

Q & ESR EXPLAINED
A JOHANSON TECHNOLOGY PRIMER
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One of the most important parameters in evaluating a high frequency chip capacitor is the Q factor, or the related equivalent series resistance (ESR). In addition to providing excellent performing RF components, JTI strives to provide our customers with accurate and complete data. Towards this end, a more detailed discussion of Q & ESR measurement issues follows.

In theory, a “perfect” capacitor would exhibit an ESR of 0 (zero) ohms and would be purely reactive with no real (resistive) component. The current going through the capacitor would lead the voltage across the capacitor by exactly 90 degrees at all frequencies.

In real world usage, no capacitor is perfect, and will always exhibit some finite amount of ESR. The ESR varies with frequency for a given capacitor, and is “equivalent” because its source is from the characteristics of the conducting electrode structures and in the insulating dielectric structure. For the purpose of modeling, the ESR is represented as a single series parasitic element. In past decades, all capacitor parameters were measured at a standard of 1 MHz, but in today’s high frequency world, this is far from sufficient. Typical values for a good high frequency capacitor of a given value could run in the order of about 0.05 ohms at 200 MHz, 0.11 ohms at 900 MHz, and 0.14 ohms at 2000 MHz.

The quality factor Q, is a dimensionless number that is equal to the capacitor’s reactance divided by the capacitor’s parasitic resistance (ESR). The value of Q changes greatly with frequency as both reactance and resistance change with frequency. The reactance of a capacitor changes tremendously with frequency or with the capacitance value, and therefore the Q value could vary by a great amount. See Equations 1 and 2.

Eq. 1 :

$$|X_c| = 1 / \{ 2 (\pi) (f) (C) \} ; \text{ where } |X_c| \text{ is the absolute value of the reactance in Ohms;} \\ f \text{ is the frequency in Hertz;} \\ C \text{ is the capacitance In Farads}$$

Eq. 2 :

$$Q = |X_c| / ESR ; \text{ where } Q \text{ is a dimensionless number meaning 'Quality Factor';} \\ |X_c| \text{ is the absolute value of the reactance in Ohms;} \\ ESR \text{ is the Equivalent Series Resistance in Ohms}$$

Johanson Technology measures ESR and Q on a Boonton 34A resonant line. The capacitor under test is resonated with an inductive line of an accurately characterized impedance and Q. From the resultant data (the center frequency and bandwidth of the resulting peak), the Q, ESR, and capacitance value of the device is output. This method is a long-standing industry standard for the measurement of Q and ESR at RF frequencies. Since this method depends on the frequency accuracy of a signal generator (which can be measured with extreme precision), the data taken in this manner is quite accurate. As the ESR of modern capacitors goes ever lower, the accuracy,

even of this method, will approach +/- 10% (reference Boonton 34A Instruction Manual, page 2.2). This is still the most accurate method for measuring Q and ESR at RF frequencies presently available. See Figure 1 for a block diagram of the test set-up. See Figures 2 & 3 for pictures of the setup.

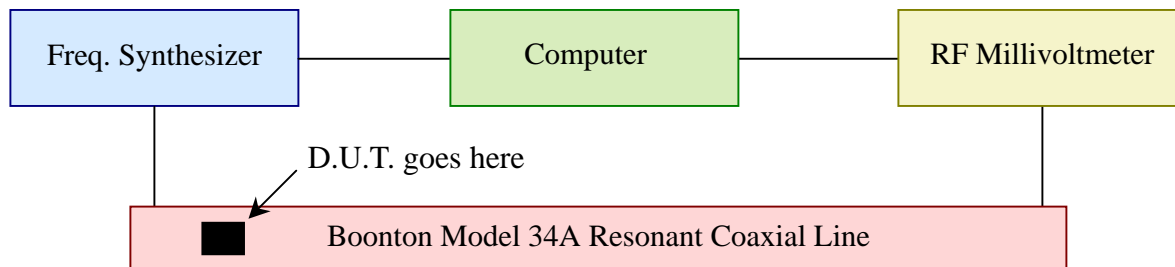


Figure 1

Using S-Parameter data collected from a Vector Network Analyzer to derive ESR is not acceptable. The predominant reason is that the accuracy of this data is limited by the accuracy of the network analyzer in a 50 ohm system (a typical amplitude calibration of $\pm .05$ dB is not accurate enough in the low-loss region of a capacitor which could be $.01$ dB). Using Q / ESR data collected from an LCR meter is also not acceptable for these high-Q devices. When the device Q is very high, the LCR meter just cannot resolve an extremely small resistance (R) against an extremely large reactance (X). For this reason, ESR and Q parameters presented in Johanson Technology's published catalog, and in the MLCSoft® program are based on the industry standard resonant line test method.



Figure 2



Figure 3

CAPACITOR RF CURRENT & POWER

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This note discusses the relationship of current handling, power dissipation, applied voltage and the maximum rated voltage of a multi-layer ceramic capacitor. Either the maximum voltage rating or the maximum power dissipation of the part limits the maximum current through a capacitor. The capacitance value and the operating frequency determine which of the two becomes the governing limit. For lower values of capacitance at a given frequency, or lower frequencies at a given capacitance, the voltage limitation is generally reached before the power dissipation limitation.

The voltage limitation depends on the capacitors reactive impedance (X_c), where as the power dissipation depends on the resistive impedance or equivalent series resistance (ESR) of the capacitor.

X_c is calculated by $X_c=1/[2\pi FC]$, where F = frequency in hertz and C = Capacitance in farads.

The maximum allowable peak current flow through a capacitor (without exceeding the capacitors rated voltage) is calculated by $I=Er/X_c$, where Er is the capacitors rated voltage, and I = the peak current flow in amperes.

The actual current flow through a capacitor is calculated by $I=Ea/X_c$, where Ea is the applied or working voltage.

The following examples illustrate how these variables effect the voltage/current limitation for some specific capacitors at a given frequency.

EXAMPLE 1: A 0.1 pF, 500 Volt capacitor is to be used at 1000 MHz:

$$X_c=1/[2(3.14)(1000 \times 10^6)(0.1 \times 10^{-12})]=1591 \text{ ohms};$$

$$I_{\text{peak}}=500/1591=0.315 \text{ A}_{\text{peak}} \text{ or } 0.22 \text{ Arms.}$$

If you exceed this current, you will exceed the voltage rating of the capacitor.

EXAMPLE 2: A 1.0 pF, 500 Volt capacitor is to be used at 1000 MHz:

$$X_c=1/[2(3.14)(1000 \times 10^6)(1.0 \times 10^{-12})]=159 \text{ ohms};$$

$$I_{\text{peak}}=500/159= 3.15 \text{ A}_{\text{peak}} \text{ or } 2.2 \text{ Arms.}$$

If you exceed this current, you will exceed the voltage rating of the capacitor.

EXAMPLE 3: A 10 pF, 500 Volt capacitor is to be used at 1000 MHz:

$$X_c=1/[2(3.14)(1000 \times 10^6)(10 \times 10^{-12})]=15.9 \text{ ohms};$$

$$I_{\text{peak}}=500/15.9=31.5 \text{ A}_{\text{peak}} \text{ or } 22.2 \text{ Arms.}$$

This current level is actually never reached because at this frequency, values over approximately 1.5 pF are limited by the power dissipation of the capacitor.

IMPORTANT NOTE: The power dissipation limited data assumes an infinite heat sink at the capacitor terminations. The heat transferred to the air is ignored.

The 10pF, 500V capacitor at 1000 MHz would actually be power limited to about $7A_{\text{peak}}$ which is about 5 Arms. At this current level the temperature of the capacitor would rise to about 125 degrees C. For reliable operation, it would be practical to limit the current to 2 Arms with a decent heat sink, or even 3Arms if there is a very good heat sink at the terminations.

SRF & PRF AND THEIR RELATION TO RF CAPACITOR APPLICATIONS

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Capacitors exhibit both series and parallel resonant frequencies. There is a frequency for a capacitor with a given physical size/construction and a given capacitance value at which the component looks like an inductive impedance. Indeed, above this frequency one can have essentially a “DC blocking inductor”. This frequency is called the Series Resonant Frequency (SRF). The magnitude of the transmission impedance the capacitor presents will be extremely low from the bottom frequency end determined by the capacitance value, right through the SRF until one approaches the first Parallel Resonant Frequency (PRF). The first PRF is frequently called simply the PRF, although in reality there is a second PRF, third PRF, and so on. A rough rule of thumb puts the PRF at twice the frequency as the SRF. The magnitude of the transmission impedance dip differs significantly at each PRF frequency, and with the various values of capacitors.

Exactly at the SRF, one will have the lowest possible impedance, and therefore, a capacitor is commonly used for narrow band RF bypass applications by choosing a capacitor whose SRF is at the required bypass frequency. In other words, at the SRF, the capacitive impedance of the device equals the parasitic inductive impedance of the device. The user is only left with the ESR (no reactive component) at that frequency.

For applications where low impedance is desired, but it is unimportant if the capacitor looks either capacitive or inductive, a capacitor could be used up to a frequency close to the PRF. Above the SRF, the user essentially has a “DC blocking inductor”. At the PRF, the transmission impedance goes relatively high, and the capacitor is virtually useless around this frequency. There is a “trick” to effectively extend the usable frequency range in this application. That is to mount the capacitor in a vertical position so that the capacitor terminations both still meet the pads where it’s mounted, and so the width of the capacitor is now effectively the height. Doing this will eliminate all odd-order PRFs including the first PRF.

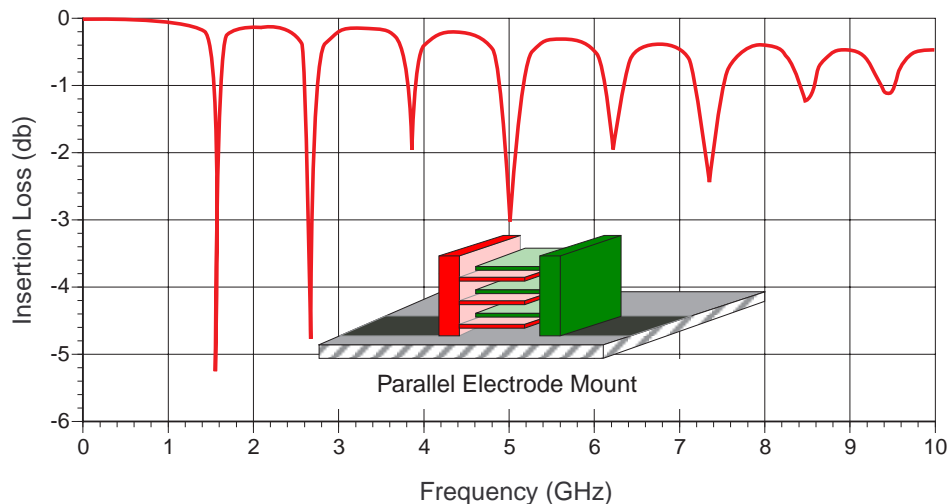


Figure A

Figure A illustrates normal mounting where the electrodes are parallel to the substrate surface and the electrical effect for a given capacitor value. Figure B illustrates vertical mounting where the electrodes are perpendicular to the substrate surface and the electrical effect for the same given capacitor value.

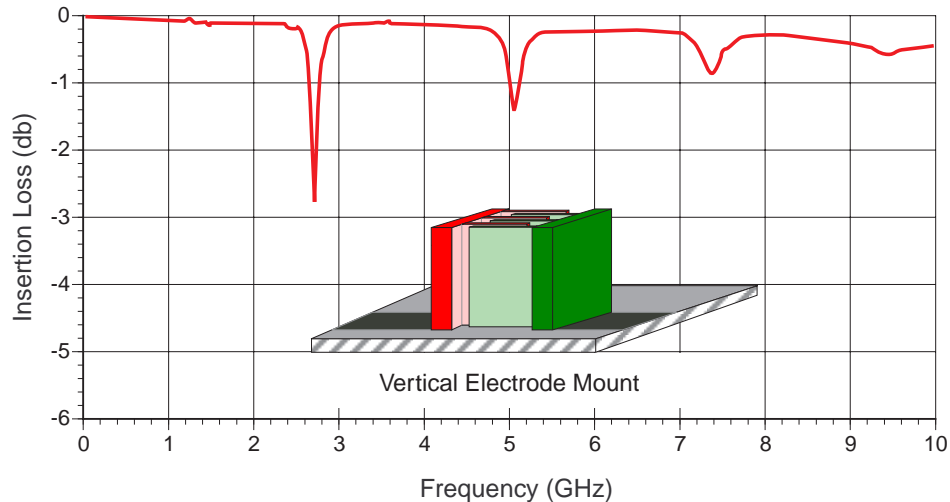
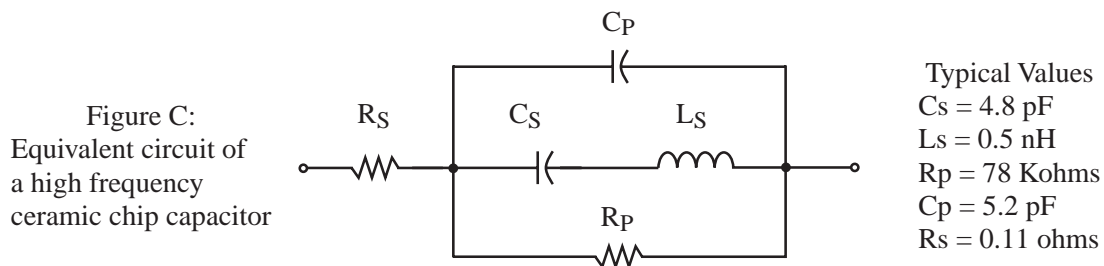


Figure B

The PRF effects are due to very complex mechanisms related to the different phase paths to the various electrodes of the multi-layer capacitor. At JTI, we typically measure the S-parameters in a normal orientation showing the first PRF, allowing the user to optionally mount it vertically which will eliminate the first PRF.

Of course, for matching applications, it is extremely important as to whether the component looks like a capacitor or an inductor. In this application, a designer will almost always want to be well below the SRF of the capacitor. We can say that, for example, a 10pF capacitor could look like a 1000pF capacitor as the SRF is approached.



See Figure C for Johanson Technology's SPICE equivalent circuit for a capacitor. The values shown are for a typical 10 pF capacitor at 900 MHz. This model tends to give a better SPICE simulation than the more common model where C_S represents the essential C at low frequencies, and C_P (if a C_P is even in the model) represents a fraction of C_S , even though this more common model is more conceptually easy to understand. Keep in mind that even our improved model's accuracy is not ideal at RF frequencies because the elements of this model themselves have a given dependence on frequency. In our model, at low frequencies, the parallel equivalent of C_S and C_P give the essential capacitance. C_S and L_S in our model are what give us the SRF effect. The network of L_S in series with C_S ; which is in parallel with C_P is what gives us the first PRF effect. Note also that our model (and the common model) has no provision for simulating a second PRF. R_P is in our model for a more accurate simulation of what the capacitor looks like at RF frequencies, so don't put an ohmmeter across a capacitor looking for R_P at DC where the Insulation Resistance will be typically greater than 10,000 Ohms! This model (as well as a more "traditional" model) is reflected in our MLCSoft® SPICE simulation software which is available on CD-ROM or from our web page.

IMPORTANT NOTE: Our value for L_S , when using the improved JTI model, may seem slightly (about 50%) higher than a competitor's advertised L_S because of the modeling difference noted above. Be cautious not to compare L_S directly without realizing the difference in modeling.