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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 (δ) of Cu at $1\ \mathrm{MHz} \approx 66\ \mu\mathrm{m}$
- Large conductors ($> 66\ \mu\mathrm{m}$ 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 $1\ \mathrm{MHz}$

Thin Foil Conductor

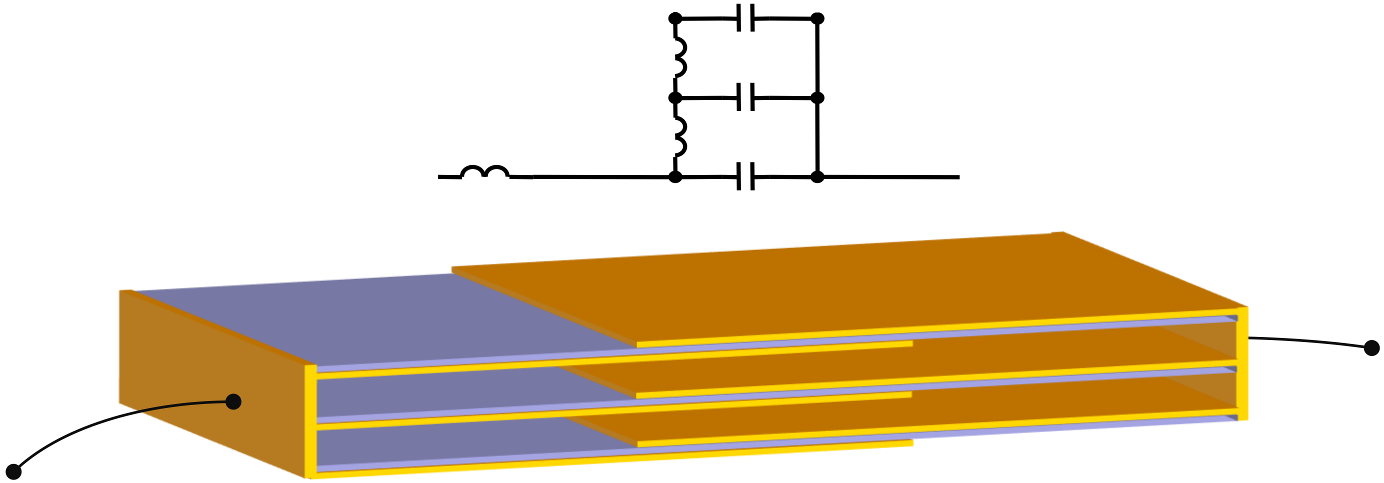
- Thin metal foils ($\ll \delta$) are commercially available.
  - Free standing foil down to 6 μm
  - Thinner layers can be coated on plastic film substrates.

- Need equal current sharing among multiple layers
- Foil cannot be twisted like litz wire for equal current sharing.

10 layers, 16 μm Al

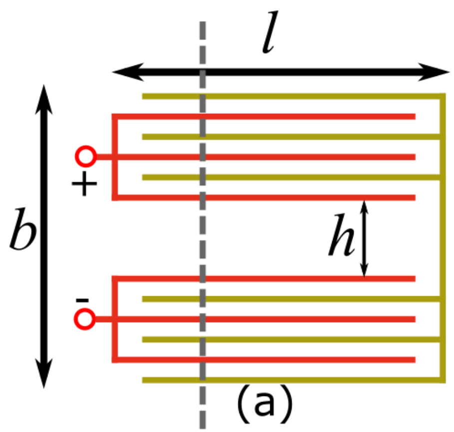
Achieving Equal Current Sharing

- 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.

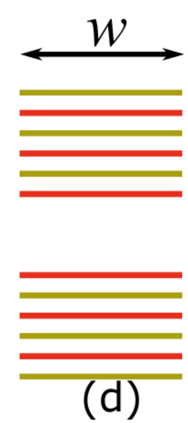


Our Resonator Concept

Layer thickness $\ll \delta$

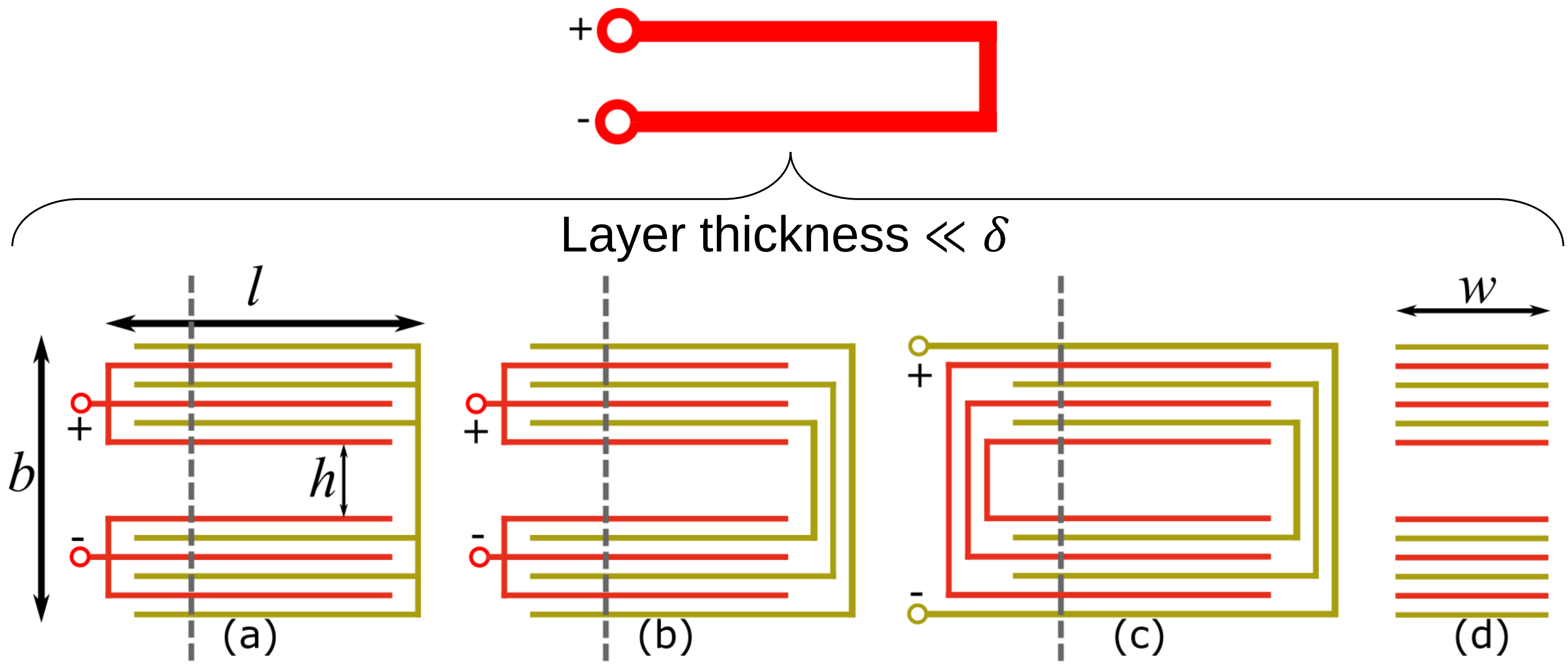


$h \ll l \approx b$
Series resonance



Cross-section

Our Resonator Concept

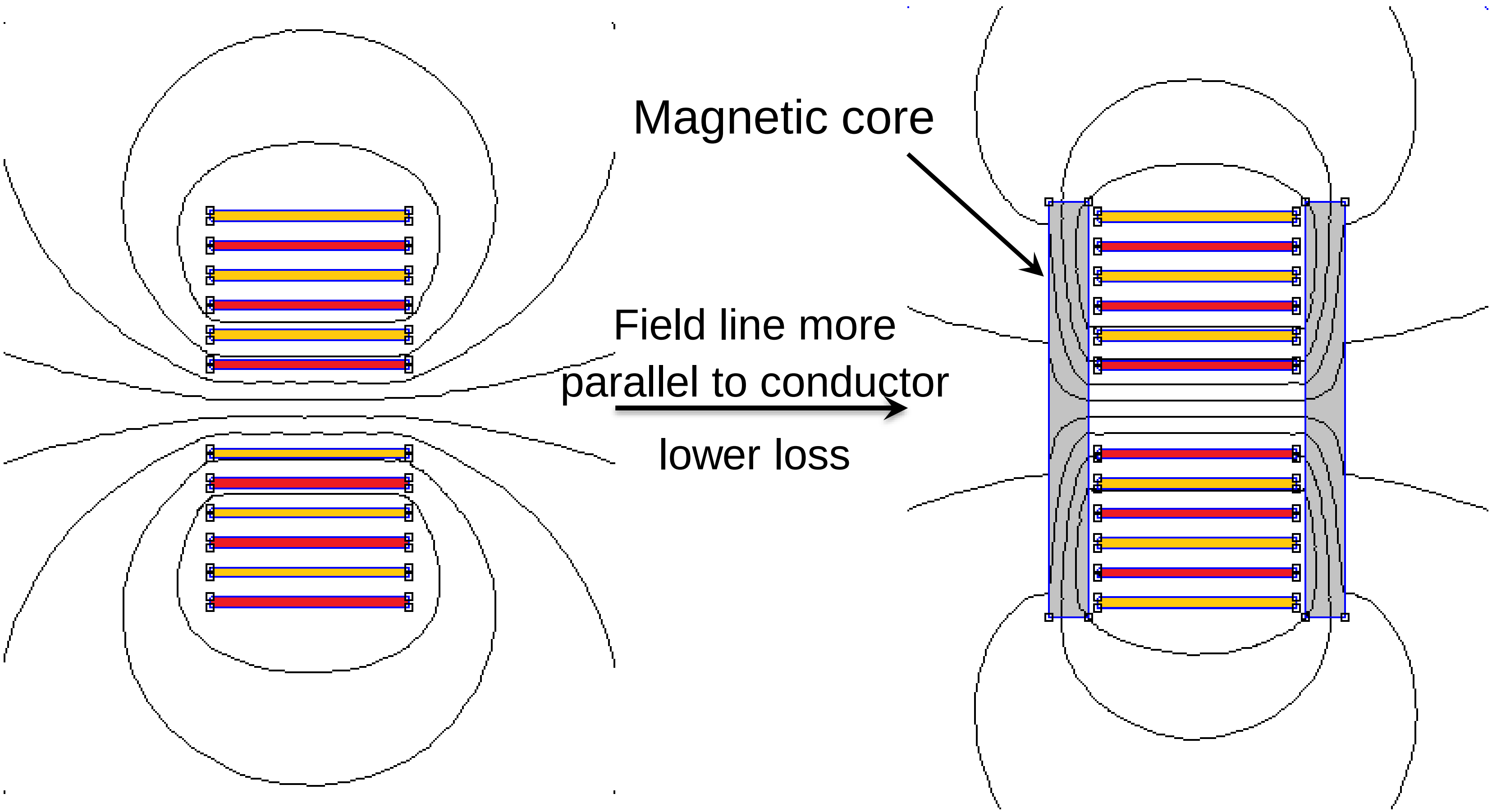


$h \ll l \approx b$	$l \approx b$	$l \approx b$	Cross-section
Series resonance	Series resonance	Parallel resonance	

Lower loss, easier to build

Our Resonator Concept

Magnetic cores can be used to straighten field lines.

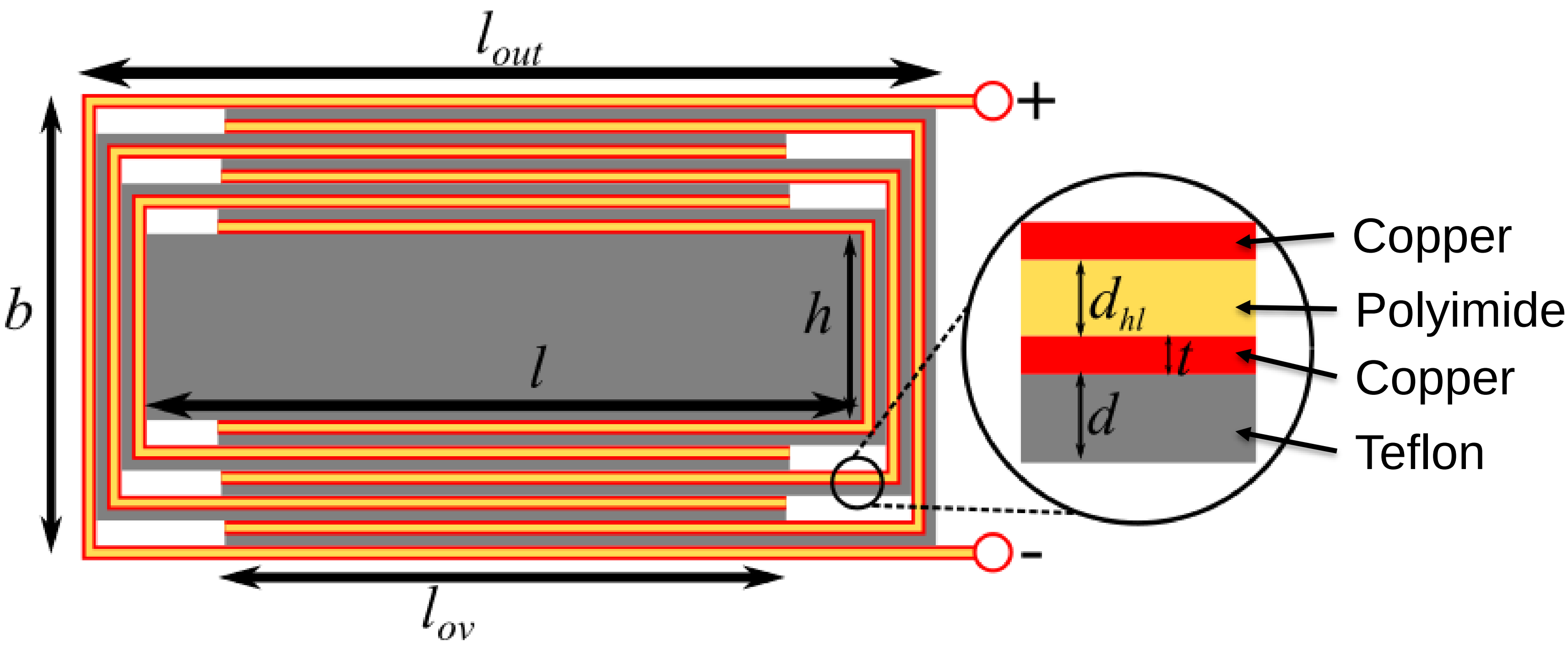


Challenge

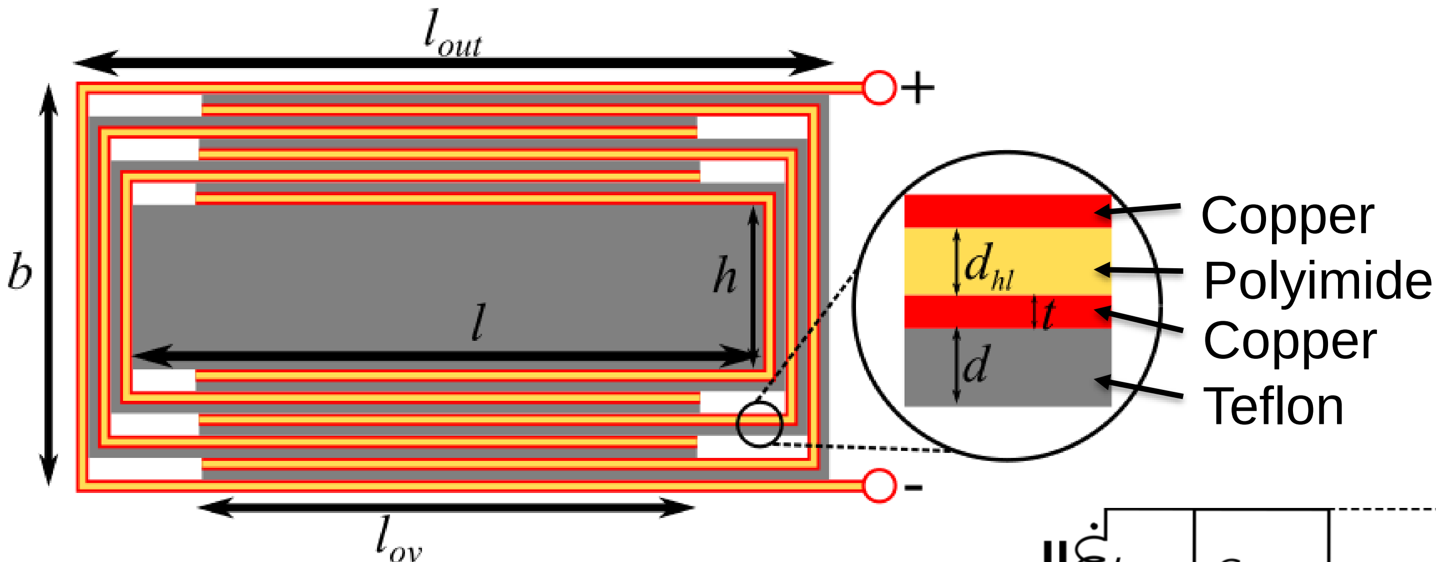
- Low loss multilayer windings require:
  - Very thin copper layers (< 10 μm)
  - Low loss dielectric for ballasting capacitance
- – Thin copper layers are hard to handle without wrinkling.
- – Copper coated on low-loss dielectric substrate (e.g. Teflon) is expensive.

Solution

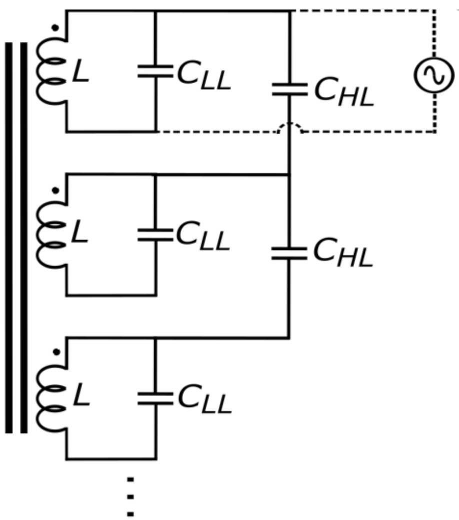
- Copper coated on polyimide substrate (PCB industry-standard)
- Free standing Teflon for ballasting capacitance



How does it work?

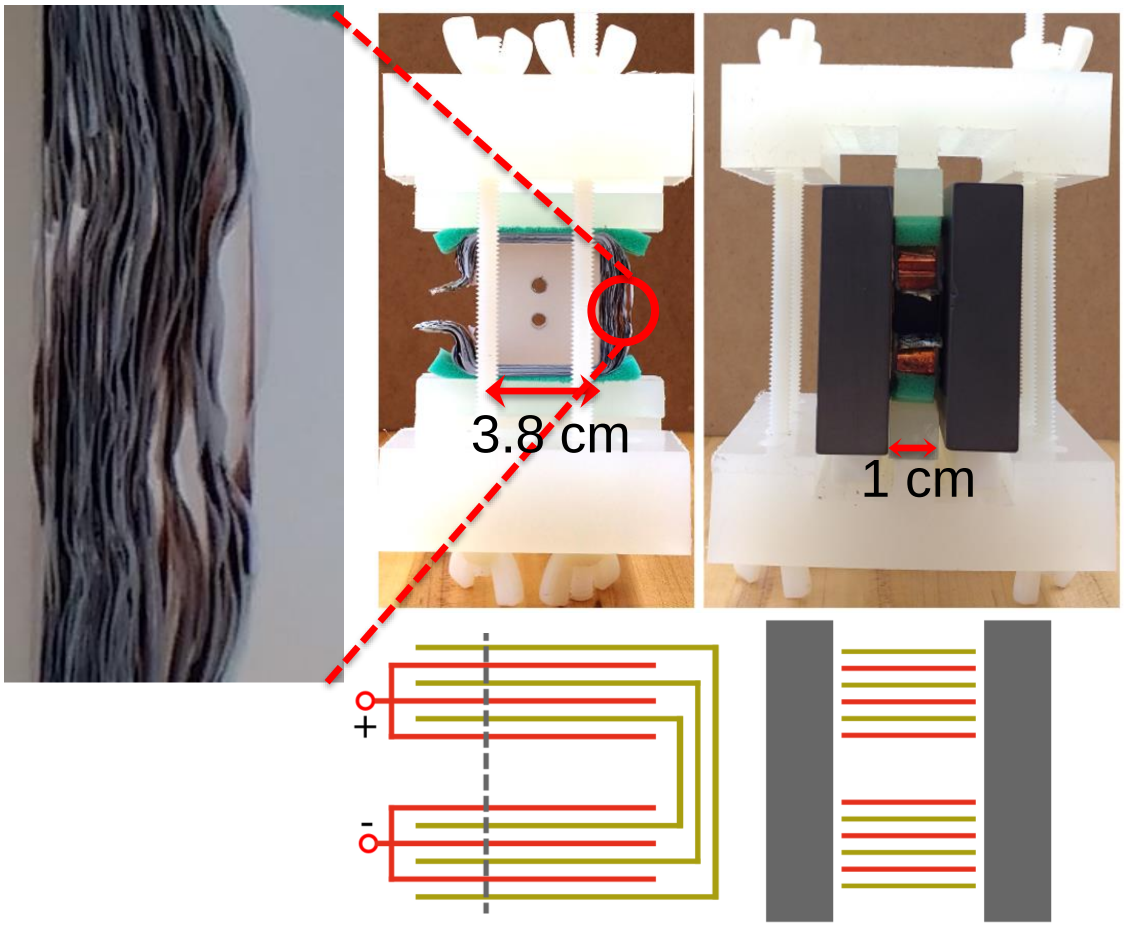


- Polyimide is low-cost but high-loss.
- But it does not experience significant electric fields.
- Very low voltage drop across C_{HL}
- Low effective loss in polyimide



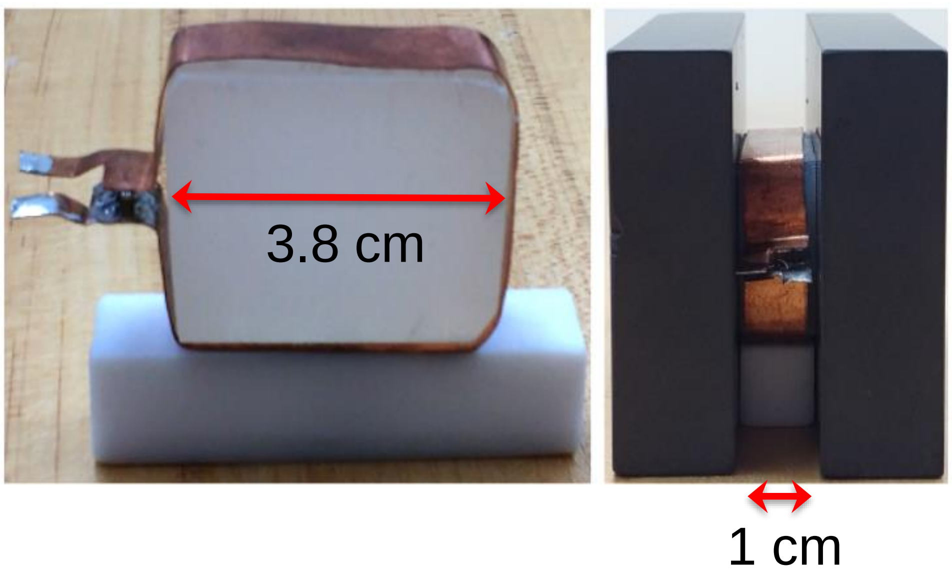
Prototype

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



- 50 Copper strips
- Cu – polyimide – Cu ($5\ \mu\text{m}\ - 25\ \mu\text{m}\ - 5\ \mu\text{m}$)
- Dielectric: $50.8\ \mu\text{m}$ PTFE
- Core: 67 Fair-Rite material
- Volume $\approx 15\ \text{cm}^3$ (Winding and center block)
- Series resonator in pictures

Single-layer Benchmark



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

Loss Model

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

ac resistance factor

- FEM simulation to accurately compute F_r

dielectric dissipation factor

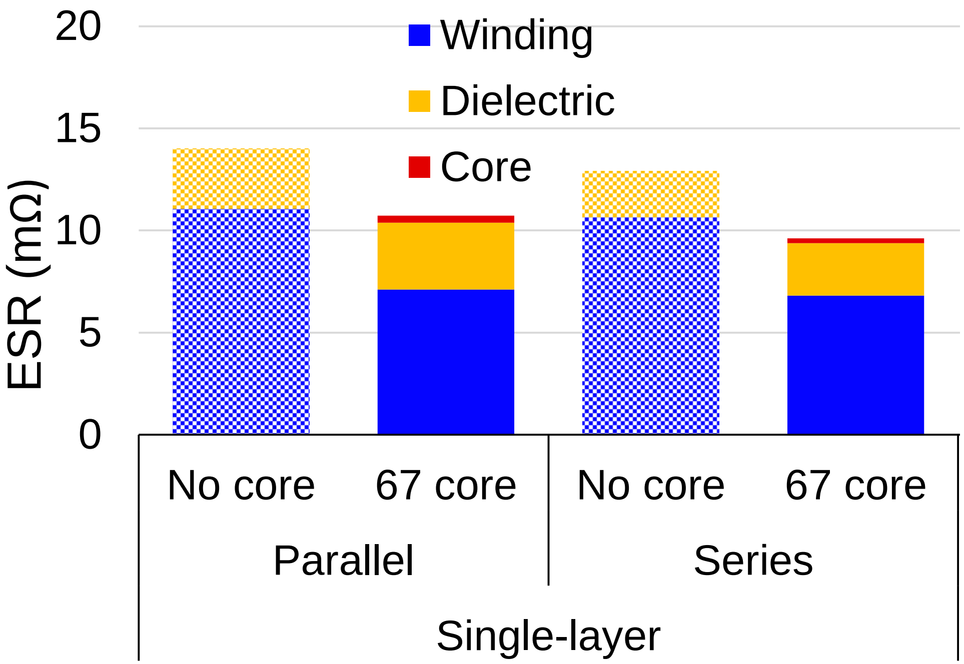
$$R_{dielectric} = \frac{D}{\omega C}$$

$$R_{core} = \mathbb{R}\left(\frac{j\omega}{\mathcal{R}_a + \mathcal{R}_c^*}\right)$$

reluctance

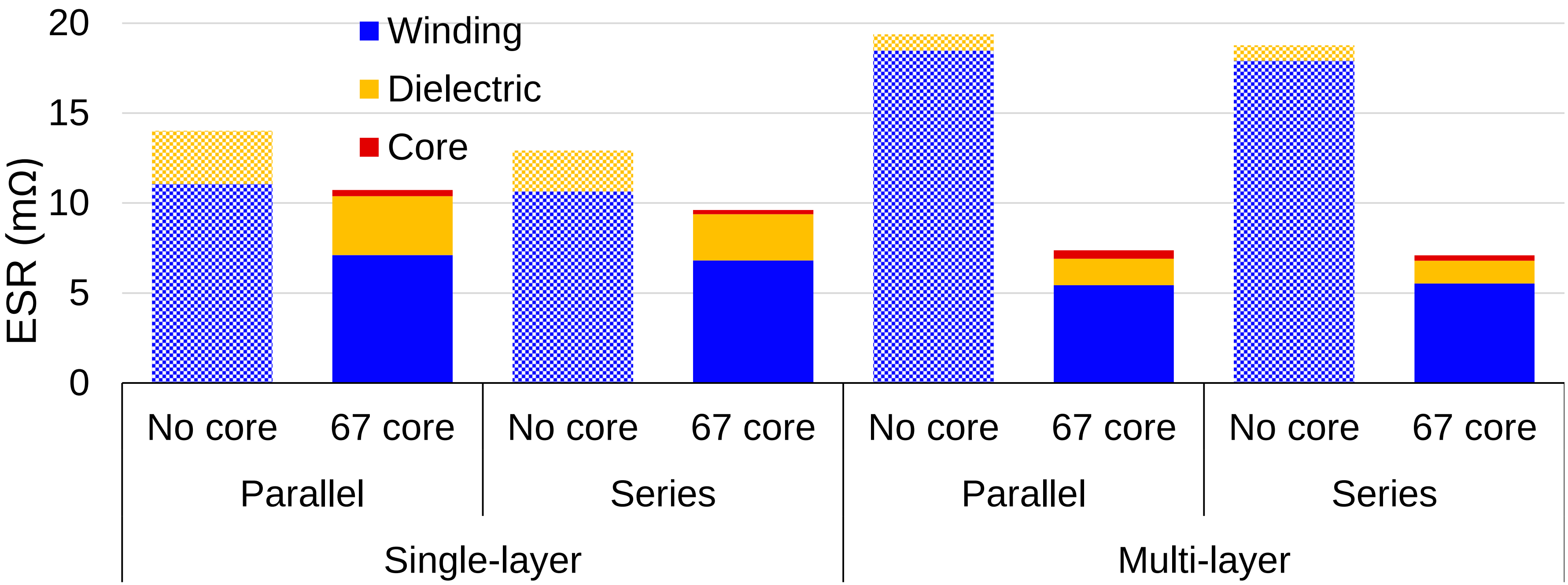
- $\mathcal{R}_a$ and $\mathcal{R}_c^*$ approximated from FEM simulation.

Loss Model (Single Layer)



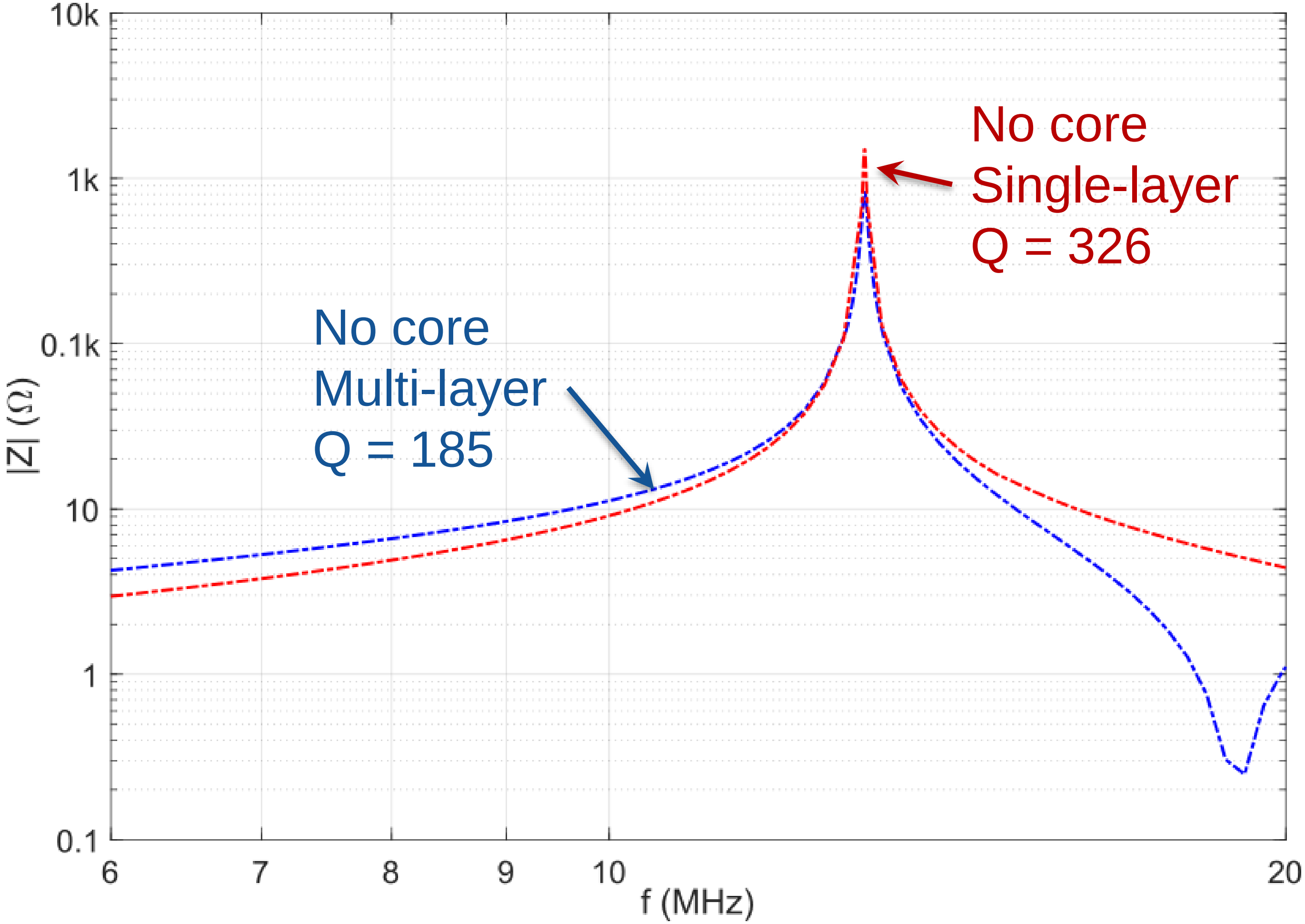
- Winding loss is dominant (70% to 96% of total loss).
- Magnetic cores reduces the winding loss (straight field lines + lower f_0).
- Dielectric loss ⇒ Dissipation in dielectric + capacitor plate loss + connection between capacitor and inductor

Loss Model

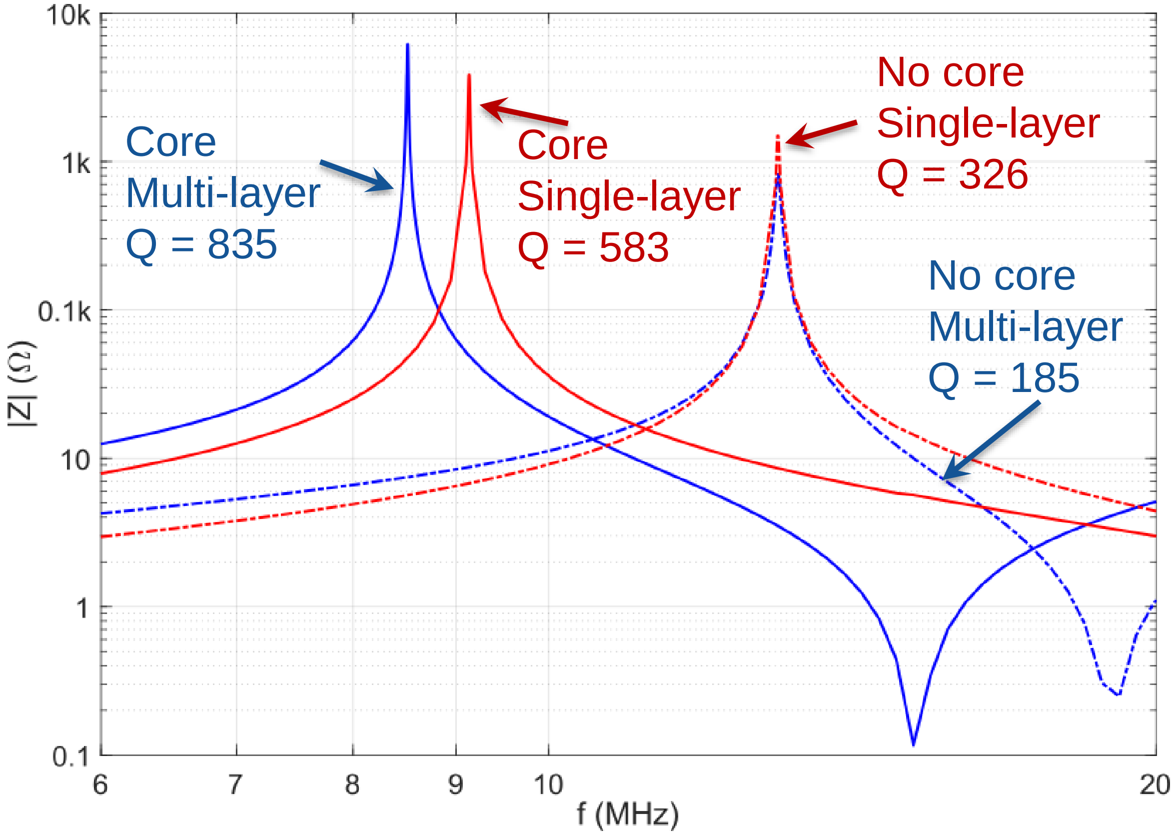


- We want multi-layer resonator to have lower loss than single-layer.
- If no magnetic core is used to straighten the field lines, multi-layer resonator has higher ESR than single-layer resonator.
- Magnetic cores make multi-layer ESR lower than single-layer ESR.

Results (Parallel Resonator)

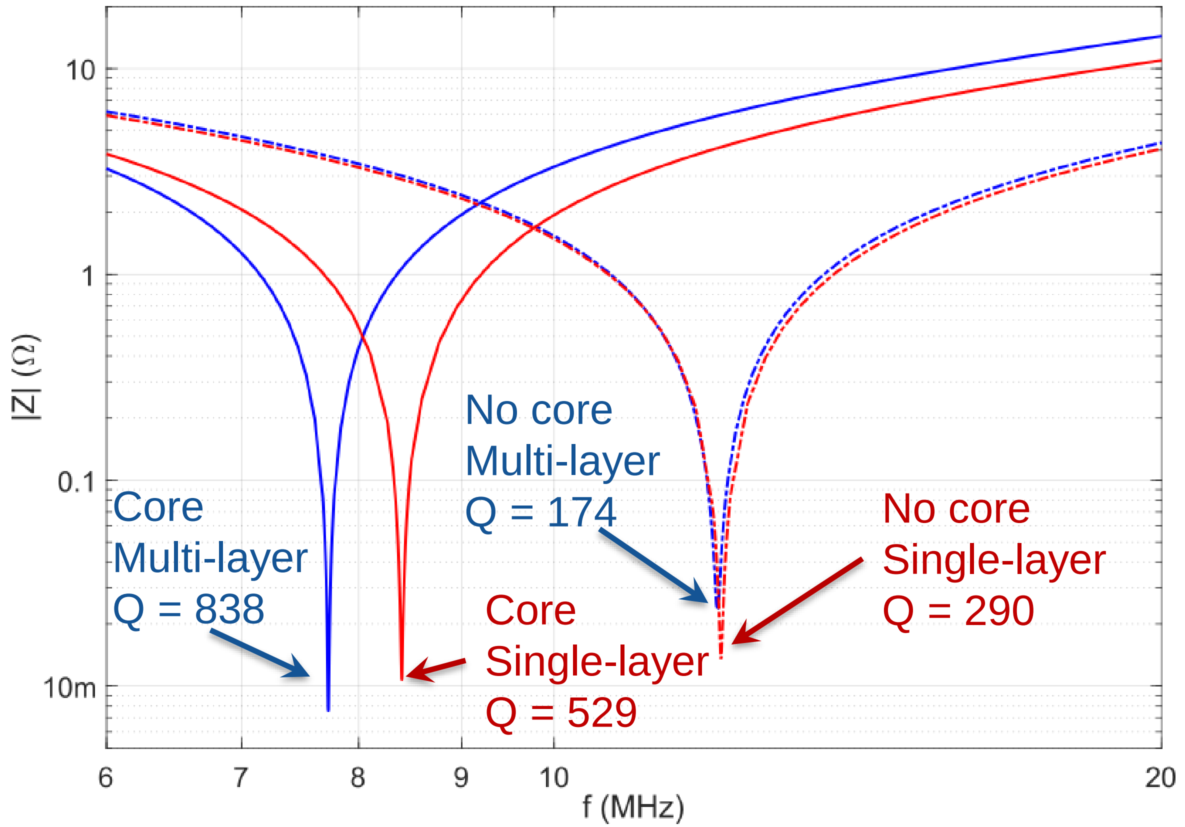


Results (Parallel Resonator)



- Core significantly improves multi-layer performance.
- The multi-layer structure provides ≈ 50% improvement (with core).

Results (Series Resonator)



- Parallel and series resonators have similar quality factors.

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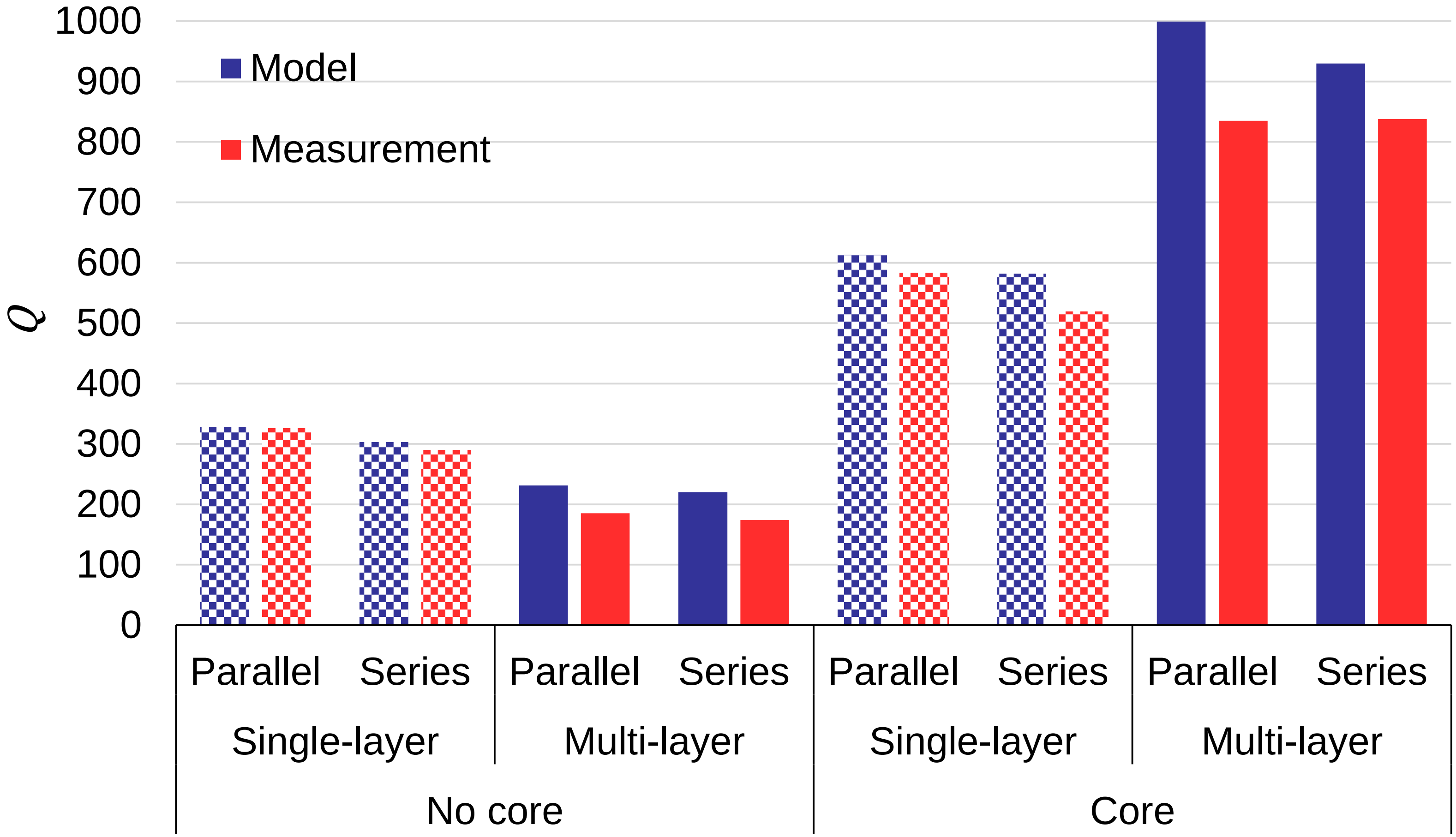
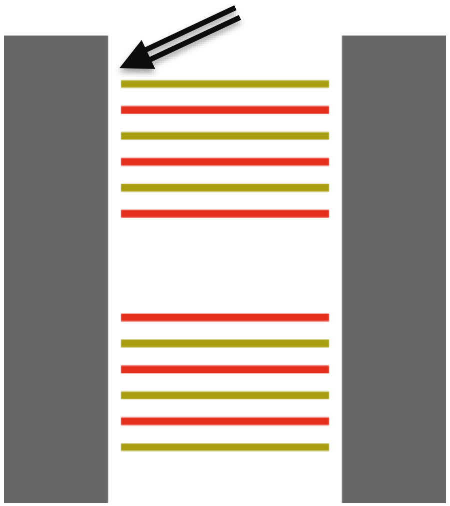
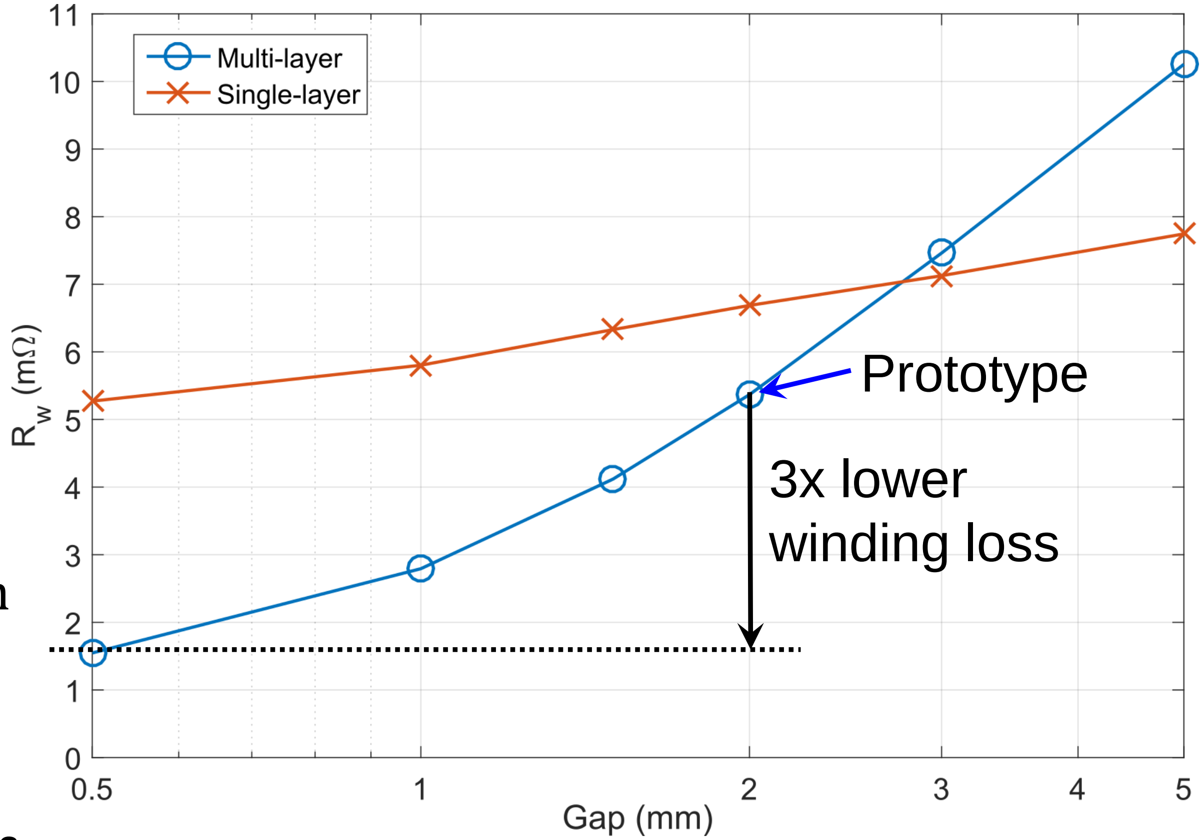
Measurement vs. Loss Model



- ➢ 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 $Q \approx 580 \text{ in} < 15 \text{ cm}^3$
- 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

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Thanks!

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