Packaging and integration of passive components to reduce board space with optimized thermal and electrical performance

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Presentation Outline

- Resonant Capacitors & Inductors for Switched Tank Converters
  - U2J Capacitors & Mn-Zn Ferrite inductors
  - Leadless Stacks for reduced footprint
  - High Current Handling

- LC Module for further size reduction

- WBG Capacitor Requirements for higher power & voltages
  - C0G Capacitors
  - Leadless Stacks for higher capacitance

- Packaging Roadmap
Switched Tank Converters

48V – 12V Step Down Power Conversion with 98.92% efficiency up to 650W [1]

Resonant Capacitors and Inductors with
- Small Footprint
- Low AC Losses
- High Frequency ~300kHz

Development of U2J Resonant Capacitors

- Change of capacitance with temperature for X7R is too large, although $K \sim 3500$
- C0G Dielectric Constant is too low $K \sim 31$
- U2J Developed $K \sim 82$

$$C = K K_0 A n / t$$

Where:
- $C$ = Capacitance
- $K$ = Dielectric constant
- $K_0$ = Permittivity of free space ($8.854 \times 10^{-12} \text{ F/m}$)
- $A$ = Overlap Area of opposed electrodes in MLCC
- $n$ = Number of active layers in MLCC
- $t$ = Thickness of active layers
Development Leadless Stacked Capacitors

Transient Liquid Phase Sintering, TLPS is used to bond the terminals of the MLCC together.

U2J 1812 0.47μF 50V MLCC
# Leadless Stacks ESR & Orientation

1.4µF Leadless Stacks have lowest ESR with electrodes perpendicular $P = i^2ESR$

<table>
<thead>
<tr>
<th>U2J Part Description</th>
<th>Part Number</th>
<th>Number of MLCC</th>
<th>E4980A ESR @ 300kHz (mΩ)</th>
<th>E4990A ESR @ 300kHz (mΩ)</th>
<th>Solder Pad Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1812, 0.47µF, MLCC C1812C47J5JACTU</td>
<td>1</td>
<td>0.4</td>
<td>1.2</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>2 x Traditional, 0.94µF C1812C944J5JLCTU</td>
<td>2</td>
<td>1.4</td>
<td>1.3</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>3 x Traditional, 1.4µF C1812C145J5JLCTU</td>
<td>3</td>
<td>1.7</td>
<td>1.6</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>2 x Low Loss, 0.94µF C1812C944J5JLC7805</td>
<td>2</td>
<td>1</td>
<td>0.9</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>3 x Low Loss, 1.4µF C1812C145J5JLC7805</td>
<td>3</td>
<td>0.8</td>
<td>0.4</td>
<td>38.4</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram of Traditional and Low Power Loss configurations](image-url)
Leadless Stacks Ripple Current Heating

Lower ESR in Low Loss Orientation 1.4µF Leadless Stack has much lower self-heating at 300kHz 20A_{RMS}

Traditional Orientation
≈ 65°C Max.

Low Power Loss Orientation
≈ 35°C Max.
Leadless Stacks Ripple Current Life Testing

- 1.4µF Leadless Stack in the Low Loss Orientation were tested for 2000 hours @ 105°C with 30A_RMS, 300kHz & 25V_DC applied
- IR remains stable and there were no failures (0/34)
U2J Leadless Stack Development

<table>
<thead>
<tr>
<th>U2J Part Description</th>
<th>Part Number</th>
<th>ESR (mΩ)</th>
<th>SRF (MHz)</th>
<th>ESL (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1812, 0.47µF, MLCC</td>
<td>C1812C474J5JACTU</td>
<td>1.6 1.9 2.2</td>
<td>8.3 400</td>
<td></td>
</tr>
<tr>
<td>2 x Traditional, 0.94µF</td>
<td>C1812C944J5JLCTU</td>
<td>1.9 2.4 2.9</td>
<td>4.8 860</td>
<td></td>
</tr>
<tr>
<td>3 x Traditional, 1.4µF</td>
<td>C1812C145J5JLCTU</td>
<td>2.4 3.3 4.9</td>
<td>3.3 1100</td>
<td></td>
</tr>
<tr>
<td>2 x Low Loss, 0.94µF</td>
<td>C1812C944J5JLC7805</td>
<td>1.4 1.8 2.2</td>
<td>7.5 450</td>
<td></td>
</tr>
<tr>
<td>3 x Low Loss, 1.4µF</td>
<td>C1812C145J5JLC7805</td>
<td>0.7 1.0 1.2</td>
<td>7.5 400</td>
<td></td>
</tr>
</tbody>
</table>

The Low Loss Orientation has:
- Low ESR
- Low ESL
- Higher SRF
Development of Resonant Inductor

- Core loss reduced with the suitable material
- Fringing loss reduced by improved structure
- High saturation current
- Positive change of inductance with temperature compensates the negative change of \( U_{2J} \)

**SATURATION CHARACTERISTIC**
56nH @ 100kHz 0.1V\(_{\text{RMS}}\)
TPI078060L056N

**SATURATION CHARACTERISTIC**
56nH @ 100kHz 0.1V\(_{\text{RMS}}\)
TPI078060L056N

**L of variation** -1%~+1.2%
LC Module

Combine Capacitors and Inductor to achieve a smaller footprint

**Component Footprints**

<table>
<thead>
<tr>
<th>Discrete 4 MLCCs &amp; Inductor</th>
<th>Leadless Stack &amp; Inductor</th>
<th>LC Tank Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>~124 mm²</td>
<td>~93 mm²</td>
<td>~69 mm²</td>
</tr>
</tbody>
</table>

Sn Plated Cu J-Lead Connector
Low impedance
Machine Placeable

1812 4 Chip MLCC
High Cap
Low ESR

56nH SMD Chip Inductor
TPI Power Series
High switching frequency
Low Core Loss & DCR

Assembled with KEMET KONNEKT TLPS Interface

Bottom Views
Impedance and ESR

Individual Inductor & Leadless Stack

Combined Inductor & Leadless Stack Vs. LC Module
Ripple Current Heating

Leadless Capacitor & Inductor were compared to the LC Module @ 20 A_{RMS}, 270kHz

LC Module does not reach significantly higher temperatures
Capacitor Requirements for Higher Power

Higher Switching Frequencies
20kHz → 100kHz → 10 MHz

- Smaller, low ESR, low ESL low loss capacitors with high dV/dt, dI/dt & current handling capability

Higher Operation Voltages
450V → 900V → 1200V → 1700V

- Reliable performance at higher voltages

High Junction Temperatures
105°C → 125°C → 150°C → 200°C+

- Reliable performance at elevated temperatures ≥ 125°C with robust mechanical performance
  - Packaging close to the hot semiconductor to:
    - Lower ESL
    - Minimize cooling costs

\[
C = \frac{P_{\text{load}}}{U_{\text{ripple}} \left( U_{\text{max}} - \frac{U_{\text{ripple}}}{2} \right) 2 \pi f_{\text{rectifier}}}
\]

Example: DC Link for 400V with 10% Ripple

Source: Modified from Prof. R. Kennel, Technical University Munich, Germany
Higher Voltages - Automotive Power Requirements

12V $\rightarrow$ 48V
- Provide higher power
  - While current lowered
  - Brake recuperation
  - Air and heaters
  - Hybrid motor

450V $\rightarrow$ 900V
- Provide higher power
  - While current lowered
  - Faster charging
- MLCC using U2J dielectric are currently limited to $< 200V$ temperatures to $125^\circ C$
- Development of C0G Ni BME MLCC

Source: ZVEI/Infineon
Performance Comparison
3640 Ni BME C0G vs. Competitor Cu PLZT

3640 0.22μF Ni BME C0G has:
- Better accelerated life
- Stable cap. with temp. & voltage
- Less ripple heating
- High MOR
- > 0.22μF with Leadless Stack Solutions

Ni BME C0G MLCC 3640 0.22µF 500V 150°C

ESR & Current Handling @ 150°C 100kHz

- Lower DF & ESR reduce the power dissipated

\[ P = \frac{i^2 d}{2\pi f C} = i^2 R \]

- \( P \) = power dissipated
- \( i \) = current
- \( d \) = dissipation factor
- \( f \) = frequency
- \( C \) = capacitance
- \( R \) = resistance, ESR

Ripple Current Life Testing

- No failures after 1000hrs @150°C
  - 15A\(_{\text{RMS}}\) 100kHz
  - 10A\(_{\text{RMS}}\) 100kHz with 400V\(_{\text{DC}}\) Bias
3640 0.22µF 500V Ni BME C0G for 150°C
Temperature Accelerated HALT

- MLCC were HALT tested at 260°C at 1000, 1100, 1200 & 1300V\textsubscript{DC} (n = 40, with Au term.)
- MTTF Vs. Voltage was recorded
- Voltage exponent ~ 19 @ 260°C
- Calc. MTTF @ 500V\textsubscript{DC} ~ 8500 years

MTTF = 2934 min.

\[ y = 7.13E+59x^{-18.6} \]
0.88µF Leadless Stacks (4 X 3640 0.22µF 500V)
Orientation: Traditional Vs. Low Power Loss

Traditional | Low Power Loss
---|---
2.9 nH | 0.9 nH

Low Loss Orientation has:
- Higher SRF
- Lower ESR

0.88μF Leadless Stacks (4 X 3640 0.22μF 500V)

Ripple Current Heating: Traditional Vs. Low Loss Mounting

At $20A_{\text{RMS}} \times 300\text{kHz}$ Low Loss Orientation has:

- Lower Temperature
- More even heating
Thermal Modeling
3640 0.22µF 500V; 2 & 4 chip Leadless Stacks

**Low Loss Model**

Study thermal resistance with other boundary conditions
- Forced air cooling or dielectric fluids
- Embedded in package

[Rohrer Versus # of MLCCs in Stack](chart)

Inverter Capacitor Trends

DC-Link Hybrid Inverter & Snubber

Battery Voltage Boost

DC-LINK

H-Bridge

Package MLCC close to SiC
- Long lifetime @ 150°C
- Higher Frequency Switching

Package Electrolytics/Films in cooled areas further from SiC
- Long lifetime @ < 105°C
- Lower Frequency Switching

MLCC snubber close to SiC
Thank You!

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