MPD MICROWAVE PRODUCT DIGEST

March 2004

Considerations for Optimal Capacitive Coupling

by Richard Fiore, Director of RF Applications Engineering, American Technical Ceramics Corp.

Capacitors used in coupling and DC blocking applications serve to couple RF energy from one part of a circuit to another and are implemented as series elements. Proper selection of coupling capacitors insures the maximum transfer of RF energy. All capacitors will block DC by definition; however, considerations for satisfying the requirements of a coupling application depend on various frequency-dependent parameters that must be taken into account beforehand.

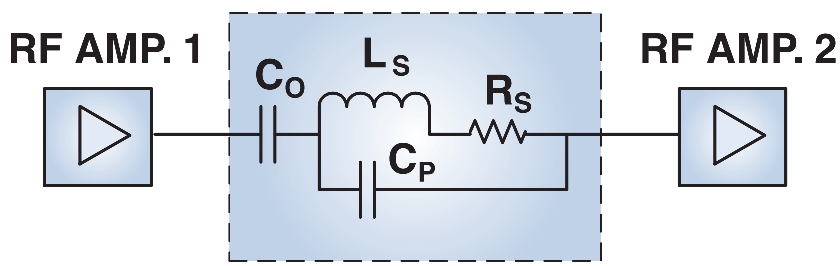


Figure 1: Interstage Coupling Block Diagram

Figure 1 illustrates two RF amplifier stages operating in a 50-ohm network interconnected by coupling capacitor C_0. **Table 1** outlines several device options for achieving interstage coupling at various wireless frequencies. Electrical parameters such as the series resonant frequency (F_{SR}), parallel resonant frequency (F_{PR}), net impedance, insertion loss, equivalent series resistance (ESR) and Q must be evaluated in order to achieve an optimal coupling solution.

Note: Coupling capacitor C_0 in **Figure 1** is represented with its equivalent series resistance (ESR) denoted as R_S, equivalent series inductance (ESL) denoted as L_S and parasitic parallel capacitance C_P, associated with the parallel resonant frequency (F_{PR}).

A capacitor's series resonant frequency (F_{SR}) also referred to as self-resonance, occurs at

$$F_{SR} = \frac{1}{2\Pi\sqrt{L_S C_0}}$$

At this frequency the capacitor's net reactance is zero and the impedance is equal to the ESR. As shown in **Table 1**, an ATC100A101, (100 pF) porcelain capacitor has an F_{SR} of 1GHz with a corresponding ESR of 0.072 ohms. At this frequency the capacitor will provide its lowest impedance path making it an ideal coupling element. In contrast the impedance of a capacitor at its parallel resonant frequency (F_{PR}) can be precipitously high. By assessing the magnitude of S21 vs. frequency for a given capacitor, extreme losses associated with F_{PR} at the frequency of interest can be readily observed. In coupling applications a capacitor's F_{SR} can usually be exceeded to some extent without posing a problem as long as the net impedance remains low.

Net Impedance

The magnitude of a capacitor's impedance is equal to

$$\sqrt{(ESR)^2 + (X_L - X_C)^2}$$

As seen by this relationship a capacitor's impedance is significantly influenced by its net reactance (X_C - X_L). It is important to know the magnitude of the impedance throughout the desired passband. A properly selected coupling capacitor will exhibit suitably low impedance at these frequencies.

As seen in **Figure 2** the net impedance below F_{SR} is capacitive and is dominated by 1/ωC yielding a hyperbolic relationship for frequencies less than F_{SR}. Conversely, the net impedance above F_{SR} is inductive and is dominated by ωL yielding a linear relationship for frequencies greater than F_{SR}.

Insertion Loss (S21)

One of the fundamental considerations for all coupling applications is the capacitor's insertion loss at the operating frequency. By evaluating the magnitude of S21 the designer can readily determine whether or not the subject capacitor is suitable. It is especially important to look for the presence of one or more parallel resonances falling within the operating passband. These resonances will generally show up as distinct attenuation notches at their frequencies of occurrence. If a parallel resonance does fall within the operating passband it will be necessary to evaluate its depth in order to determine whether or not the loss is acceptable. In many instances the magnitude of S21 for a given capacitor may be excessive, rendering it unusable for the application. An insertion loss of several tenths of a dB is generally an acceptable crite-

Frequency (MHz)	Device Options	FSR (MHz)	Insertion Loss S21 (dB)	ESR (ohms)	Package Size
900	100A101 – 100 pF	1000	< 0.1	0.072	55 mil x 55 mil
	600S101 – 100 pF	1340	< 0.1	0.070	0603
1900	100A270 – 27 pF	1870	< 0.1	0.161	55 mil x 55 mil
	600S560 – 56 pF	1890	< 0.1	0.085	0603
2400	100A160 – 16 pF	2410	< 0.1	0.218	55 mil x 55 mil
	600S390 – 39 pF	2340	< 0.1	0.140	0603

Table 1: Examples of Coupling Capacitors & Associated Parameters

rion for most coupling applications. Losses that exceed several tenths of a dB within the passband could easily compromise the end performance of a circuit design. Therefore the decision is ultimately left up to the discretion of the designer to determine whether or not these losses are acceptable for a particular design requirement.

Figure 3 illustrates the insertion loss characteristic of an ATC100A101 (100pF) capacitor. The sample was measured in a series through configuration from 50 MHz to 4 GHz with the capacitor's electrodes parallel to the substrate, i.e. flat mount orientation. As seen in **Figure 3** the capacitor's insertion loss is less than 0.1 dB between 200 MHz to 1.5 GHz. By edge mounting the capacitor, i.e. electrodes perpendicular to the substrate, the first parallel resonant notch at 1.6 GHz will be suppressed. As a result the usable frequency range will be extended to approximately 2.4 GHz. In this orientation the same capacitor can be used to extend frequency coverage making it suitable for broadband coupling applications.

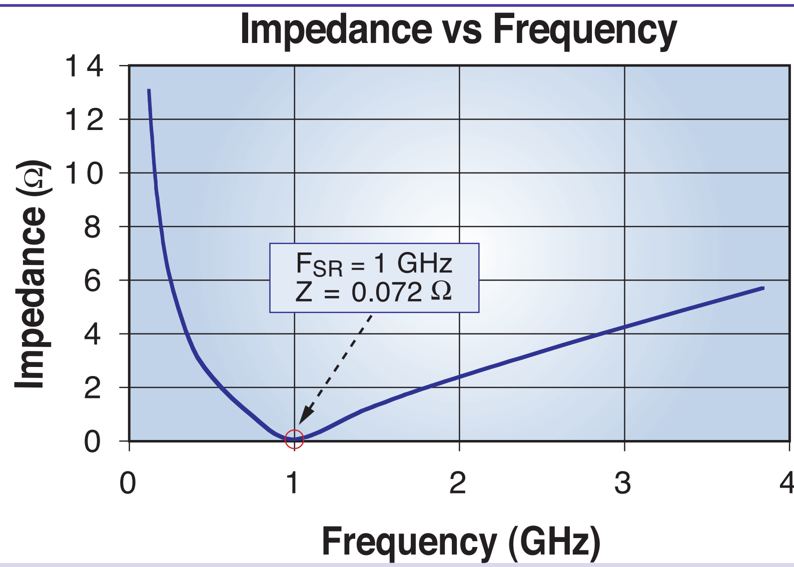


Figure 2: Impedance vs. Frequency for ATC100A101 (100pF)

ESR and Q

ESR is the summation of all series losses in a capacitor and is typically expressed as milli-ohms. ESR losses are comprised of both dielectric loss (R_{SD}), and metal loss (R_{SM}). **ESR = $R_{SD} + R_{SM}$.**

Dielectric loss (R_{SD}) is determined by the specific characteristics of the dielectric material. Each dielectric material has an associated loss factor most commonly referred to as the loss tangent or dissipation factor (DF). The effect of this loss will cause the dielectric to heat. In extreme cases thermal breakdown due to this loss factor may lead to catastrophic device failure. The dissipation factor (DF) provides a good indication of dielectric loss, and is typically characterized at low frequencies i.e. 1MHz, where this loss factor is predominant.

Metal loss (R_{SM}) is determined by the specific conductive properties of all metallic materials in the capacitor's construction. This includes electrodes, terminations plus any other metals such as barrier layers etc. The effect of R_{SM} will also cause heating of the capacitor. In extreme cases thermal breakdown may lead to catastrophic failure. These losses encompass 'skin effect' at higher frequencies and follow a $\sqrt{f}$ relationship.

Catalog ESR curves typically denote ESR values for frequencies where the losses are predominantly due to the metal. At these frequencies the dielectric losses are negligible and do not significantly influence the overall ESR.

A capacitor's quality factor (Q) is numerically equal to the ratio of its net reactance (X_C - X_L) to its equivalent series resistance

$$Q = \frac{X_N}{ESR}, \text{ where } X_N = \text{net reactance} = |X_L - X_C|$$

From this expression it can be seen that the capacitor's Q varies inversely to its ESR and directly with the net reactance. A capacitor's ESR should be known at all frequencies within the passband especially at frequencies above the capacitor's F_{SR}. At the frequency where 'skin effect' has started to effect ohmic losses, the ESR will increase as the $\sqrt{f}$, for increasing frequencies. This becomes the dominant loss factor. As previously mentioned an attenuation notch will occur at the capacitor's F_{PR}, the depth of which is inversely proportional to the ESR. Therefore the capacitor's ESR will largely determine the depth of the attenuation notch at the parallel resonant frequency.

Conclusion

In conclusion, this article has outlined the importance of frequency dependent characteristics of capacitors in coupling applications. Designing for these applications requires knowledge of a capacitor's series and parallel resonant frequencies, its ESR, as well as its impedance characteristics within the frequency range of interest. Premium suppliers such as ATC provide detailed technical information, which includes S-Parameter files and design software. This affords the designer the flexibility to select various options to meet the most stringent performance requirements.

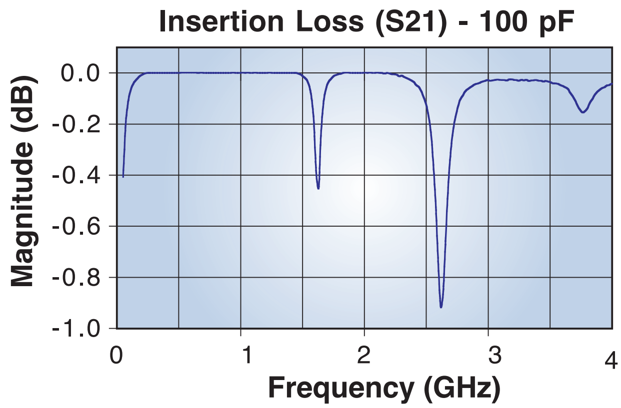
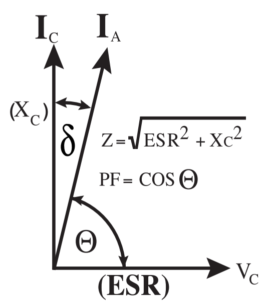


Figure 3: Insertion Loss vs. Frequency for ATC100A101, 100pF Chip Capacitor in Flat Mount Orientation



ESR =	Q =	DF =	X_C =
$X_C \times DF$	$1/DF$	$1/Q$	$1/2\pi \times F \times C$
X_C/Q	X_C/ESR	ESR/X_C	ESR/DF
$X_C \times \tan\delta$	$1/\tan\delta$	$\tan\delta$	$ESR \times Q$

Table 2: Relationship between ESR, Q, DF and Xc

About the Author

Richard Fiore has over 25 years of experience in RF engineering. His professional experience includes design and implementation of RF automated test systems for the defense electronics industry, filter design for both military and commercial markets, EMC design and testing, and the design, prototype and evaluation of RF components, modules and systems. He is presently Director of RF Applications Engineering at American Technical Ceramics, 1 Norden Lane, Huntington Station, NY 11746, and has been with the company since 1994. He may be reached by e-mail at rfiore@atceramics.com.

ATC # 001-1003 Rev. B 6/06

AMERICAN TECHNICAL CERAMICS

ATC North America
sales@atceramics.com

ATC Europe
saleseur@atceramics.com

ATC Asia
sales@atceramics-asia.com

THE ENGINEERS' CHOICE®
ISO 9001 REGISTERED

www.atceramics.com