FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF INFORMATION TECHNOLOGY
RESEARCH GROUP ELECTROMAGNETICS

A FULLY 3-D BIE EVALUATION OF THE RESISTANCE AND INDUCTANCE OF ON-BOARD AND ON-CHIP INTERCONNECTS

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OUTLINE

- Motivation
- Proposed technique
- Examples
- Conclusions

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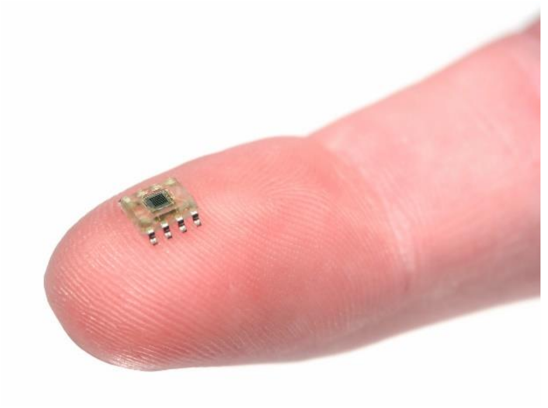
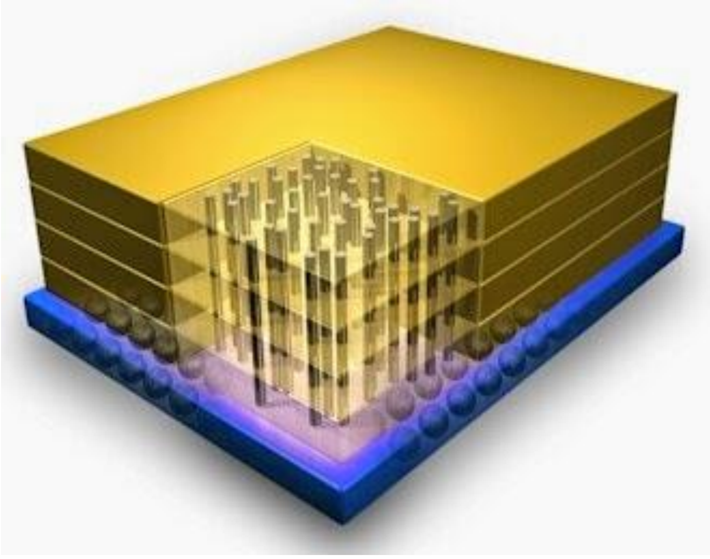
MOTIVATION

Smaller & faster electronics



Increasing complexity,
functionality,
signal integrity,
power constraints, …

New solutions such as 3-D ICs



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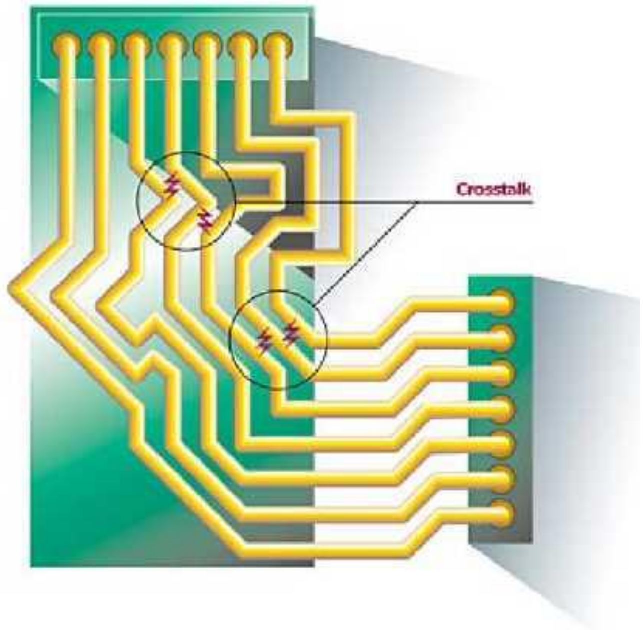
MOTIVATION

Many challenges

Heat distribution

Signal integrity (crosstalk, dispersion, distortion, …)



Rigorous modeling increasingly essential !

PROBLEM STATEMENT

- Finite conductivity, skin effect, proximity effect

  $\longrightarrow$ difficult to model broadband

- Solved in 2-D [1, 2] using a Dirichlet-to-Neumann operator
- Open question in 3-D
- Recently proposed for 3-D cylinders and cuboids [3, 4]

[1] D. De Zutter and L. Knockaert, IEEE MTT, vol. 53, pp. 2526-2538 (2005)
[2] T. Demeester and D. De Zutter, IEEE MTT, vol. 56, pp. 1649-1660 (2008)
[3] M. Huynen, M. Gossye, D. De Zutter and D. Vande Ginste, IEEE AWPL, vol. 16, pp. 1052-1055 (2017)
[4] M. Huynen, D. De Zutter and D. Vande Ginste, accepted for IEEE MWCL

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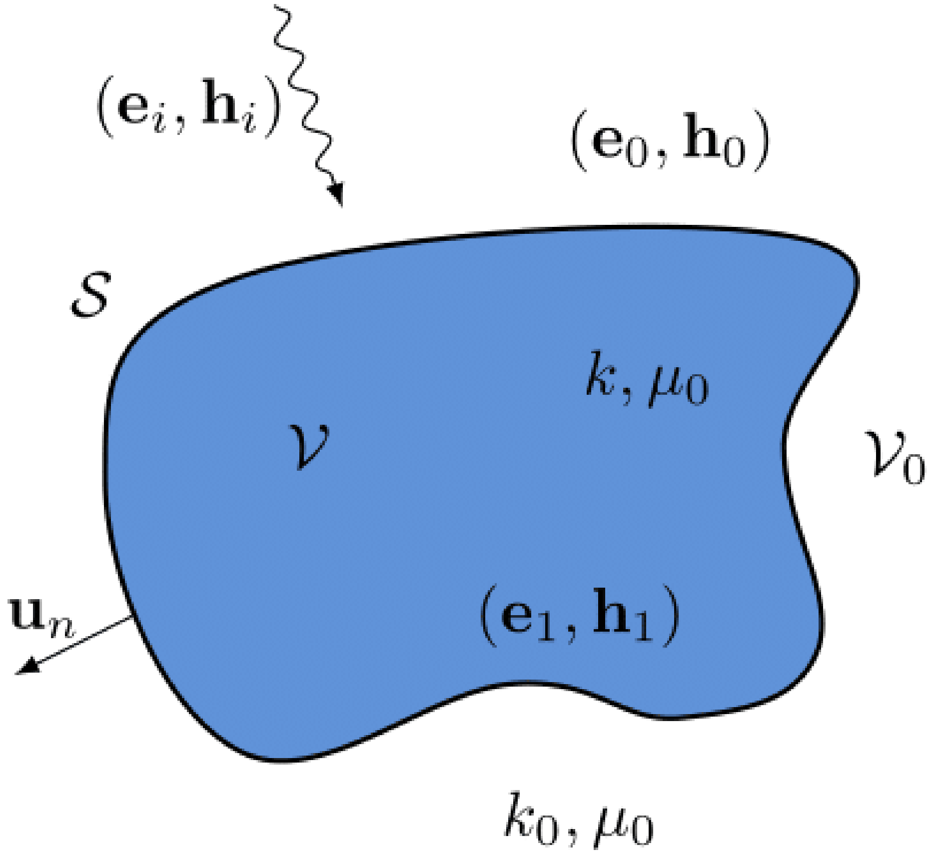
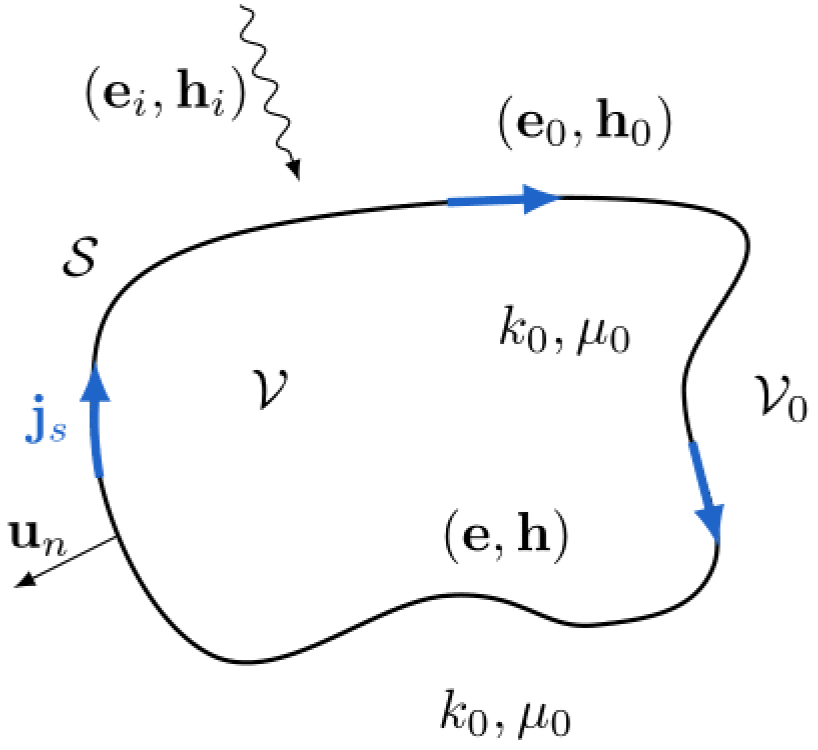
PROPOSED TECHNIQUE



Original situation

Field equivalence principle

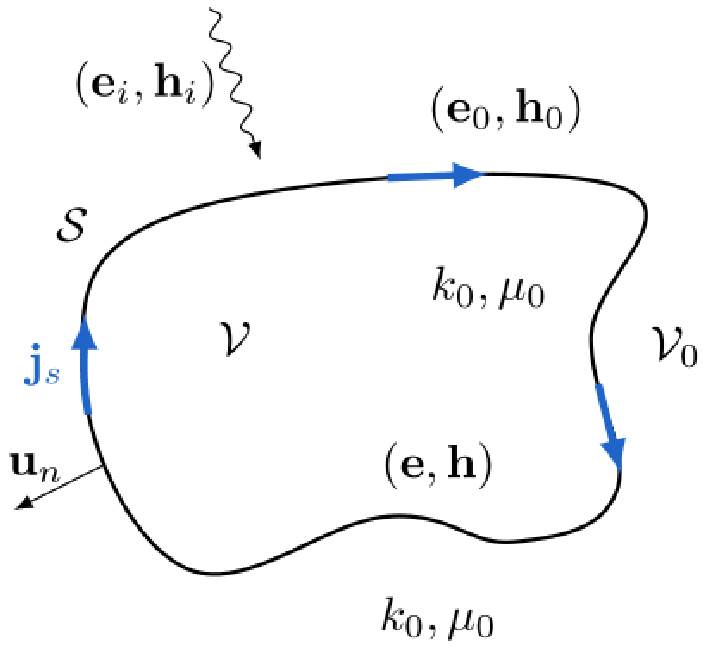


Equivalent situation

PROPOSED TECHNIQUE

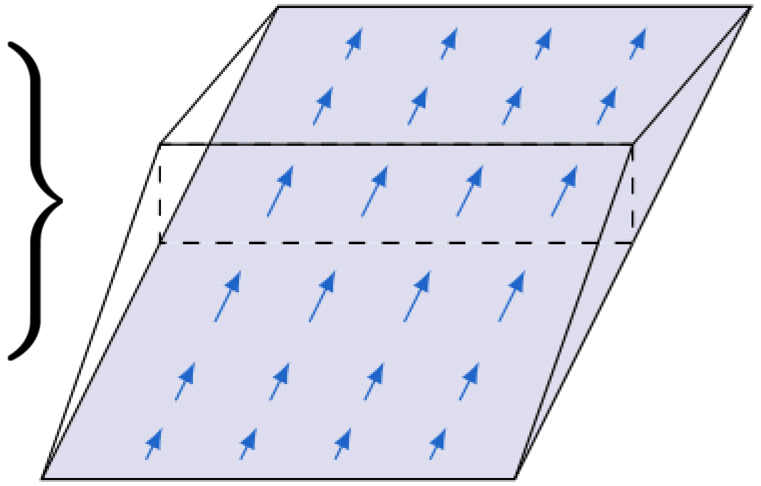
Electric field integral equation

$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega\mathbf{a} - \nabla\phi$$

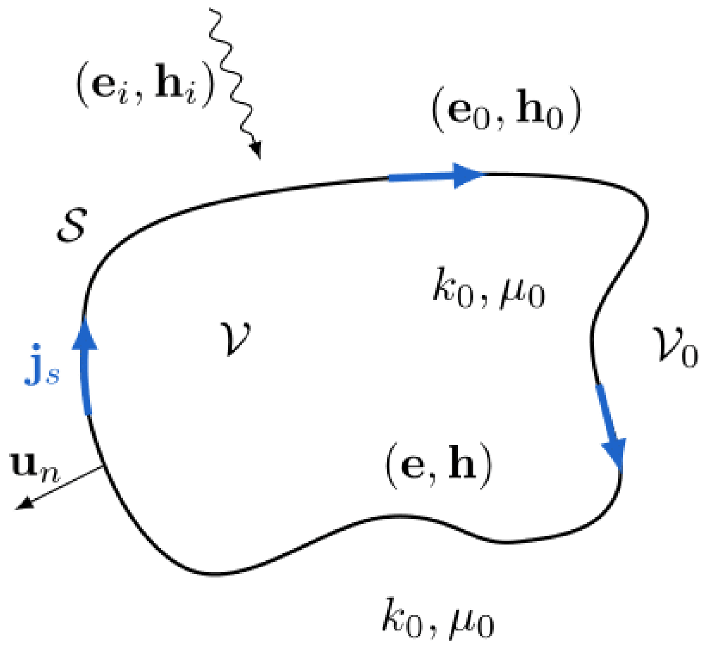


Test and basis functions

$$\begin{Bmatrix} \mathbf{j}_s \\ \mathbf{e}_0 \end{Bmatrix} = \sum_m \begin{Bmatrix} I_m \\ E_{0,m} \end{Bmatrix}$$



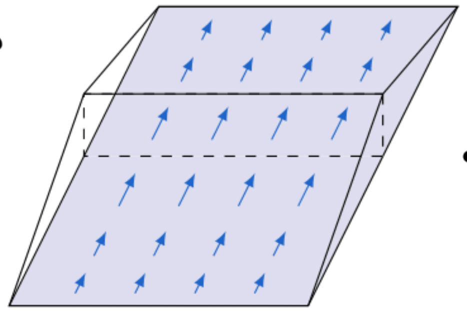
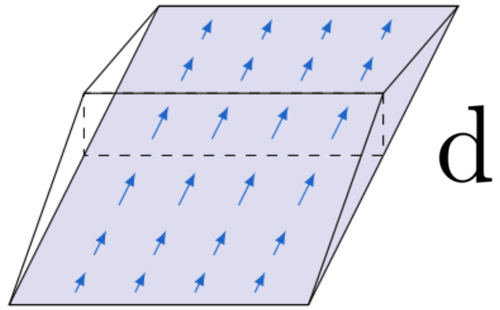
PROPOSED TECHNIQUE



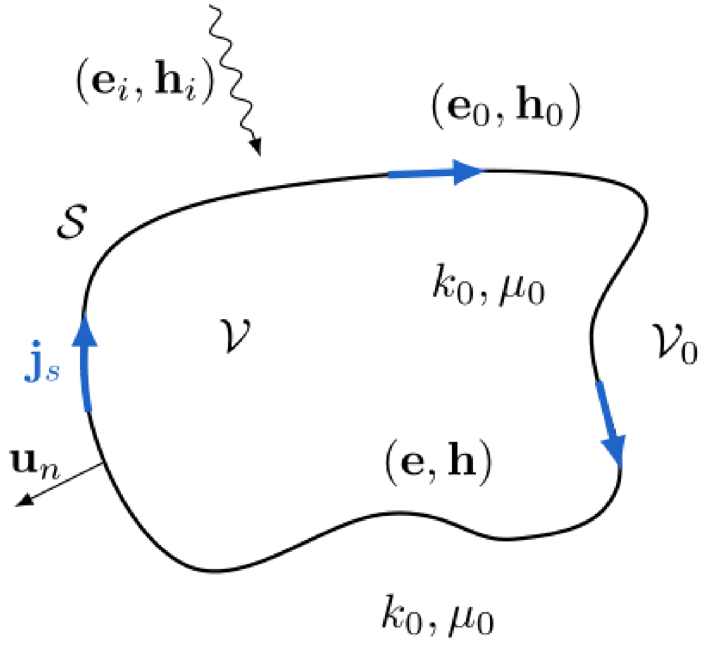
$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega\mathbf{a} - \nabla\phi$$

Discretization

$$\overline{\overline{G}}\mathbf{E}_0$$

$$\overline{\overline{G}}_{m,n} = \int_{\mathcal{S}}$$  $\cdot$  $\mathrm{d}S$

PROPOSED TECHNIQUE

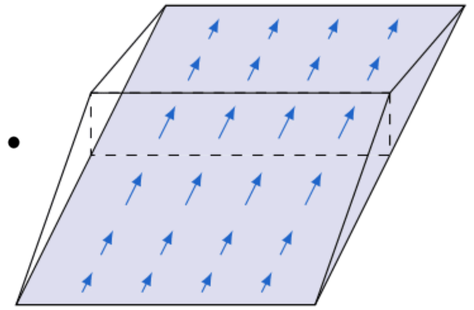


$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega\mathbf{a} - \nabla\phi$$

Discretization

$$\overline{\overline{G}}\mathbf{E}_0 \quad - \quad \mathbf{V}_i$$

$$(\mathbf{V}_i)_m = \int_{\mathcal{S}_m} \mathbf{e}_i \cdot$$



$$\mathrm{d}S$$

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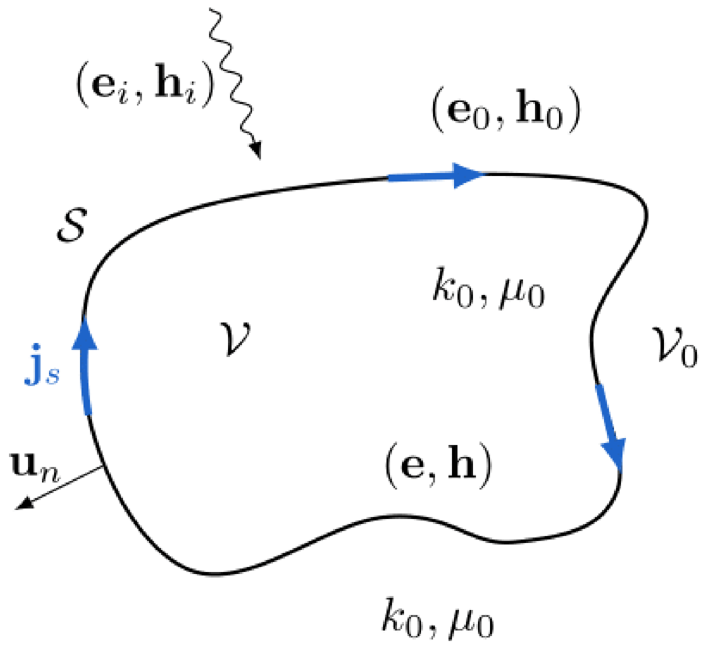
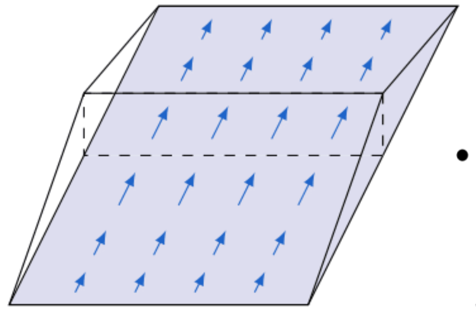
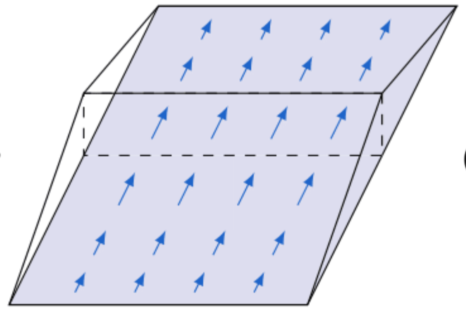
PROPOSED TECHNIQUE



$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega\mathbf{a} - \nabla\phi$$

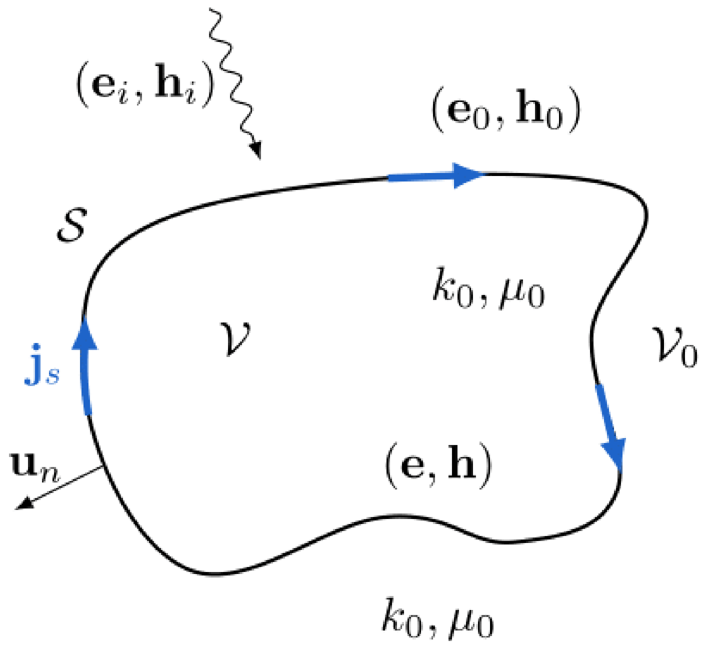
Discretization

$$\overline{\overline{G}}\mathbf{E}_0 - \mathbf{V}_i = -j\omega\overline{\overline{L}}\mathbf{I}$$

$$\mathbf{L}_{m,n} = \mu_0 \int_{\mathcal{S}_m}\int_{\mathcal{S}_n} G\left(\mathbf{r}, \mathbf{r}'\right)$$  $\cdot$  $\mathrm{d}S$

PROPOSED TECHNIQUE

$$\mathbf{e}_0 - \mathbf{e}_i = -j\omega\mathbf{a} - \nabla\phi$$



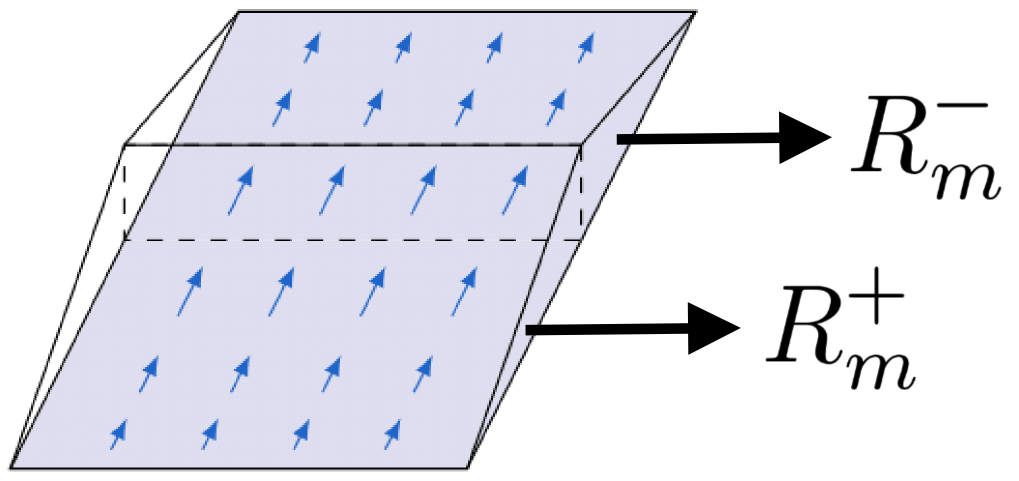
Discretization

$$\overline{\overline{G}}\mathbf{E}_0 - \mathbf{V}_i = -j\omega\overline{\overline{L}}\mathbf{I} + \mathbf{V}^+ - \mathbf{V}^-$$

Via partial integration:

$$\mathbf{V}_m^{\pm} = \int_{R_m^{\pm}} \frac{\phi}{A_m^{\pm}} \mathrm{d}S$$

Average potential
on each rectangle $R_m^{\pm}$



PROPOSED TECHNIQUE

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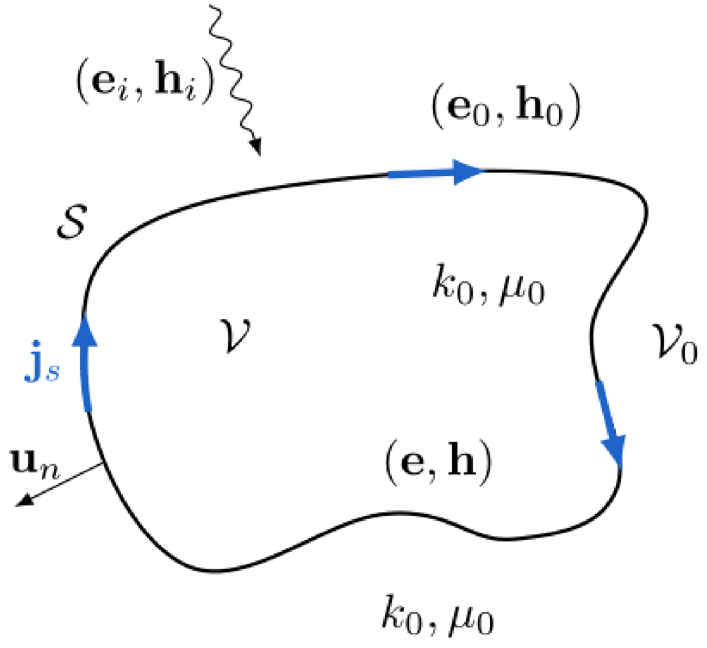
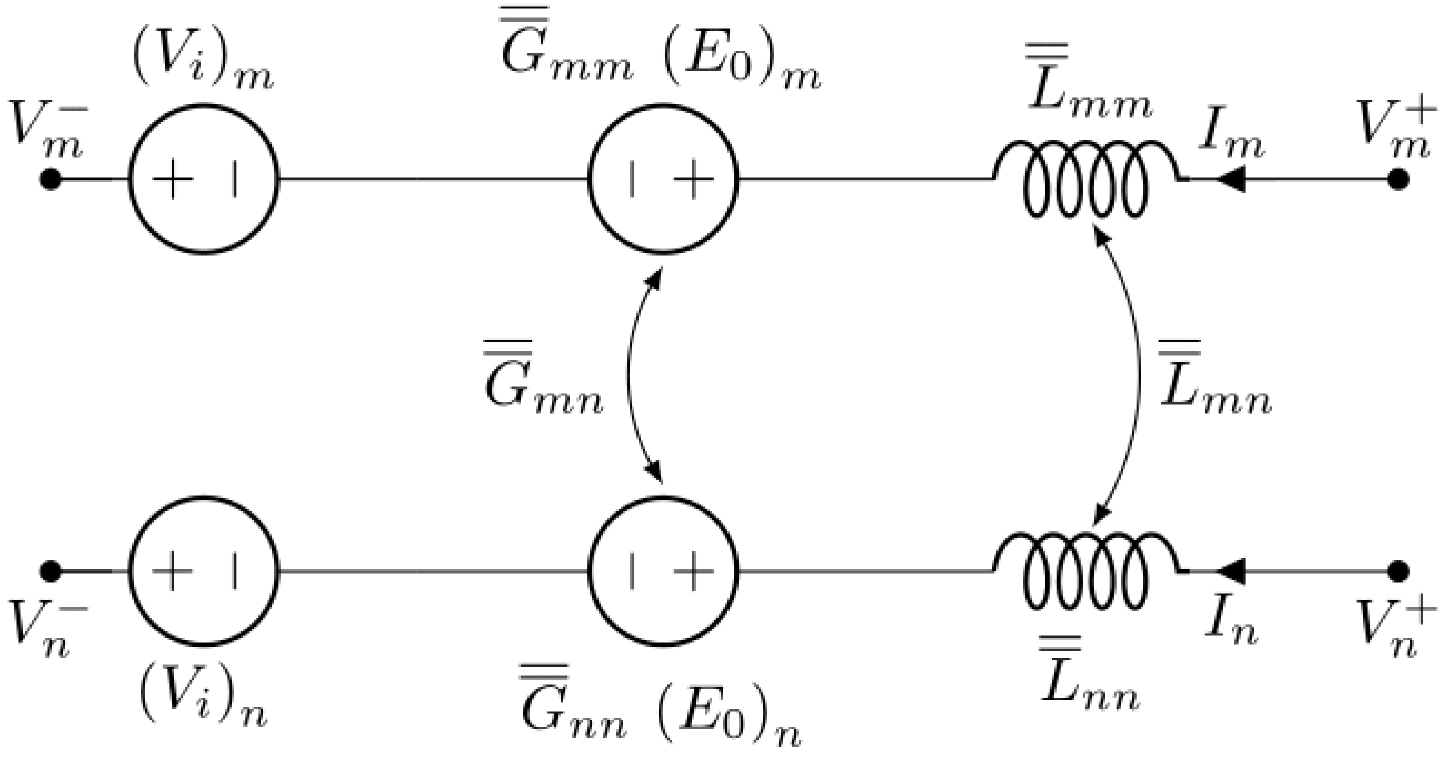


Circuit interpretation

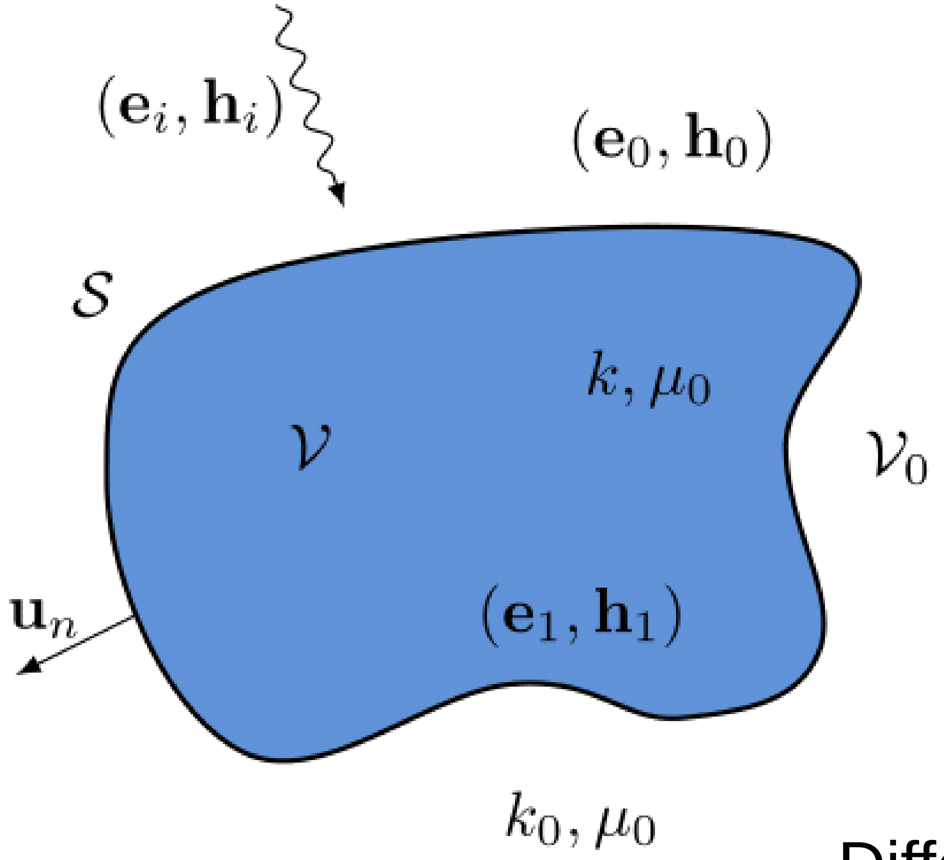


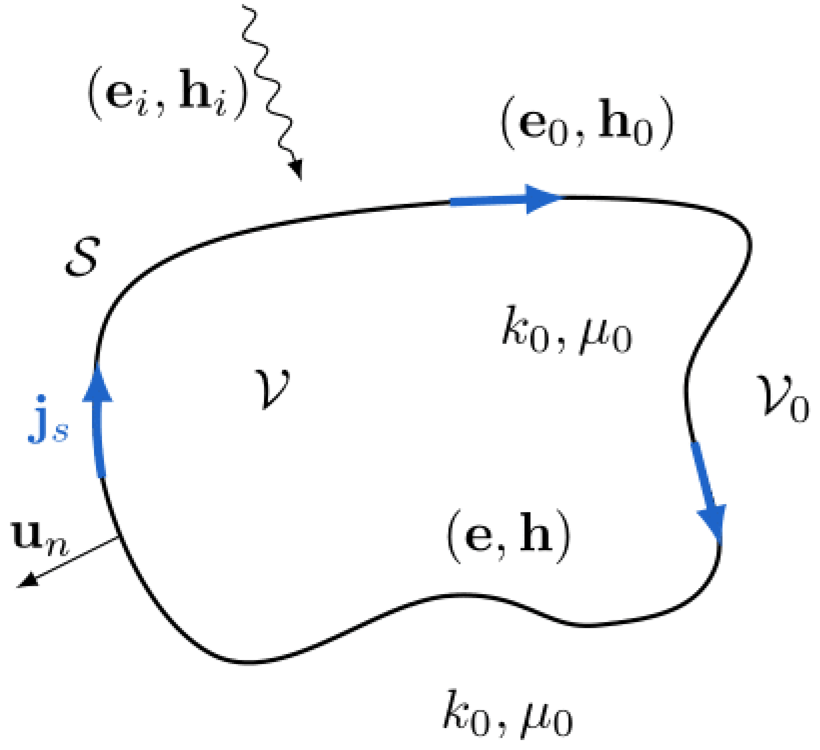
Still 2 sets of unknowns:

- $\mathbf{I}$
- $\mathbf{E}_0$

PROPOSED TECHNIQUE

3-D Dirichlet-to-Neumann operator $\mathcal{D}_k$ [3, 4]





Differential surface admittance operator

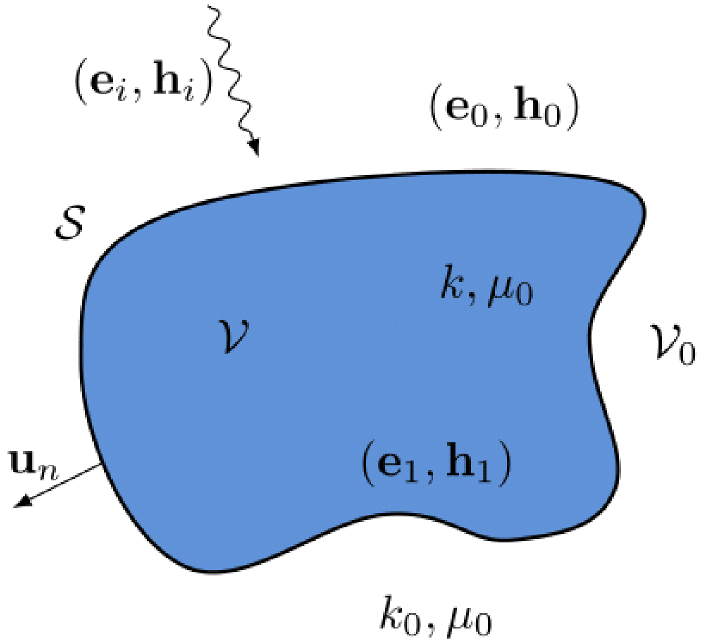
$$\mathbf{u}_n \times \mathbf{h}_1 = \mathcal{D}_k \mathbf{e}_1^t$$

$$\mathbf{u}_n \times \mathbf{h} = \mathcal{D}_{k_0} \mathbf{e}^t$$

$$\Rightarrow \mathbf{j}_s = \mathcal{Y}\mathbf{e}_0^t = \left(\mathcal{D}_k - \mathcal{D}_{k_0}\right)\mathbf{e}_0^t$$

[3] M. Huynen, M. Gossye, D. De Zutter and D. Vande Ginste, IEEE AWPL, vol. 16, pp. 1052-1055 (2017)
[4] M. Huynen, D. De Zutter and D. Vande Ginste, accepted at IEEE MWCL

PROPOSED TECHNIQUE



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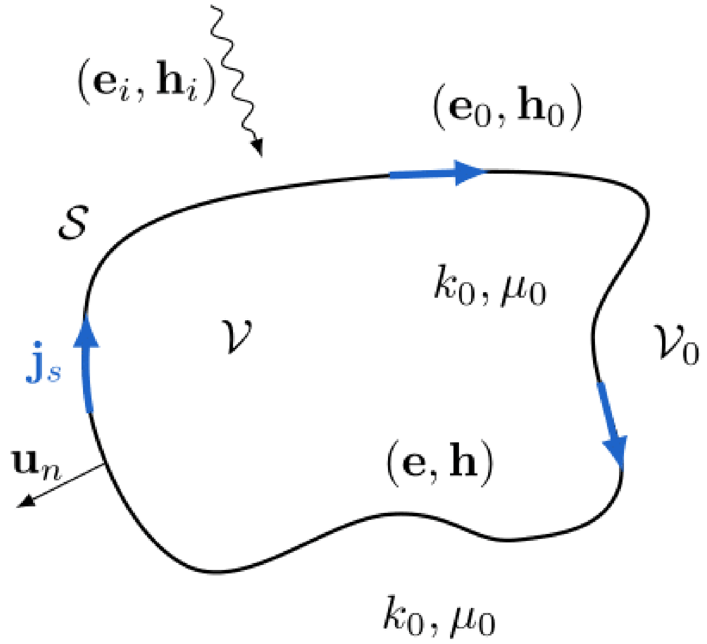


$$\mathbf{j}_s = \eta \sum_l \left[\frac{|k_l|^2}{\left(k_l^2 - k^2\right)\left(k_l^2 - k_0^2\right)\mathcal{N}_l^2} \int_{\mathcal{S}} \left(\mathbf{u}_n \times \mathbf{e}_0\right) \cdot \mathbf{h}_l^* \, \mathrm{d}S \right] \left(\mathbf{u}_n \times \mathbf{h}_l\right)$$

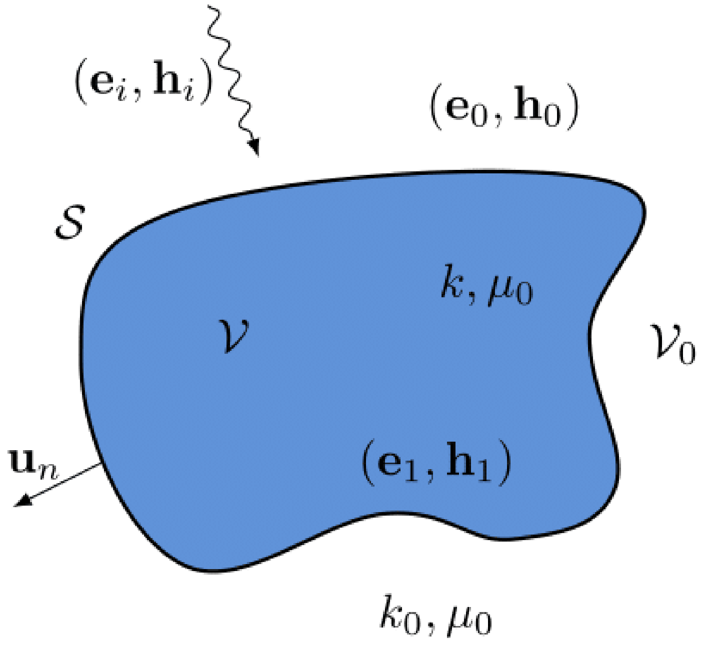
η: $\sigma_0 - \sigma + j\omega\left(\epsilon_0 - \epsilon\right)$

Wavenumber of $\mathbf{h}_l$

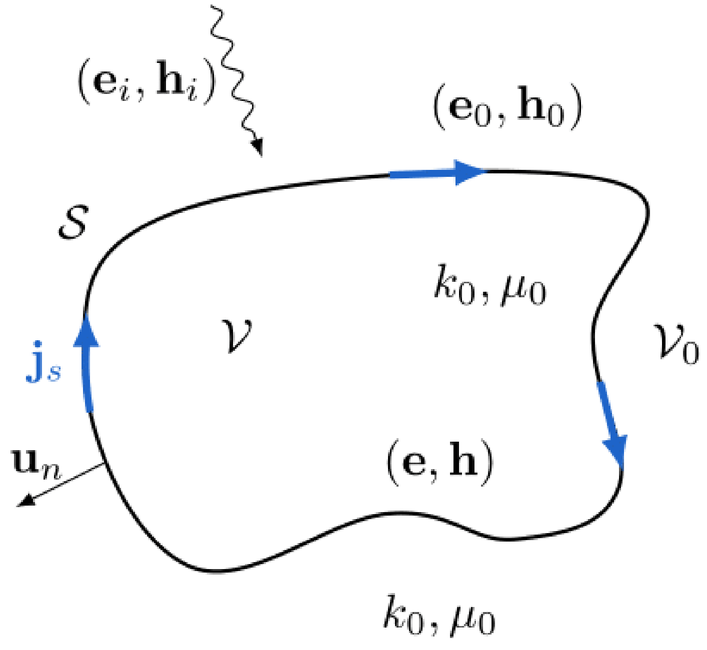
Magnetic eigenfunctions of $\mathcal{V}$

Normalization of $\mathbf{h}_l$

PROPOSED TECHNIQUE



$$\mathbf{j}_s = \mathcal{Y}\mathbf{e}_0^t = (\mathcal{D}_k - \mathcal{D}_{k_0})\,\mathbf{e}_0^t$$



Discretization

$$\mathbf{E}_0 = \left(\overline{\overline{Y}}^{-1}\,\overline{\overline{G}}\right)\mathbf{I}$$

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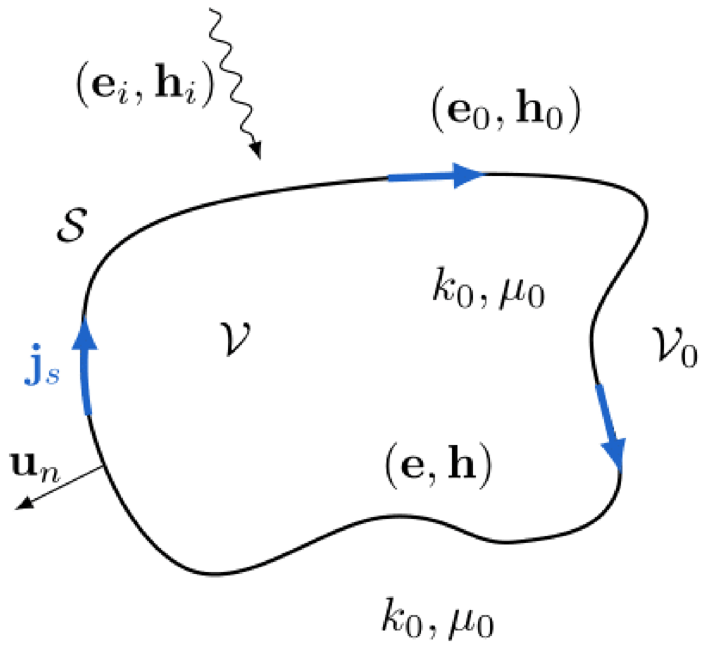
PROPOSED TECHNIQUE

$$\left(\overline{\overline{G}}\,\overline{\overline{Y}}^{-1}\overline{\overline{G}}\right)\mathbf{I} - \mathbf{V}_i = -j\omega\overline{\overline{L}}\mathbf{I} + \mathbf{V}^+ - \mathbf{V}^-$$



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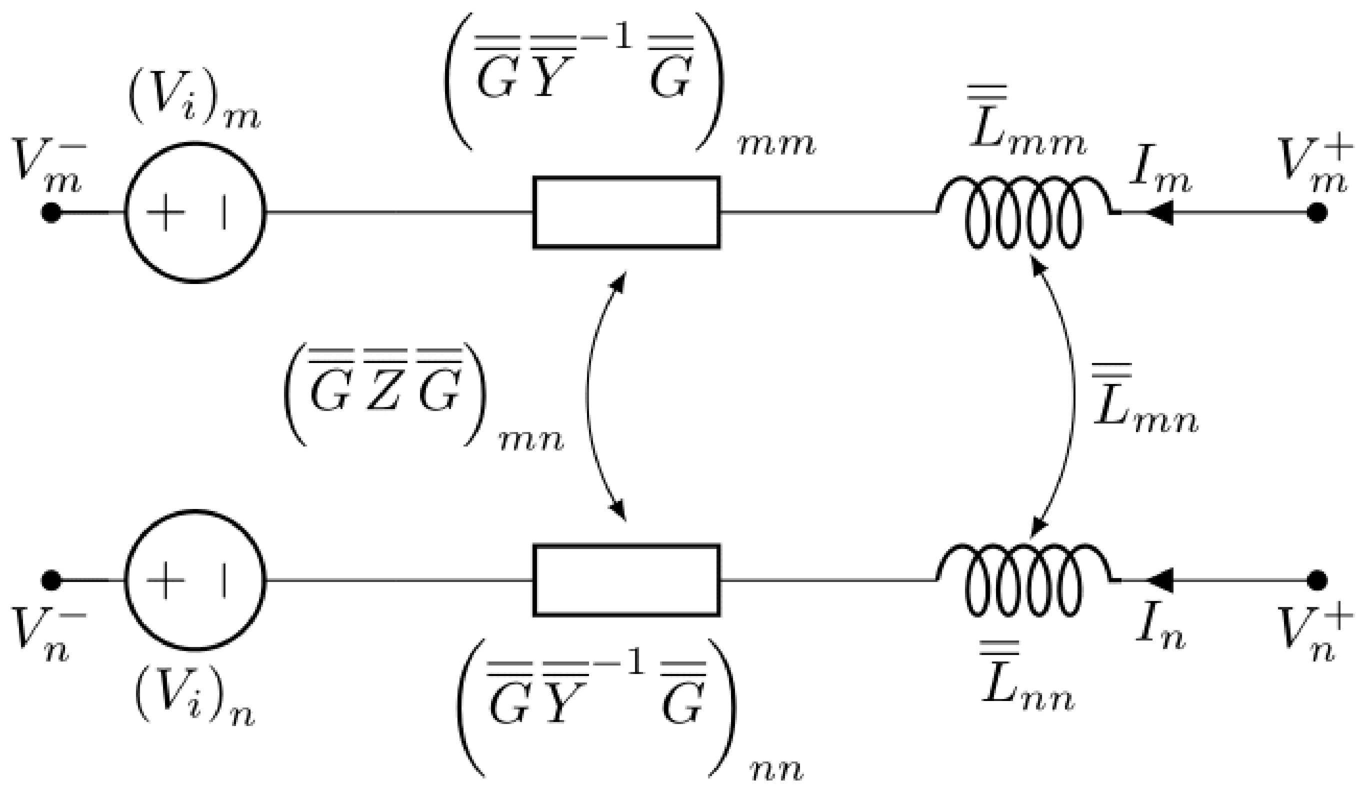

Only 1 set of unknowns left:

- $\mathbf{I}$

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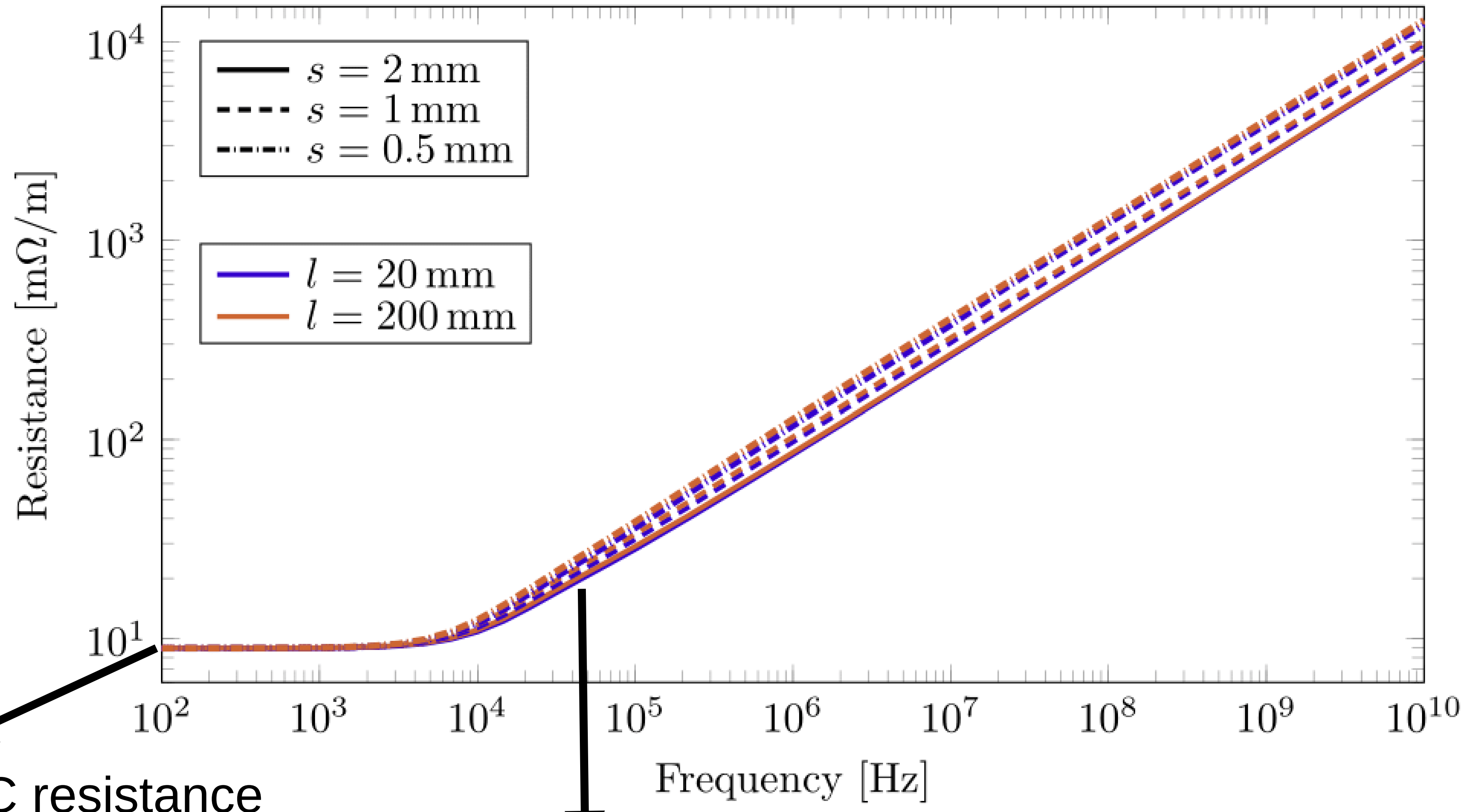
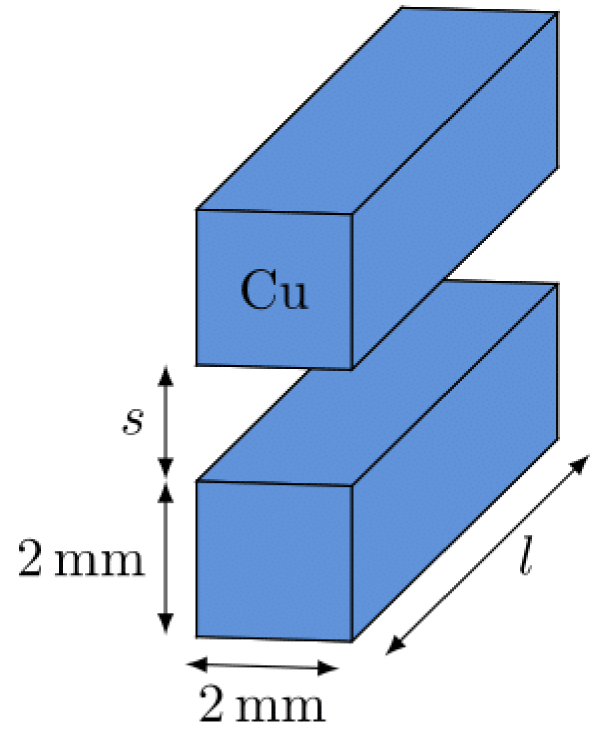
EXAMPLE: PARALLEL CONDUCTORS

Normalized resistance = total resistance (3-D) / length





Pouillet DC resistance

Proximity effect → fan out

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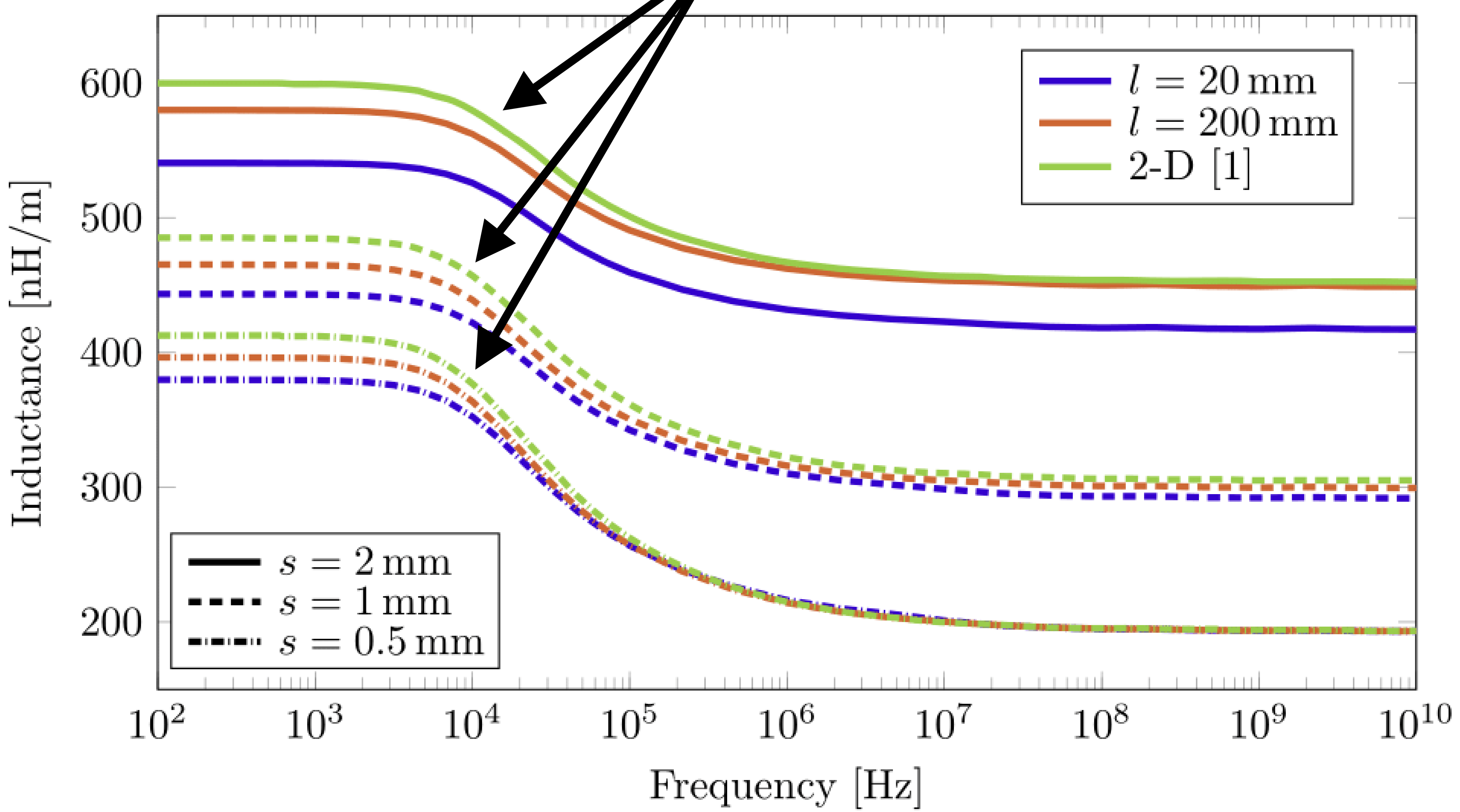
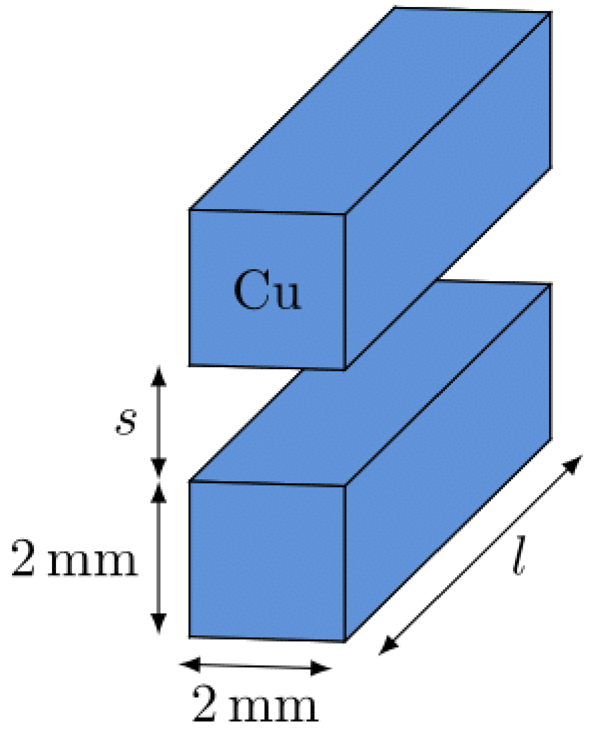
EXAMPLE: PARALLEL CONDUCTORS

Normalized inductance

Increasing length → 2-D results

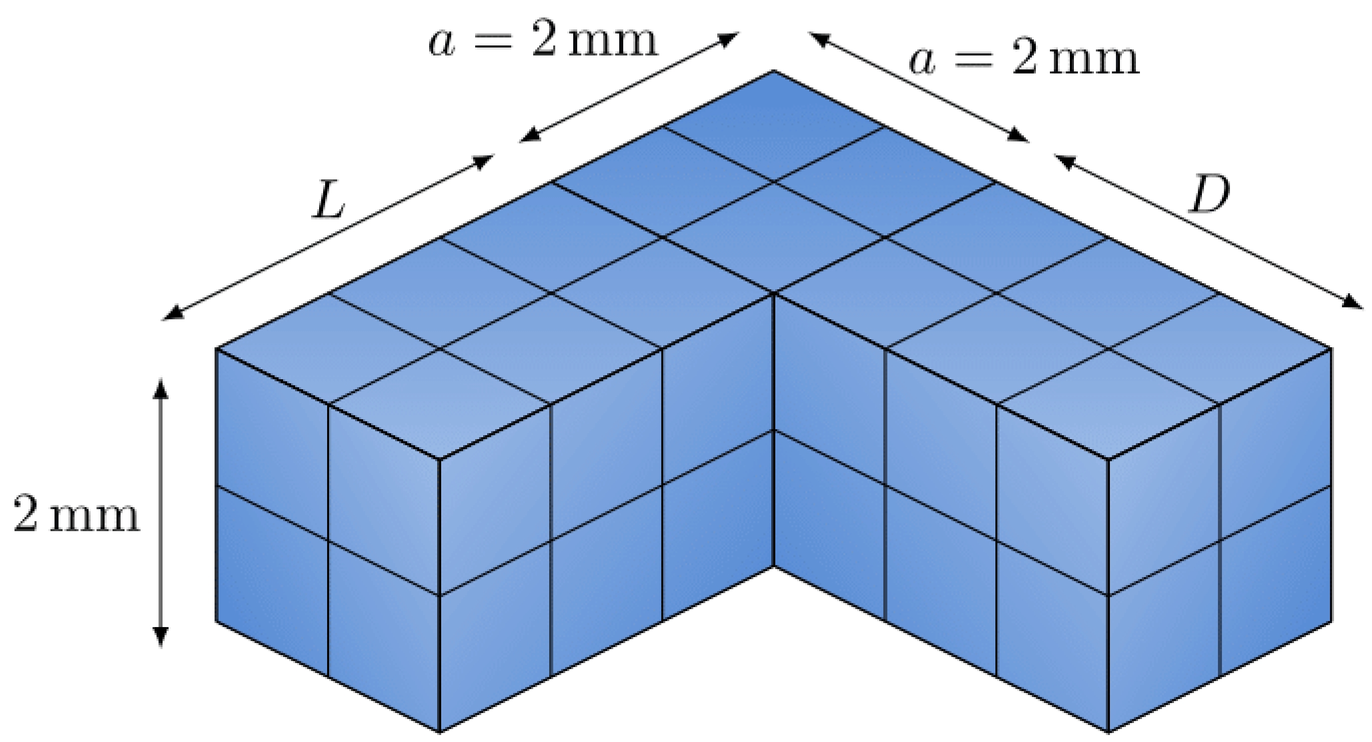


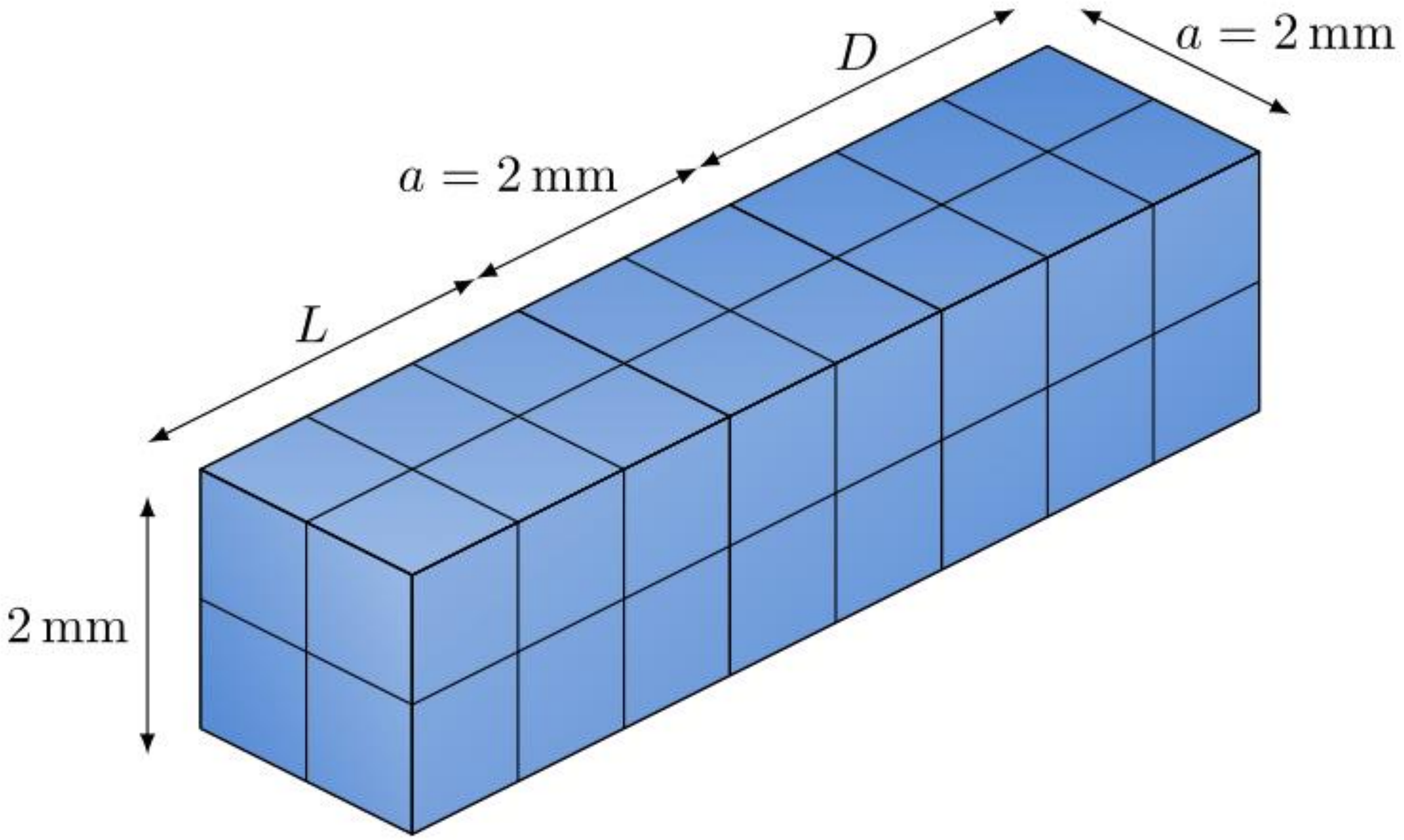


[1] D. De Zutter and L. Knockaert, IEEE MTT, vol. 53, pp. 2526-2538 (2005)

EXAMPLE: RIGHT-ANGLED CORNER

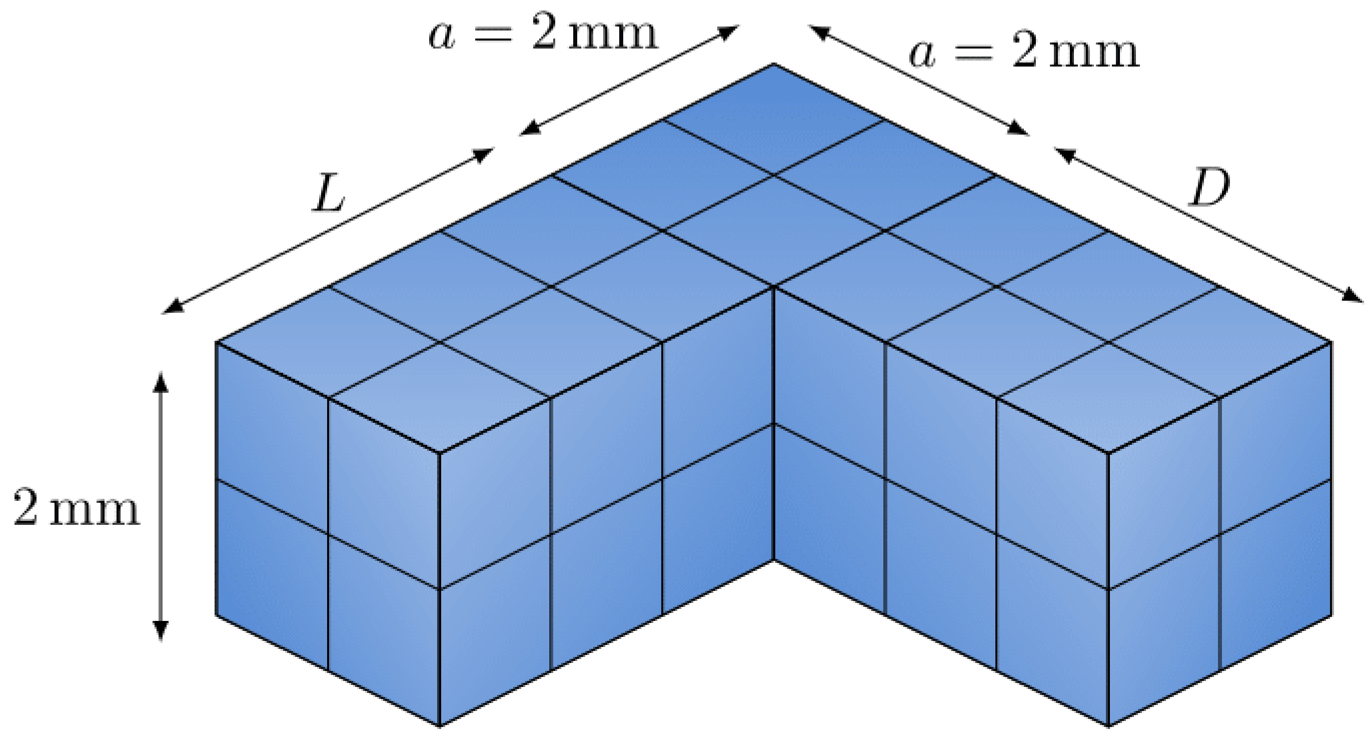
right-angled corner ⟷ cuboid

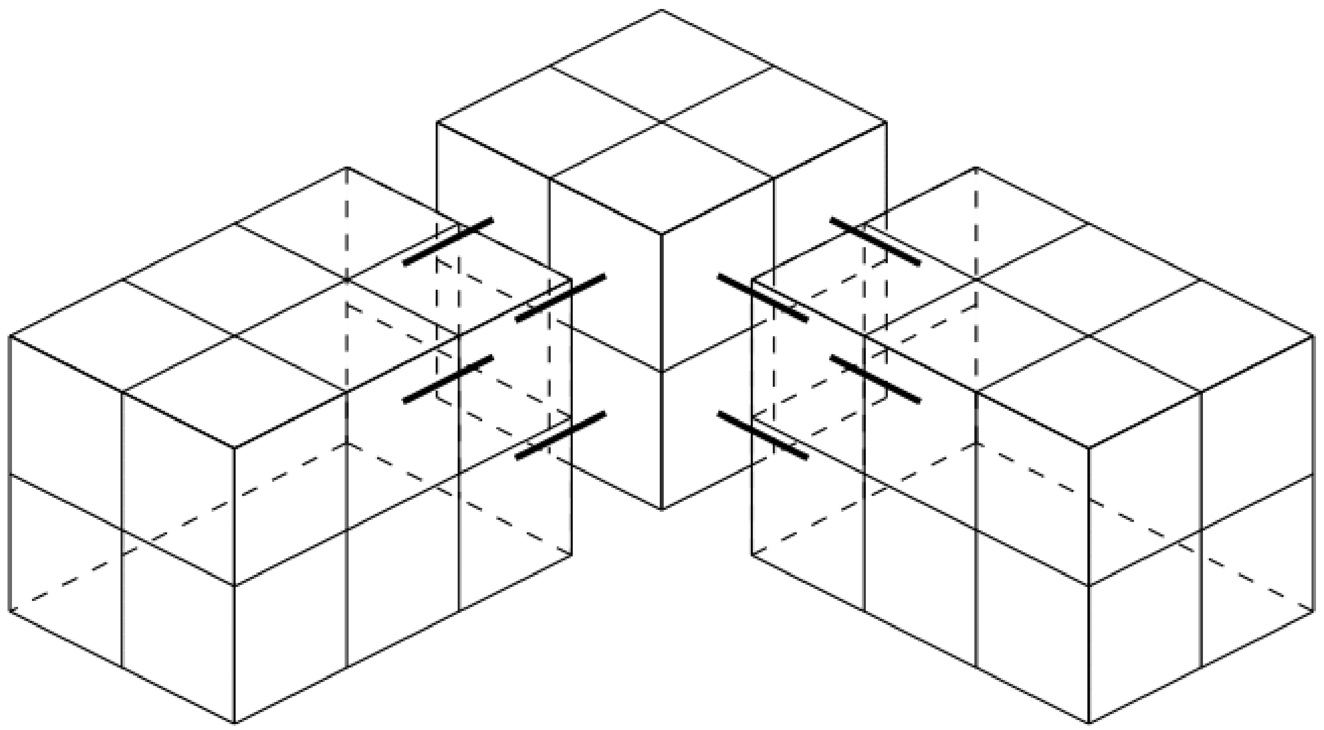




EXAMPLE: RIGHT-ANGLED CORNER

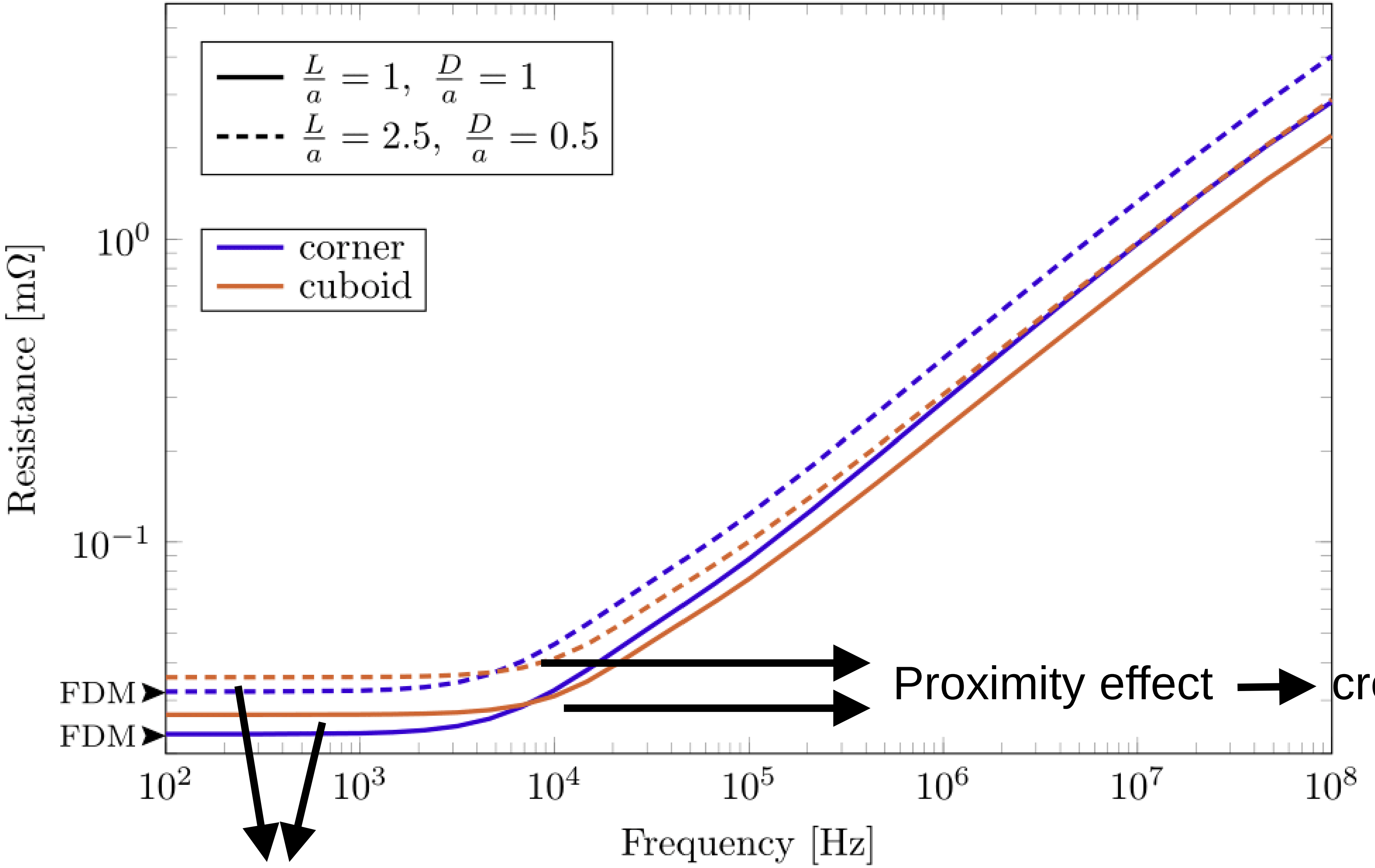
right-angled corner





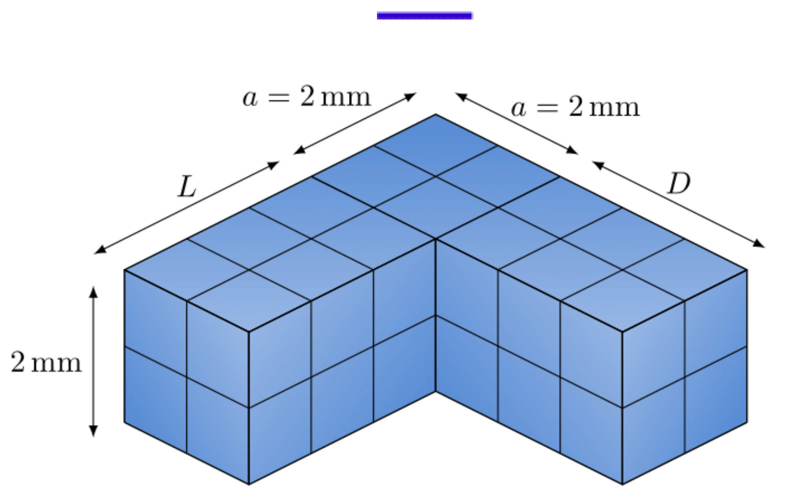
EXAMPLE: RIGHT-ANGLED CORNER

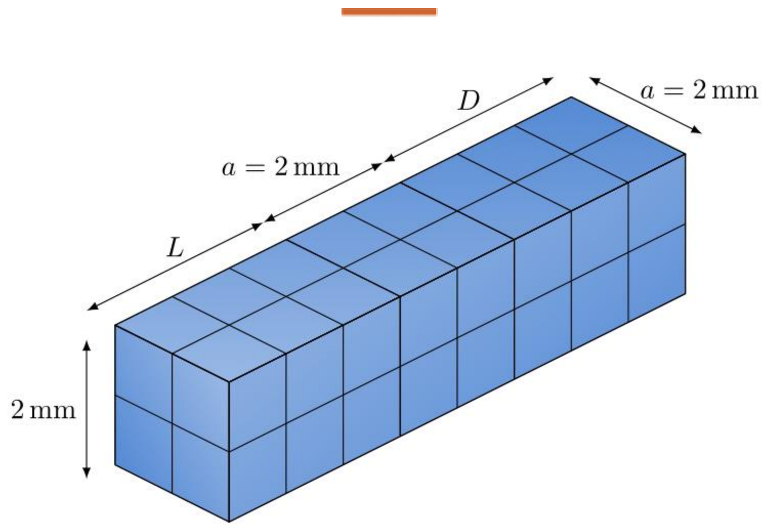
Resistance



Proximity effect → crossover

$R_{\text{corner}} < R_{\text{cuboid}}$





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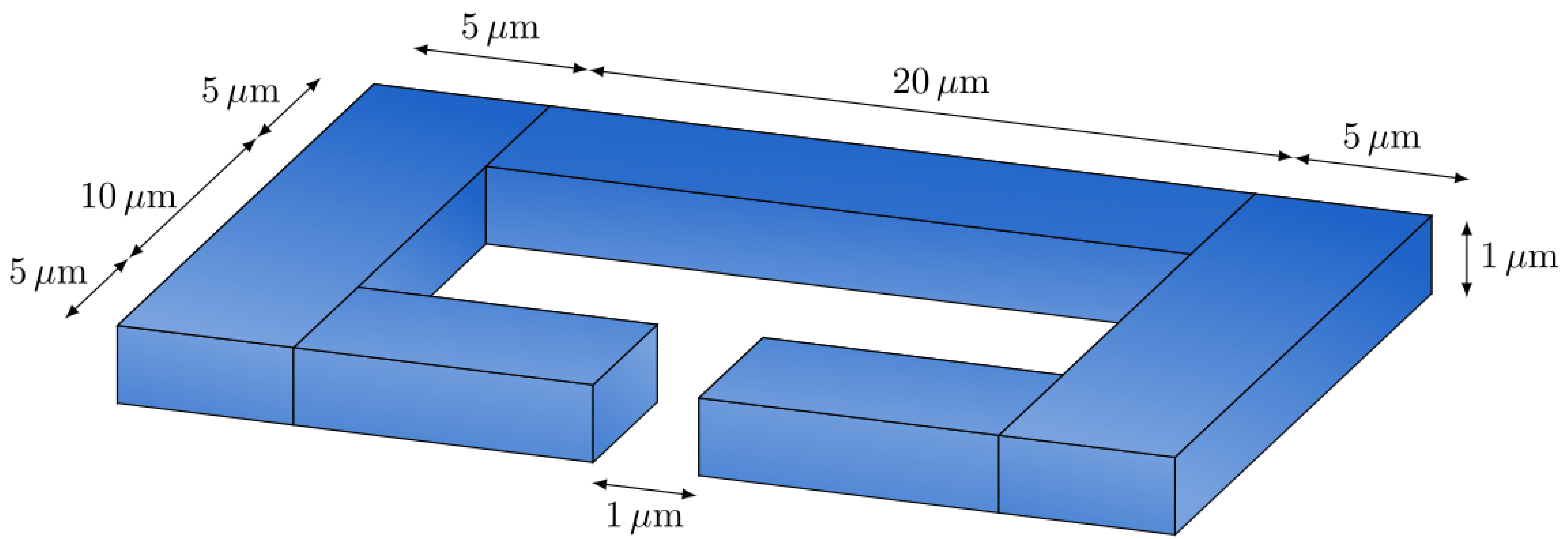
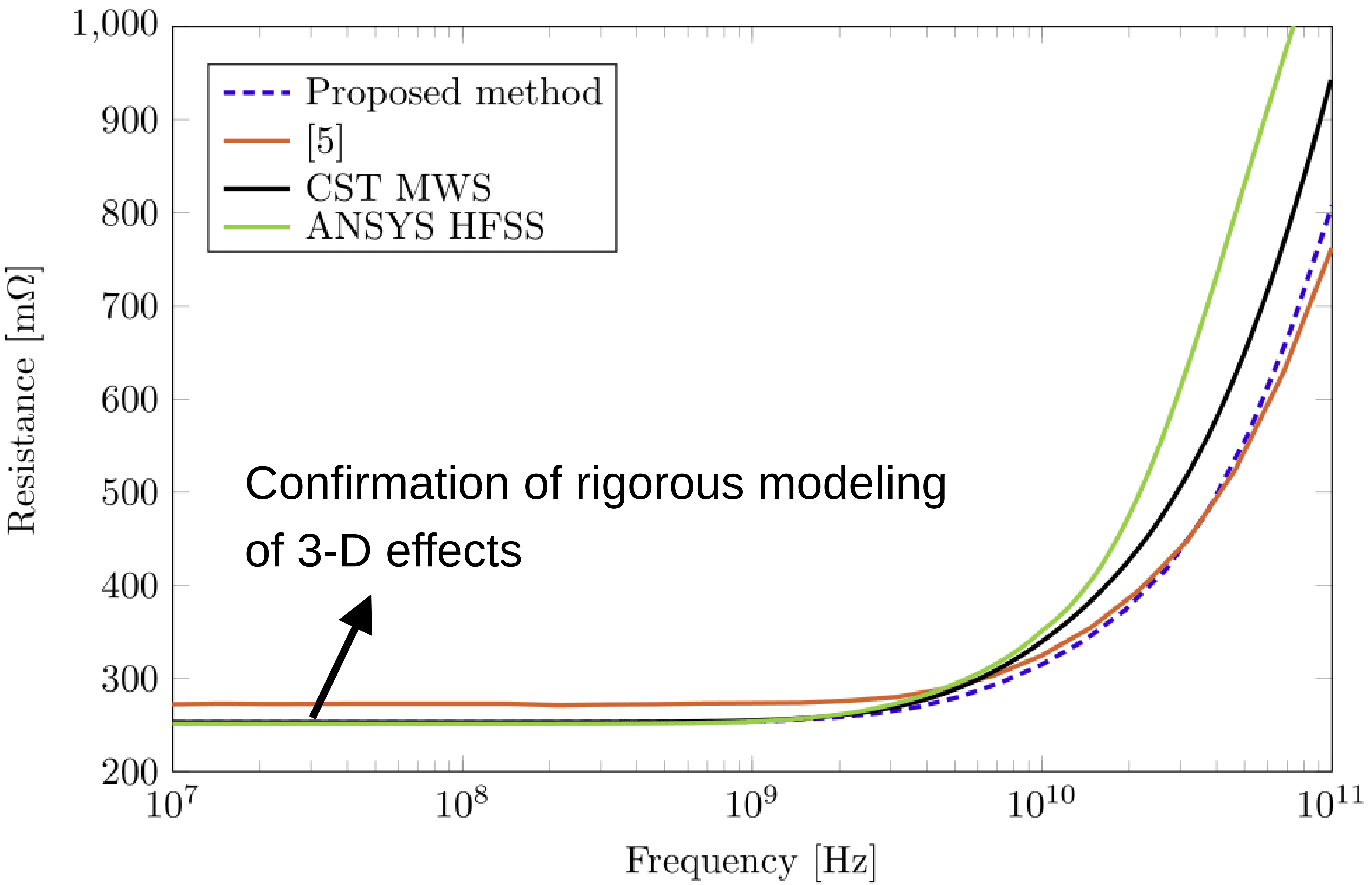
Finite difference method (FDM) → DC value

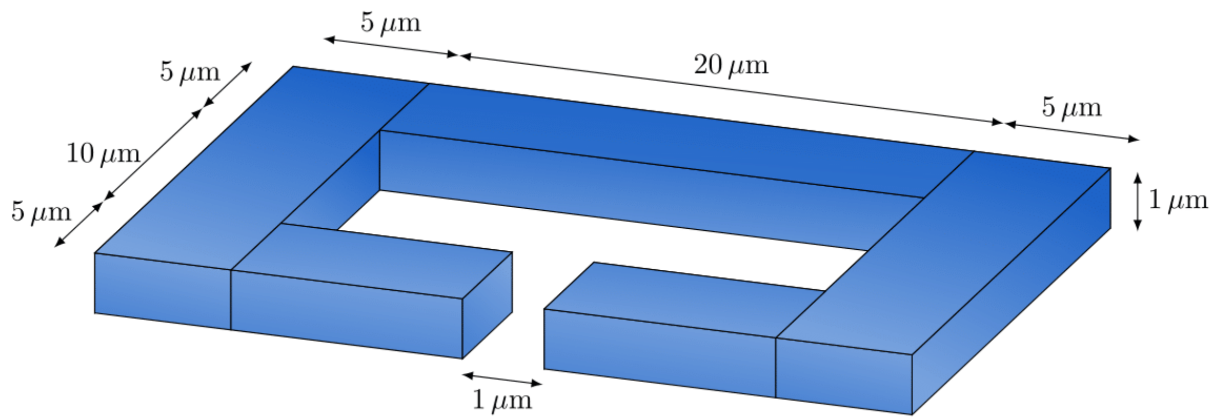
EXAMPLE: RECTANGULAR LOOP



EXAMPLE: RECTANGULAR LOOP

Resistance





[5] U. R. Patel, S. V. Hum and P. Triverio, IEEE 21st Workshop on SPI, pp. 1-4 (May 2017)

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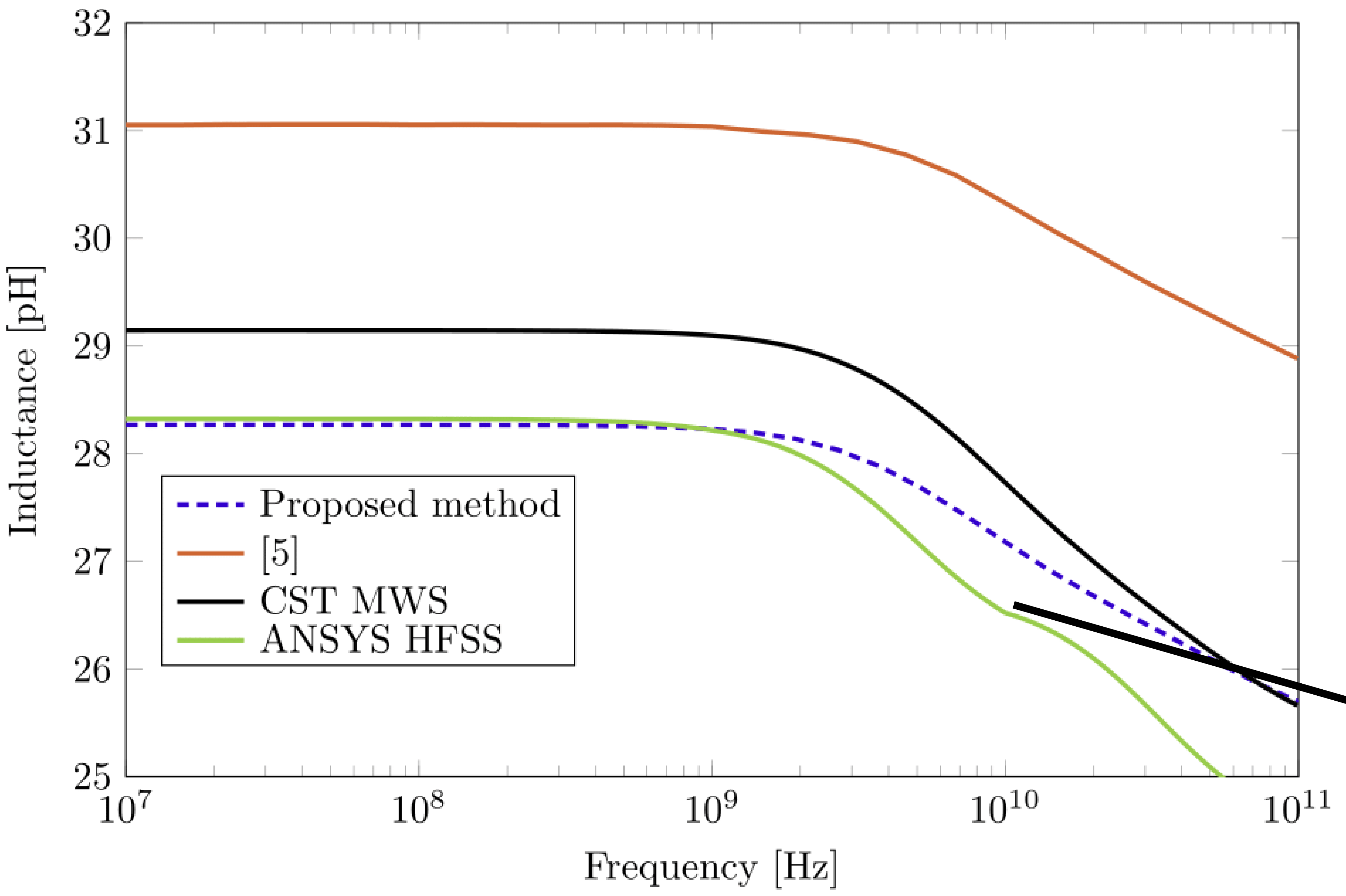
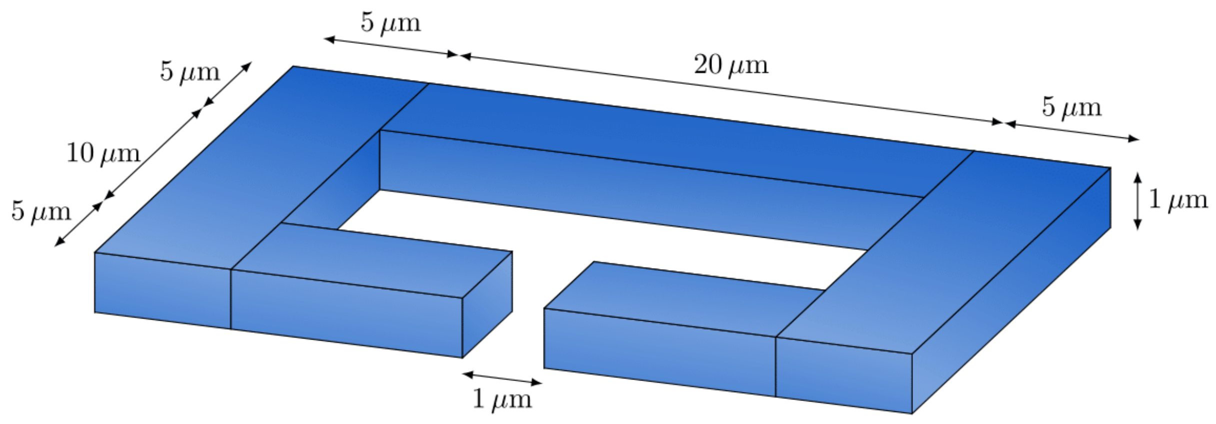
EXAMPLE: RECTANGULAR LOOP

Inductance



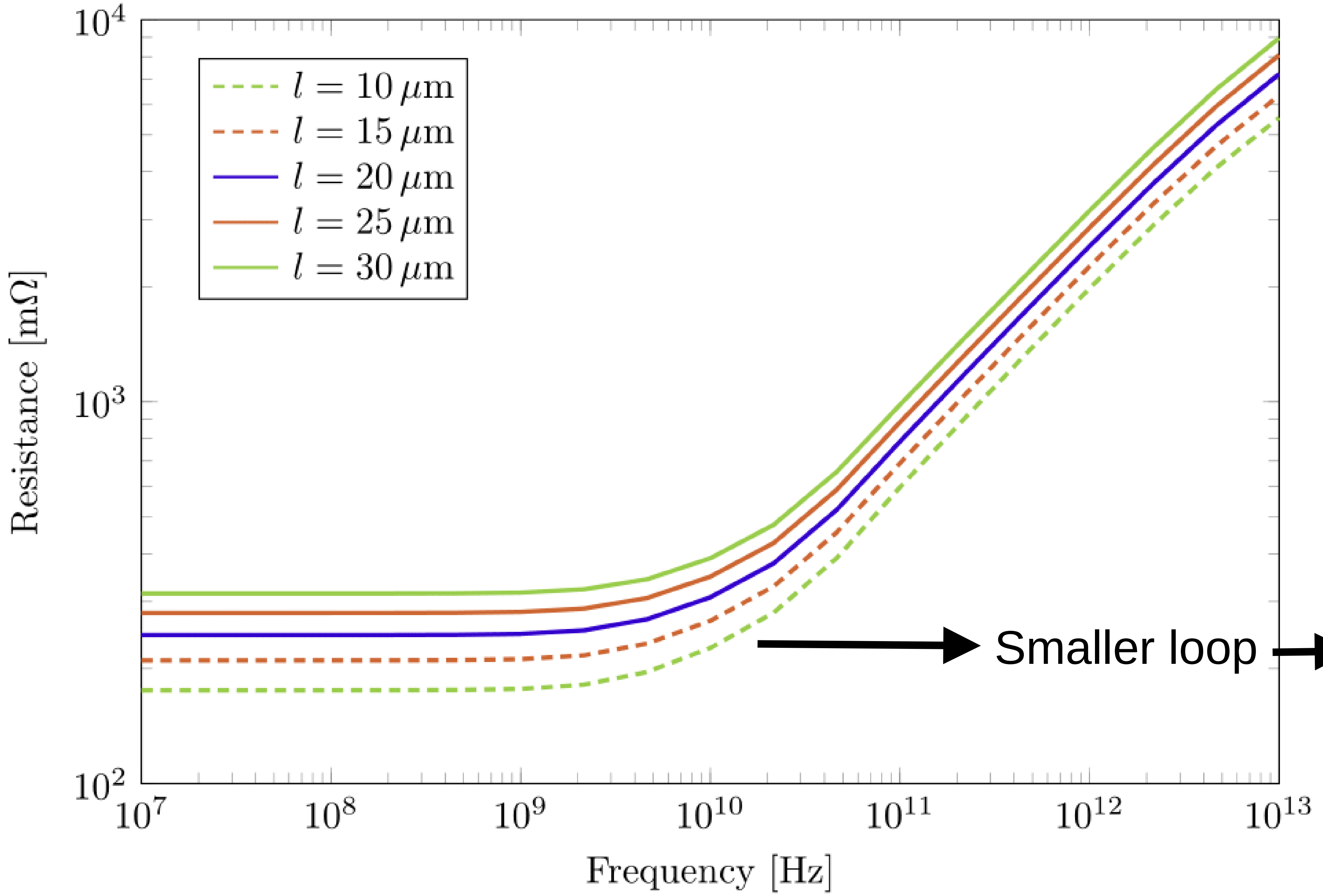


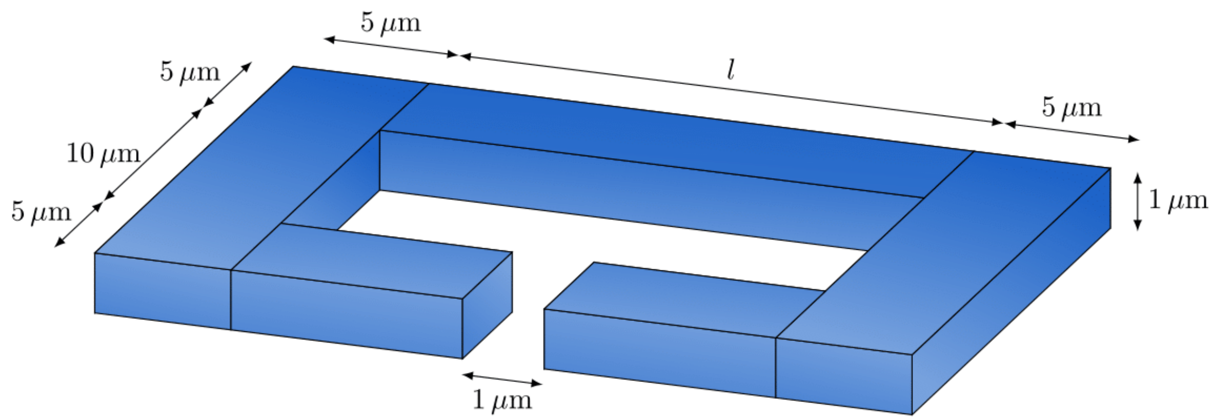
Faulty meshing → unphysical *kink*

[5] U. R. Patel, S. V. Hum and P. Triverio, IEEE 21st Workshop on SPI, pp. 1-4 (May 2017)

EXAMPLE: RECTANGULAR LOOP

Resistance





Smaller loop → stronger proximity effect

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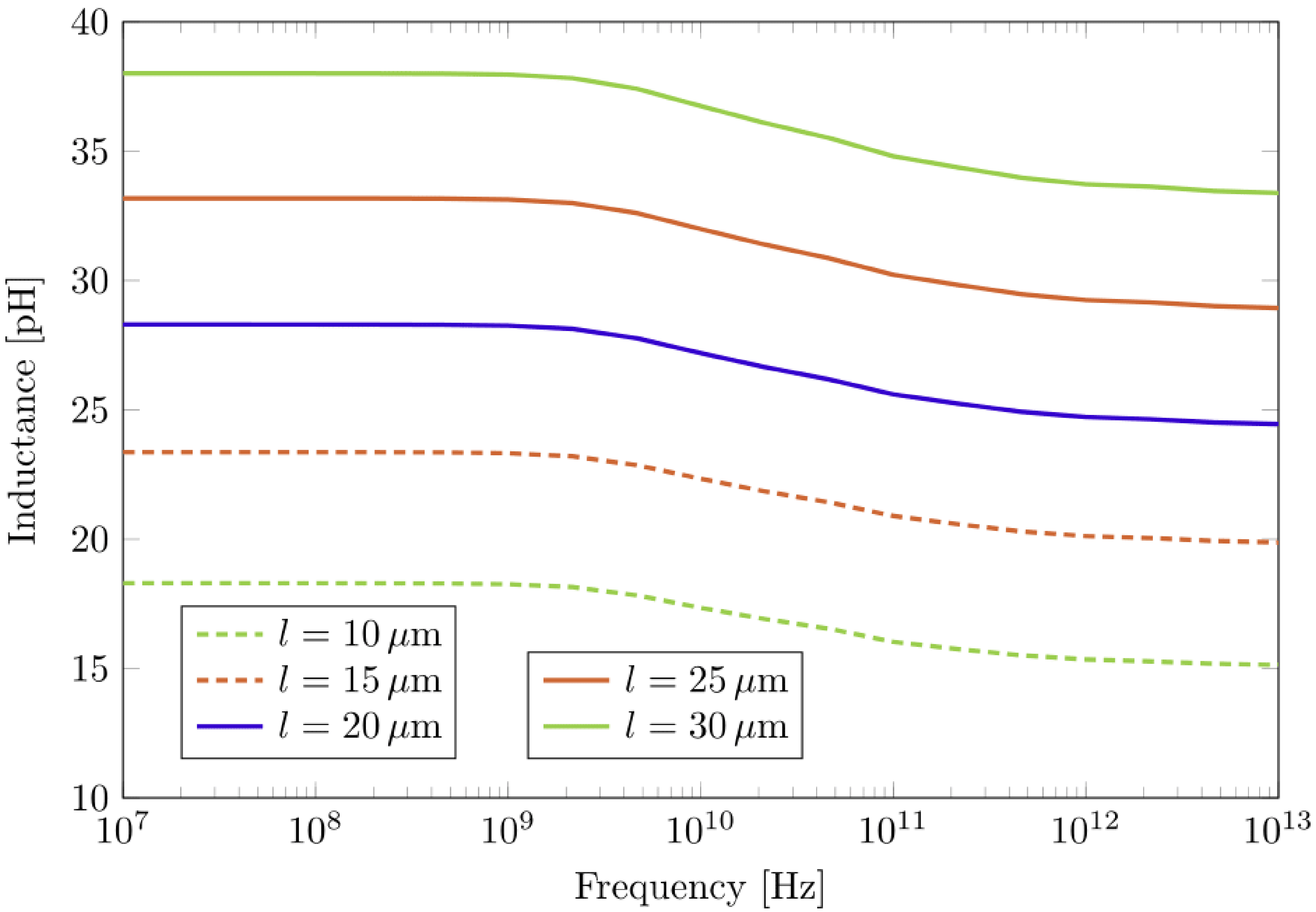
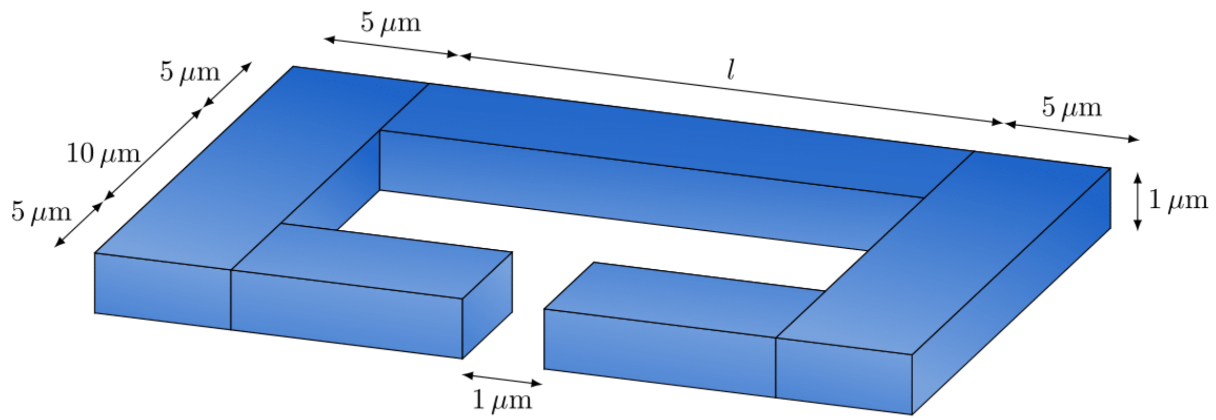
EXAMPLE: RECTANGULAR LOOP

Inductance





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CONCLUSIONS

Novel 3-D interconnect modeling tool

- Based on BIE (without volume meshing)
- Fully 3-D differential surface admittance operator

⇒ Rigorous approach for skin effect, proximity effect, etc. in 3-D interconnects

Validation and applications

- Application to PCB and IC interconnect structures
- Accurate modeling of corners
- Broadband extraction of R- and L-parameters
- Thoroughly compared to industry standards

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FURTHER READING

2-D:

D. De Zutter and L. Knockaert, “*Skin effect modeling based on a differential surface admittance operator*”, IEEE MTT, vol. 53, pp. 2526-2538 (2005)

T. Demeester and D. De Zutter, “*Quasi-TM Transmission Line Parameters of Coupled Lossy Lines Based on the Dirichlet to Neumann Boundary Operator*”, IEEE MTT, vol. 56, pp. 1649-1660 (2008)

3-D:

M. Huynen, M. Gossye, D. De Zutter and D. Vande Ginste, “*A 3-D Differential Surface Admittance Operator for Lossy Dipole Antenna Analysis*”, IEEE AWPL, vol. 16, pp. 1052-1055 (2017)

M. Huynen, D. De Zutter and D. Vande Ginste, “*Boundary integral equation study of the influence of finite conductivity on antenna radiation using a 3-D differential surface admittance operator*”, ACES Symposium - Italy (March 2017)

M. Huynen, D. De Zutter and D. Vande Ginste, “*Rigorous full-wave resistance and inductance computation of 3-D interconnects*”, accepted at IEEE MWCL

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