

Fundamentals of Passive Component Behavior at High Frequencies

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This review of basic component behavior highlights the frequency-dependent factors that are a major part of what defines “high-frequency” as a unique engineering discipline

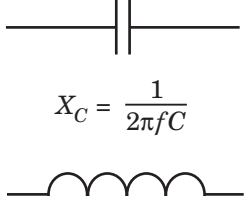
Frequency-dependent behavior of passive components is one of the key concepts of RF, microwave, high-speed and all other types of high frequency design. An old saying among engineers

goes, “At high frequencies, *all* components are R, L and C.” As application frequencies increase further, we can add that all those components are also transmission lines and antennas!

This tutorial is a review of the factors that combine to create the effects referred to in these descriptive phrases. We will not try to rigorously define all the relationships—there are excellent textbooks for that—but we will try to instill an overall understanding of the types and relative magnitude of major frequency-dependent behaviors. While this discussion is limited to passive components, the general concepts certainly apply to active components as well, since their active regions are surrounded by the real-world environment that includes those “R, L, C, transmission line and antenna” elements.

Frequency-Dependence in Ideal Lumped Components

Lumped-element passive components include resistors, capacitors and inductors. AC circuit theory tells us that the latter two are reactive, where the relationships between voltage and current vary with the value of inductance or capacitance, and with frequency. The familiar X_C and X_L reactance formulas are shown in Figure 1.



$$X_C = \frac{1}{2\pi fC}$$

$$X_L = 2\pi fL$$

(X in ohms, f in hertz, C in farads, L in henries)

Figure 1 · The simplest frequency-dependent behaviors are capacitive and inductive reactance.

First-Order Parasitic Effects

Of course, the components we use do not behave according to simple mathematical formulas; they have size, shape, and are constructed using non-ideal materials. What I call first-order effects are the additional resistance, capacitance and inductance the result from these real-world factors.

In actual resistors, capacitors and inductors, the physical length, width and height of the device, the properties of the conductors and dielectric, plus the electrodes for attachment to an external circuit are all part of the “component.” A simple resistor has an inductance associated with its length and capacitance created by the two “plates” that are the end electrodes. Similarly, a capacitor has inductance associated with its length and a resistance due to losses in the dielectric that separates the plates. The additional capacitance due to the attachment electrodes is normally included in the nominal value.

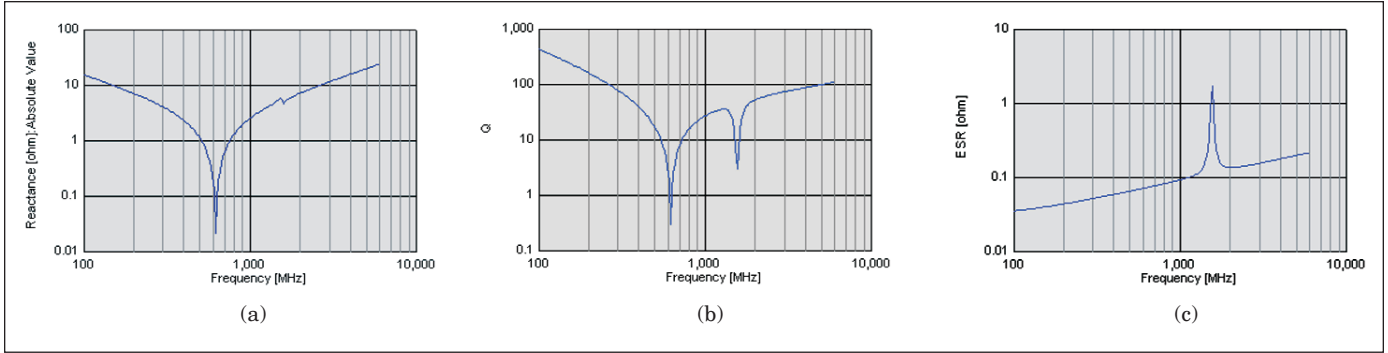


Figure 2 · Frequency-dependent behavior of a 100 pF chip capacitor: (a) reactance, (b) Q , and (c) effective series resistance (ESR).

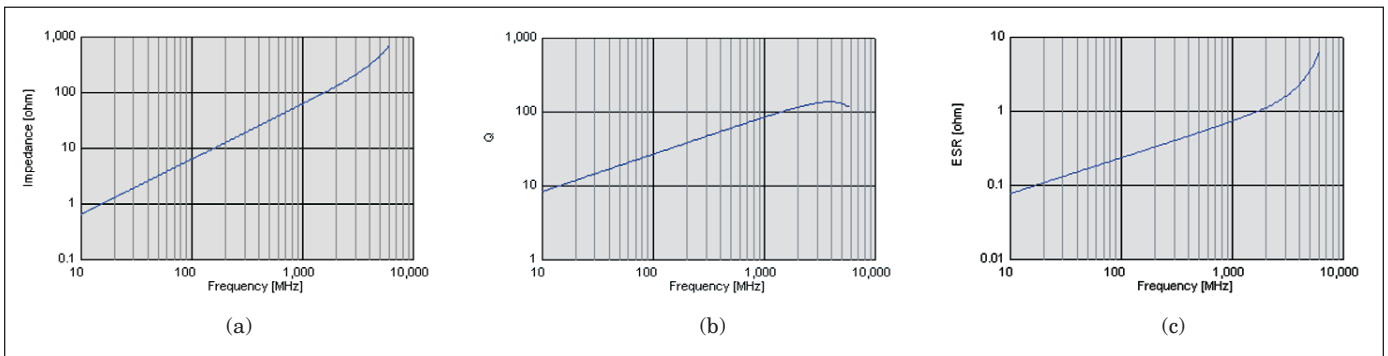


Figure 3 · Frequency-dependent behavior of a 10 nH chip inductor: (a) impedance, (b) Q , and (c) effective series resistance (ESR).

Likewise, an inductor will include the effects of its interconnecting terminals, but it has capacitance between those terminals, as well as capacitance between conductors of the winding.

These first-order effects are usually the largest of all parasitic resistances and reactances, although the mounting of devices on a printed circuit board can introduce significant additional capacitance to the body of the component. This capacitance, and the added inductance of the pads and traces used to attach a component are normally considered part of the circuit, to be discussed separately from the individual components.

How do these additional resistances and reactances affect the behavior of the components?

In a resistor, the largest parasitic reactance is inductance. Inductive reactance is near zero at low frequen-

cies, increasing linearly with frequency. Thus, a resistor will see an increasing inductive reactance that is in series with its resistance. Rather than try to compensate for this reactance, the best approach is to make resistors with very low inductance, which is practical to do. Usually, “non-inductive” resistors are made with bulk or thick film resistive materials rather than commonly-used thin resistive films.

The two main factors in a capacitor—dielectric loss resistance and series inductance—can be described in several ways. Resistance affects Q , which is a function of reactance and resistance. The series inductance creates a resonance at some high frequency where the increasing inductive reactance equals the decreasing capacitive reactance. The typical figure of merit for a capacitor at high frequencies combines these two

effects as *effective series resistance* (ESR). Figure 2 shows how the values of reactance, Q and ESR vary with frequency. This data is for a Murata 100 pF chip capacitor in an 0805 package. Manufacturer’s data shows that this device has a series inductance of 0.66 nH.

The plots of Figure 2 clearly show how capacitors become series resonant, as well as having a parallel resonant point at a frequency above the series resonant frequency. When capacitors are selected for coupling or bypassing applications, it is essential to know these resonant points and be certain that the desired low reactance characteristics are maintained within the desired range of operating frequencies.

Inductors are slightly more complicated, having both inter-winding capacitance and an end-to-end capacitance. Also, the wire of an inductor

has more loss than the dielectric of a capacitor, so the Q values are significantly lower for this component. Figure 3 shows plots for impedance, Q and ESR for a Murata chip inductor. This component has a nominal value of 10 nH in a 0603 package, with a specified parallel capacitance of 0.04 pF.

Figure 3 demonstrates the increasing reactance with frequency, and eventual parallel resonance, of inductors. Although these effects seem small in the example given, remember that large-value inductors are often used as RF chokes, and if improperly selected, may exhibit self-resonance within the desired frequency range.

Transmission Line Effects

The next high frequency behavior to note is that of a transmission line. Often, components are sufficiently small that these effects are minimal, and can be ignored. But, the use of lumped element components at microwave frequencies may create significant transmission line effects.

Figure 4 is a review of the voltage and phase of a signal as it travels one wavelength on a transmission line. Each goes through a full cycle, ranging from a maximum to minimum at various points along the line. Since impedance = V/I (complex values), we can see that this example has a low impedance (minimum voltage, maximum current) at each end, and a high impedance (maximum voltage, minimum current) at the points 1/4 wavelength from each end. At the center point (1/2 wavelength), the magnitude of the impedance is same as at either end, but the sign is opposite—after all, a half-wavelength delay is identical to a 180-degree “phase inversion.”

At any point other than the ends and center of this line section, the impedance will be transformed to a new value. What physical dimensions will cause transmission line effects? Almost any—a 0.01 wavelength (3.6

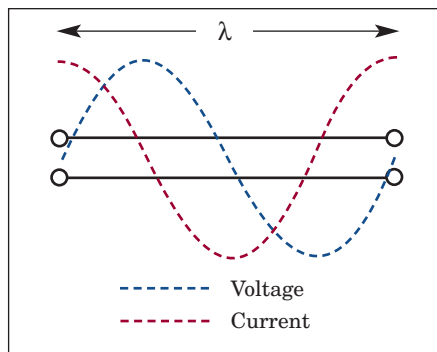


Figure 4 · Voltage and current on a one-wavelength long transmission line.

degrees) transmission line with a characteristic impedance that is twice (or one-half) that of the system will change the magnitude of the impedance by 10 percent, and shift the reactive part in the direction of capacitance. Characteristic impedances that have a greater difference from the system impedance will have a greater effect.

At 100 MHz, 0.01 wavelength is more than an inch, so common SMT components are much less than this size. Note, however, that at 1 GHz, 0.01 wavelength is nearly 1/8 inch, or about 3 mm. At this frequency, even a tiny 0201 component may have sufficient physical size to introduce an impedance change due to transmission line effect. Of special interest are inductors, with their additional conductor length in the coiled winding. This has the effect of increasing the effective length of the component as a transmission line element.

Whenever transmission line effects become significant at the component level, they are certainly going to be substantial at the board level. The area surrounding the components now takes on greater importance, as pads and traces become distributed microstripline circuit elements (transmission lines), often with poorly-defined characteristic impedances.

Most lumped element components are characterized and tested in fix-

tures that minimize transmission line effects by maintaining low characteristic impedance and de-embedding the test fixture effects to ensure that the measured impedance is of the component alone. These test methods are not intended to hide transmission line effects; they are simply intended to provide a consistent, repeatable test methodology.

The component manufacturer does not know the circuit impedance or the layout that their component will be installed in. Thus, it is up to the engineer to determine the magnitude of these effects in a circuit. Such decisions may be a subtle as deciding between an 0201 or an 0805 component based on a comparison of factors other than the nominal value. For example, is the reduction in circuit length with the smaller 0201 part most important, or does the lower characteristic transmission line impedance of the larger 0805 part result in better performance?

Electromagnetic Coupling—Components as Antennas

Our discussion has introduced effects that become significant as the frequency increases. The final characteristic in this article is electromagnetic radiation and coupling. Radiation causes losses and creates interference within, and external to, the circuit. Coupling between components may be included in the category of internal interference, or it can also be an integral part of the circuit design. Or, it can be both if not understood and controlled.

A basic tutorial can barely introduce a topic as complex as electromagnetics, so we will emphasize the nature of its effects and the design issues that must be dealt with.

These effects are present at low frequencies, mainly involving inductive components. The magnetic fields surrounding an inductor can couple to other inductors, or more weakly, to the parasitic inductances of other components and circuit board traces.

Of course, these fields are also used intentionally to implement transformers, often using magnetic materials to enhance the coupling and help contain magnetic fields.

As the frequency increases, coupling via radiation will also increase, as a result of both larger size relative to wavelength, and the fact that electromagnetic waves become more energetic with increasing frequency. For a more rigorous discussion of EM theory, I'll refer you to your favorite textbook, but here are some notes on the way EM radiation can occur in practical circuits:

At frequencies below actual resonance, the efficiency of a radiator is related to its size—the length of an end-fed radiator or the area enclosed by a loop. The magnitude of the radiation is also related to the impedance at that point in the circuit. High impedances will radiate better with an end-fed (voltage-fed) “antenna,” while low impedances will radiate

better with a loop (current-fed) structure. Both are problematic in high frequency design, but with the common use of low impedances, loops are of special concern.

A loop may consist of a component mounted above a p.c. board, with a ground plane on the back side. The area of the loop is established by the gap between the component and board, plus the thickness of the dielectric. Large components, and those that are mounted higher off the board will have larger loop area than their smaller, lower profile counterparts. The effects seem small until you try to keep signals from coupling to one another on a tightly-packed wireless handset board! Then, attention to the fine details of layout may mean the difference between acceptable performance and excessive LO radiation or CPU clock coupling into the radio.

As low-cost consumer equipment has reached the 5 GHz frequency

range, the use of electromagnetic simulation is imperative for successful design. These circuits typically combine traditional lumped components with distributed circuits. These two types cannot be considered separately, so accurate physical representation and high-performance EM modeling is required.

Summary

Frequency-dependent behavior of passive components, transmission line concepts and electromagnetics are the factors that have traditionally set high frequency engineering apart from other electronic specialties. Today, engineers working on nearly all electronics must consider high frequency design characteristics, whether within the equipment or in its interaction with the many high frequency/high speed devices they must work with.