NØAX

HANDS-ON RADIO

Experiment #63 — About Capacitors

Last month's column on resistors alerted you to how seemingly minor differences in resistor construction can have a major effect on resistor behavior in different uses. The variations in capacitor construction are even more significant!

Terms to Learn

Dielectric — Insulating material that efficiently stores energy in the form of an electric field.

Relative dielectric constant — Measure of the relative ability of an insulating material to store energy in the presence of an electric field compared to that of a vacuum.

Capacitor Fundamentals

A capacitor is formed from a pair of conducting plates separated by an insulator (*dielectric*) as shown in Figure 1. If a voltage is applied between the plates, electrons are forced onto one and removed from the other. The resulting charge imbalance creates a voltage and an electric field between the plates, storing energy in the dielectric. Creating such an imbalance is called *charging* the capacitor. Larger area, thinner separation between the plates, or a dielectric with a higher *dielectric constant* increases capacitance. All capacitor types are just variations on this general theme.

If a constant voltage is applied to the capacitor, an opposing voltage builds with the growing charge imbalance. As a result, charging current gradually reduces until the opposing voltage reaches the applied voltage. At that point, current flow ceases. Thus, dc cannot flow between the two plates except during the time the capacitor charges or discharges. AC is considered to flow between the plates as the electrons flow onto and off the plates with each half cycle.

Capacitance in farads (F) specifies the amount of charge stored in a capacitor for a given amount of voltage between the plates. Farads are units of coulombs/volt or $\text{coulombs}^2/\text{joule}$. The energy stored in a capacitor in joules is $E = C \times V^2 / 2$. The area of the plates, the spacing and the material used for the dielectric determine the amount of capacitance:

$$C = k \times \varepsilon_0 \times A / d$$

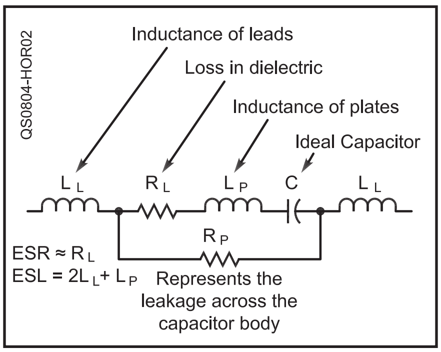

Figure 2 — The equivalent circuit for a capacitor includes parasitic effects. Inductance from the capacitor's shape and connecting leads forms ESL. Loss in the dielectric is shown as ESR. Leakage current across and through the capacitor's body is shown as R_P.

where:

A = the area of the capacitor's plates in square meters.

d = the separation between the plates in meters.

k = the relative dielectric constant (vacuum = 1).

ε_0 = the permittivity of empty space = 8.85 pF/m.

As with resistors, a capacitor's value has a precision or an allowed variation from the labeled or nominal value. Capacitors also have a temperature coefficient because as the materials expand and contract with temperature, the area and separation of the plates also changes.

Figure 2 shows the parasitic effects as parts of the circuit model for a capacitor. The size and shape of the plates and the leads used to connect them to circuits introduce a small amount of inductance called *equivalent series inductance* (ESL). At dc and low frequencies, ESL in the pH to nH range can be ignored, but as the frequency increases, so does its reactance. In fact, the ESL and capacitance form a series circuit (**en.wikipedia.org/wiki/LC_circuit**) with a self-resonant frequency of f_0. Above f_0, the capacitor acts more like a small inductor than a capacitor!

Dielectric materials dissipate a small amount of the stored energy, creating an *equivalent series resistance* (ESR). There is also a little *leakage* current between the plates whenever voltage is present. ESR can be as high as several tens of ohms, but is generally only important when the capacitor current is high, such as in transmitting and power supply circuits.

Leakage resistance, R_P in Figure 2, provides a path for current around or through the dielectric and is typically several megohms. You can ignore leakage resistance except in very low-power and high-impedance circuits.

Capacitor Construction

Figure 3 shows a roll-type capacitor made of two strips of very thin metal foil separated by a dielectric. After leads are attached to the foil strips, the sandwich is rolled up and either placed in a metal can or coated with plastic. *Radial* leads both stick out of one end of the roll while *axial* leads exit from

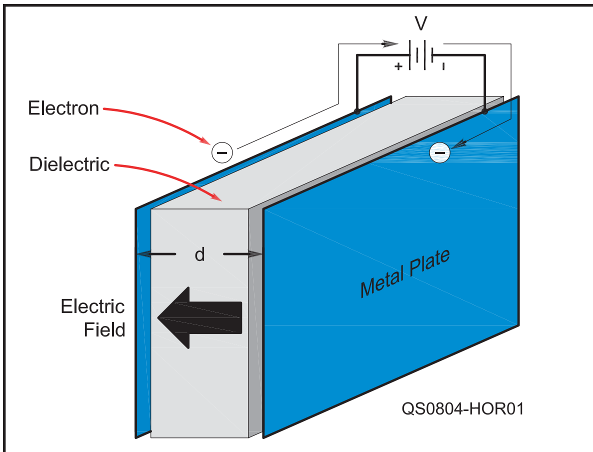

Figure 1 — A capacitor is formed from two metal plates separated by a dielectric. When a voltage is applied, electrons leave one plate and are forced on to the other, creating an electric field and storing energy in the dielectric.

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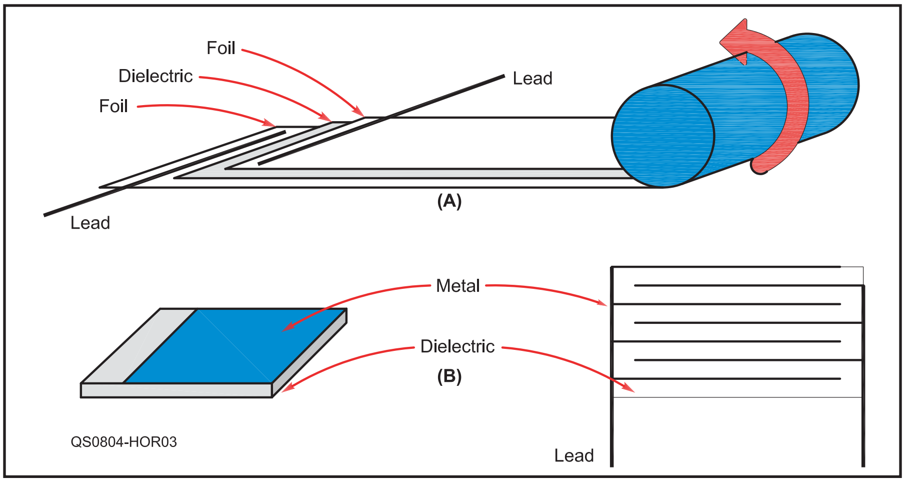

Figure 3 — Two common types of capacitor construction. (A) Roll construction uses two strips of foil separated by a strip of dielectric. (B) Stack construction layers dielectric material (such as ceramic or film), one side coated with metal. Leads are attached and the assembly coated with epoxy resin.

both ends along the roll's axis. Because of the rolled strips, the ESL is high. Electrolytic and many types of film capacitors are made using roll construction.

In the stack capacitor, thin sheets of dielectric are coated on one side with a thin metal layer. A stack of the sheets is placed under pressure and heated to make a single solid unit. Metal side caps with leads attached contact the metal layers. The ESL of stack capacitors is very low, making them useful at high frequencies. Ceramic capacitors are the most common stack-style capacitor.

Capacitor Types

Electrolytic

A roll-type capacitor, the dielectric is a porous paper-like fiber, impregnated with gel that acts as a dielectric. Electrolytics have very high capacitance for their volume and cost. They also have high ESL and ESR and are relatively leaky (low R_P). They can be made to withstand substantial voltages. Electrolytics are polarized, meaning that voltage can only be applied in one polarity due to the chemical electrolyte. They generally have very wide tolerances, on the order of ±20%.

A recent advance in electrolytics, *super-* or *ultra-caps* use advanced plate materials to create amazing amounts of capacitance in a small volume. Capacitance of several farads is not uncommon.

Tantalum

A cross between roll and sheet construction, one plate is formed by an extremely porous *slug* of tantalum and an outer metal capsule the other. The dielectric is an oxide coating on the tantalum slug. The slug has a tremendous amount of area and the oxide layer is very thin, so capacitance is high — but ESR is also high. Short leads and small size means that tantalums have low ESL compared to electrolytics. The maximum applied voltage for tantalum capacitors is under 100 V. As with electrolytics, tantalums are polarized and have wide tolerances of ±20%.

Film

Film capacitors have a plastic film dielectric with polyethylene and polycarbonate being the most common material. Most film capacitors are of roll construction, so ESL is moderate although stack types are available. Film capacitors are non-polarized. R_P is high and ESR is low. Special types of film are used for highly stable capacitance values or extremely low leakage. See **www.filmcapacitors.com/specsum.htm** for a good table summarizing the different types of film capacitors.

Ceramic

Ceramic capacitors are widely used in high-frequency applications. Stack construction keeps ESL extremely low so they are useful to hundreds of MHz. They offer low loss and have good leakage specifications. Ceramic capacitors are very rugged and pack a lot of capacitance into a small package. Ceramics are non-polarized and have a wide range of tolerances and temperature coefficients.

Mica and Glass

Silvered mica and glass capacitors are used in RF and transmitting circuits due to extremely low ESR and ESL. A stack-style capacitor, mica and glass form the dielectric layers. Because these capacitors are used at higher voltages than ceramic capacitors, the thicker dielectric layers limit available capacitance to 100 nF or less. Both types typically have a 5% tolerance.

Trimmer or Variable

Air variable capacitors, with plates separated by air, have very low loss and ESL, working well at RF. Because the plates have a wide separation, the larger capacitors can withstand the high voltages present in high power RF amplifier output stages and impedance matching circuits. Air variable capacitors have a voltage rating of 30,000 V/inch of plate separation (at sea level). Vacuum variable capacitors are available with even higher voltage ratings.

An adjustable variation of the mica capacitor in which the stack is compressed by a screw is called a *compression trimmer*. Ceramic and plastic variables are also available with values of up to several hundred pF.

Comparing Self-Resonant Frequencies

It's an illuminating exercise to compare the self-resonant frequency of several different types of capacitors, all of which have the same nominal value of capacitance. This is where the SWR analyzer can be put to good use once again.

Obtain several 0.01 µF film capacitors of different construction styles. Radial leads almost always indicate roll-type construction and axial leads a stack-type construction. A ceramic capacitor can serve as the reference.

Connect a 47 or 51 Ω resistor across the output of the analyzer as in the previous experiment. Sweep the frequency through the analyzer's range and note where reactance begins to increase beyond a few ohms. This will be the upper end of the comparison range.

Now connect each capacitor in series with the resistor and repeat the sweep, first with long leads and then with short leads. Self-resonance should be observed as a sharp return to minimum reactance after a slow increase. Above f_0, reactance will again increase. Compare the self-resonant frequencies of the different film styles with that of the ceramic capacitor. Which would be better at RF?

If you have access to some small tantalum or electrolytics of less than 1 µF, sweep them, too, and compare their performance.

Recommended Reading

Review the capacitor section of Chapter 6 of *The ARRL Handbook* or browse **www.faradnet.com**. Cletus Kaiser's *The Capacitor Handbook,* 2nd Edition (CJ Publishing) covers all subjects capacitive, as well.[1] Capacitor manufacturers often have excellent comparisons of the different styles available on their Web sites.

Next Month

We're going to make some circuit measurements using a new type of oscilloscope that plugs directly into your computer's USB port!

[1] *The ARRL Handbook for Radio Communications,* 2008 Edition. Available from your ARRL dealer or the ARRL Bookstore, ARRL order no. 1018. Telephone 860-594-0355, or toll-free in the US 888-277-5289; **www.arrl.org/shop/**; **pubsales@arrl.org**.