Introduction

This paper explores how recent advances in ceramic material and package technologies have now increased the choices for a designer when selecting the best capacitor for by-passing, de-coupling, filtering, and non-critical timing circuitry. These technology improvements have made it possible to add more capacitance (1 µF & greater) into smaller case sizes (1210 down to 0402) while maintaining the largest possible operating voltage (6.3 up to 50 V), improving the electrical performance, and lowering the cost of MLCC Capacitors.

No longer is a designer restricted to SMT - Chip Aluminum Electrolytic ('wet' or 'solid-polymer') or Chip Tantalum ('solid-polymer' or 'low ESR'). The superior equivalent series resistance (ESR) and equivalent series inductance (ESL)/impedance and reliability of MLCCs can now be found in the higher capacitance values.

These improved MLCC mechanical and electrical attributes will enable you to make your electronic products smaller, with less weight, better electrical performance, and at a lower cost; thereby making your products more competitive.

Multi-Layer Ceramic Capacitor Basics

Equivalent Circuit Model of a MLC Capacitor

‘Ideal’ Capacitors have only a capacitance property and therefore have no power loss. ‘Real-world’ capacitors, on the other hand, have intrinsic resistive and inductive parasitic elements which cause power loss. These losses can be characterized by Equivalent Series Resistance (ESR), Equivalent Series Inductance (ESL). The nominal capacitance value is represented by the element (C) and its Insulation Resistance and inherent leakage current is represented by the element (Rp). Lower intrinsic losses result in a higher capacitor quality factor (Q), a higher Self-Resonance Frequency (SRF), less self-heating, and better performance more closely approaching an ideal capacitor.

The basic structure of a Multi-Layer Ceramic Chip (MLCC) Capacitor is comprised of two sets of inter-leaved electrodes. Each set of inter-leaved electrodes is connected to one end termination of the MLCC assembly. Each of those two sets of electrodes is terminated with a tin plated metallization.

Ceramic Material Technology Advances

The recent state-of-the-industry ceramic material technology advances for MLCC Capacitors include:

- Finer size ceramic grains (~0.5 µm)
- Thinner dielectric-sheets (~2.0 µm)
- Thinner inner-electrodes (~1.4 µm)
- And faster speed stacking processes

Larger Capacitance values are made possible by:

- Larger Dielectric Constant Values
- Increased number of layers
- Larger Electrode Areas
- Thinner layers of dielectric *
* Note: As the dielectric layer gets thinner, the Maximum Operating Voltage decreases.
making possible 800 layers, resulting in a 100 µF / 6.3 V / X5R MLCC Capacitor in 1210 Case Size!

**MLCC Metallization Technology Advances**

**Base Metal Electrodes (BME)**

Not only are advances in ceramic material technology important, but also is that of the choice of metal used for the electrode metallization. To cope with escalating costs, many suppliers have converted from palladium-based precious metal electrodes (PME), such as Palladium (Pd) or Silver Palladium (Ag-Pd) to that of nickel base metal electrodes (BME). This conversion is primarily applied to MLCCs with Class II dielectrics such as X5R, X7R, and Y5V and some Class I C0G (a.k.a. NPO) dielectrics which are not intended for high reliability applications.

**Ceramic Package Technology Advances**

**Lead-free Terminations & Solder Assembly to PCBs**

In accordance to the world-wide trend to reduce the quantity of lead within electronic products, these Large Capacitance Value MLCCs have lead-free end-terminations of plated Tin. Higher temperatures are usually needed for assembling/attaching components onto Printed Circuit Boards (PCBs) with lead-free solders. Compared with the Tin/Lead eutectic (63% Sn / 37% Pb, respectively) which has a maximum temperature of approximately 185°C, a lead-free solder may require a temperature as high as 250°C. There are no problems exposing MLCCs to this higher temperature as is the possible case with other technologies.

**Board-Area & Volumetric Efficiency**

MLLCs have a physical volumetric advantage over some other capacitor technology candidates. For example, refer to the following table:

<table>
<thead>
<tr>
<th>MLCC (0805)</th>
<th>Chip Tantalum Low ESR (A-size)</th>
<th>Polymer Al Lytic (‘solid’-type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µF, 6.3 V, X5R 2.0 x 1.25 x 1.25 mm (Reference Volume)</td>
<td>10 µF, 10 V 3.2 x 1.6 x 1.6 mm ~ 2.6 to 1</td>
<td>10 µF, 6.3 V 7.3 x 4.3 x 1.8mm ~ 18 to 1</td>
</tr>
</tbody>
</table>

**Low Height / Profile Case Sizes**

While MLCCs are commonly used in the standard EIA Case Sizes, they are also available in low-profile versions to fit your ‘tight’ clearance needs. For example, while the L x W x H of the standard 0805 (2012 metric) is 2.0 x 1.25 x 1.25 mm; a 0805 version having a height of only 0.85 mm is also available.

**Reverse-Geometry / Low Inductance (ESL) Type**

Reverse-geometry/width-width packages make it possible to reduce the equivalent series inductance by approximately a factor of two. The reverse-geometry construction accomplishes this by making the capacitor’s terminations physically wider, using what normally would be the length (L) dimension of a 0805 package as the terminations. (see below)

**MLCC Capacitor Application Notes**

‘Aging’ / ‘De-aging’ Behavior of Class II dielectric MLCCs

Please note that Class II type dielectric Ceramic Capacitors have a normal ‘aging’ behavior characteristic. That is, the capacitance value of the capacitor decreases with time from its value when the capacitor was first manufactured.

From that date, the capacitance value begins to decrease at a logarithmic rate defined by:

\[ C_t = C_{48} (1 - k \log_{10} t) \]

where:

- \( C_t = \) Capacitance Value, t hours after the start of ‘aging’
- \( C_{48} = \) Capacitance Value, 48 hours after its manufacture
- \( k = \) aging constant (capacitance decrease per decade-hour)
- \( t = \) time, in hours, from the start of ‘aging’

The capacitance value is typically guaranteed by suppliers for up to \( t = 1000 \) hours after being manufactured.

**Piezo-electric Effect Considerations**

The base structure of the ceramic dielectrics are crystalline in nature. Mechanical shock or vibration through the PCB can induce noise into the electronic circuitry via the MLCC. Mechanical displacement can also be triggered by sharply rising voltages which can create a ‘ringing’ or ‘oscillatory noise’ signals onto the line. Therefore, due to these potential piezoelectric effects, take note when using MLCCs in higher voltage audio or lower frequency applications.

**Assembly Considerations**

Try to eliminate board flex as much as possible since it can cause mechanical strain on the MLCCs potentially causing a crack, and with the incursion of moisture, could result in a ‘short’ as its subsequent failure mode. A prudent design practice is to place MLCCs as close to the edge of the PCB as possible to minimize the stress being applied to them.

**Handling Considerations**

The non-polarized electrodes of MLCCs make for worry-free handling and for easier assembly onto Printed Circuit Boards. Electrolytic capacitor technologies, on the other hand, have a polarity. Therefore, reverse-attachment, even temporarily, can result in instant failure of the capacitor, degradation of its lifetime, or worst yet, a latent failure in the field.
Operating Voltage - De-rating

Ceramic Capacitors do not have to be de-rated as do Chip Tantalum Capacitors, either the low ESR or polymer types. The suggested de-rating of the polymer type is 80% while the de-rating of the low-ESR type can require between 30 – 70%.

Comparison of Capacitance Value vs. Applied DC Voltage

The capacitance change versus applied bias voltage is another consideration when choosing the capacitor technology. The following graph shows the relative capacitance change as a function of the representative dielectric material types, Class I type (C0G) and Class II types (X5R / X7R & Y5V).

From the Class II types X5R / X7R, 1 µF, 6.3, 10, 16, 25, & 50 V shown below, it can be noted that the larger case sizes have less capacitance change versus the applied DC voltage. This is due to thinner layers and higher dielectric materials.

Capacitance Value Change versus DC Bias Voltage
1 µF in various Case Sizes / Voltage Ratings

Comparison of ESR versus Case Size

As seen below with this example of a 1 µF capacitance value, larger case sizes also have the advantage having less ESR.
MLCC Performance Characteristics versus Chip Tantalum and other Capacitor Technologies

The table below is a guide of the main considerations when determining the most appropriate capacitor for your application.

<table>
<thead>
<tr>
<th>Capacitor Type</th>
<th>MLCC (X5R, X7R)</th>
<th>Tantalum (Low ESR)</th>
<th>Tantalum (Polymer)</th>
<th>Aluminum Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage</td>
<td>6.3 - 50 V</td>
<td>4 - 35 V</td>
<td>2 - 20 V</td>
<td>2 - 16 V</td>
</tr>
<tr>
<td>Voltage De-Rating</td>
<td>100%</td>
<td>30 - 70 %</td>
<td>80%</td>
<td>100%</td>
</tr>
<tr>
<td>Capacitance Value (max)</td>
<td>220 µF</td>
<td>330 µF</td>
<td>1,000 µF</td>
<td>470 µF</td>
</tr>
<tr>
<td>ESR / Impedance (Z)</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>ESL (Equivalent Series Inductance)</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Capacitance vs Frequency</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Capacitance vs Temperature</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Capacitance vs DC Bias</td>
<td>Fair</td>
<td>Excellent</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Ripple Current / Self-Heating</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Special Handling due to Polarity</td>
<td>None</td>
<td>Has Polarity</td>
<td>Has Polarity</td>
<td>Has Polarity</td>
</tr>
<tr>
<td>Safety Performance</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
</tr>
<tr>
<td>Volumetric Efficiency</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Cost</td>
<td>Excellent</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

As you may note from above, MLCCs offer many advantages over that of capacitors of other technologies.

Of those many advantages, MLCCs have a distinct electrical performance advantages when it comes to lower ESR, ESL, and Impedance (Z), especially at the higher frequencies.

MLCC capacitors are one of the main alternatives to that of chip tantalum capacitor technology. The following graphs illustrate the performance advantage of MLCC capacitors.

MLCCs have lower Equivalent Series Resistance (ESR)

MLCCs have lower Impedance (Z)

MLCCs have less temperature rise due to Ripple Current

When used in ‘smoothing’ circuit applications, MLCCs offer significant advantages over Tantalum Capacitors. Reduced ESR results in lower component operating temperature than other capacitor solutions making it and your product more reliable.

MLCCs have lower Equivalent Series Inductance (ESL)

Improved ESL, especially at higher frequencies, reduces the harmonic content of ripple current and high frequency noise.

It is suggested to carefully review the above parameters when evaluating the candidates for your power supply design.

The following information focuses upon how these electrical performance characteristics relate to relate to the applications.
Applications of MLCCs

Of the various capacitor technologies, ceramic capacitors have the dominant usage, approximately 80%. Of the single-layer (primarily for the higher voltages) and multi-layer ceramic capacitors, the majority usage is of multi-layer construction.

The ubiquitous MLCCs are found in all types of electronic products. Those products include Communications (Telecom & Datacom), Computers & Peripherals, and Industrial types.

Computer & Peripheral Products

The need for lower ESR & ESL continues to increase in high-frequency, lower working-voltage, and higher current applications. This is occurring in the computer marketplace, especially with its higher clock speeds of 3 GHz and higher. They are also for Laptop & Tablet Personal Computers, PCs, PDAs, Hard Disk Drives, Electronic Games, and MP3 Audio Players.

Examples of applicable MLCCs are: 6.3 V / 2.2 µF or 2.2 µF in 0805 Case Sizes. Others include: 6.3 V / 22 µF or 4.7 µF in a 0603 Case Size. Examples of applicable MLCCs are: 6.3 V / 2.2 µF or 2.2 µF in a 0805 Case Size. Others include: 6.3 V / 22 µF or 2.2 µF in a 0603 Case Size or 6.3 V / 47 or 100 µF in a 1210 Case Size.

Communication Products

The small / low profile parts are especially suited for handheld / mobile communication (voice & data) products such as Wireless Accessories (WLAN / Bluetooth).

Examples of applicable MLCCs are: 6.3 V / 1 µF in 0402 Case Size. Others include: 6.3 V / 4.7 µF in a 0603 Case Size or 6.3 V / 10 µF in a 0805 Case Size having height of 0.95 mm max or an array comprised of two 1 µF capacitors in a 0405 Case Size package.

Industrial Products: DC to DC Converter Example

MLCCs offer lower Impedance and ESR needed for the 100–500 KHz frequencies of today’s Switch Mode Power Supplies such as DC to DC Converters. The performance advantage is so great that lower capacitance values provide better decoupling than higher values in other dielectrics.

Ideal Application for Large Capacitance Value MLCCs

Visually, the following chart illustrates the present and future capacitance values available (X5R unless otherwise noted) and the suitability of these for the various Switch-Mode Power Supply applications requiring: Large or Small Capacitance, ESR Values, and Rated Voltages

A candidate for the input capacitor of a typical DC to DC Converter might be 50 V / 1 µF in 1210 Case Size while the output capacitors might be 6.3 V 22 / 47 / or 100 µF in either a 1210 or 1206 Case Size.

Regarding ESR, it is prudent to account that the impedance at 100 Hz may be from 10 to 1,000 times higher than that at 100 KHz. The ESR also changes from component to component, as well as increases with temperature.

The ESL of a MLCC capacitor does not effect its impedance until over its Self Resonant Frequency (SRF), usually beyond 1 MHz and higher. Please take into account that the ESL parasitic increases with temperature.

The Future of Multi-Layer Ceramic Capacitors

As you have seen, advances in ceramic material and package technology has allowed the development of more and more capacitance within a given package size.

As a result, the chart below lists the presently available and planned Values, Case Sizes, Rated Voltages from one of the major suppliers of MLCC Capacitors.

Look for larger capacitance values becoming available as ceramic technology improves.

Two major application trends effecting electronic circuitry are continuing. One of the trends is a reduction of Operating Voltages (down from 15, 12, 5, 3.3, 2.5, 1.0, 0.8, and lower) with accompanying higher currents. Another trend is a reduction in product size.

The component size reduction with regard to MLCC components is happening in two major ways. As seen, one way is that individual larger capacitance values are being put into a given package size. Another way is the development of a higher degree of integration by putting two or four large capacitance values (array) into a single package to increase its placement density and efficiency.

Ceramic technology is ideally poised to take advantage of these trends as well as that of Integrated Passives, MLCC + other components within a package, and Integral Passives, MLCCs + embedded components within a ceramic substrate.