Not Your Grandfather's Capacitors: MLCCs Aren't What They Used To Be

There comes a time, when a familiar, everyday product accumulates a series of performance improvements and design modifications, that we suddenly recognize the need to look at it in a whole new way. Such is the case with one of the industry's most widely used passive devices: the multilayer ceramic capacitor (MLCC).

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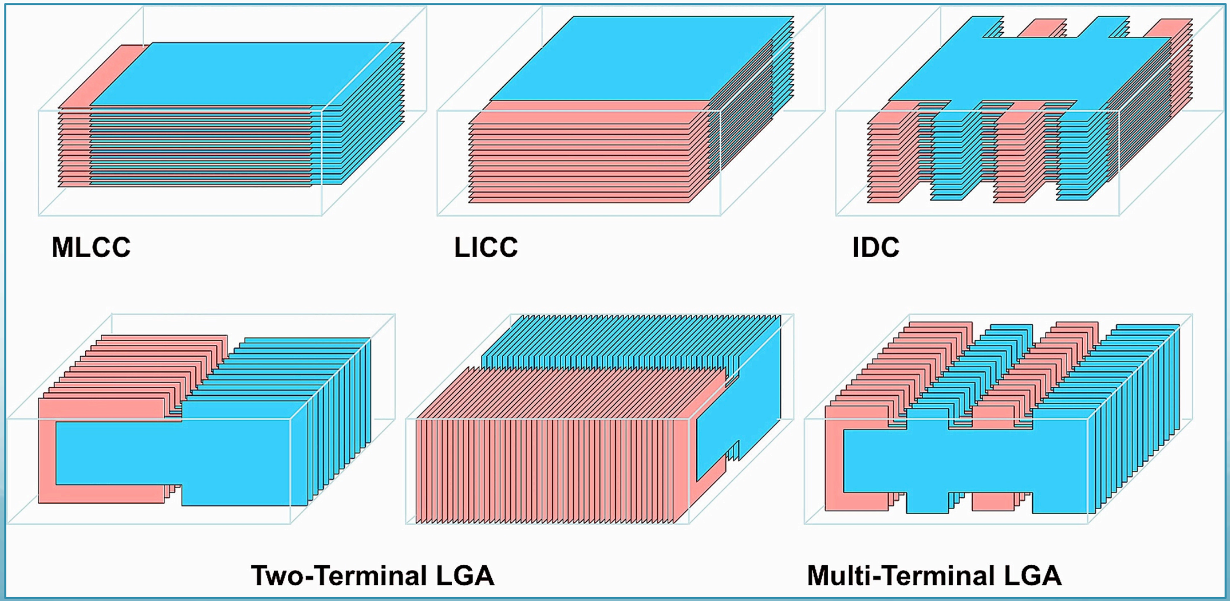
For decades, MLCCs have experienced incremental progress regarding their materials, design, and manufacturing methods. As such, material purity has improved, capacitor K factor (dielectric constant) has increased, and more exacting manufacturing methods have evolved to enable an increase in the number of electrode/dielectric pairs. The combination of these factors has resulted in smaller, higher reliability capacitors with enhanced electrical specifications that deliver improved electrical performance in an extended range of applications, following the general path of circuit evolution.

However, at some point along this evolutionary path, device designers realized that additional modifications could optimize MLCCs to the point that they could have a significant impact on the overall electrical performance of the end circuit or system. As a result, an increasing number of designs now have capacitors as a primary driver of circuit performance.

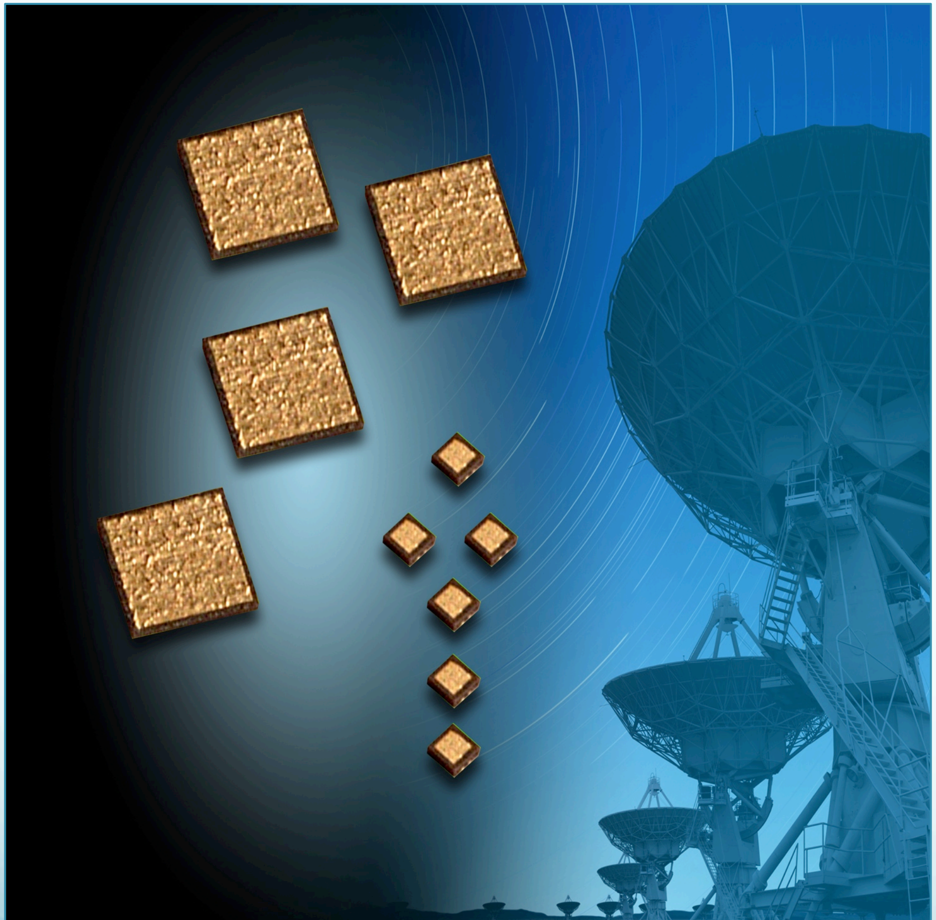


MLCC Evolution: Material Advancements

Material advancements in the dielectrics, electrodes, and terminations have enabled:

- Extremely high value capacitors resulting from K factor increases
- Ultra-low-loss RF capacitors that operate across a wider RF spectrum
- High temperature capacitors capable of >200°C operation
- Capacitors that can withstand both bending and higher coefficient of thermal expansion differences without failure

High Capacitance Values



In the early 1990s, manufacturers' efforts to improve capacitance values began to pay off, and significant improvements were made to improve the K factor of traditional dielectrics like X7R, Z5U, and Y5V. In parallel, proprietary dielectrics based on SrTiO3 emerged with K factors in the 20,000 to 30,000 range and ±15% capacitance stability from -55°C to +125°C.

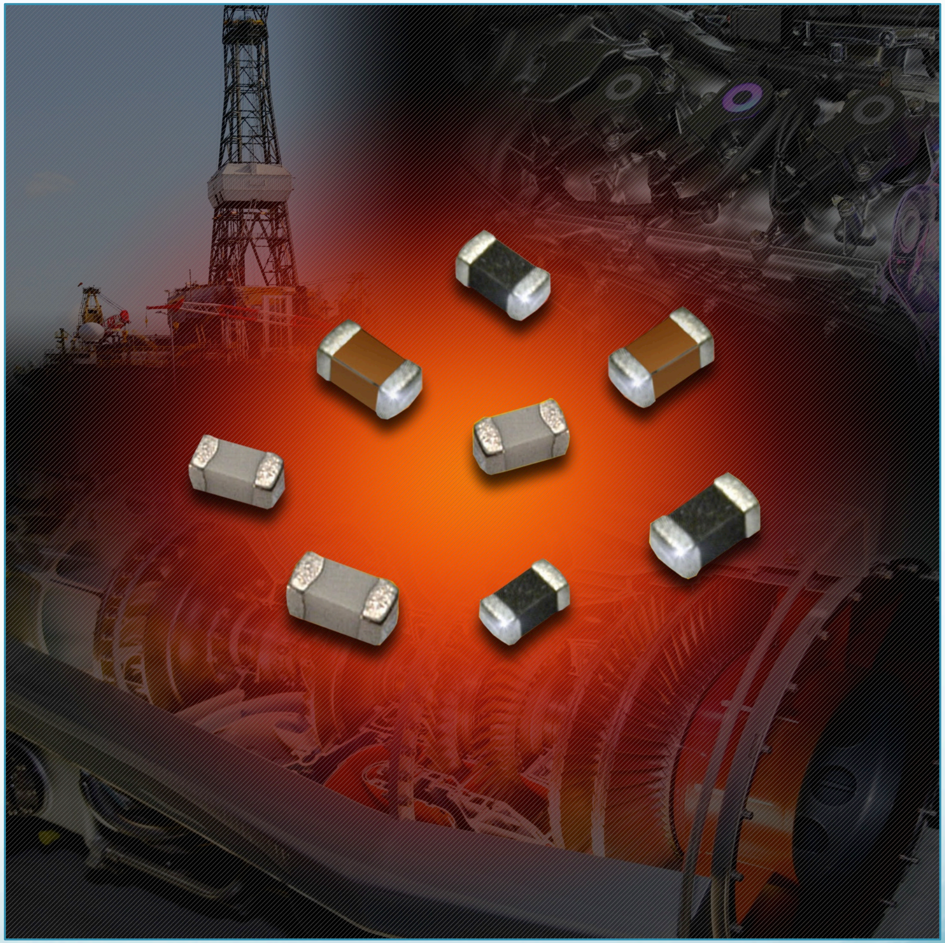
Several variations of these new high-K materials were used to develop small, high capacitance, low-loss MLCCs that are capable of enabling better DC isolation in between stages, as well as higher voltage quality, and are ideally suited for use in extreme frequency applications, like DC Blocking and power line decoupling, and hybrid circuit applications, including power amplifiers, receivers, and filters.

Ultra-Low-Loss Capacitors

U-dielectric MLCCs, another proprietary design, are C0G (NP0) chip capacitors developed over a decade ago using an optimized combination of electrodes, dielectric materials, and processing methods to satisfy application demands for improved performance over traditional NP0 capacitors. Especially designed for ultra-low ESR applications in the communications market, U- dielectric MLCCs feature a hardened/ conservative design, low loss, and AEC-Q200 performance capabilities that makes them ideal for automotive RF applications, like Bluetooth links. If your car's audio system connects to your phone, chances are that you are the proud owner of a U-dielectric MLCC. Similarly, U-dielectric capacitors are poised to prove quite useful in the continued proliferation of new IoT designs due to the system impacts of low-loss RF capacitors. High-performance capacitors like these improve the efficiency of RF designs, enabling better reception, wider range, lower power requirements, and extended battery life.

High Temperature Capacitors

In recent years, new materials developments have enabled capacitors capable of stable operation across a much wider temperature range than previous generations of capacitors. Currently, three temperature ranges have emerged as the basic building blocks for designers: -55°C to + 150°C, -55°C to + 200°C, and -55°C to + 250°C.

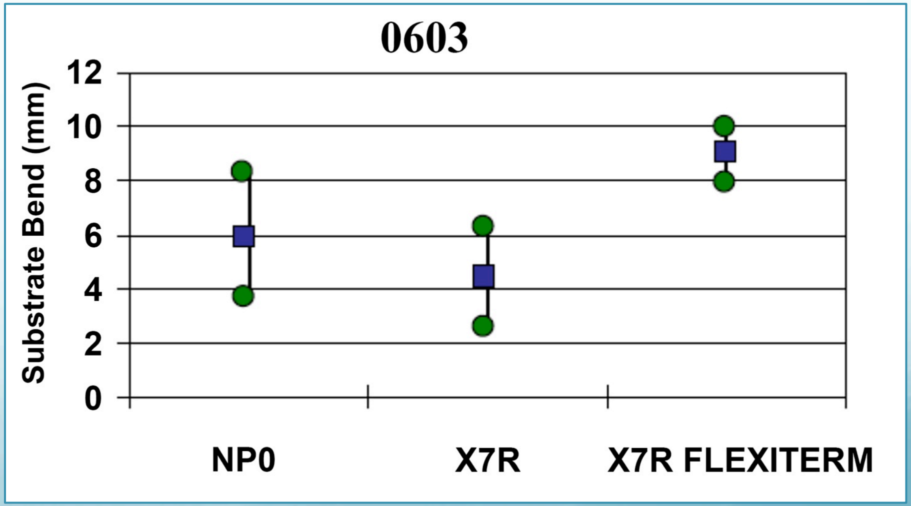


High temperature MLCCs have been available for some time, but early iterations exhibited relatively high losses and only low to moderate stability when operating at or near the upper limit of their temperature range. Now made with high purity ceramic dielectrics that were especially formulated to increase capacitance values, maintain or improve capacitance stability across temperature and voltage bias, improve signal-to-noise ratios, and reduce power demands in high-temperature circuits, these capacitors can currently operate at temperatures up to 250°C, but even higher ratings are expected to be released to market in the near future.

Flexible Terminations

In the late 1990s, there was high market demand for MLCCs that could withstand harsh environment scenarios, ranging from manufacturing to end-use applications like automotive and avionics, without increasing instability or ESR, or diminishing reliability or long lifetime performance capabilities. In response, manufacturers quickly capitalized on material advances in conductive epoxy terminations and processing to yield an MLCC termination design that acted like a shock absorber. This enabling technology featured conductive epoxy under the final termination finish that could expand or compress as needed to alleviate stress concentrations encountered throughout the capacitor's intended lifetime much more effectively than previous generations of rigid termination capacitors could.

Designed to enhance the mechanical flexure and temperature cycling performance of MLCCs, FLEXITERM® layer technology — the first of these technologies introduced to market, introduced by AVX — provides up to 5mm of flexure without internal cracking, effectively protecting ceramic components from damage resulting from mechanical stress during PCB assembly or end-customer use. This is especially beneficial since mechanical damage resulting from board flexure accounts for a vast majority of MLCC failure, and increasing temperature cycling performance to 3,000+ cycles.



This graph depicts different dielectrics' flexure capability compared to an 0603 X7R FLEXITERM MLCC

MLCC Evolution: Manufacturing Advancements

Manufacturing advancements in stacking thickness and accuracy, terminations, and testing have enabled capacitors that are:

- So small that they can be considered inhalation hazards
- So thin that they can be embedded inside a PCB or an integrated circuit package
- So rugged, in terms of transient immunity, that they can withstand tens of kilovolts of electrostatic discharge (ESD) without damage

Ultraminiature Capacitors

There are two primary drivers that prompt component manufacturers to consistently push the boundaries of device design to make smaller form factors, the most apparent of which is to enable the ever smaller and lighter end-electronics that the market demands. However, designers also play a role in driving the continual demand for smaller MLCCs due to their desire for less parasitic loss and the ability to put capacitors in close proximity to the IC/ load for more ideal performance, both of which can be achieved with smaller case size MLCCs. Most recently, industry efforts have resulted in 01005 capacitors, which measure an almost unbelievably slight 0.4mm by 0.2mm (0.016" by 0.08"), and enable extremely dense modules and enhanced mobile consumer electronic devices.

Ultrathin Capacitors

Recent manufacturing advancements have also led to the realization of capacitors with height profiles that are so thin they can be mounted inside of — rather than on the surface of — a PCB, providing design engineers with significantly more space for the IC and other passive and active components. Ultrathin MLCCs are utilized under IC packages to provide efficient decoupling in the smallest board size possible, and are also widely employed in high-end patient monitoring systems and ultraminiature security tagged devices, like some banking cards, due to the PCB surface savings they provide.

Rugged, ESD-Resistant Capacitors

Designed and developed for general protection against electrostatic discharge (ESD), ESD-resistant MLCCs have been evolving for the better part of a decade, and typically feature a small footprint to accommodate high-density electronics. These MLCCs are most commonly used to protect I/O lines, and are used on nearly every low-priority pin of automotive modules to provide critical protection against ESD strikes by averaging the module's voltage with the voltage that the wiring harness can be charged to.

ESD-resistant capacitors also tend to feature a broad range of capacitance values for enhanced protection. Lower capacitance ESD-resistant MLCCs don't offer the same level of protection as those with higher capacitance values do, but do exhibit less signal distortion. As such, the selection of ESD-resistant MLCC capacitance values is a trade-off between signal distortion and the level of protection an application demands.

Further, in addition to ESD protection, these MLCCs can also exhibit an EMI filtering function, which can help enable smaller, more densely populated electronics by negating the need for separate filtering components and either freeing up board space or shrinking the size of the PCB.

MLCC Evolution: Design Advancements

In addition to material and manufacturing advancements, the proliferation of in-house and commercially available software that allows engineers to create 3-D renderings, model electromagnetic and thermal performance, and even estimate reliability data has significantly contributed to MLCC design improvements. These advanced design capabilities have enabled capacitors that:

- Have terminations so dense that they can become the carrier for ICs
- Have inductors and capacitors integrated inside the MLCC case
- Have multiple capacitors placed in series within a single capacitor case

High-Density Termination Capacitors

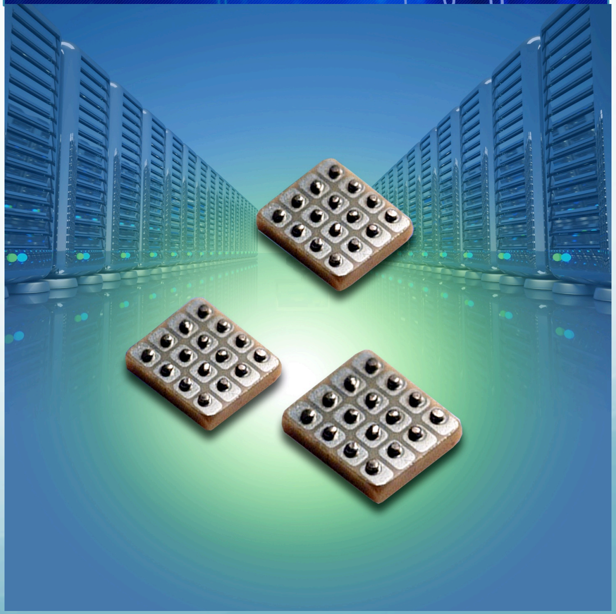
Like many MLCC innovations, two of the most effective examples of high-density termination capacitors are based on proprietary technologies: the fine copper technology (FCT) technique and low inductance capacitor arrays (LICA).

The FCT technique was developed to overcome issues concerning termination thicknesses and their variations by enabling the creation an extremely thin and flat termination layer. The average thickness of FCT is 8.3 μm with a standard deviation 0.5 μm, which is a significant improvement over the 17 μm ±1.95 μm that can be achieved using conventional processes on standard SMD MLCC capacitors.

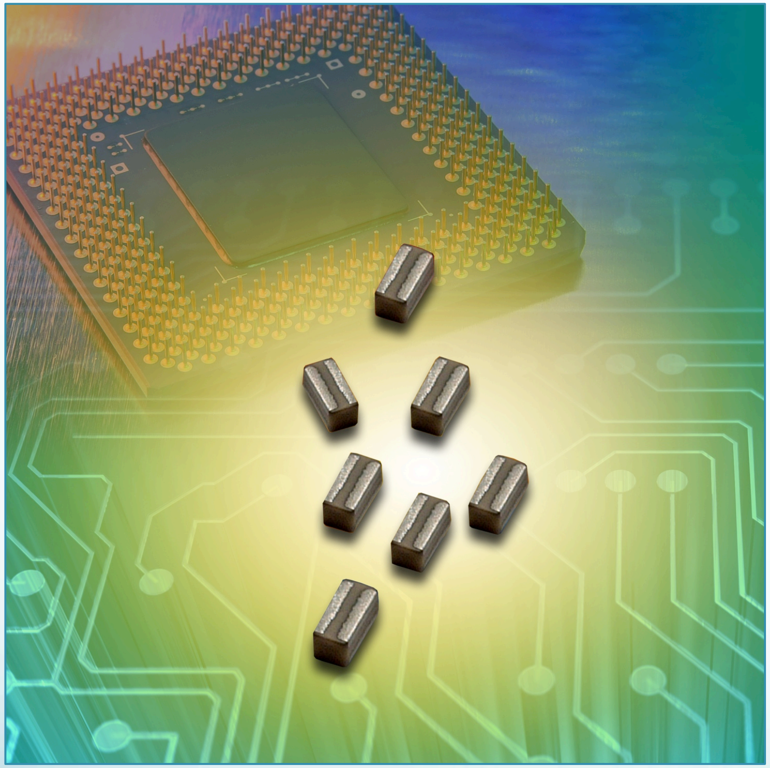
LICA® arrays utilize up to four separate capacitor sections in one ceramic body to achieve several technical advancements, the foremost of which is low inductance achieved through a combination of low-resistance platinum electrodes in a low aspect ratio pattern, double electrode pickup and perpendicular current paths, and C4 “flip-chip” technology for minimal interconnect inductance. In these devices, the charging current flowing out of the positive plate returns in the opposite direction along adjacent negative plates to minimize mutual inductance.

The short aspect ratio of LICA electrodes, the arrangement of their tabs, and the vertical orientation of their electrodes to the mounting surface are all critical to the MLCCs ability to reliably ensure such low inductance.

High-density termination count capacitors like FCT and LICA devices are widely used in computer applications to both dramatically reduce the inductance of the decoupling capacitor and to optimize power quality, emissions, and reliability by designing several capacitors into a single ceramic package that then connected to key IC power and ground pins.



Low Inductance Capacitors



The key physical characteristic that determines a capacitor's equivalent series inductance (ESL) is the size of the current loop it creates. The smaller the current loop, the lower the ESL.

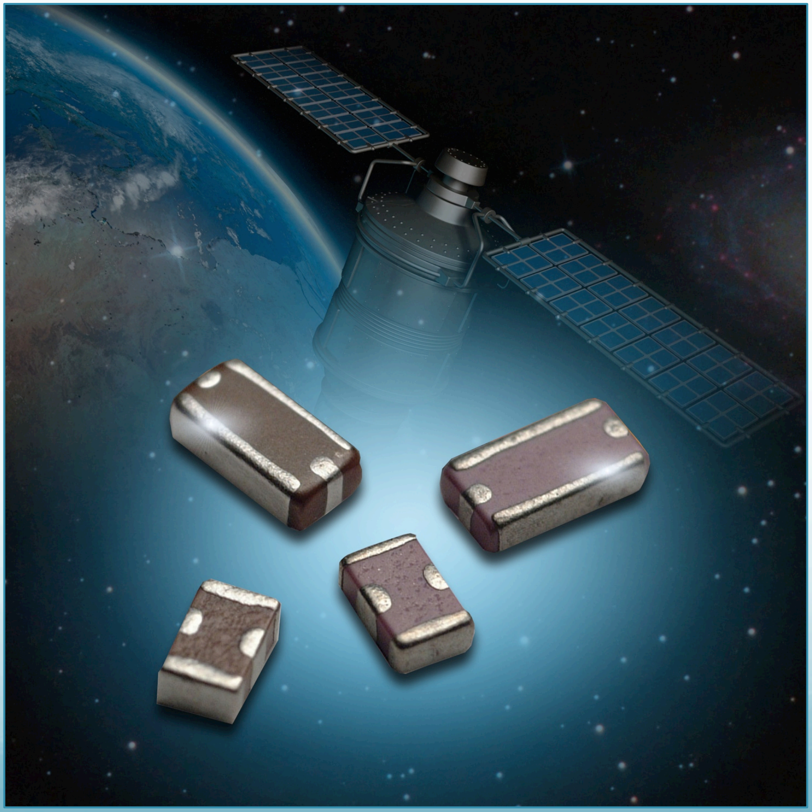
Capacitor manufacturers solve this inductance problem by creating designs that control the parasitic losses within the capacitor and its connection path. Low inductance chip capacitors (or reverse geometry capacitors) are created by terminating on the longer sides of their rectangular shape, rather than on the shorter sides, like standard surface mount MLCCs. This reversal reduces the distance between terminations and, as such, the size of the current loop.

For example, since the size of the current loop is the primary driver of inductance, a 0306 MLCC with a smaller current loop will have a significantly lower ESL then a standard 0603. The reduction in ESL varies by EIA size; however, low inductance chip capacitors typically reduce ESL by 60% or more compared to a standard MLCC.

Low inductance chip capacitors were first introduced to the market in the early 1990s, and have since become fairly prevalent, largely due to the fact that they integrate the low inductance values required for advanced processor applications, spanning avionic FPGAs all the way to automotive ECUs.

Multi-Device MLCCs

Process improvements in MLCC manufacturing have also enabled the development of entirely new families of components, including broadband LCT-configured EMI filters. Now that electrode screening has become so accurate, complex inductors can be created and laced in unique configurations along with capacitors to create a T filter, which effectively reduces parasitic losses to near zero since the inductor and capacitor occupy virtually the same space. Incorporating a wideband EMI filter function into these feedthrough filters allows designers to replace discrete LCT filter circuits in fly-by-wire drive and joystick applications, which range from spacecraft to automobiles and construction equipment, with a device that is 75% smaller and 60% lighter.



Summary

Over the past 20 years, significant advancements in MLCC materials, manufacturing methods, and designs have led to the development of whole new classes of capacitors with capabilities well beyond anything that even engineers would have imagined a generation or two ago.

Delivering benefits including: simplified board design, enhanced reliability, extended operating temperatures, and improved signal-to-noise ratios, amongst several others, these new capacitors are often the primary drivers of circuit performance in a system, and are frequently responsible for enabling size, performance, and reliability specifications that were once thought impossible to achieve.

Further, several of the innovations that have been incorporated to advance MLCC technology can be extended to other types of capacitors. In fact, these and other materials, process, and design innovations of the same magnitude are already being incorporated in new tantalum, film, thin film, double-layer super capacitors, and more.