Multi-objective Design Optimization for High-bandwidth Printed Circuit Board Shielded Rogowski Coils

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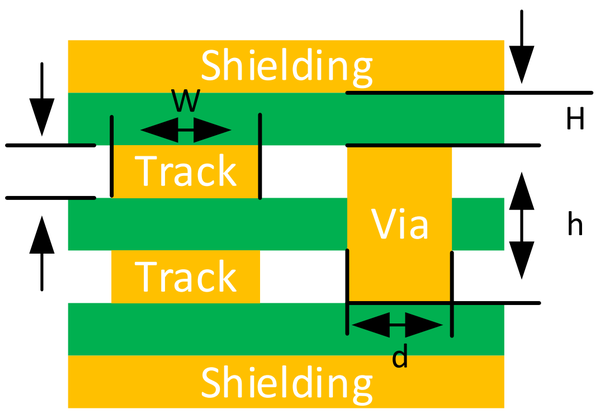
Motivation for Optimization Shielded PCB RC

- Fast-switching current measurement is a challenging task with the development of Gallium Nitride (GaN) devices
- Rogowski coils gain attention for their potential bandwidth, compact size, high accuracy, and ease of integration.
- PCB shielded Rogowski coils present a more intricate structure with numerous geometric parameters to design.

Modeling of Shielded PCB Rogowski Coil



$$\frac{V}{I} = \frac{M}{L_S} \times \frac{1}{R_l^{-1} - j\sqrt{C_s/L_s}\cot\left(\omega\sqrt{L_s C_s}\right)}$$

$$f_L = \frac{R_l}{2\pi L_S}$$

$$f_H = \frac{R_l}{2\sqrt{L_s C_s}}$$

$$M = \frac{\mu_0 N h}{2\pi} ln\frac{b}{a}$$

$$C_S = \frac{1.10 * 10^{-10} * \varepsilon_r}{ln\frac{2(2H+h)}{0.268w + 0.335T}}$$

$$L_S = \frac{\mu_0 N^2 h}{2\pi} ln\frac{b}{a} + Cs \times \frac{80}{\epsilon_r}\left[1 - \frac{H}{4(H+h)}\right] \times ln\frac{1.9(2H+T)}{0.8w+T}$$

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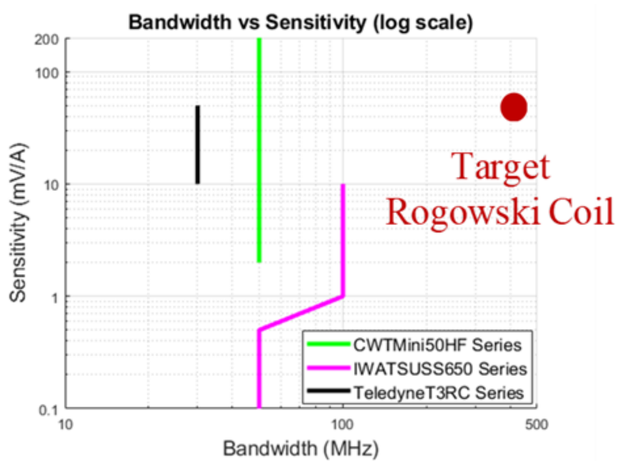
Optimization Goal & Boundary Conditions

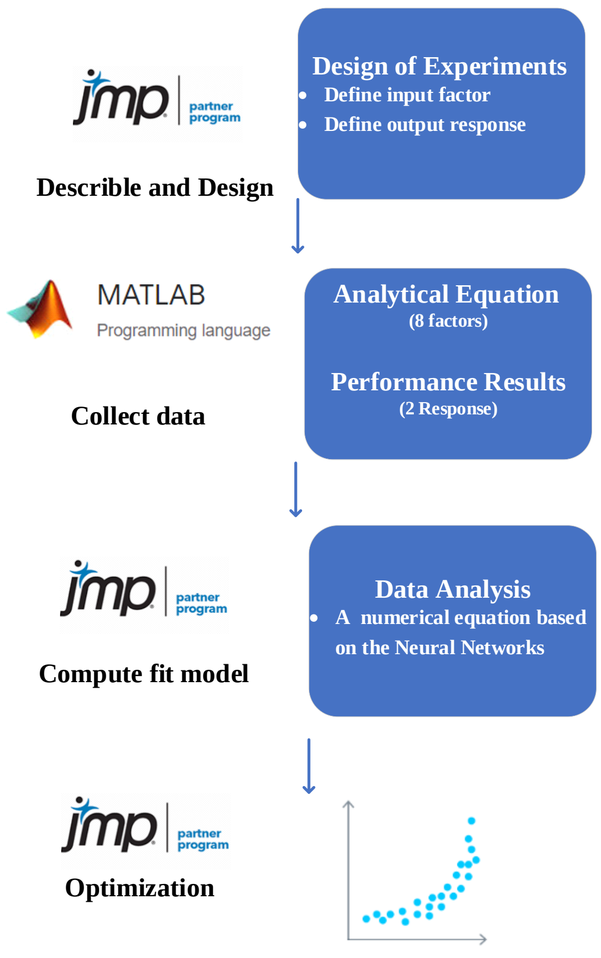
- The boundary conditions are determined by size limitation and physical 4 layer PCB

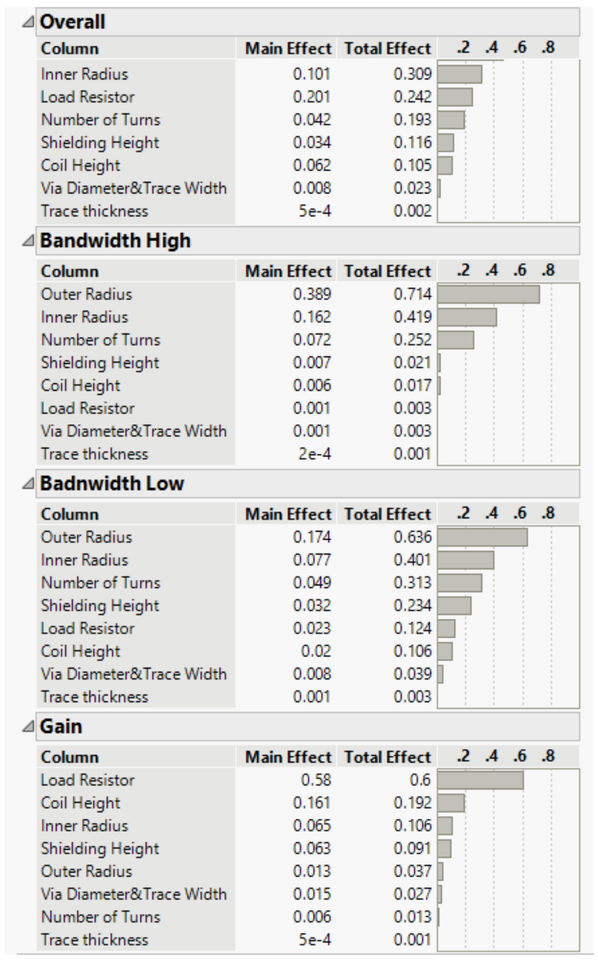


Design parameters	Boundary Condition	
	Minimum	*Maximum*
Number of Turns (N)	10	Constrained by a and b
Shielding Hieght (H)	0.08 mm	2 mm
Coil Heigh (h)	0.2 mm	2.2 mm
Trace Thickness (T)	1 oz	3oz
Via Diameter (d)	0.1524 mm	0.254 mm
Trace Width (w)	0.1524 mm	0.254 mm
Inner Radius (a)	1.5 mm	7 mm
Outer Radius (b)	2.5 mm	10 mm
Load Resistance (R_l)	0.1 Ω	5 Ω

Rogowski coil Design Optimization Process

- OFAT approach) can lead to massive data and huge computational complexity
- Geometric parameters affect sensitivity and bandwidth by directly changing parasitic parameters.





Overall		
Column	Main Effect	Total Effect
Inner Radius	0.101	0.309
Load Resistor	0.201	0.242
Number of Turns	0.042	0.193
Shielding Height	0.034	0.116
Coil Height	0.062	0.105
Via Diameter&Trace Width	0.008	0.023
Trace thickness	5e-4	0.002

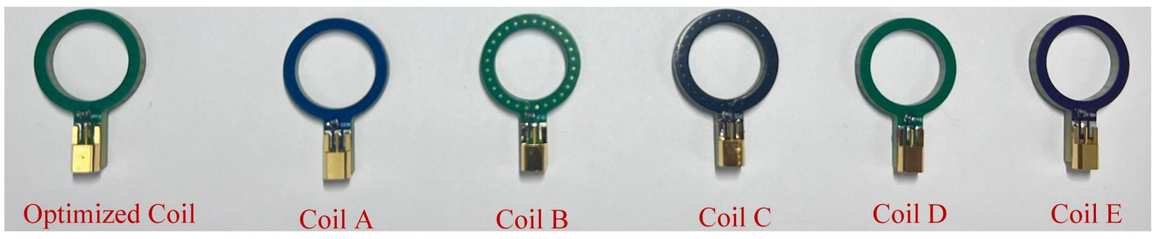
Bandwidth High		
Column	Main Effect	Total Effect
Outer Radius	0.389	0.714
Inner Radius	0.162	0.419
Number of Turns	0.072	0.252
Shielding Height	0.007	0.021
Coil Height	0.006	0.017
Load Resistor	0.001	0.003
Via Diameter&Trace Width	0.001	0.003
Trace thickness	2e-4	0.001

Badnwidth Low		
Column	Main Effect	Total Effect
Outer Radius	0.174	0.636
Inner Radius	0.077	0.401
Number of Turns	0.049	0.313
Shielding Height	0.032	0.234
Load Resistor	0.023	0.124
Coil Height	0.02	0.106
Via Diameter&Trace Width	0.008	0.039
Trace thickness	0.001	0.003

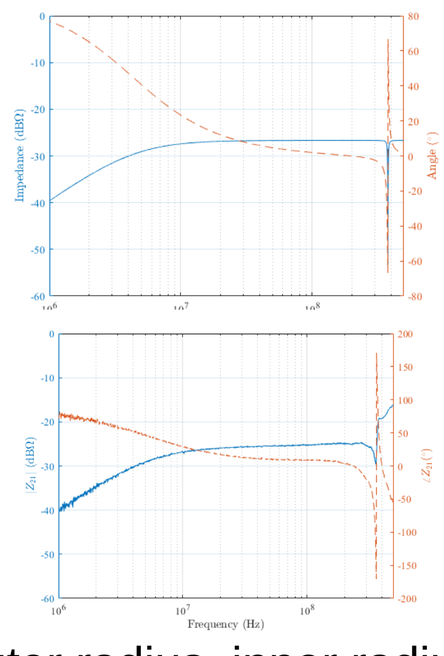
Gain		
Column	Main Effect	Total Effect
Load Resistor	0.58	0.6
Coil Height	0.161	0.192
Inner Radius	0.065	0.106
Shielding Height	0.063	0.091
Outer Radius	0.013	0.037
Via Diameter&Trace Width	0.015	0.027
Number of Turns	0.006	0.013
Trace thickness	5e-4	0.001

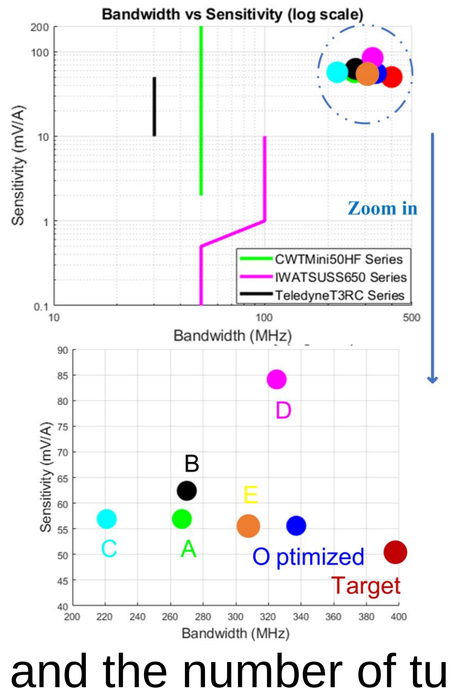
- DoEs involve generating a few representative, high-quality geometrical parameter input combinations.
- Sensitivity and bandwidth are calculated based on the analytical model in MATLAB
- Optimization results after model fitting by Neural Networks embedded in JMP

Experimental Verification and Comparison



Name of parameter	Change in parameter	Gain	High-frequency Bandwidth
Number of Turns	25%	-0.8%	-20.8% ↓
Inner radius	-5.6%	-4.0% ↓	-19.9% ↓↓
Outer Radius	5.9%	-0.8%	-34.4% ↓↓↓
Shielding Height	13.2%	-0.4%	-8.6%
Load resistance	42.2%	-14.3% ↓↓↓	-3.7%





- The outer radius, inner radius, and the number of turns are the most crucial factors in PCB Rogowski coil design

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