field probe near the open-circuited end.

Conclusions

Non-contact probes offer a rapid and accurate method for measuring the center frequency and Q of resonant circuits across a broad range of frequencies. They can be used to measure both low frequency and microwave resonators. Resonators can be measured and tuned without the need for custom-designed coupling networks. Furthermore, the coupling can be adjusted very easily to ensure that the Q of the resonator is not degraded by the test equipment.