High-Q Resonator with Integrated Capacitance for Resonant Power Conversion

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Motivation

➢ Miniaturize power converters using high switching frequency

➢ WBG semiconductors can switch efficiently at high frequency.

➢ Realizing miniaturization of magnetics through high frequency is hard.

   • Winding loss is high due to skin and proximity effects.

   • Inductor performance degrades as size scales down.

➢ Need low-loss winding structures at MHz frequencies
Solid and Litz Wire

Solid Wire

➢ Skin depth \((\delta)\) of Cu at 1 MHz \(\approx 66 \mu m\)

➢ Large conductors \((> 66 \mu m\) AWG 42) are not utilized well.

➢ Small conductors have high resistance.

Litz Wire

➢ Parallel connection of small conductors with equal current sharing

➢ Effective litz wire needs diameter \(\ll \delta\) (much smaller than AWG 42).

➢ Increasingly cost-prohibitive above 1 MHz
Thin Foil Conductor

➢ Thin metal foils (≪ δ) are commercially available.
- Free standing foil down to 6 µm
- Thinner layers can be coated on plastic film substrates.

➢ Need equal current sharing among multiple layers

➢ Foil cannot be twisted like litz wire for equal current sharing.

10 layers, 16 µm Al
Achieving Equal Current Sharing

➢ Similar to twisting litz wire

➢ Add “ballast” impedance to each layer to force equal current

➢ The ballast impedance needs to be capacitive to reduce loss.
Our Resonator Concept

Series resonance

Layer thickness $\ll \delta$

Cross-section

$h \ll l \approx b$

Series resonance
Our Resonator Concept

Layer thickness $\ll \delta$

$h \ll l \approx b$
Series resonance

$l \approx b$
Series resonance

$l \approx b$
Parallel resonance

Cross-section

Lower loss, easier to build
Our Resonator Concept

Magnetic cores can be used to straighten field lines.

- Magnetic core
- Field line more parallel to conductor
- Lower loss
Challenge

➢ Low loss multilayer windings require:
  
  • Very thin copper layers (< 10 μm)
  
  • Low loss dielectric for ballasting capacitance

   – Thin copper layers are hard to handle without wrinkling.

   – Copper coated on low-loss dielectric substrate (e.g. Teflon) is expensive.
Solution

➢ Copper coated on polyimide substrate (PCB industry-standard)

➢ Free standing Teflon for ballasting capacitance

![Diagram of copper coated on polyimide substrate with Teflon for ballasting capacitance]
How does it work?

- Polyimide is low-cost but high-loss.
- But it does not experience significant electric fields.
- Very low voltage drop across $C_{HL}$
- Low effective loss in polyimide
Prototype

Proof-of-concept prototype for performance of multi-layer structure

➢ 50 Copper strips
➢ Cu – polyimide – Cu (5 μm – 25 μm – 5 μm)
➢ Dielectric: 50.8 μm PTFE
➢ Core: 67 Fair-Rite material
➢ Volume ≈ 15 cm³ (Winding and center block)
➢ Series resonator in pictures
Single-layer Benchmark

- 254 μm (≫ δ @ ~10 MHz)
- \( L, C \approx \text{Multilayer} \ L, C \)
- No core: \( L \approx 55 \text{ nH}, C \approx 3 \text{ nF} \)
- Core: \( L \approx 120 \text{ nH}, C \approx 3 \text{ nF} \)
- Low ESR NP0 capacitor (ATC 800B Series)
- Pictures show a parallel resonator
Loss Model

\[ R_{winding} = \frac{R_{LF,loop}}{M} F_r \]

- FEM simulation to accurately compute \( F_r \)

\[ R_{dielectric} = \frac{D}{\omega C} \]

\[ R_{core} = \Re \left( \frac{j\omega}{R_a + R_c^*} \right) \]

- \( R_a \) and \( R_c^* \) approximated from FEM simulation.
Winding loss is dominant (70% to 96% of total loss).

Magnetic cores reduce the winding loss (straight field lines + lower $f_0$).

Dielectric loss $\Rightarrow$ Dissipation in dielectric + capacitor plate loss + connection between capacitor and inductor.
We want multi-layer resonator to have lower loss than single-layer.

If no magnetic core is used to straighten the field lines, multi-layer resonator has higher ESR than single-layer resonator.

Magnetic cores make multi-layer ESR lower than single-layer ESR.
Results (Parallel Resonator)

- No core: Single-layer, $Q = 326$
- No core: Multi-layer, $Q = 185$
Core significantly improves multi-layer performance.

The multi-layer structure provides $\approx 50\%$ improvement (with core).
Parallel and series resonators have similar quality factors.
Very good agreement between the loss model and measurement.
Discussion (Core-Conductor Gap)

- Gap in prototype ≈ 2 mm
- PTFE wider than copper
- Multi-layer resonator performance can be even better with smaller gap.
Summary

Goal: Design low-loss resonators that allow miniaturization of power converters using high frequency

Approach: Multi-layer windings of thin foil conductors with equal current sharing

➢ Lower winding loss because total conductor thickness is not skin depth limited.
➢ Integrated capacitance eliminates capacitor plate loss and inductor-capacitor connection loss.

Results (Proof-of-concept)

➢ Single-layer resonator provides high $Q \approx 580$ in $< 15 \text{ cm}^3$
➢ Multi-layer structures provide at least 50% improvement if magnetic cores are used to straighten the field lines, and better with smaller gap between conductor and core.
➢ Application in Wireless Power Transfer: Paper ID 1504, Thursday, T40.5

Future Work

➢ Optimize the resonator design for particular applications
➢ Practical fabrication approaches, considering core-conductor gap
Thanks!