Modeling and design optimization of micro-inductor using genetic algorithm

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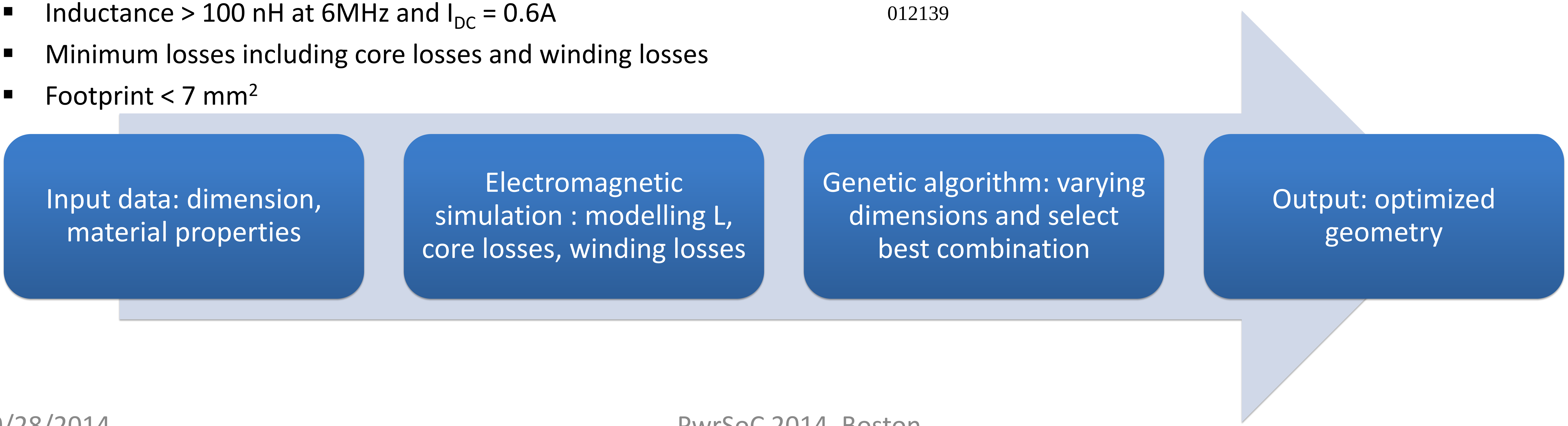
Introduction

This work focused on the miniaturization and design optimization of micro inductors.

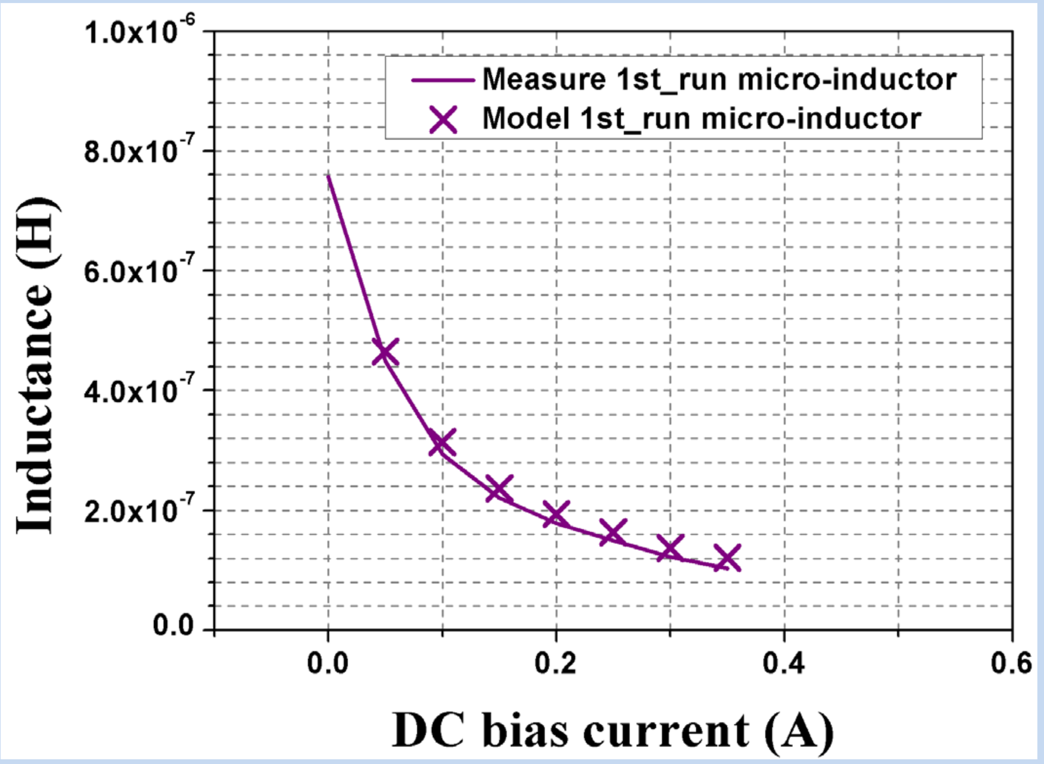
- Experimental approaches including monolithic and hybrid integration to realize ferrite-based integrated inductors have been investigated in our previous works [1] [2].
- Soft ferrite based micro-inductors with high performance in terms of inductance density and low losses have been proposed [1][2].
- In this work, 2D/3D finite element simulation in FEMM and Maxwell to model the electromagnetic behaviors of micro inductors was carried out.
- Optimization for micro-inductor was done using genetic algorithm
- Optimization criteria:
  - Inductance > 100 nH at 6MHz and I_{DC} = 0.6A
  - Minimum losses including core losses and winding losses
  - Footprint < 7 mm^2

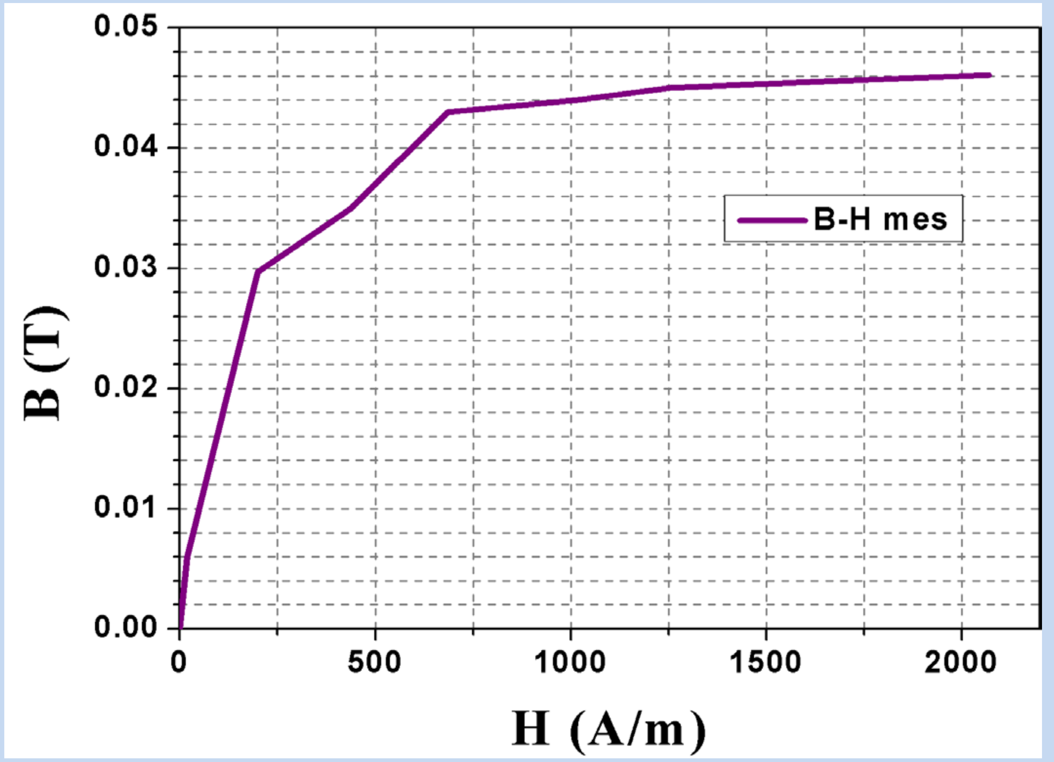
[1] Yen Mai Ng et al 2013 Low-profile small-size ferrite cores for powerSiP integrated inductors *Power Electronics and Applications (EPE), 15th European Conference (IEEE, Lille)*
[2] Yen Mai Ng et al 2013 Soft ferrite cores characterization for integrated micro-inductors *13th International Conference on Micro- and Nano-Technology for Power Generation and Energy Conversion Applications (PowerMEMS)Imperial Coll London, England, J. Phys.: Conf. Ser.* **476** 012139

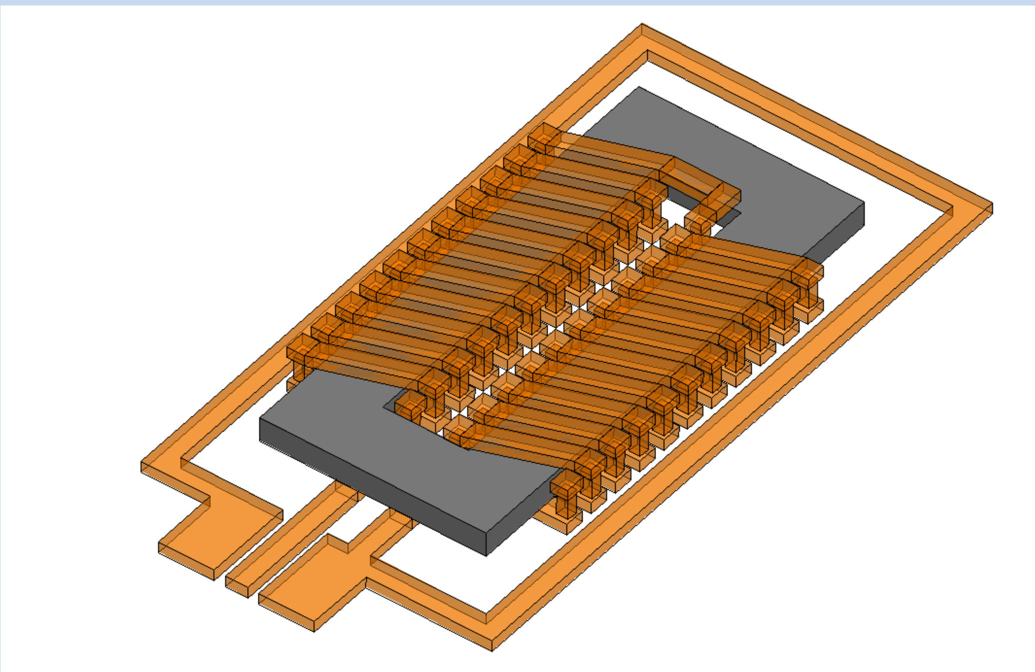


Material characterization with first run micro-inductor

- **Extrapolated dynamic non-linear B-H curve:**
  - Step 1: From measured curve L vs I_{DC}, simulation in Maxwell to obtain the raw non-linear B-H curve
  - Step 2: Using Maxwell solution for non-linear magnetic material, feed in the raw B-H curve
  - Step 3: Export the fine B-H curve extrapolated from Maxwell







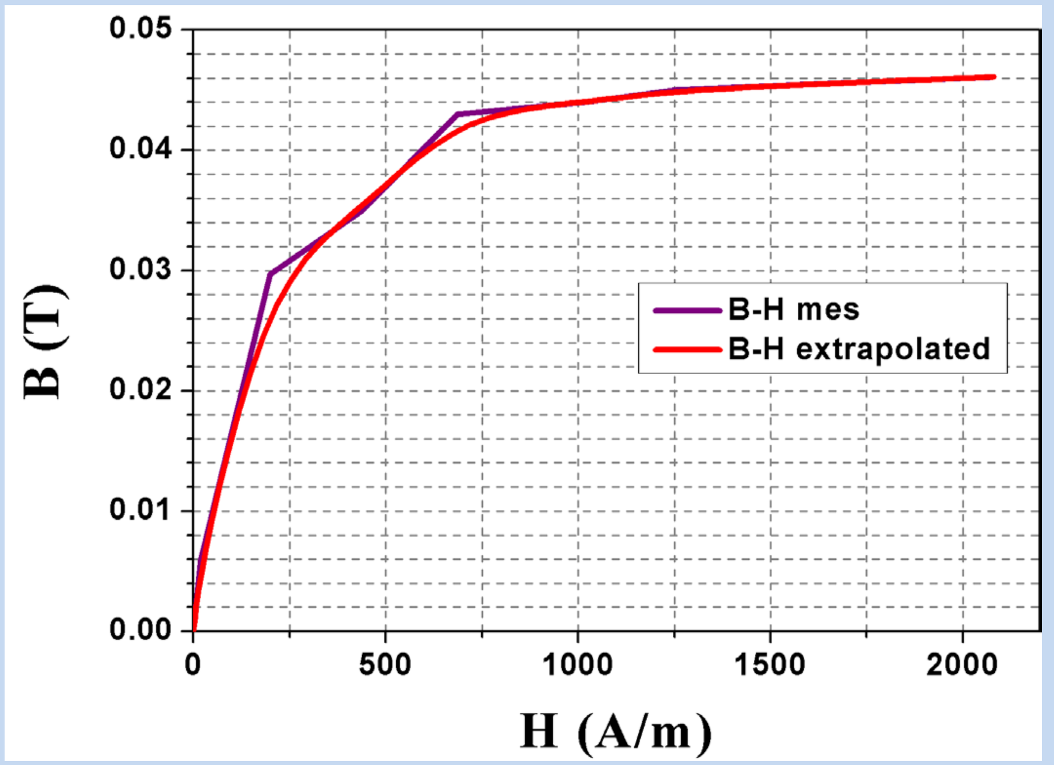


Fig 1: Model of micro-inductor simulated in Maxwell Ansoft 3D

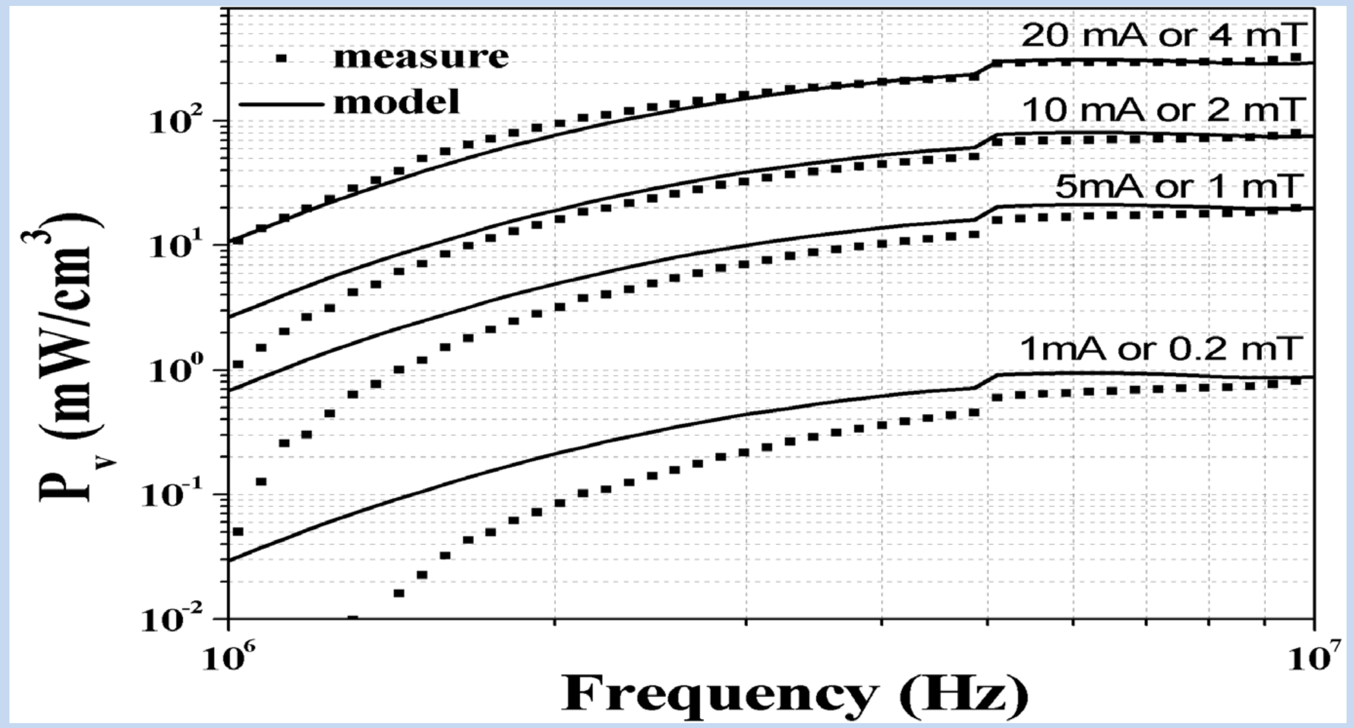
- **Loss model:**
  - Impedance measurement and extract losses

$$P_V = \frac{R_S * I_{AC}^2}{A_e * l_e}$$

  - Formula core losses Steinmetz

$$P_{core} = K f^{\alpha} B^{\beta}$$

  - Fitting result



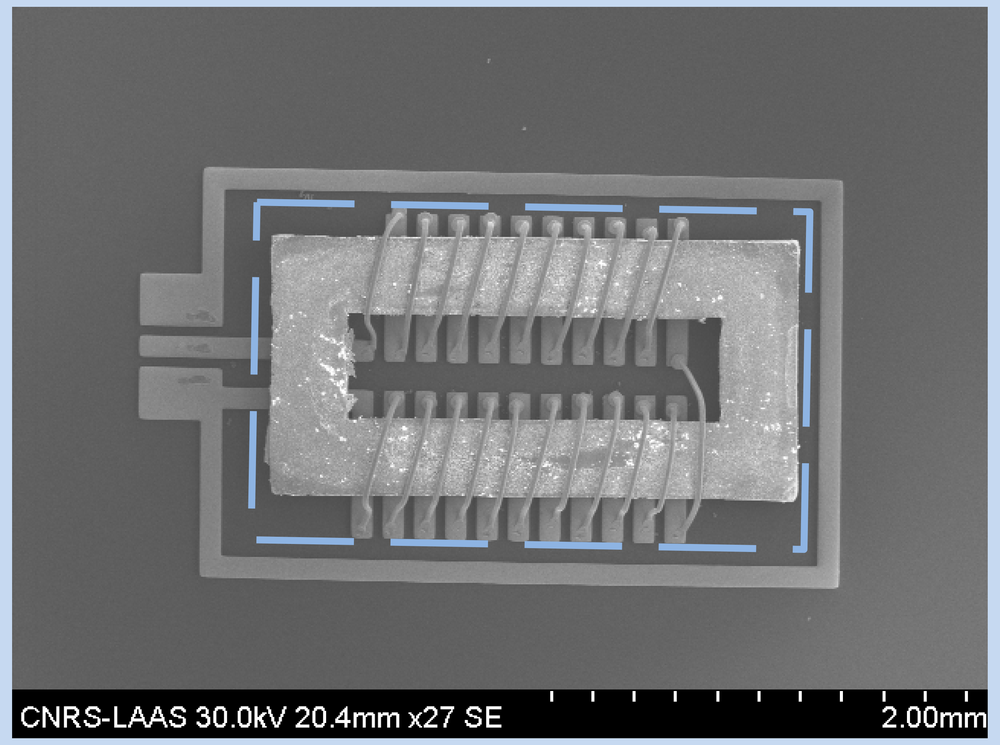


Fig 2: Ferrite-based test inductor with electroplated bottom Cu tracks and gold bond-wire as winding [2].

H_{DC} (A/m)	K	α	β
0	2.457E-08	2.071	1.79
244	0.241	1.014	1.688
488	258.935	0.64	1.77
732	5.018E4	0.372	1.852
1212	9.017E6	0.149	1.939
1708	7.31E7	0.081	1.97

These analytical loss models and the extrapolated non-linear B-H curves will be used in FEMM model for optimization.

Electromagnetic Modeling of inductor

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- Input: Dimension, material data (magnetic B-H curve, losses, copper properties), DC, AC current and frequency excitation.
- FEMM calculates B and H of all the meshed points. All other parameters like: winding losses, magnetic energy, magnetic flux in the core are known.
- Magneto-static simulation (F=0Hz) to calculate inductance in function of DC current: by energetic method or by flux method:

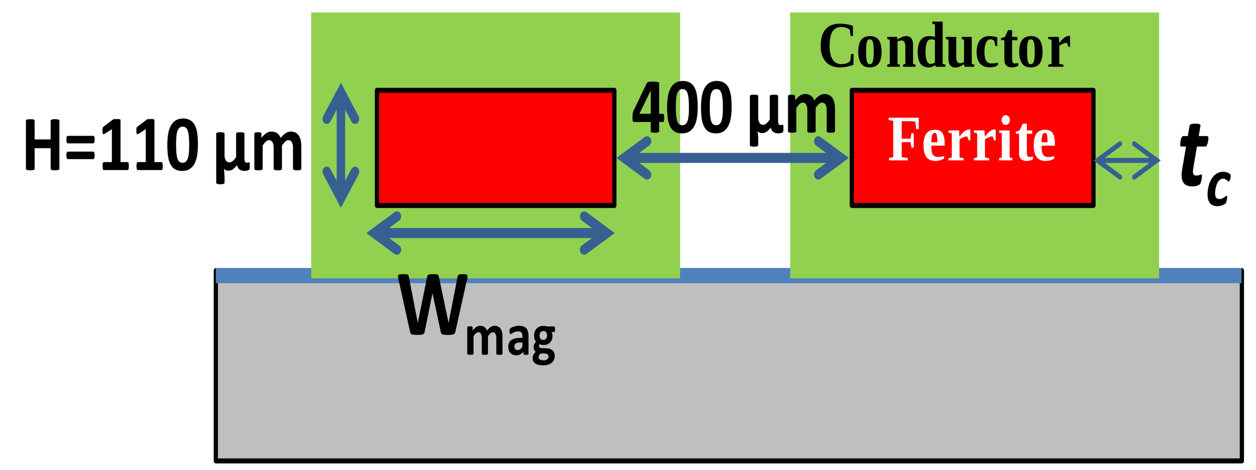
$$L_{flux} = \frac{\varphi_{core}}{I_{DC}} \qquad L_{energy} = \frac{2W_{magnetic}}{I_{DC}^2}$$

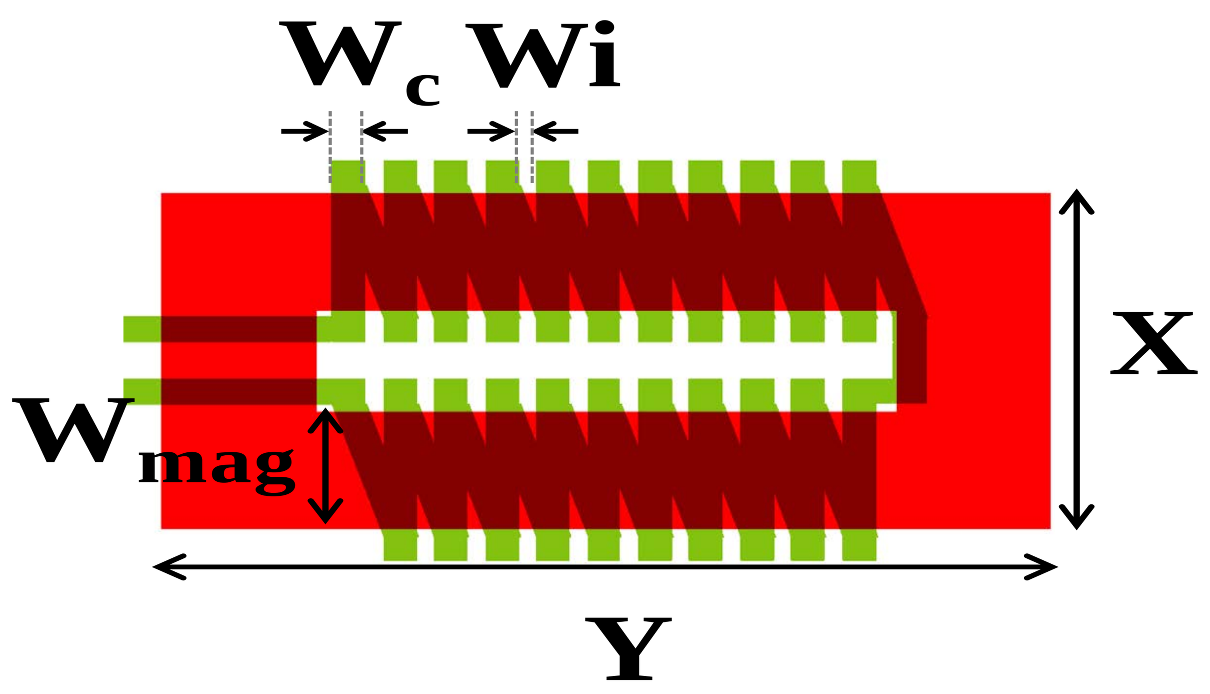
- Magneto-harmonic simulation (F=6MHz) to evaluate AC resistance of winding and core losses:

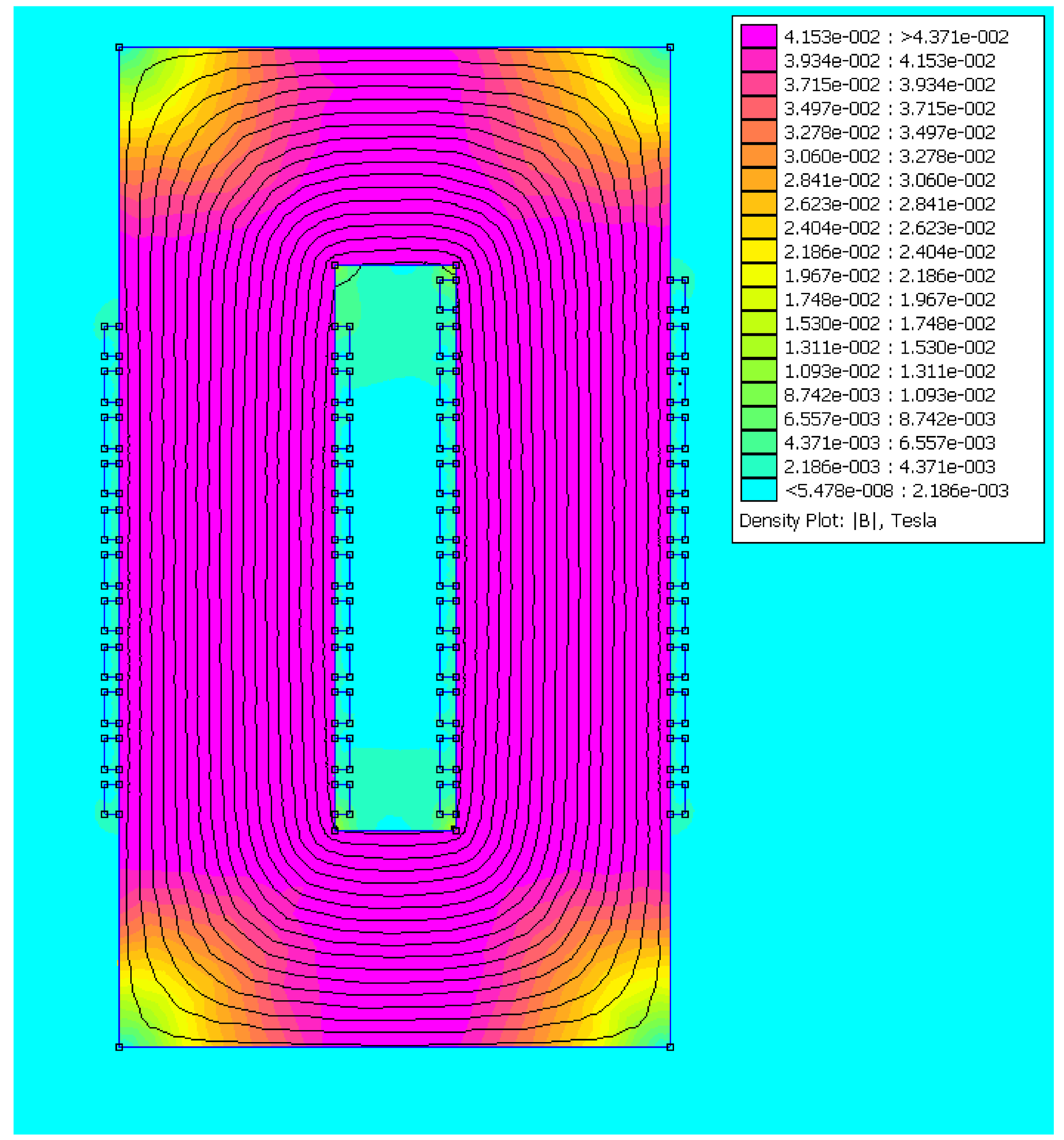
$$R_{AC} = \frac{P_{winding}}{I_{AC\_RMS}^2}$$

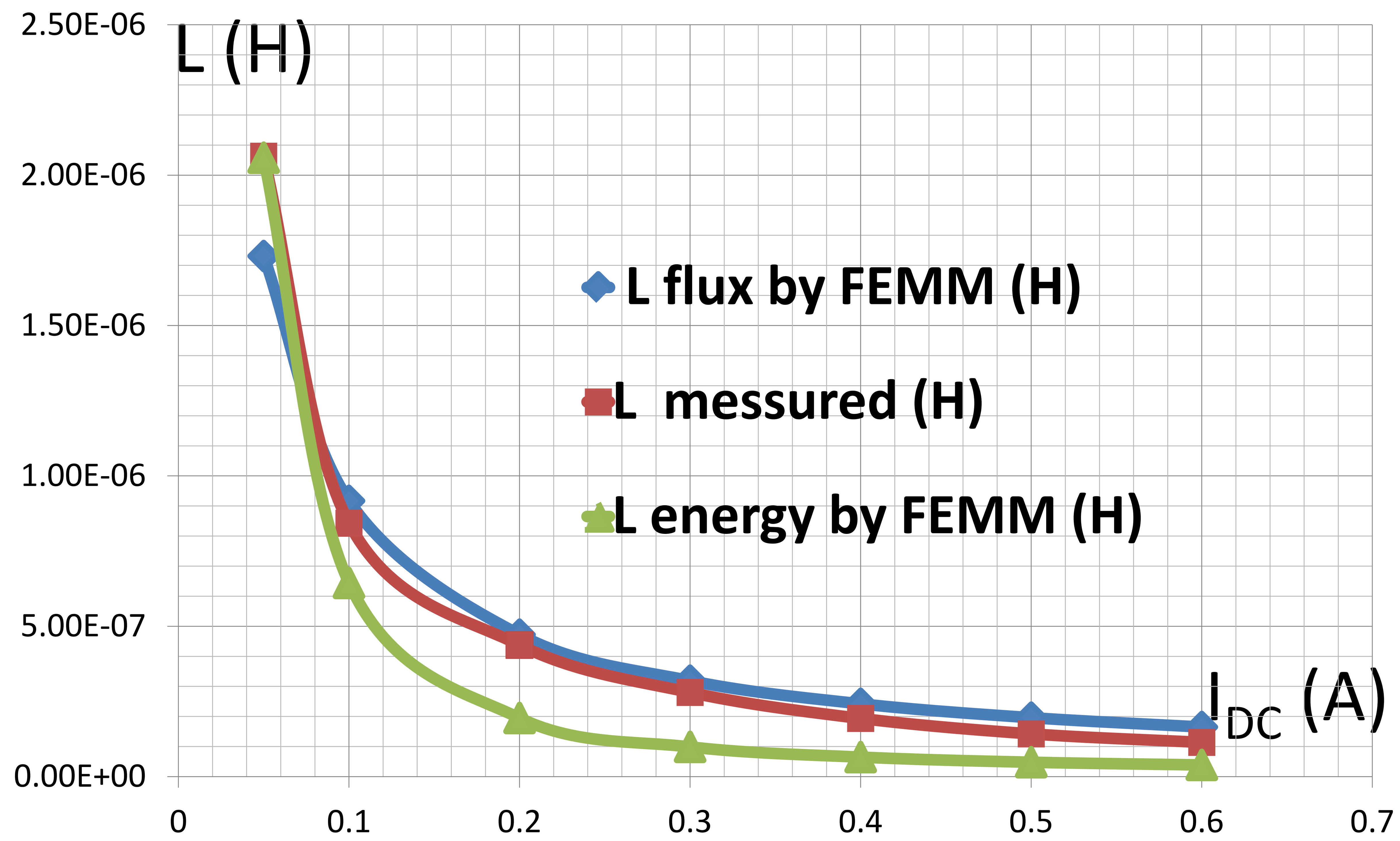
- Core losses calculation: as B is known at all the meshed points of the magnetic core. Core losses are deduced:

$$P_{core} = K \cdot f^{\alpha} \cdot \int_{core} B^{\beta} dV$$









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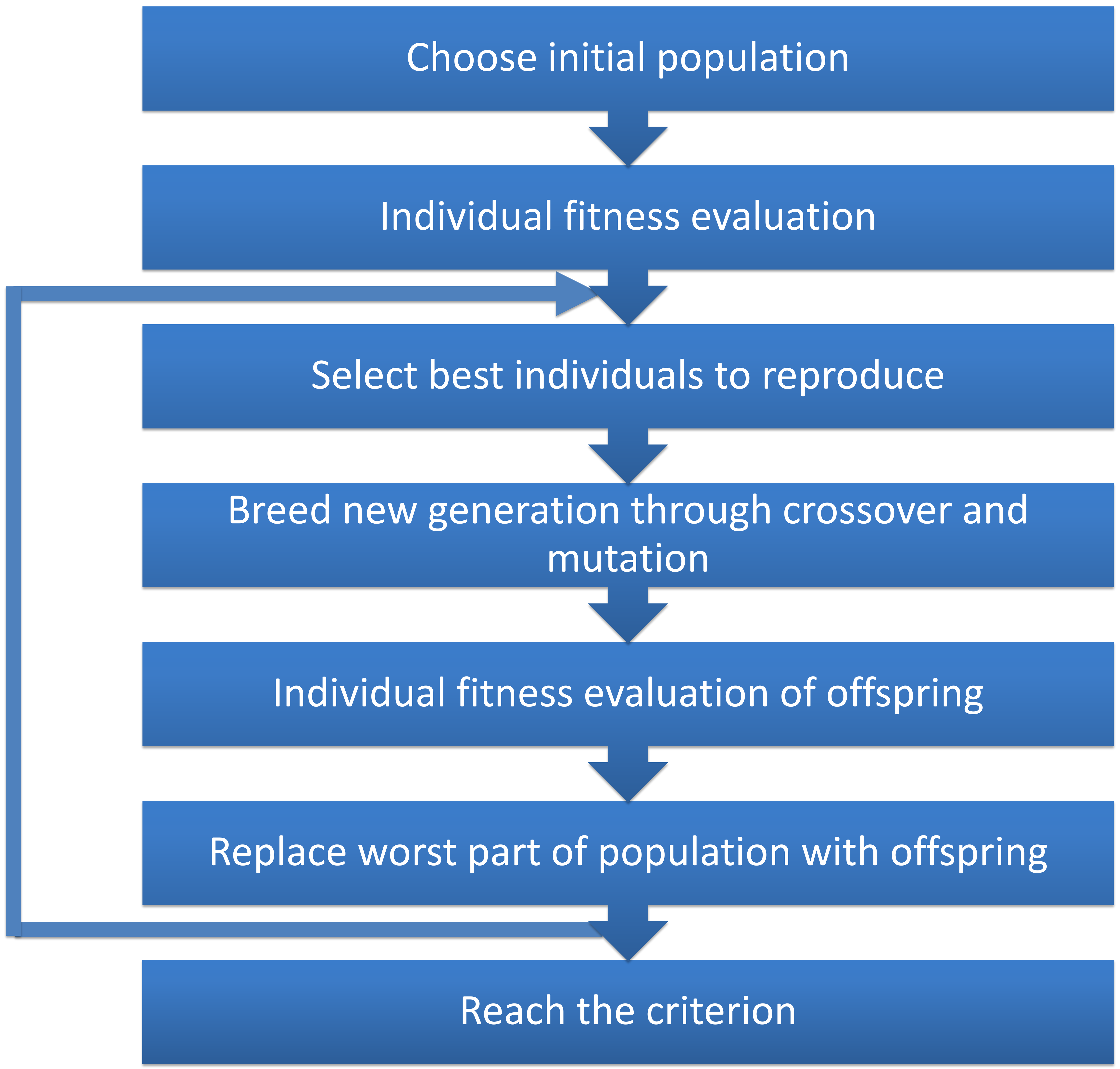
Optimization by genetic algorithm

- Based on natural genetics, technical algorithms is inspired by evolutionary

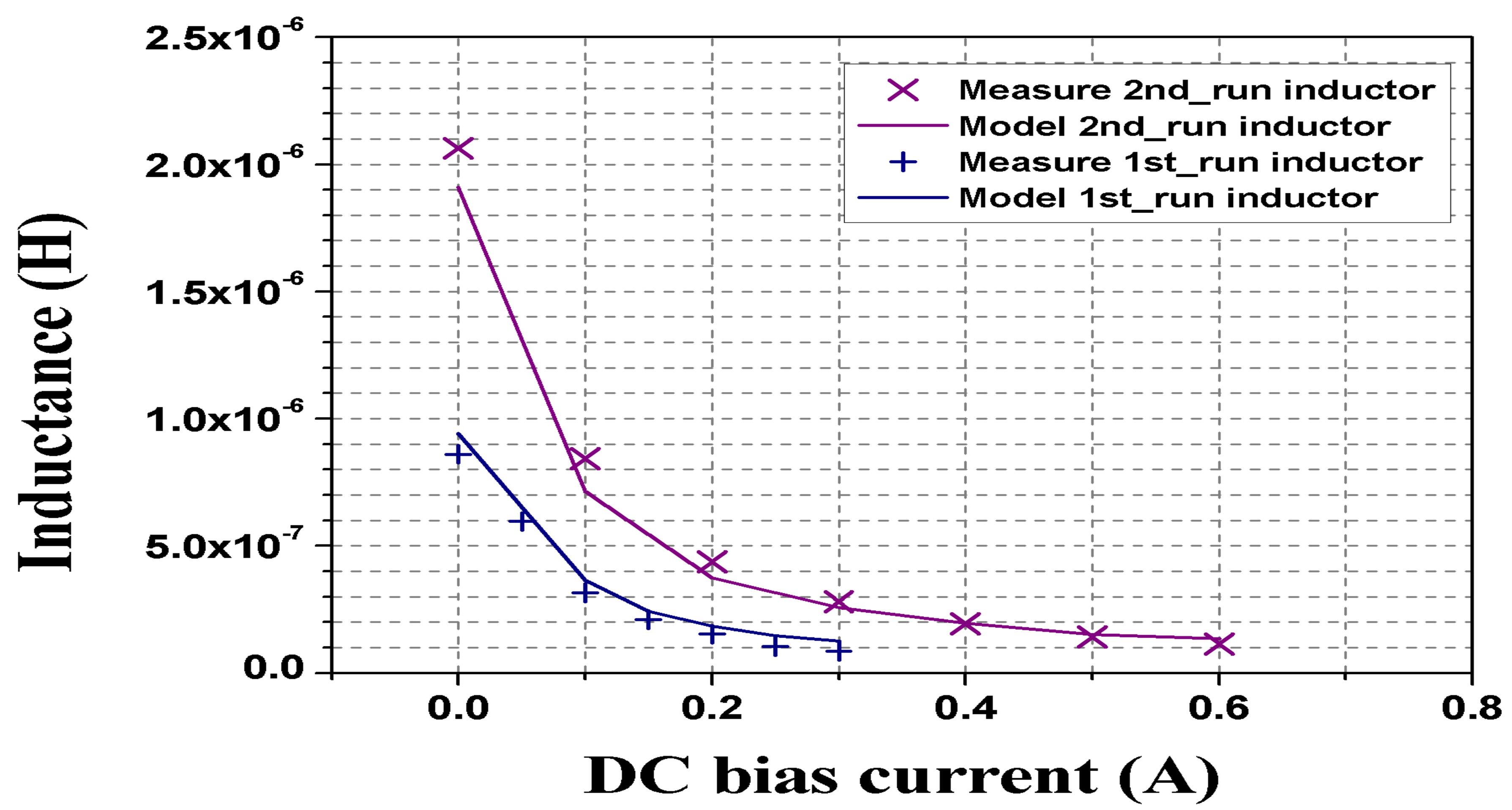


- Optimization result for micro inductor (2nd run versus 1st run)

Parameter	First run (not optimized)	Second run (optimized)
Number of turns N	21	27
Length Y [mm]	2.6	3.6
Width X [mm]	1.14	1.7
Depth H [mm]	0.11	0.11
Footprint [mm^2]	3	6
Magnetic core width Wmag [mm)	0.43	0.65
Conductor thickness t_c [µm]	50	55
Conductor width [µm]	100	105

Parameter	First run (not optimized)	Second run (optimized)
Inductance at 0.6A DC [nH] (6MHz, 20mA AC)	38	107
DC resistance [mΩ]	93*	140*
AC resistance at 6MHz [mΩ]	128*	180*
Core losses [mW]	0.012* (37 mW/cm^3) 0.033 (101 mW/cm^3)	0.033* (49 mW/cm^3) 0.067 (99 mW/cm^3)
Energy density [nJ/mm3]	21.0*	28.6*
Quality factor ($2\pi f\ L/R_{AC}$)	11*	22*

(* *According to the calculation*)



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Fabrication of micro inductor:

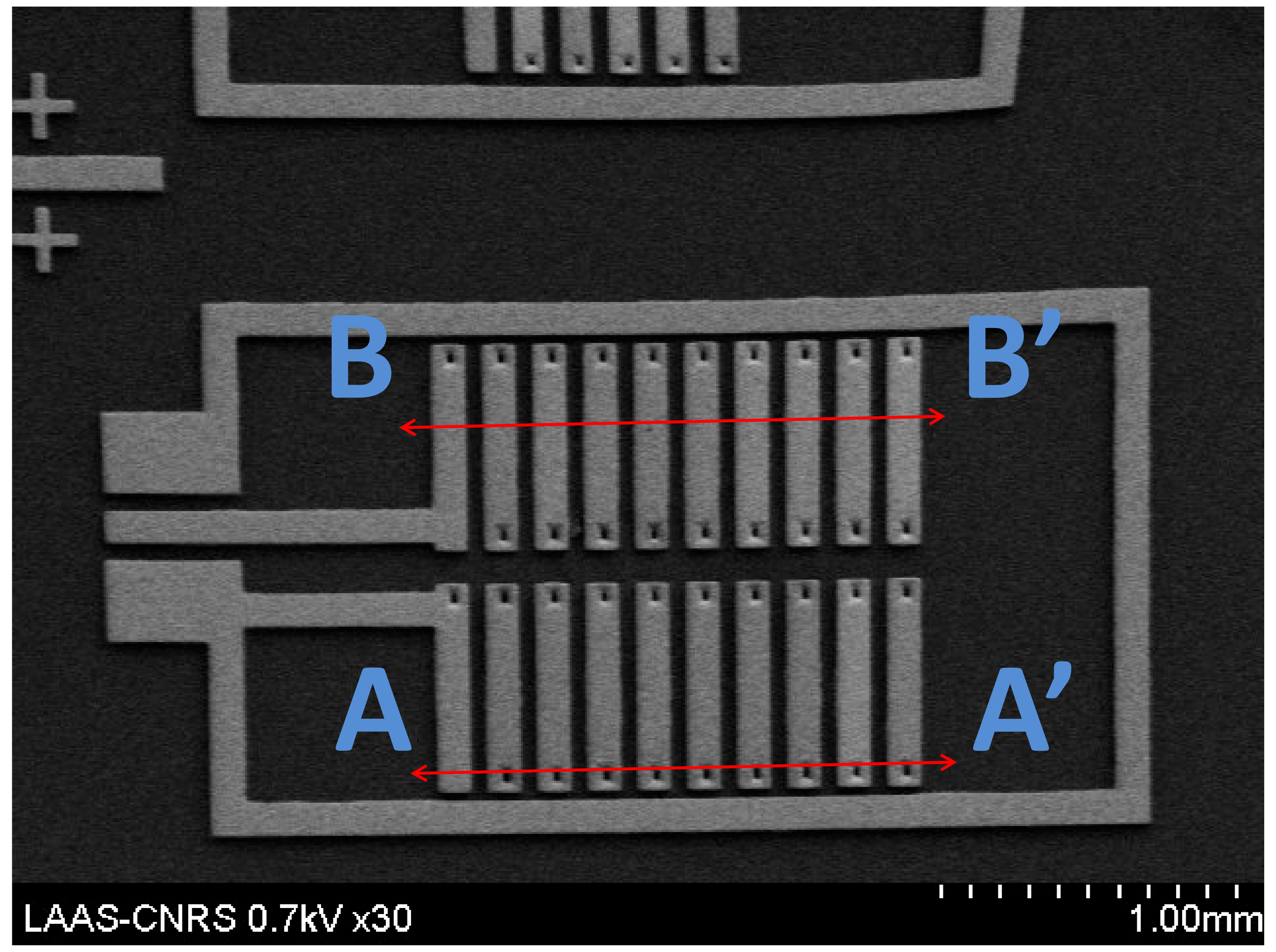

Fig 3: Top view of fabricated micro-inductor

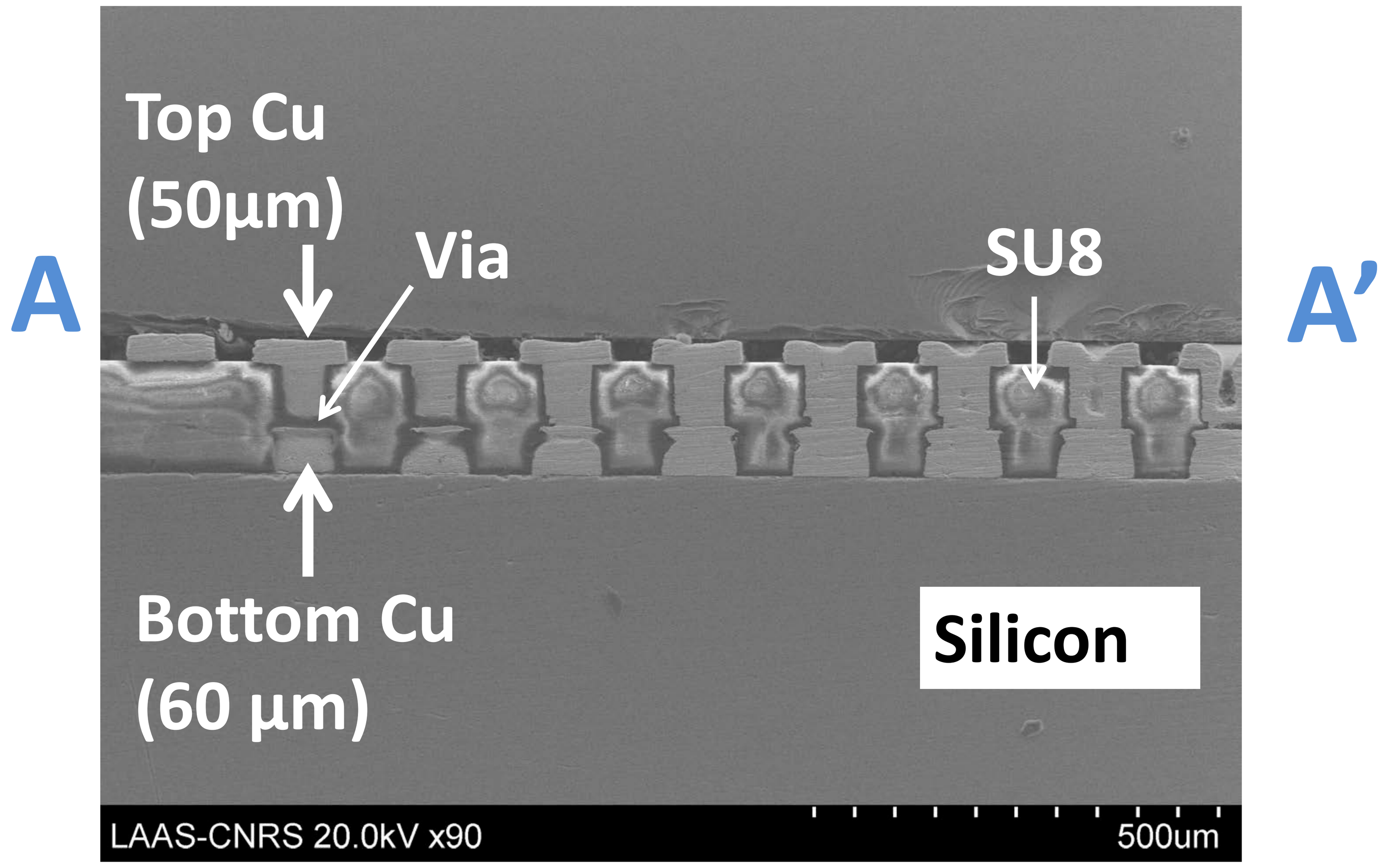

Fig 4: Cross section of electroplated top copper tracks-copper vias – bottom copper tracks

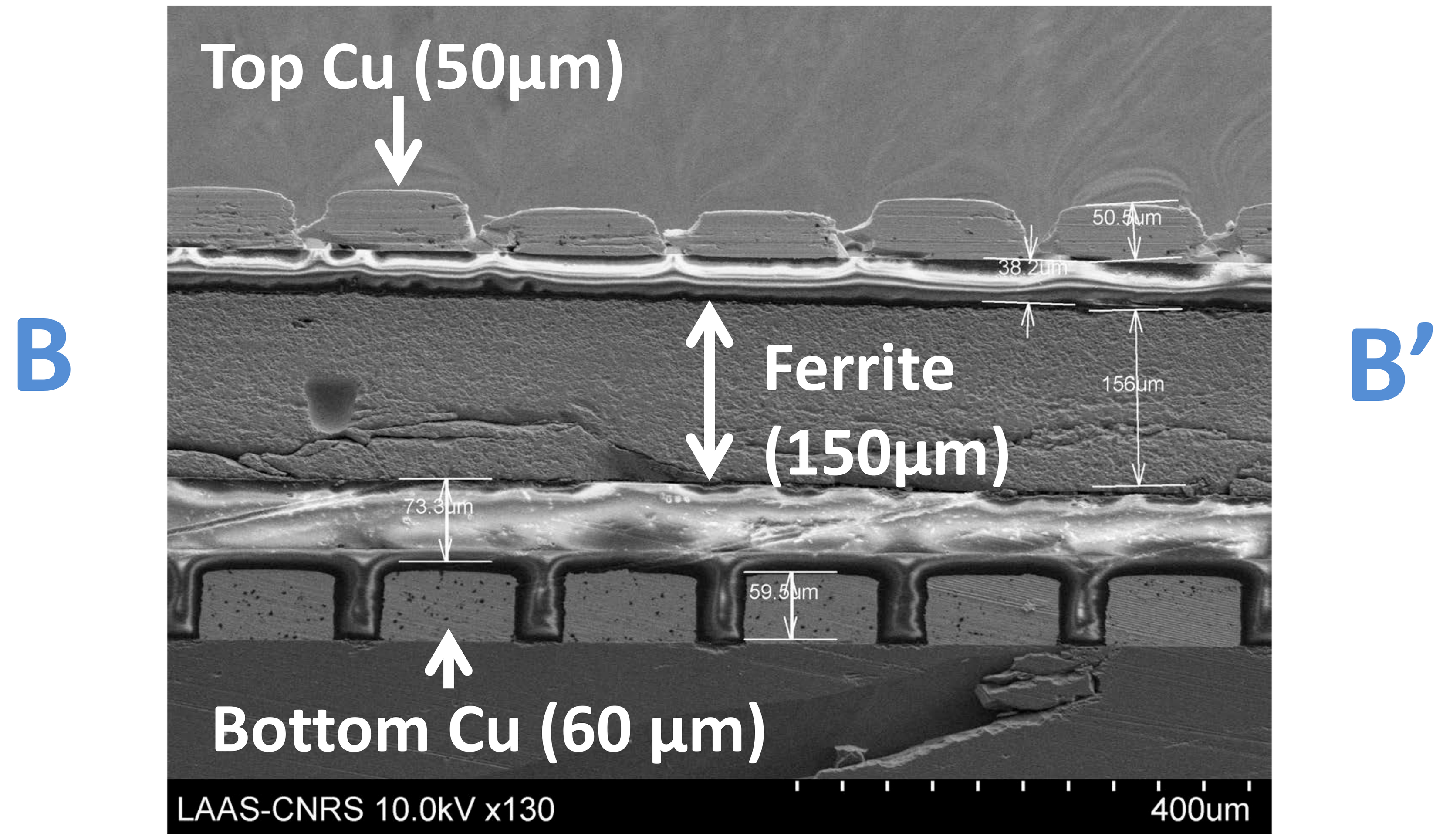

Fig 5: Cross section of electroplated top copper tracks-ferrite core – bottom copper tracks (to be added before submission)

Conclusions

- Electromagnetic behaviors have been simulated by finite elements method.
- A micro-inductor was optimized by genetic algorithm and finite element simulation.
- The 2nd_run inductor with optimization has proved better performance than the first run micro inductor with higher energy density by factor of 1.4 and higher quality factor by factor of 2.

Perspectives

- Problem to be solved: Finish the winding by electroplated copper to realize final micro-inductor and measure the DC and AC resistances.
- Measure losses and obtain the analytical model in the condition close to the real operation mode i.e. triangular signal
- Computation speed to be improved by simplifying the inductor model in FEMM by modeling half or quarter of symmetrical geometry.