TESTING AND MEASUREMENT PRACTICES OF HIGH CAPACITANCE CERAMIC CAPACITORS

BY NATHAN BAILEY
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What is the Issue?
Inability to measure high capacitance multilayer ceramic capacitors (MLCCs) correctly: Many capacitance testers and LCR meters used throughout the industry are not designed to, nor have the capability to correctly measure capacitance of high capacitance (Hi-Cap) MLCCs. This is the case whether we are measuring capacitors at 1 VAC and 1 KHz or 0.5 VAC and 120 Hz. This has become a growing issue in our industry, and there is no sign it is going away anytime soon. The inability to correctly measure high capacitance MLCCs is due to two reasons. First, many LCR meters do not have the capability of supplying enough current to the capacitor being tested at 1KHz and 1 VAC, resulting in a reduced measurement voltage which results in an artificially reduced capacitance reading. Second, Hi-Cap MLCCs typically utilize Class 2 dielectrics (e.g. X5R, X6S, X7R, X7S, etc.) that are sensitive to test voltage in the sense that changing test voltage results in change in capacitance. The change in capacitance occurs because Class 2 dielectrics are typically made with ferroelectric dielectric materials that are non-linear in behavior with respect to test voltage. These two reasons explain why it is essential to ensure that you apply the correct test voltage to the MLCC when measuring or testing a capacitor and trying to obtain its actual capacitance value. Incorporating the right bridge and applying the correct parameters is essential in obtaining an accurate capacitance measurement.

What is the definition of a high value Capacitor?
Historically, 1µF and above is considered a high capacitance value for MLCCs. With advances in technology, MLCCs with much higher nominal capacitance values (e.g., 10 µF, 22µF, 47µF, 100 µF and above) are now commercially available.

Explanation:
To ensure that capacitance is correctly measured, each capacitor must be tested under the correct conditions. The correct conditions for measurement depend upon the capability of the measurement equipment as well as the nominal capacitance to be measured, as defined and discussed below.
Effective Measurement Frequency and Voltage

The impedance of a capacitor as a function of frequency may be determined from the relationship:

\[
Z = \sqrt{ESR^2 + \left(\frac{1}{2\pi \cdot f \cdot C} - (2\pi \cdot f \cdot L)^2\right)^2}
\]

Where:
- \(Z\) is impedance in Ohms
- \(ESR\) is equivalent series resistance in Ohms
- \((1/(2\pi \cdot f \cdot C))\) is the capacitive reactance or \(X_C\) in Ohms
- \(2\pi \cdot f \cdot L\) is the inductive reactance or \(X_L\) in Ohms
- \(f\) is frequency in Hz
- \(C\) is capacitance in Farads
- \(L\) is inductance in Henries

Capacitance measurements are typically performed at relatively low frequency (e.g. 1KHz or 120Hz). At these relatively low frequencies, the capacitive reactance \(X_C\) typically dominates the impedance equation, and \(Z\) may be estimated from the relationship:

\[
Z \approx X_C = \frac{1}{2\pi \cdot f \cdot C}
\]

From this relationship, it is evident that the impedance of a capacitor is dependent upon frequency and capacitance value.

The impedance \((Z)\) vs. frequency relationship of capacitor values ranging from 0.1µF to 1000µF is illustrated in Figure 1 below, while the impedance values at two common measurement frequencies (120Hz and 1000Hz) for the same capacitance values is indicated in Table 1 below. Figure 2 illustrates the AC current required to drive either a 0.5VAC or a 1.0VAC signal across capacitors ranging from 0.1µF to 1,000µF, by decade value, at either 120Hz or 1 KHz. Figure 2 also indicates the AC current capability of the power supply of a typical LCR meter. The figure indicates that the current required to drive a 1KHz signal across a 10µF DUT (device under test) capacitor at either 0.5VAC or 1.0VAC may exceed the AC current capability of a typical LCR meter, while the current required to drive a 120Hz signal across a 10µF DUT at either 0.5VAC or 1.0VAC is not likely to exceed the current capability of the capacitance meter. Because of this, it may not be prudent to measure capacitance values of 10µF or above at 1KHz, as this may cause the test voltage at the DUT to be reduced significantly below the setting value, leading to erroneously low measured capacitance. Thus, it is important to consult the owner’s manual of your capacitance meter to understand the current capability of its power supply. If the current capability of the power supply of your meter exceeds approximately 70 mARMS, it may be suitable to use it to measure capacitance of 10µF capacitors at 1 KHz. Otherwise, it is likely not suitable for 1KHz, and it will be necessary to measure capacitance at 120Hz.
While most MLCC manufacturers specify a test frequency of 1KHz for values ≤10µF, it has been my experience that the recommended test frequency for values ≥10µF should be set at 120Hz due to the limitations previously mentioned and based on feedback, test data and analysis using both the 1KHz and 120Hz test frequencies on a variety of different LCR meters. Based on all this data, the largest influential parameter in obtaining the actual capacitance value is applying the correct rms test voltage (and the DUT actually seeing the intended applied value) and in some cases dropping the frequency of the LCR test meter to 120Hz. This will allow the machine to “keep up” with supplying the correct test voltage for the DUT, thus eliminating erroneous capacitance readings. This has been the case in several instances where the LCR meter is older or a less expensive model.

Impedance vs. Frequency

Figure 1. Z vs. frequency for capacitors ranging from 0.1µF to 1000µF

<table>
<thead>
<tr>
<th>Capacitance (µF)</th>
<th>Z (Ω) @ 120 Hz</th>
<th>Z (Ω) @ 1 KHz</th>
<th>RMS Current Required to Drive Test Voltage (I_{RMS})@ 120 Hz</th>
<th>RMS Current Required to Drive Test Voltage (I_{RMS})@ 1 KHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>13,263</td>
<td>1,592</td>
<td>0.000037</td>
<td>0.000008</td>
</tr>
<tr>
<td>1</td>
<td>1,326</td>
<td>159</td>
<td>0.000377</td>
<td>0.00075</td>
</tr>
<tr>
<td>10</td>
<td>133</td>
<td>15.9</td>
<td>0.003770</td>
<td>0.00754</td>
</tr>
<tr>
<td>100</td>
<td>13.3</td>
<td>1.59</td>
<td>0.037699</td>
<td>0.07540</td>
</tr>
<tr>
<td>1000</td>
<td>1.33</td>
<td>0.16</td>
<td>0.376991</td>
<td>0.75398</td>
</tr>
</tbody>
</table>

Table 1. Capacitor impedance at 120Hz and 1KHz
Required Current to Drive a Test Voltage

![Graph showing current required to drive a test voltage at different frequencies and capacitance values in comparison with the current capability of a power supply of a typical LCR meter.]

Figure 2. Current required to drive a test voltage (either 0.5VAC or 1.0VAC) at 120Hz or 1 KHz vs. capacitance in comparison with the current capability of a power supply of a typical LCR meter

The test voltage may be reduced from 1.0VAC to 0.5VAC in order to further extend the capability of a capacitance meter with respect to AC test current. The use of 0.5VAC test voltage instead of 1.0VAC may enable accurate measurements of capacitance values up to ~47µF at 120Hz for an LCR meter with 20mA RMS AC current capacity.

Some LCR meters have enhanced current capability that may enable it to deliver up to 200mA RMS. This should enable measurement of 10µF capacitance at 1KHz and 1.0VAC and higher (up to ~33µF and up to almost ~68µF at 1KHz and 0.5VAC). Above these values, it is necessary to switch to lower measurement frequency. Since tantalum capacitors were traditionally measured at 120Hz, it was logical to specify 120Hz measurement frequency for high capacitance value MLCCs.
Measurement Summary

To summarize, as capacitance is increased, impedance at a given frequency decreases. Normally, the measuring equipment compensates for this by switching to lower internal impedance which enables the power supply of the meter to drive the specified AC voltage accurately as specified. However, the ability of certain capacitance meters to drive a specified AC voltage at a specified frequency is limited. With the advent of very high value MLCC (10µF and higher, which have very low impedance at 1 KHz, it is necessary to measure the capacitance of these devices at lower frequency (120Hz) as well as lower voltage (0.5VAC) as the AC test voltage drops below the specified value during test resulting in an artificially low capacitance reading. As an example, a measurement of capacitance, taken at 1 VAC and 1 KHz, may actually be at 0.5 - 0.6 VAC or even lower if the capacitance of the DUT is very high (and correspondingly low Z). This will result in an erroneously low capacitance measurement.

Some capacitance meters have a built in ALC (Automatic Level Control) or high speed option that should be used to measure high capacitance values (≥1 µF). This ALC function automatically maintains the specified measurement voltage in order to enable correct measurement of capacitance. However, these meters are still limited, and depending upon the capacitance measured may still need to revert to lower frequency for accurate measurements. These erroneous capacitance readings may indicate that the capacitors are out of specification on the low side of nominal capacitance when they are not.

How to properly measure High Value Ceramic Capacitors

Use correct equipment (like the Agilent E4980A (with the -001 option), HP 4284A or 4268A or Genrad 1639 with the high speed option.

Turn on the A.L.C. or high speed function, if available.

Test at the correct frequency for the capability of your capacitance or LCR meter:

To address the above issue, the capacitor industry (i.e. the ECIA/EIA) has agreed to use of a lower test frequency for higher Capacitance values (i.e. 120Hz for capacitance >10 µF). Unfortunately, we have encountered numerous instances of 10 µF capacitors being measured at 1 KHz, leading to erroneous capacitance readings as described above, as a result of making the measurements with LCR testers that cannot adequately drive the specified AC test voltage at 1 KHz. Hence, we believe that 10µF MLCCs should also be tested at 120Hz as indicated in the recommended specifications for capacitance measurement tabulated below.

<table>
<thead>
<tr>
<th>Recommended Measurement Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
</tr>
<tr>
<td>&lt;10uF</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>&gt;10uF</td>
</tr>
</tbody>
</table>

Verify that the correct voltage is being applied during capacitance measurement:

To confirm that the measuring equipment is supplying the specified AC test voltage to the capacitor, measure the voltage being supplied to the capacitor with a Digital Multimeter (DMM). While measuring the capacitance, place the test leads of the Digital Multimeter on the contacts of the test fixture, and if the voltage has dropped below the specified AC test voltage range (RMS basis), one can expect an error in the measured capacitance. Therefore, the specific meter being used is incapable of accurately measuring the capacitor under the specified and applied parameters.
Additional Factors Concerning Class 2 Ceramic Dielectrics in MLCCs and how it effects their behavior

Multilayer Ceramic Capacitors (MLCCs) utilizing formulated Barium Titanate are different from other capacitors in that they use special and unique dielectric materials that are ferroelectric and non-linear. These non-linear ferroelectric materials provide a high dielectric constant (K) value that changes with temperature and other environmental factors. Formulated ferroelectric Barium Titanate (BaTiO₃) ceramic dielectric materials are typically sensitive to temperature, aging time, DC Bias and AC voltage while relatively insensitive to frequency below approximately 100MHz. This is in contrast to Class 1 capacitors with the C0G/NP0 designations which contain materials that are linear or paraelectric and generally more stable and predictable over the operating temperature range. However, Calcium Zirconate based ceramics, Barium Neodymium Titanate ceramics etc. (e.g. CaTiZrO₃/ZrSnTiO₄) or other C0G dielectric materials have a low dielectric constant and thus limited capacitance capability. Having a very low dielectric constant is an intrinsic characteristic of the C0G/NP0 dielectric that makes it so that these formulations are unable to achieve capacitance values of more than 0.1uF in a 1206 package at the present time.

Capacitance Formula and Definitions

Contemporary high capacitance MLCCs are typically made with dielectric materials having a high dielectric constant, so that high capacitance in a small case size may be achieved. This is evident through the relation:

\[ C = \frac{nA\varepsilon_0 K}{t} \]

Where:

- \( C \) is capacitance in Farads
- \( n \) is the number of dielectric layers in the MLCC
- \( A \) is the active (overlap) area of each layer in the MLCC in m²
- \( \varepsilon_0 \) is the dielectric permeability of free space (8.854 x 10^-12 F/m)
- \( t \) is the thickness of the dielectric layers separating each set of electrodes (m)
- \( K \) is the dielectric constant

Therefore, in order to achieve high capacitance in a small case size, it is important to maximize \( K \) and to minimize \( t \). We will discuss how \( K \) is maximized below.

Barium Titanate (BaTiO₃) Crystal Structure (Perovskite) and Understanding Domains and Dipoles

Barium Titanate (BaTiO₃) based dielectrics may have very high dielectric constant (K) values that enable very high capacitance values in small MLCC case sizes when formulated to properly take advantage of their associated crystal structures. Dielectric constant (K) is directly related to the concentration and amplitude of operating dipoles within a material, as well as the ability of the dipoles within the material to align with an applied electric field. Ferroelectric Barium Titanate is an excellent material for maximizing dielectric constant. Quantifying high dielectric constants for Barium Titanate typically means \( K_s \) in the 2000-5000 range. Barium Titanate has a perovskite-type crystal structure, represented by the unit cell illustrated in Figure 3 below.
The perovskite crystal structure is named for the mineral perovskite, which is Calcium Titanate (CaTiO₃) and was named after the Russian mineralogist Lev Perovskite after its discovery by Gustav Rose in 1839. Barium Titanate (BaTiO₃) has the same crystal structure and thus is in the perovskite family.

The Barium Titanate characteristic crystal structure is a face centered structure with Ti⁺⁴ in the center of the cell, Ba⁺² on each of the corners of the cell, and O⁻² on each of the face centers. The physical structure of this unit cell is such that the Ti⁺⁴ ion, which is relatively small and highly charged, in concert with the O⁻² ions, can “rattle” or have movement within the structure as illustrated in Figure 4 below when perturbed by or in the presence of an electric field. As the electric field changes, the relative positions of the Ti⁺⁴ and the O⁻² ions change accordingly. This changing displacement of Titanium and Oxygen ions in each unit cell enables a high concentration of highly charged and directional dipoles per unit volume to occur. With all other (capacitance determining) factors remaining equal, the higher the number of directional dipoles per unit volume, the higher the K value and the higher the corresponding capacitance value.

The way that the dipoles and domains are contained and operate within the perovskite crystal structure of BaTiO₃ warrants further discussion in order to help explain why ceramic capacitors made with ferroelectric materials exhibit non-linear dielectric behavior. A crystal is said to be ferroelectric when it has two or more orientational states or alignments in the absence of an electric field and can have these states or alignments directionally changed or shifted by an electric field. This behavior results in the capacitor changing its properties when in a changing environment such as changes in temperature or applied bias, AC voltage, or time. This is similar to and a model for many ABO₃ type materials which are important in the study of ferroelectrics.
Groups of (electric) dipole alignment make up regions called Ferroelectric domains. With a changing electric field, these regions of dipoles or domains contained within the dielectric material spontaneously align themselves in a similar direction that combined with the high relative magnitude of the aligned dipoles, results in a higher K. Ferroelectric domains may also be called Curie-Weiss domains, and in the case of Barium Titanate, are comprised of titanium cations and oxygen anions within the perovskite crystal structure. The size of each domain is typically on the order of about 1µm and domains of alignment are separated by domain walls. In the event the domain is the size of a ceramic grain, which is now more commonplace due to the fine grain ceramic dielectrics required for thin layer multilayer ceramic capacitors, the grain boundary serves as the domain boundary. When influenced by an electric field, the dipole moment points from negative charge to the positive charge and has a magnitude equal to the separation of the charge times the strength of the charge. The number of aligned dipoles is directly proportional to the strength of the applied electric field.

![Figure 4. Dipole displacement within the Barium Titanate unit cell (top view)](image)

Certain forms of the BaTiO$_3$ perovskite crystal structure (i.e., Rhombohedral, Orthorhombic and Tetragonal), are non-centrosymmetric, meaning that the unit cell is stretched slightly and the position of the Ti$^{4+}$ ion will tend toward one of two thermodynamically preferred positions that are not exactly at the body center of the unit cell, as illustrated in Figure 5 below. The spontaneous alignment of the dipoles into domains and the ability of those domains to align with an applied electric field as discussed above is called the ferroelectric effect. Ferroelectric domains are illustrated in Figure 6. This spontaneous alignment results in the ability to create a very high dielectric constant within ferroelectric BaTiO$_3$ which is useful in enabling the manufacture of high capacitance MLCCs.
There are four polarization mechanisms that occur in dielectric materials: electronic, atomic, dipole, and space charge. In ferroelectric Barium Titanate, the dipole polarization mechanism dominates and we limit our discussion here to that specific mechanism. Additionally, the crystallographic structure of Barium Titanate changes over temperature, which greatly influences the dipole polarization effects. This very fascinating phenomenon provides some insight into how the material properties change with a changing environment. As previously discussed, the unit cell of Barium Titanate may distort slightly, changing its crystal structure from cubic to Tetragonal, to Orthorhombic to Rhombohedral as the material is cooled from above the Curie temperature ($T_C$) to subzero temperatures. These distortions can be considered as elongations of the cubic unit cell along an edge (tetragonal), face diagonal (orthorhombic), and body diagonal (rhombohedral).
Additional considerations regarding formulated BaTiO$_3$

Most would agree that, for the selection of a component for any specific circuit design, there is no one perfect component, there are only tradeoffs. The circuit designer must consider all the component performance specifications and any relevant data for a specific selection and make what he or she believes to be best choice for the intended application. Formulated BaTiO$_3$ based dielectrics used throughout our industry have the capability of to produce very high capacitance in a small package (currently up to 220µF in 1210 (EIA) package, for an X5R, 6.3V rated MLCC) as well as provide very good overall reliability, low ESR and low Impedance. The FIT (failures in time) and MTBF (median time before failure) data for these devices proves that to be the case. The ability of specially formulated BaTiO$_3$ to enable very high capacitance in small volume MLCCs has some drawbacks, however. These capacitors utilize non-linear dielectric materials in that their dielectric constant is not linear with an applied electric field. Hence, these materials exhibit changes with changing environmental factors such as temperature, DC bias, AC voltage and time.
Also, since ceramic capacitors are generally made of materials that are considered brittle solids, they are more susceptible to mechanical stress fractures or cracking during PCB processing and assembly. Failure signatures contained within a “failed” and typically shorted MLCC, usually exhibit corner cracks indicating an upward or downward force applied to the mounted and soldered MLCC during processing or assembly. Corner cracks (flex cracks) or similar type (micro) cracks, are generally consistent with failure signatures generated by excessive flexure of the PCB, which results in excessive mechanical force applied to the capacitor through its rigid mount to the PCB. This failure mechanism accounts for over 90% of all failed MLCCs in our industry. Alternatively, having MLCCs that do not crack on a PCB could also have bad ramifications such as cracked or broken terminations or solder joint reliability issues in areas of excessive stress.

Additionally, there are piezoelectric, electrostrictive, and microphonic effects that can affect the capacitor and circuit performance. Piezoelectric and electrostrictive effects result in changes in physical size with the application of an applied field. When an AC voltage is applied across the capacitor, the capacitor will mechanically change with the frequency of the signal. If the amplitude of the signal is high enough and in the audible frequency range (~20Hz-20KHz), the mechanical displacement creates pressure waves in the air which is the ringing or buzzing sound you may hear in specific circuit designs utilizing high capacitance MLCCs under certain circumstances. The Microphonic effect is the reverse of the buzzing effect whereby the MLCC tends to act like a microphone by way of the piezoelectric or electrostrictive effects. Pressure waves and mechanical disturbances, which are usually generated by some kind of noise, affect the MLCC in the circuit, mechanically displacing its body, and the MLCC begins to acts like a microphone. This displacement causes the MLCC to put a “ripple” or other unwanted noise on the circuit signal. The unwanted portion of the signal or “ripple” can affect circuit performance and may cause issues in tight tolerance circuits. Piezoelectric materials exhibit this displacement vs. applied field and the curves that represent this phenomenon are similar to hysteresis curves discussed later in this paper. Formulated C0G dielectrics (such as Calcium Zirconate based ceramics or Barium Neodymium Titanate ceramics etc.) are paraelectric and do not exhibit these piezoelectric, electrostrictive, or microphonic effects to any significant degree.

Ferroelectric BaTiO$_3$, which is typically used as the basis for Class 2 ceramic dielectrics, is a material having relatively high dielectric constant value (K), which enables high capacitance in a small case size. The sensitivity of capacitance or dielectric constant that results from temperature changes defines the type of dielectric used in the MLCC. For example, the Electronic Industries Association (EIA) has defined the Class 2 category of dielectric for high K ferroelectric dielectric materials as tabulated in table 2 below. Ceramic capacitors with X5R/X7R dielectric materials are allowed to change up to 15% (but no more) from room temperature up through their maximum rated operating temperature and down to their minimum rated operating temperature. Associated temperature envelopes for X7R, X6S, X5R and Y5V, etc., are illustrated in Figure 8 below as well.
Table 2. EIA Class 2 Dielectric Classification Chart

<table>
<thead>
<tr>
<th>Letter code</th>
<th>Number code</th>
<th>Letter code</th>
</tr>
</thead>
<tbody>
<tr>
<td>low temperature</td>
<td>upper temperature</td>
<td>change of capacitance over the temperature range</td>
</tr>
<tr>
<td>X = -55 °C (-67 °F)</td>
<td>4 = +65 °C (+149 °F)</td>
<td>P = ±10%</td>
</tr>
<tr>
<td>Y = -30 °C (-22 °F)</td>
<td>5 = +85 °C (+185 °F)</td>
<td>R = ±15%</td>
</tr>
<tr>
<td>Z = +10 °C (+50 °F)</td>
<td>6 = +105 °C (+221 °F)</td>
<td>S = ±22%</td>
</tr>
<tr>
<td></td>
<td>7 = +125 °C (+257 °F)</td>
<td>T = +22/−33%</td>
</tr>
<tr>
<td></td>
<td>8 = +150 °C (+302 °F)</td>
<td>U = +22/−56%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>V = +22/−82%</td>
</tr>
</tbody>
</table>

Temperature Envelope for Common Class 1 & 2 Dielectrics

The Aging Phenomenon of Ferroelectric Dielectric Materials

Ferroelectric Barium Titanate also exhibits a dielectric aging phenomenon where the dielectric constant (K) tends to decrease with time in a logarithmic fashion. This decay results in decreased capacitance over time and will continue to decrease with time from the last de-aging heat treatment above the Curie Temperature ($T_C$), continuing to decrease in a manner that depends upon the logarithm of elapsed time since the last reheat above $T_C$ (~120°C-125°C). Most MLCC manufacturers recommended de-aging specification is $T > 150°C$ or 30 minutes to one hour if possible. During the deaging process, the ferroelectric domains within the Barium Titanate crystal structure gradually change to the cubic from the tetragonal phase in a second order transition. Upon cooling, the crystal structure changes to a tetragonal crystallographic structure and the ferroelectric domains are reformed. The dielectric constant of the material “resets” as it is cooled back below $T_c$. The material becomes “de-aged” as stresses within the crystal structure are “reset” and the ferroelectric domains are reformed. The cause of dielectric aging is not exactly known, but is generally thought to be associated with relief of crystal lattice strain and to subdivision of ferroelectric domains into smaller domains, resulting in a reduced K that occurs over the time that has elapsed since cooling below $T_c$. The rate of aging (A) typically increases with increasing K of the dielectric material.
The equation used to predict capacitance loss as a function of time is:

\[ C_t = C_i \cdot \left[ 1 - \left( \frac{A}{100} \cdot \log_{10} \left( \frac{t}{t_i} \right) \right) \right] \]

Where:
- \( C_t \) is the capacitance at time \( t \) in F
- \( C_i \) is the initial capacitance in F
- \( A \) is the aging rate in %/decade
- \( t_i \) is the time since de-aging at the initial capacitance measurement in hours
- \( t \) is the time since de-aging at time \( t \) in hours

Typical aging rates are 2-3% per decade for X7R, 3-5% per decade or less for X5R, and 5-9% for Z5U and Y5V. The general trend is that the aging phenomenon and corresponding aging rate is exacerbated as dielectric layers become thinner and dielectric constant (K) becomes higher. This may be an important consideration when specifying a capacitor for a circuit design if a relatively tight tolerance is required.

Hysteresis Loops – Polarization, Electric Field Effects and Applications

The K value and thus capacitance of a high value MLCC made with Class 2 dielectric typically decreases with increasing DC bias as the ferroelectric domains (see Figure 6 above) tend to become "held" or "pinned" with high bias relative to a small AC measurement signal. To illustrate this effect, a typical hysteresis loop or P-E (polarization vs. electric field) curve is shown in Figure 9 below. The hysteresis is important in that it shows the polarization level as a function of electric field. From a dielectric standpoint and as defined at a given set of temperatures and conditions, a set of hysteresis curves help to characterize the effect of electric field on K and the dissipation factor or DF. Hysteresis curves characterize the electric field sensitivity of a dielectric material, since the slope of the hysteresis curve (e.g. \( K_1 \), \( K_2 \) in Figure 9) represents the dielectric constant (K) under a given applied electric field (\( \mathcal{E} \)) as further discussed below. As the electric field is increased, the polarization increases in a parabolic fashion until saturation is achieved at the top right of the curve.

Figure 9. Hysteresis loop for a ferroelectric dielectric material\(^7\)
As the electric field is decreased, the polarization is reduced in a manner shown by the leftward curve of the hysteresis loop. It is noted that, even as the field is reduced to 0, the domains that were aligned by the relatively high and positive electric field at saturation, want to remain arranged in that stable domain structure. That phenomenon is indicated as the remnant polarization which is \( P_r \) on the hysteresis curve in the figure. As electric field (\( E \)) is decreased below 0, the polarization is decreased in the manner shown by the leftward portion of the hysteresis curve until a state of 0 polarization is achieved. This is called the coercive field (\( E_C \)). With further negative \( E \), the domains rearrange such that they flip and saturate at the lower left of the curve. As \( E \) is increased from negative saturation, the domains again, want to stay arranged, until a significant positive field is impressed upon the dielectric at the \( E_C \) value to the right of the curve where the domains begin to flip back to the original state.

The absolute value of the tangential slope of the hysteresis curve at any point on the curve is the dielectric constant (\( K \)) under the given condition of \( E \). A good estimate of the overall \( K \) that would be measured during capacitance measurements will depend upon the AC measurement signal voltage used as well as upon the DC bias impressed upon the dielectric. Additionally, and a very important point and use of the hysteresis curves (theoretically), is that the area of the hysteresis curve is proportional to the dielectric loss or dissipation factor. If no DC bias is used during the capacitance measurement, the overall \( K \) tends to be represented by a line averaging the hysteresis curve in a best fit manner as indicated by the solid gray line in Figure 9 (from bottom left to upper right). When a relatively large and positive DC bias (field) is imposed upon the ferroelectric dielectric, however, the hysteresis loop is effectively compressed to the upper right of the curve and the slope of tangential points and the average tend to decrease overall as the domains become “restrained” in one orientation. This is because the DC voltage “locks up” some of the aligned dipoles in place preventing the AC voltage from re-orientating them. The relatively low AC measurement voltage that is impressed upon the dielectric as it is being measured is ineffective in switching the domains such that the overall measured capacitance is reduced as the polarization and thus \( K \) are reduced under these conditions. With relatively high imposed DC fields, this effect can be quite considerable, reducing the \( K \) of the material, and thus capacitance by 70% or more from nominal when a DC bias of 6.3V (rated voltage in this case) is applied as indicated in Figure 10 below. This figure illustrates the DC bias effect for a high capacitance value MLCC utilizing a BaTiO\(_3\) based ferroelectric material as its dielectric. Because of this, very high value X5R MLCCs are not typically used in circuit designs that exceed ~50% of rated voltage (Vr).

**DC Voltage vs. Capacitance**

![Typical Capacitance Change vs. DC Voltage for a 6.3V rated MLCC](image)

Figure 10. Percent initial capacitance as a function of DC Bias typical Class 2 MLCC. These are typical curves for high value capacitors (\( \sim > 1\mu F \)). Capacitance value and % of rated voltage applied will impact slope and total % drop of capacitance.
Hysteresis curves and AC test Voltage vs. Capacitance

Hysteresis curves may also be used to explain the effect of AC measurement voltage upon capacitance of Class 2 ferroelectric MLCCs. The area inside the curve represents the energy required to re-orient the dipoles and domains and is proportional to the dissipation factor of the dielectric. As the AC test voltage is reduced, the test signal becomes less capable of switching domains back and forth, and the hysteresis loops tend to lose slope (green colored line in Figure 11) resulting in reduced K of the dielectric, and thus reduced capacitance. In Figure 11 a hysteresis loop or Q-V (Coulomb-Voltage) plot is demonstrated using a Sawyer-Tower circuit for a 10 µF capacitor with an approximate 1 µm dielectric thickness as a function of test voltage. This hysteresis loop below is analogous to the P-E hysteresis loop previously shown, but the loop below shows hysteresis curves for 4 different peak and increasing voltages in order to demonstrate the hysteresis characteristics of the 10 µF capacitor by measuring charge (µC) at various Voltages (V) using a Sawyer-Tower circuit configuration. The Peak-to-Peak value for each voltage used in calculating and determining its corresponding hysteresis loop in this diagram were ~ 0.5v, ~1.5V, ~ 10V, and ~ 20V respectively.

The Q-V curve is valuable in that it can be used to determine dynamic capacitance of the device for each of the voltages within each of the four hysteresis curves illustrated. An example of the dynamic capacitance (C*) of this device at dielectric saturation is shown in the diagram below and is defined as C* = dQ/dV ~ 10µC/10V ~ C sat ~1µF using the relationship: C sat = Q sat/V sat where Q sat = polarization saturation, C sat = capacitance at saturation and V sat is the applied voltage that causes dielectric saturation as the ferroelectric domains have all aligned at V sat, as described in the discussion of ferroelectric hysteresis behavior above. The saturation polarization (P sat) or charge at saturation (Q sat), occurs at a given voltage V sat, resulting in a given C sat or P sat.

As can be seen in the hysteresis diagram below, the capacitance of the device at voltages up to saturation would vary, and capacitance would be on the order of ~8-10 µF at relatively low and increasing voltages. Then as voltages are further increased, the overall capacitance would decrease to as low as ~ 3 µF or 30µC/10V as voltage approaches near ~10V. However, once capacitance saturation (C sat) is achieved, the contribution of the ferroelectric domains to K, and thus Q, become exhausted, and the dielectric begins to behave as a linear dielectric. This saturation results in a relatively lower K and thus a lower contribution to Q at test voltages above V sat of ~10V in this case, and capacitance will be further and significantly reduced. Any additional applied voltage will only serve to stretch the dipoles in a similar and typical manner as would be observed in a linear dielectric device such as a C0G or Film capacitor. Because of this, the dielectric constant (K) and dynamic capacitance (C*) would be lower than the specified value (~1 µF in this case). This can be an issue in decoupling applications. For instance, as the decoupling voltage reaches V sat, the actual capacitance may be significantly lower than the specified capacitance value such as the case illustrated in Figure 11 below where capacitance is ~1 µF at saturation versus the 10 µF specified capacitance.
The representative effect of AC measurement signal voltage upon measured capacitance is illustrated in Figure 12 below. As illustrated in the figure, the capacitance of the MLCC increases with increasing AC measurement voltage, then begins to decrease as saturation is approached, showing behavior analogous to that displayed in Figure 1.

Again, the effect of AC voltage can be significant, and a 10% or more decrease in capacitance may be anticipated for a high value X5R MLCC measured at 0.5V AC in comparison to a 1V AC measurement, while a measurement taken at ~0.25V AC may result in measured capacitance that is 20% or more less than the 1V AC measured capacitance. Thus, it is important to carefully consider AC voltage in your application, as well as any measurement voltages for device testing during your manufacturing process, such as “in circuit test” or ICT, into consideration when developing circuitry or circuit characterization tests.

**AC Test Voltage vs. Capacitance**

![Hysteresis curve for a 10µF ferroelectric dielectric as a function of AC test signal voltage.](image11.png)

**Figure 11.** Hysteresis curve for a 10µF ferroelectric dielectric as a function of AC test signal voltage.

**Figure 12.** Effect of AC measurement signal voltage upon measured capacitance at 120Hz.
Conclusion and Final Comments

In conclusion, it is very important to properly measure all capacitors using capable equipment at the right frequency and signal voltage as discussed above. It is important to know the capabilities and limitations of the specific LCR meter or tester you are using so that the tester can be appropriately utilized to correctly assess and determine the actual capacitance of any capacitor. Knowing the power output capabilities of LCR test equipment will also help you determine what limitations you may come across in determining if your tester has the ability to test a high value ceramic capacitor accurately and what possible corresponding actions can be taken to achieve accurate readings. The diversity of machines and LCR test equipment used throughout our industry makes this increasingly difficult.

Additionally, for MLCCs utilizing Class 2 dielectrics, it is important to consider the effects of temperature, aging time, DC bias and AC voltage upon the capacitance of the associated MLCC as it is not uncommon for the capacitance of Class 2 capacitors to change as much as 15% with changing temperature (typically ~7% under most circuit conditions), or as much as 5% or more over a year of aging without a de-aging heat treatment. Most manufacturer’s specifications for de-aging of Class 2 dielectric materials are T > 150°C for 30 minutes to one hour. Capacitance values can also change as much as 70% or more at DC bias levels that are at, or near, rated voltage, and can lose as much as 20% capacitance when measuring capacitance at 0.25VAC instead of 1VAC.

Knowing how a specific capacitor selection will perform and change in various environmental conditions is critically important in the overall performance of the circuit, so be sure to consult your supplier for the particular Class 2 MLCC of interest prior to designating MLCCs for use in your circuit. In many situations, these factors are not significant and the Class 2 MLCC is the best, low cost option for the application, but for applications requiring a more stable capacitor, Class 1 MLCCs or other should be considered for your circuit design.
Endnotes:

1. Agilent E4980A without option -001
2. Agilent E4980A with option 001 and the A.L.C function turned on.
3. See for example MIL-PRF-55365 or MIL-STD-202
6. EIA-198-1-F
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