High-Frequency Capacitor Performance of Novel Embedded Electrode Design

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ABSTRACT

High-frequency electronic systems demand capacitors that provide low inductance, high capacitance density, and robust stability across frequency, temperature, and voltage. This paper evaluates a novel capacitor architecture using an embedded electrode structure. Test results up to 67 GHz demonstrate improvements in impedance matching, decoupling, and filtering applications. This study compares the embedded design with conventional capacitors including MLCCs and SLCs, emphasizing reductions in ESR and ESL.

INTRODUCTION

Modern applications in 5G, radar, autonomous vehicles, and high-performance computing are pushing capacitors to meet increasingly stringent frequency and performance requirements. In these systems, capacitors serve vital roles such as:

- Filtering: Eliminating unwanted noise and spurious signals.
- Decoupling: Providing a stable power supply by suppressing voltage fluctuations due to transient currents.
- Signal Coupling and DC Blocking: Allowing AC signals to pass between circuit stages while blocking DC.
- Impedance Matching: Optimizing signal transfer between circuit stages by minimizing reflections.

Conventional capacitor technologies often struggle to meet these requirements due to parasitic elements. This paper investigates the electrical performance of an embedded electrode capacitor with coplanar terminals and single-layer construction that aims to address those limitations.

LIMITATIONS OF CONVENTIONAL TECHNOLOGIES

Single-Layer Capacitors (SLCs) offer low ESR and high SRF but are limited in capacitance and mechanical robustness. MLCCs provide higher capacitance but at the cost of increased ESR, reduced SRF, and susceptibility to failure under mechanical stress or temperature cycling. More advanced options such as broadband blocking and X2Y capacitors also face trade-offs in complexity, cost, or parasitic performance.

These limitations lead to degraded performance in signal processing, power delivery, and high-speed computing, and exacerbates issues related to the extremely fast transient current demands of modern AI processors. At high frequencies, parasitic inductance can cause these capacitors to act more like inductors, further degrading performance.

INNOVATIVE CAPACITOR DESIGN

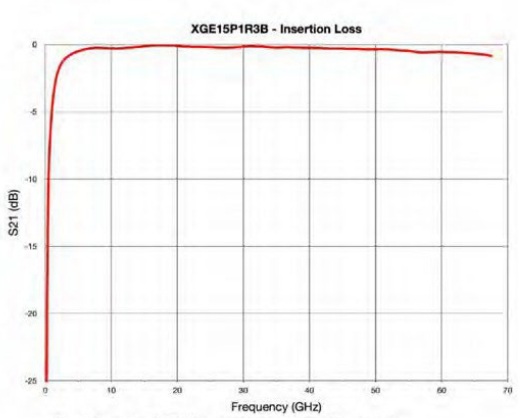
The capacitor evaluated in this study features a coplanar electrode design with one electrode partially embedded within the dielectric as follows:

2-Terminal [XG2] Configuration

- Embedded Electrode and Close Proximity: While the electrodes are coplanar externally, one of the electrodes is partially embedded within the dielectric material, positioned in close proximity to the other electrode. This arrangement reduces the spacing between the electrodes, minimizing the effective dielectric thickness leading to an increase in capacitance, reduced parasitics and overall low ESR and ESL due to the via-free integration mechanism.
- Single-Layer Construction: Unlike MLCCs with their stacked layers, this design emulates a true single- layer construction, minimizing resistive losses and enhancing high-frequency performance.
- Elimination of Wire Bonds and Vias: The coplanar electrode design eliminates wire bonds and obviates the need for vias – the primary sources of parasitic inductance and mechanical vulnerability.

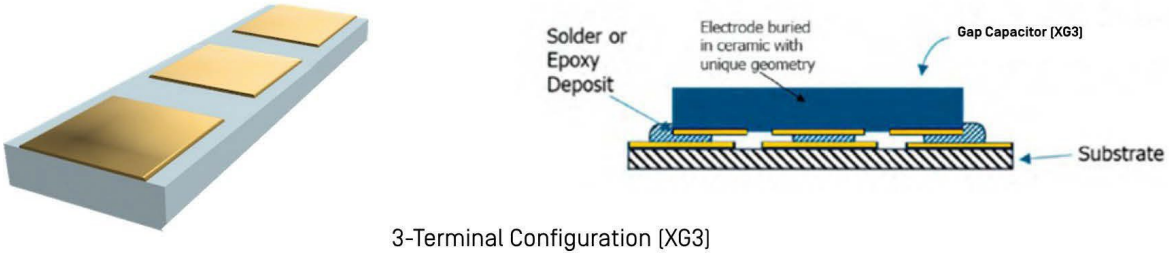
The design of this 2-terminal configuration offers the following performance advantages:

- Reduced Inductance: By eliminating wire bonds and minimizing the distance between electrodes, the 2- terminal capacitor reduces parasitic inductance, resulting in a higher SRF and improved impedance characteristics.
- Increased Capacitance Density: The design enables an order of magnitude higher capacitance density compared to traditional SLCs.
- Enhanced Reliability: The absence of wire bonds eliminates a point of failure, making the capacitor . less susceptible to mechanical stress, vibration, and temperature cycling.
- Extended Frequency Performance: The 2-terminal variant demonstrates extended frequency performance beyond 67 GHz. Measurements of insertion loss and impedance stability were conducted using standard microstrip test structures.



Test data to 67GHz supplied by X-Microwave.

The 3-terminal design features dedicated ground terminals that directly connect to the PCB ground plane, minimizing the current loop area and further reducing parasitic inductance.



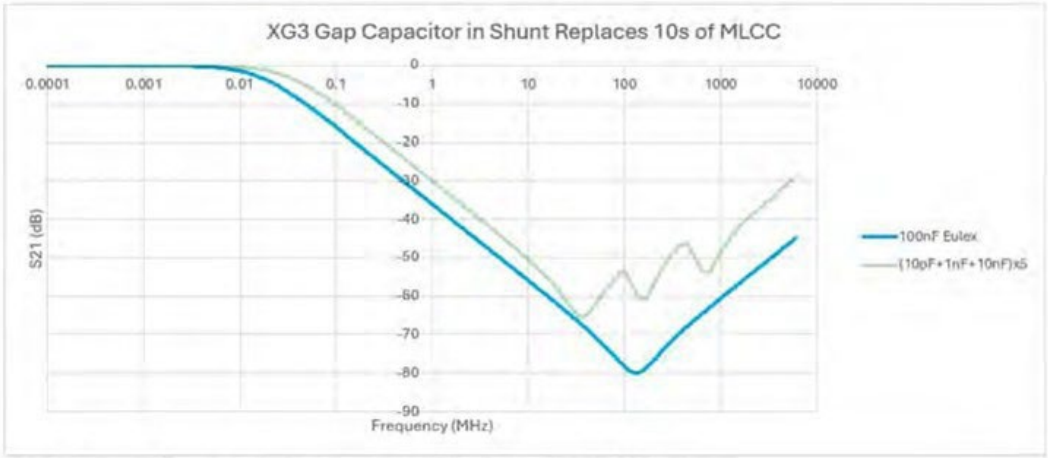
3-Terminal Configuration (XG3)

Improved Signal Integrity: The low inductance of the 3-Terminal design improves signal integrity, reducing reflections and minimizing noise.

Enhanced Stability Under DC Bias: The 3-Terminal design maintains its capacitance value consistently under DC bias compared to some MLCCs.

Key Advantages of the 3-Terminal:

- Extremely low ESL (typically <15pH)
- Low ESR enables high power handling
- Large capacitance achievable in reasonable size
- Broadband performance from kHz to 10s of GHz
- For DC Bias line filtering/EMI filtering
- Can replace 10s of MLCC with a single component



XG3 Series Equivalent Circuit (XG3A1809Y104MGW)

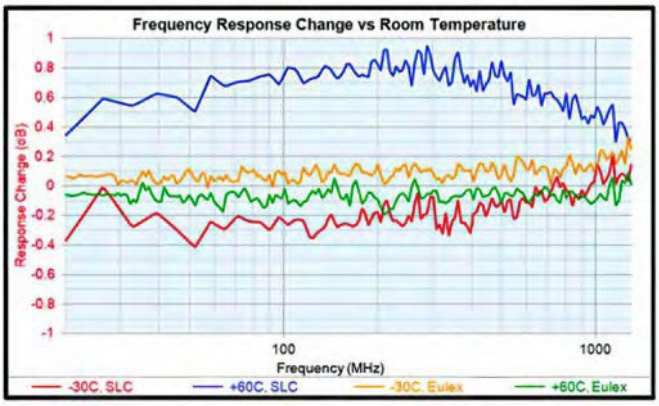
TESTING AND VALIDATION

Bird Technologies Testing

Bird conducted testing on the 3-Terminal design within a Grounded Coplanar Waveguide (GCPW) design. The GCPW, a common transmission line structure in high-frequency circuits, provided a controlled environment to evaluate the capacitor's performance as a shunt component. The testing focused on characterizing the insertion loss and stability of the capacitor over a wide frequency range and under varying temperature conditions.

"*The [3-Terminal design] is our answer to a 5-year search for a better capacitor that has Class 1 stability, high capacitance and great frequency response, allowing us to better meet our specifications over time and temperature.*"

Martin Dummermuth, Chief Technologist, Bird Technologies



Key outcomes from Bird's Testing:

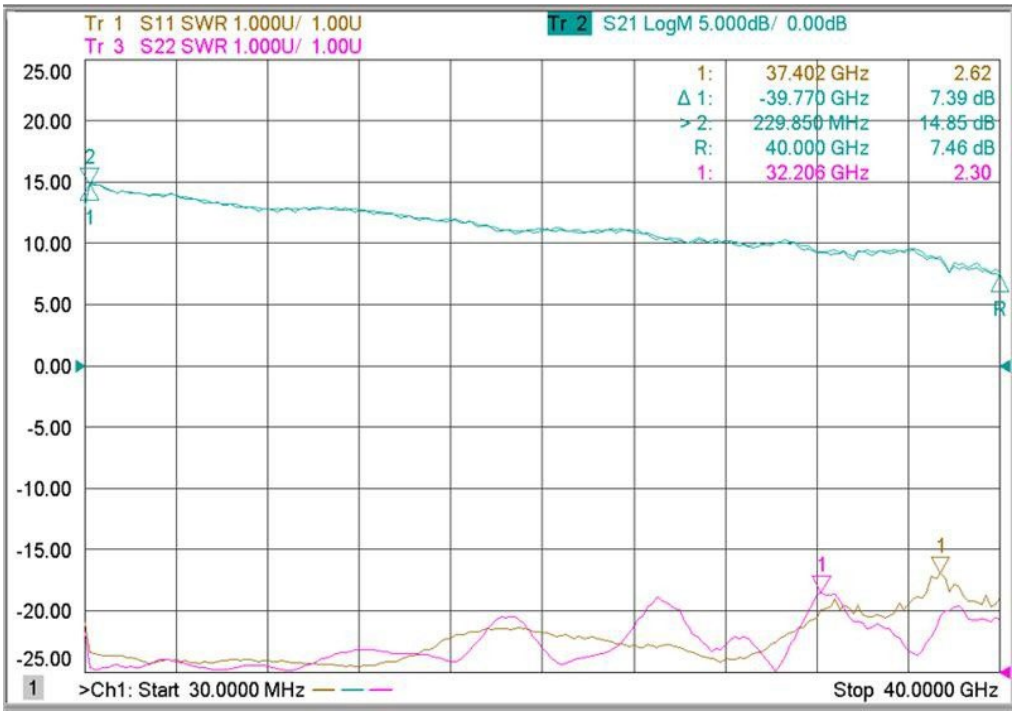
- The 3-Terminal exhibited exceptional performance, especially at lower frequencies, where traditional capacitors often struggle due to increased impedance.
- The 3-Terminal also showed remarkably stable performance over a wide temperature range, outperforming a standard single layer capacitor in the same GCPW configuration.

PMI Testing

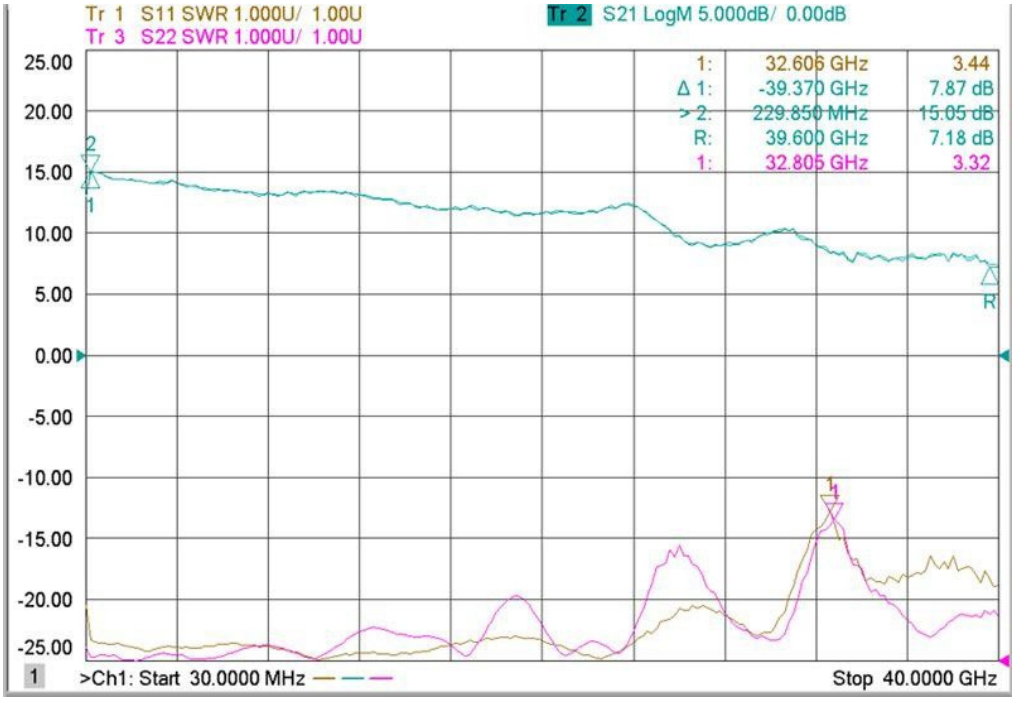
PMI tested the 3-Terminal design in a Low Noise Amplifier (LNA). By replacing one (1) single layer capacitor (SLC) with one (1) 3-Terminal Capacitor in PMI's PE2-12-30M40G-5R5-18-12-292FF LNA, the test yielded the following significant performance improvements.

- Reduced Voltage Standing Wave Ratio (VSWR) from 3.3:1 to 2.3:1, indicating a better impedance match and reduced signal reflection.
- Improved gain ripple from +/-2dB to +/-0.5dB, demonstrating a more consistent gain performance across the frequency band.

3-Terminal



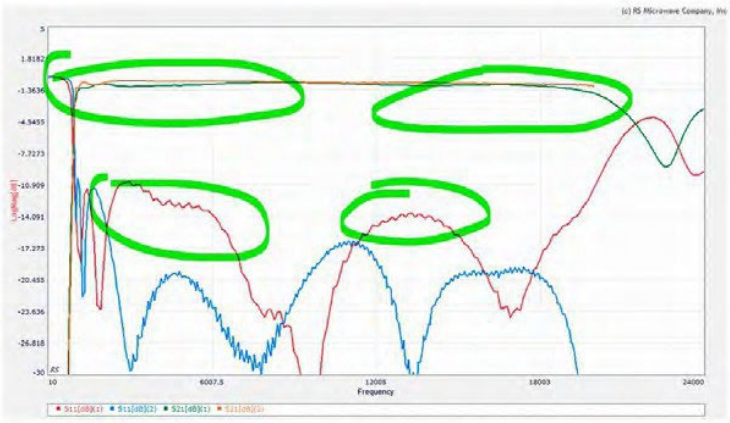
SLC



SLC Results: S-Parameters show the wire-bonded and tuned circuit has +/-2dB ripple.

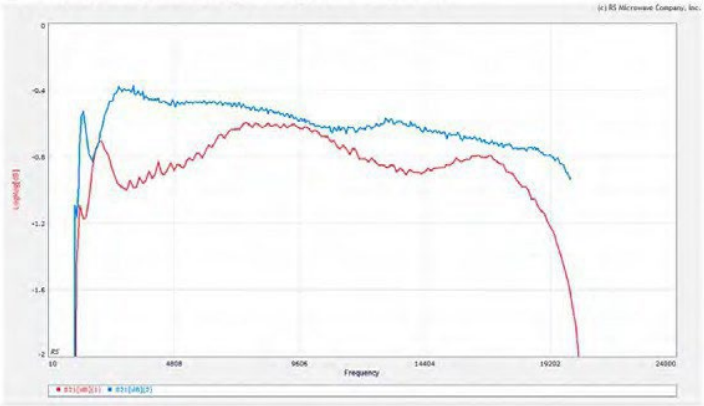
PMI further tested the 3-Terminal design in a High Pass Filter. By replacing one (1) single layer capacitor (SLC) with one (1) 3-Terminal Capacitor in PMI's HP-118-CD- SFF, twith the following outcomes:

- Improved return loss from 11dB (typical) to 20dB (typical).
- Improved insertion loss (approximately 0.4 dB improvement up to 18GHz and 1dB at 20GHz.
- Lower coupling loss at the cutoff frequency (fc); that is, the cutoff angle closest to 90 degrees.
- Maintained performance up to 20 GHz, enabling a broader frequency range without self- resonance.
- Increased power handling capability from 1W to 50W. Note: While this improvement included an inductor upgrade, the 3-Terminal Capacitor was a key enabler for achieving this higher power handling.



Orange and Blue - XG3 Eulex Gap Capacitor
Green and Red - Single Layer Capacitor

Note: for BW print: orange are the top flat line, blue is the bottom line.



Blue - XG3 Eulex Gap Capacitor
Red - Single Layer Capacitor

Note: for BW print: blue is the top line, red is the bottom line.

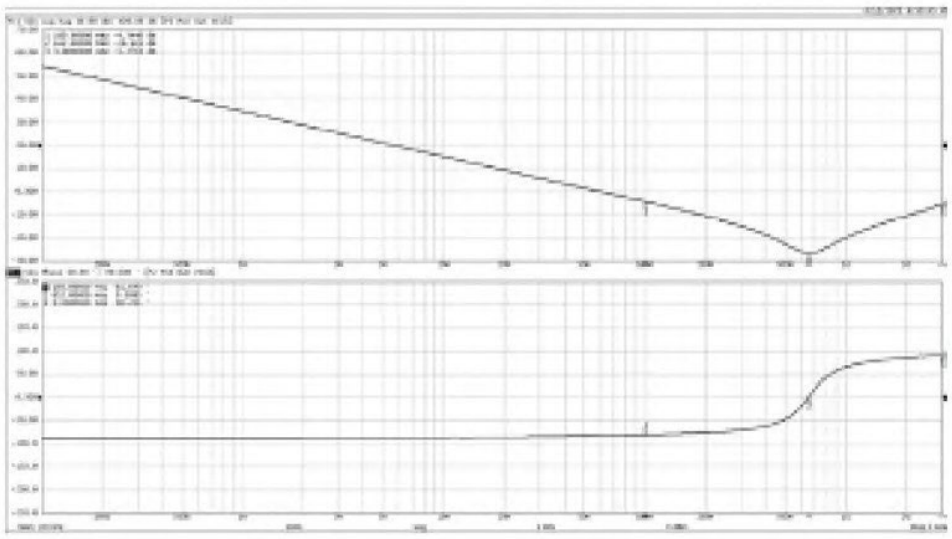
PMI's overall testing highlighted several key advantages of the 3-Terminal design:

- Higher Q (Quality Factor): Demonstrating lower losses and greater rejection before the cut-off frequency and improved efficiency.
- Lower Parasitic Effects: Reducing unwanted inductance and resistance, leading to better high- frequency performance.
- Consistent Performance: Maintaining similar performance characteristics across different capacitance values within the same footprint.
- High-Frequency Capability: Sustaining performance at frequencies up to 67GHz and beyond.
- Simplified Design: Reducing the need for complex tuning or wire bonds, simplifying the manufacturing process, easy to assemble, reducing labor costs Enhanced Power and Voltage Handling: Providing improved performance compared to traditional SLC capacitors.

"Our independent evaluation of the [3-Terminal] has revealed outstanding performance across a range of critical parameters. The combination of lower cost, higher Q, better RF metrics (VSWR, SRF, flatness, Loss etc.) increased power/voltage handling and the elimination of wire bonds represents a significant advancement in capacitor technology. These capacitors offer a compelling solution for high performance RF designs."

Sebastian Palacio VP/GM PMI

Picotest Testing



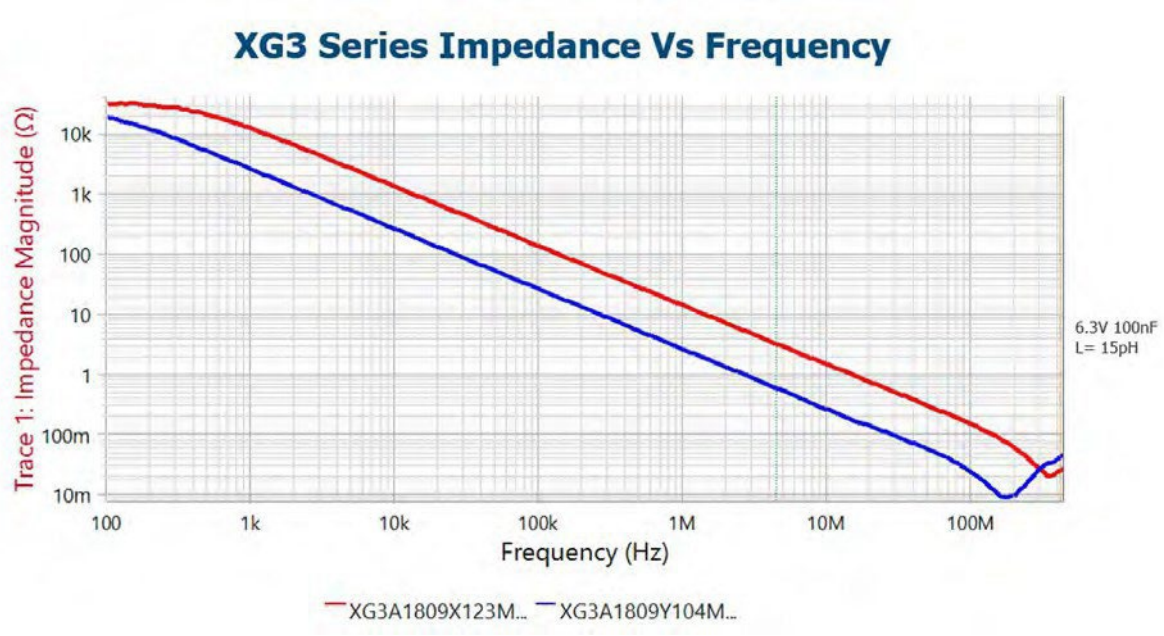
Picotest conducted a low frequency high power application test utilizing its specialized Bode 500 measurement tool to independently verify the inductance of the 3-Terminal Capacitor. The testing protocol focused on quantifying the capacitor's Equivalent Series Inductance (ESL) with the aim of accurately measuring inductance values at the pico-Henry level

Key outcomes from Picotest's Testing:

- Successful measurement of pico-Henry level inductance, demonstrating the capacitor's ultra-low inductance characteristics and validating accurate measurement at these levels.
- The significance of these results lies in demonstrating superior performance of the 3- Terminal Capacitor compared to traditional Multilayer Ceramic Capacitors (MLCCs). While typical MLCCs exhibit inductance values on the order of 200 pico-Henries, the 3-Terminal Capacitor exhibited significantly lower inductance, as low as 15 pico-Henries.

"Your [3-Terminal] capacitor exhibits remarkably low ESL, making them well-suited for coupling in microwave applications. They successfully passed 500 watts in testing."

Steve Sandler, Managing Director Picotest



This validation confirms the 3-Terminal's suitability for applications in RF circuits, DC blocking, power integrity solutions, and high-reliability markets where minimizing inductance is paramount. The results provided independent confirmation of its low inductance, underscoring its benefits for demanding high-frequency applications.

Reliability Testing

Reliability testing demonstrated stability under 2x rated voltage at 125°C for over 7,000 hours and no failures in humidity testing.

Dielectrics

Both configurations of the capacitor use Class I dielectrics such as porcelain and NPO, chosen for their high stability, high Q, and low loss characteristics, with temperature coefficients (TCC) of negligible to 0 ±30ppm/°C, making them suitable for applications requiring
minimal capacitance drift over temperature (-55 to +125°C) in high frequency.

Application Suitability

These capacitors were tested in scenarios involving DC blocking, bias line filtering, and impedance matching. Applications ranged from microwave filtering to power integrity management in digital and RF systems.

CONCLUSION

The embedded electrode capacitor architecture demonstrates meaningful advances in high- frequency passive component performance. Measured improvements in capacitance density, low inductance, and high reliability position this technology as a viable alternative to conventional MLCCs and SLCs in demanding RF and high-speed digital applications.

REFERENCES

[1] Bird Technologies test reports
[2] PMI application test data, LNA and filter evaluations
[3] Picotest ESL characterization
[4] Eulex internal test reports

Alex Moalemi is the Founder and Technical Director of Quantic Eulex.
Mark Simpson is the Business Development and Sales Operations Manager of Quantic Eulex.

Quantic Eulex develops innovative ceramic components for the most demanding high-frequency microwave, millimeter-wave, and 5G applications. Our solutions deliver design advantages through small-footprint, low-profiling packaging, and a wide voltage range, fully tested up to 67Ghz.