Quantum Mechanical & Electromagnetic Systems Modelling Lab

Broadband Impedance Response Extraction of On-Chip Interdigital Capacitors using a 3-D DSA operator for Piecewise Homogeneous Structures

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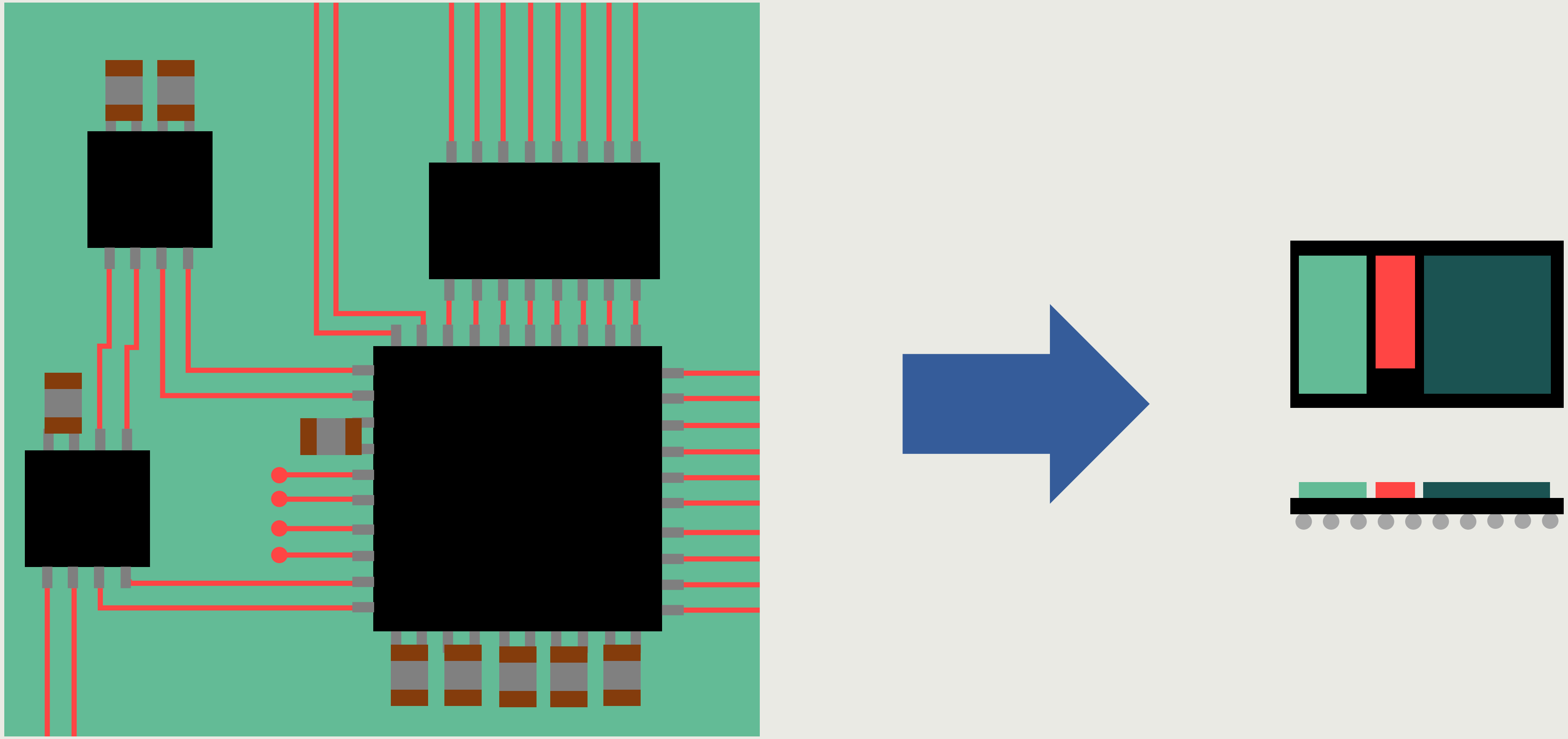
quest.

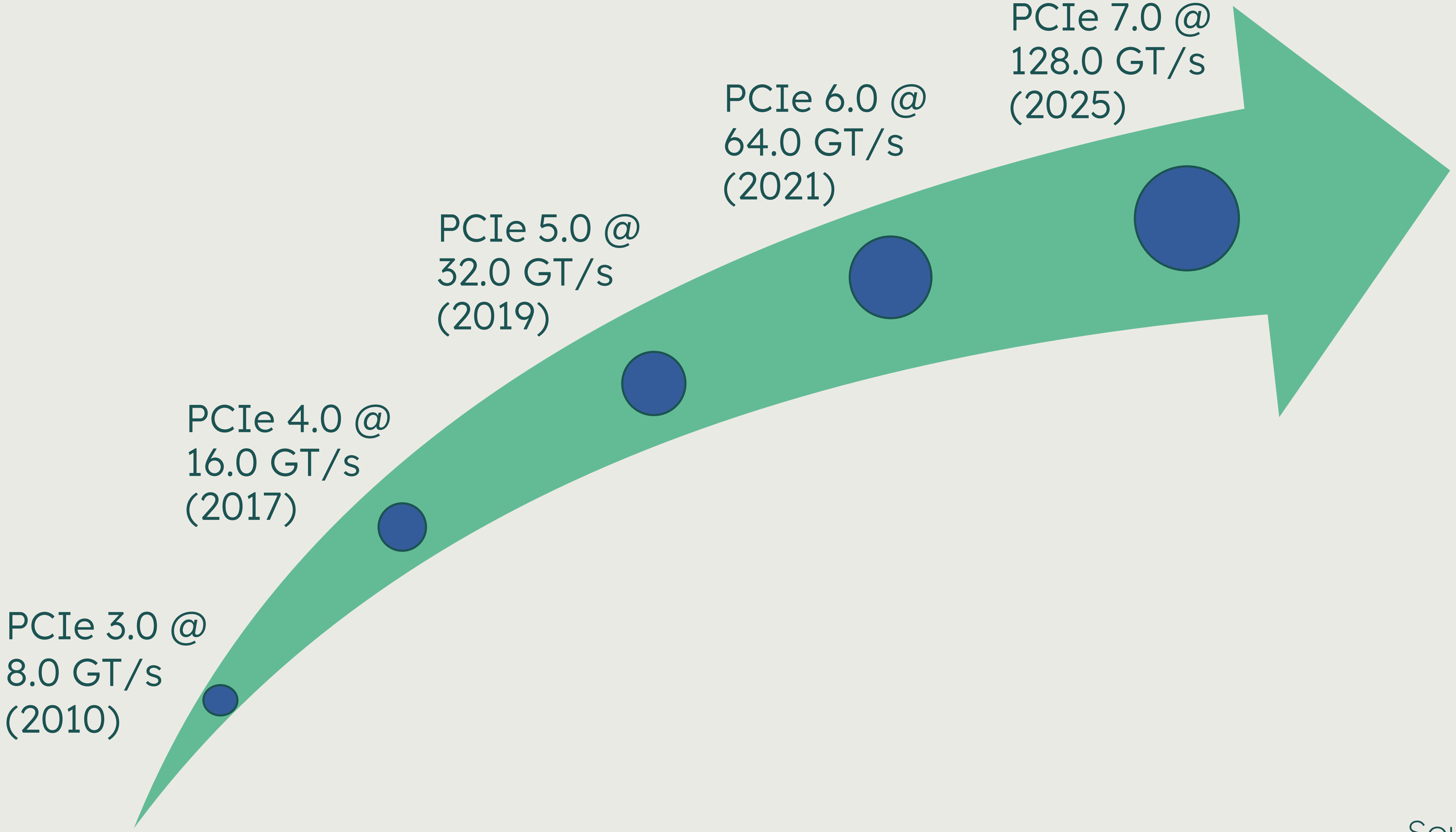
Ever-increasing trend towards higher integration density…

From System On PCB to System On Chip



And also to higher circuit speeds

Evolution of PCI Express data rate



Source: PCI-SIG, 2022

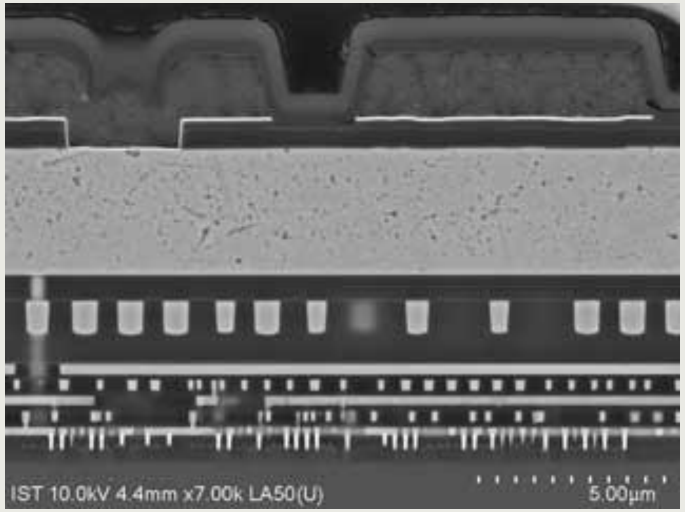
These trends require accurate modeling

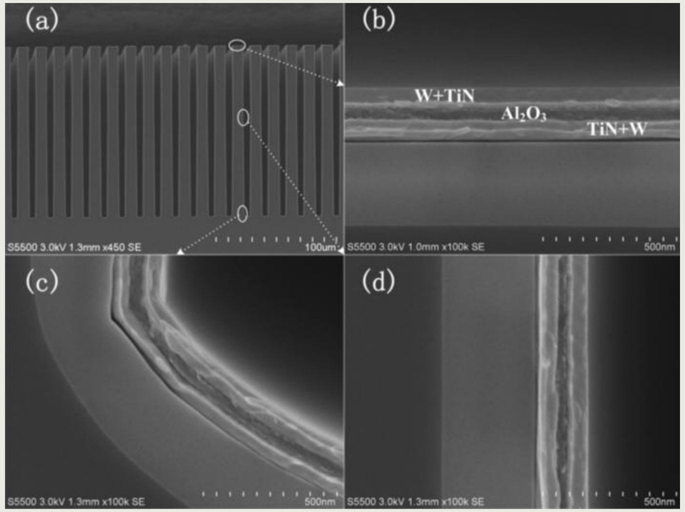
Full-wave effects become fully apparent at higher frequencies, so traditional circuit simulations no longer suffice

Heterogeneous material properties of state-of-the-art components demand precise modeling to accurately capture all electromagnetic effects

Wide variety of modeling techniques already available: FEM, VIE, PEEC, PMCHWT, GIBC, …, but each has its own benefits and drawbacks

Differential surface admittance (DSA) formalism provides an elegant framework that allows for efficient and accurate modeling, in particular broadband characterization of good conductors





At quest, we developed a novel DSA formulation that allows incorporation of piecewise homogeneous volumes

DSA operator already available for various 3-D topologies

However, existing DSA-based solutions for piecewise homogeneous volumes introduce additional unknowns

Leverage analytical properties of dedicated entire domain-basis functions (EDBFs) during operator construction

Accurately simulate piecewise homogeneous volumes with a reduced number of unknowns

Poincaré-Steklov operator for piecewise homogeneous volumes

DSA-EFIE formulation for piecewise homogeneous volumes

Numerical results

Conclusions

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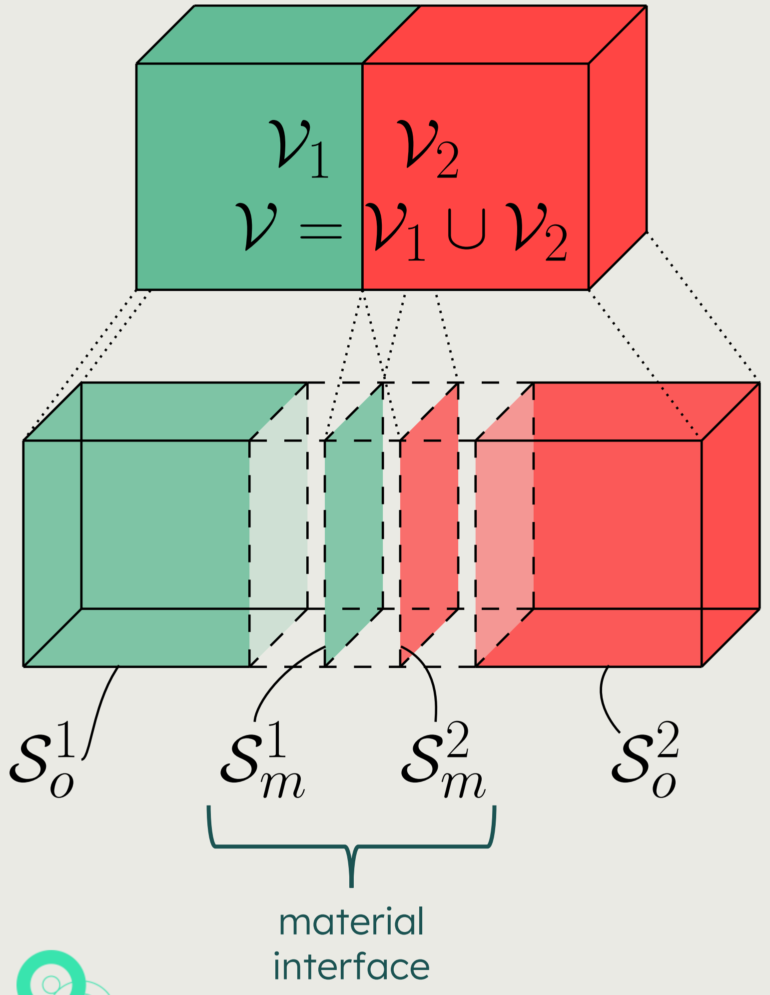
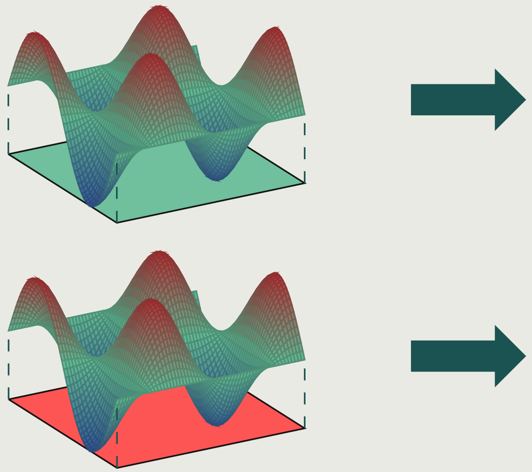
EDBFs provide favorable properties to construct Poincaré-Steklov (PS) operators



Discretize $\mathbf{e}$ and $\mathbf{u}_n \times \mathbf{h}$ on all surfaces using entire-domain basis functions



$$\bar{\mathbf{h}}^1 = \begin{bmatrix} \bar{\mathbf{h}}^{1,o} \\ \bar{\mathbf{h}}^{1,m} \end{bmatrix} \quad \bar{\mathbf{e}}^1 = \begin{bmatrix} \bar{\mathbf{e}}^{1,o} \\ \bar{\mathbf{e}}^{1,m} \end{bmatrix}$$

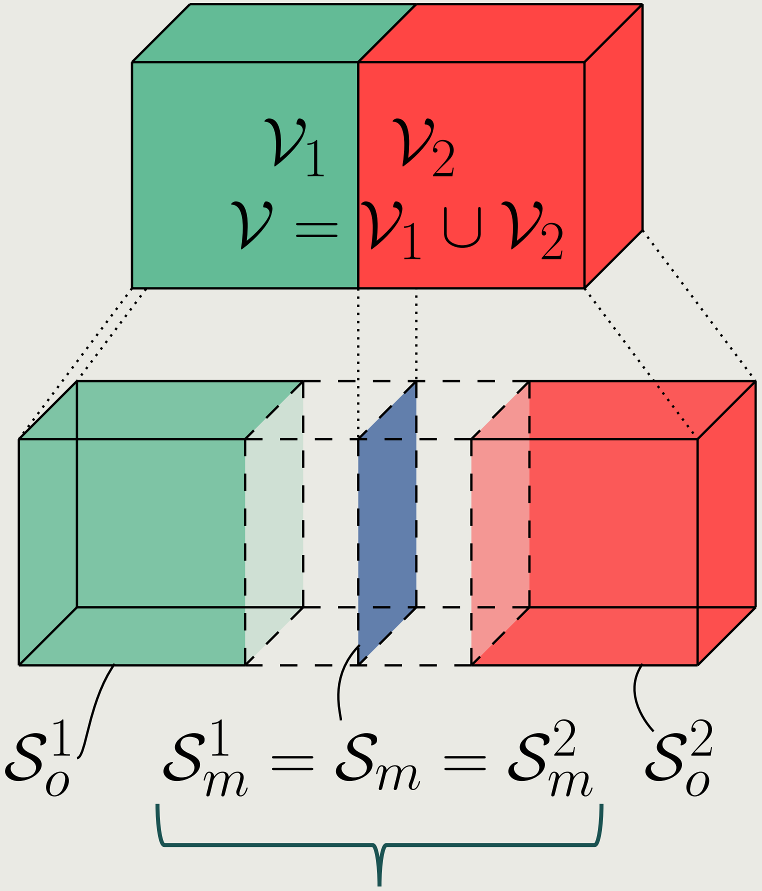
$$\bar{\mathbf{h}}^2 = \begin{bmatrix} \bar{\mathbf{h}}^{2,o} \\ \bar{\mathbf{h}}^{2,m} \end{bmatrix} \quad \bar{\mathbf{e}}^2 = \begin{bmatrix} \bar{\mathbf{e}}^{2,o} \\ \bar{\mathbf{e}}^{2,m} \end{bmatrix}$$

Use of EDBFs allows for analytical entries of PS matrices linking discretized $\mathbf{e}$ and $\mathbf{u}_n \times \mathbf{h}$

$$\begin{bmatrix} \bar{\mathbf{h}}^{1,o} \\ \bar{\mathbf{h}}^{1,m} \end{bmatrix} = \begin{bmatrix} \bar{\bar{\mathcal{P}}}^{1,oo} & \bar{\bar{\mathcal{P}}}^{1,om} \\ \bar{\bar{\mathcal{P}}}^{1,mo} & \bar{\bar{\mathcal{P}}}^{1,mm} \end{bmatrix} \begin{bmatrix} \bar{\mathbf{e}}^{1,o} \\ \bar{\mathbf{e}}^{1,m} \end{bmatrix}$$

$$\begin{bmatrix} \bar{\mathbf{h}}^{2,o} \\ \bar{\mathbf{h}}^{2,m} \end{bmatrix} = \begin{bmatrix} \bar{\bar{\mathcal{P}}}^{2,oo} & \bar{\bar{\mathcal{P}}}^{2,om} \\ \bar{\bar{\mathcal{P}}}^{2,mo} & \bar{\bar{\mathcal{P}}}^{2,mm} \end{bmatrix} \begin{bmatrix} \bar{\mathbf{e}}^{2,o} \\ \bar{\mathbf{e}}^{2,m} \end{bmatrix}$$

Impose continuity of tangential electric and magnetic field at material interface



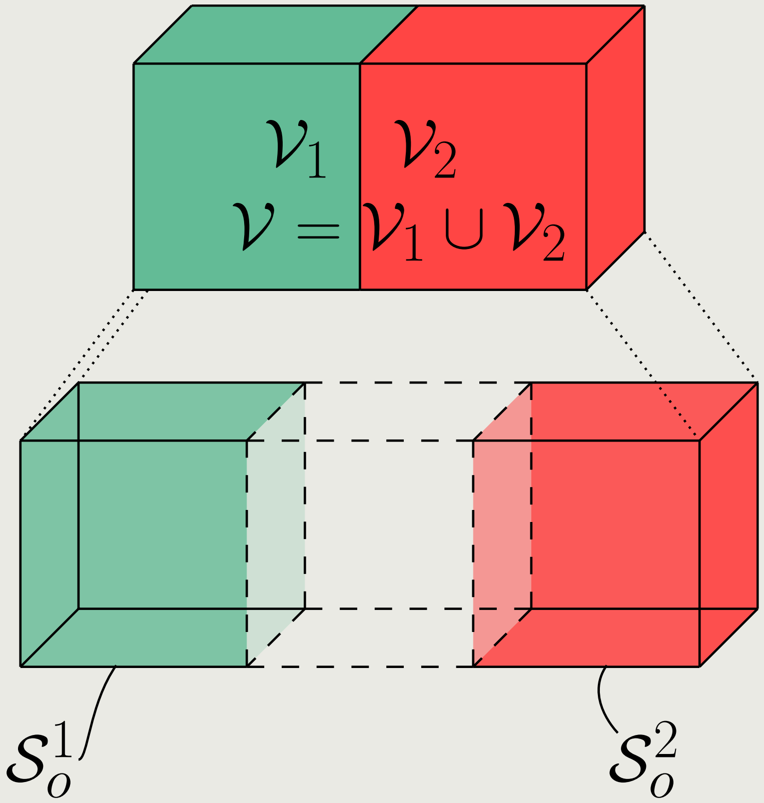
$\mathcal{S}_\mathrm{m}^1$ and $\mathcal{S}_\mathrm{m}^2$ have same EDBFs → continuity on function-by-function basis

$$\bar{\mathbf{h}}^1 = \begin{bmatrix} \bar{\mathbf{h}}^{1,o} \\ \bar{\mathbf{h}}^m \end{bmatrix} \quad \bar{\mathbf{e}}^1 = \begin{bmatrix} \bar{\mathbf{e}}^{1,o} \\ \bar{\mathbf{e}}^m \end{bmatrix} \qquad \bar{\mathbf{h}}^2 = \begin{bmatrix} \bar{\mathbf{h}}^{2,o} \\ -\bar{\mathbf{h}}^m \end{bmatrix} \quad \bar{\mathbf{e}}^2 = \begin{bmatrix} \bar{\mathbf{e}}^{2,o} \\ \bar{\mathbf{e}}^m \end{bmatrix}$$

Allows to write $\bar{\mathbf{e}}^m$ as function of $\bar{\mathbf{e}}^{1,o}$ and $\bar{\mathbf{e}}^{2,o}$

$$\bar{\mathbf{e}}^m = -\bar{\bar{\mathcal{A}}}^{-1} \cdot \left(\bar{\bar{\mathcal{P}}}^{1,mo}\bar{\mathbf{e}}^{1,o} + \bar{\bar{\mathcal{P}}}^{2,mo}\bar{\mathbf{e}}^{2,o}\right)$$
$$\bar{\bar{\mathcal{A}}} = \bar{\bar{\mathcal{P}}}^{1,mm} + \bar{\bar{\mathcal{P}}}^{2,mm}$$

Insert expressions for electric field in the original DtN operator



Insert expression for $\bar{\mathbf{e}}^m$ into original PS matrices

$$\begin{bmatrix} \bar{\mathbf{h}}^{1,o} \\ \bar{\mathbf{h}}^{2,o} \end{bmatrix} = \begin{bmatrix} \bar{\bar{\mathcal{P}}}_{11} & \bar{\bar{\mathcal{P}}}_{12} \\ \bar{\bar{\mathcal{P}}}_{21} & \bar{\bar{\mathcal{P}}}_{22} \end{bmatrix} \cdot \begin{bmatrix} \bar{\mathbf{e}}^{1,o} \\ \bar{\mathbf{e}}^{2,o} \end{bmatrix} = \bar{\bar{\mathcal{P}}} \cdot \begin{bmatrix} \bar{\mathbf{e}}^{1,o} \\ \bar{\mathbf{e}}^{2,o} \end{bmatrix}$$

Where all block matrices are found as linear combinations of previous matrices

No more dependencies on $\bar{\mathbf{e}}^m$ and $\bar{\mathbf{h}}^m$ so the resulting matrix is the discretized PS operator of $\mathcal{V}$ with bounding surface $\mathcal{S} = \mathcal{S}_o^1 \cup \mathcal{S}_o^2$

Effectively reduced the number of unknowns!

Poincaré-Steklov operator for piecewise homogeneous volumes

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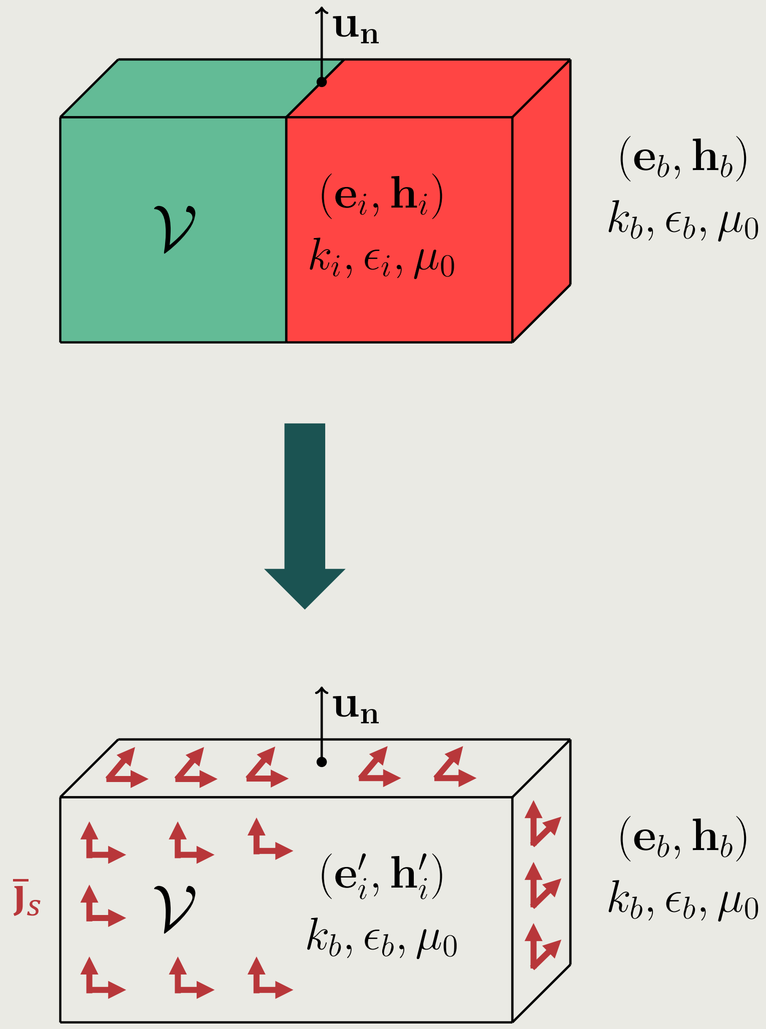
Construction of discretized DSA operator



The equivalence principle replaces materials by the background medium

$$\bar{\mathbf{J}}_s = \bar{\mathbf{h}}_i - \bar{\mathbf{h}}'_i = \left(\bar{\bar{\mathcal{P}}} - \bar{\bar{\mathcal{P}}}_0\right) \cdot \bar{\mathbf{e}}_\mathrm{b} = \bar{\bar{\mathcal{Y}}} \cdot \bar{\mathbf{e}}_\mathrm{b} \qquad \text{, on } \mathcal{S}$$

DSA operator $\bar{\bar{\mathcal{Y}}}$ is constructed as difference of two PS operators $\bar{\bar{\mathcal{P}}}$ and $\bar{\bar{\mathcal{P}}}_0$ for the full piecewise homogeneous volume

Now, only current sources in background medium → easier to solve numerically

Projecting DSA operator $\bar{\bar{\mathcal{Y}}}$ onto rooftop functions and integration with the **Augmented Electric Field Integral Equation [1]** provides full characterization of the electromagnetic problem

[1] Z.-G. Qian and W. C. Chew, IEEE Trans. Antennas Propag., vol. 57, no. 11, pp. 3594–3601, 2009.

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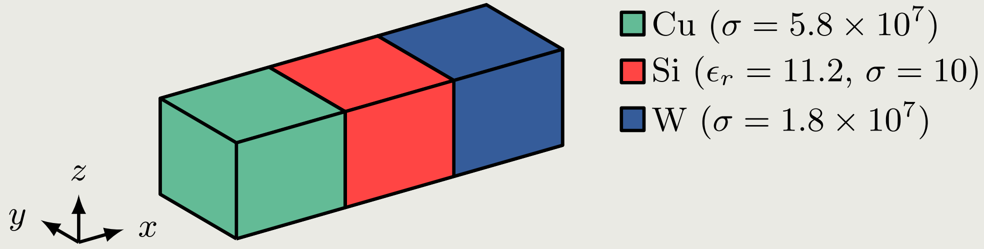
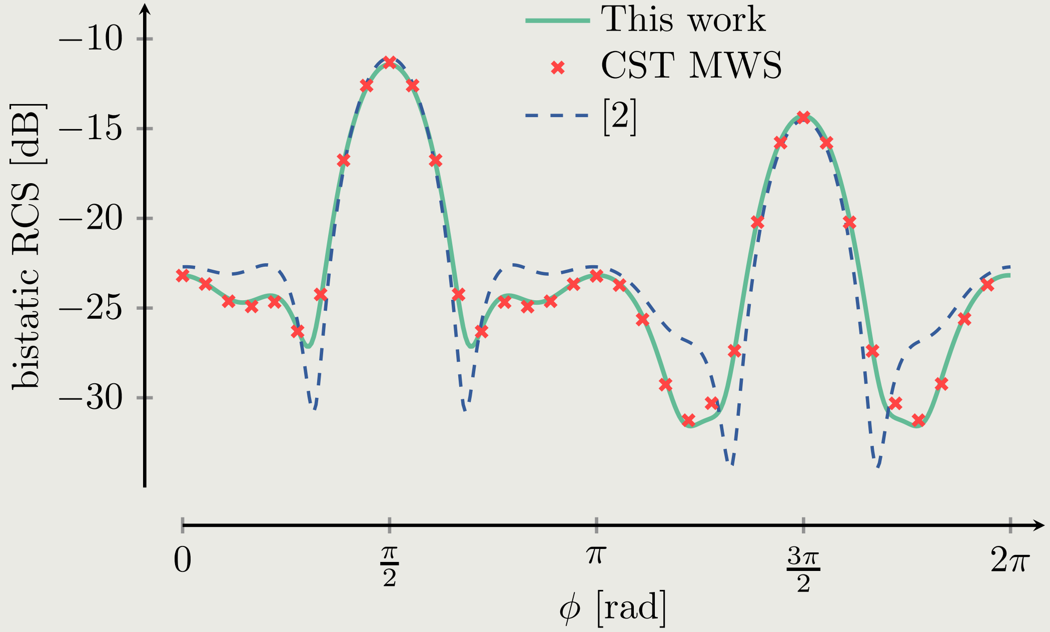
Composite cuboid made of copper, doped silicon and tungsten



Illuminated by plane wave propagating in **+y-direction** with polarization vector $\overline{\mathbf{p}} = (1,0,1)$

Very good agreement with CST MWS reference solution

Wire method [2] loses accuracy in presence of semiconductors



[2] M. Huynen et al., IEEE Trans. Microw. Theory Techn., vol. 68, no. 4, pp. 1217–1233, 2020.

Numerical results

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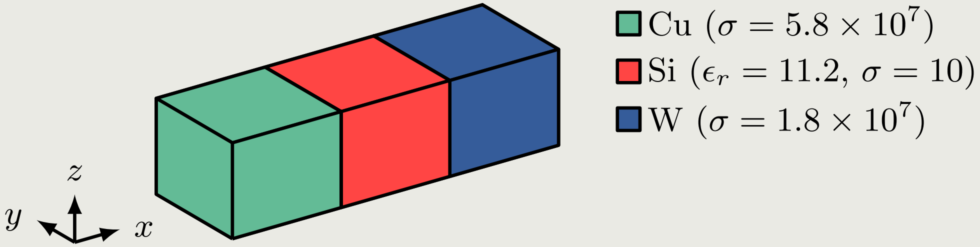
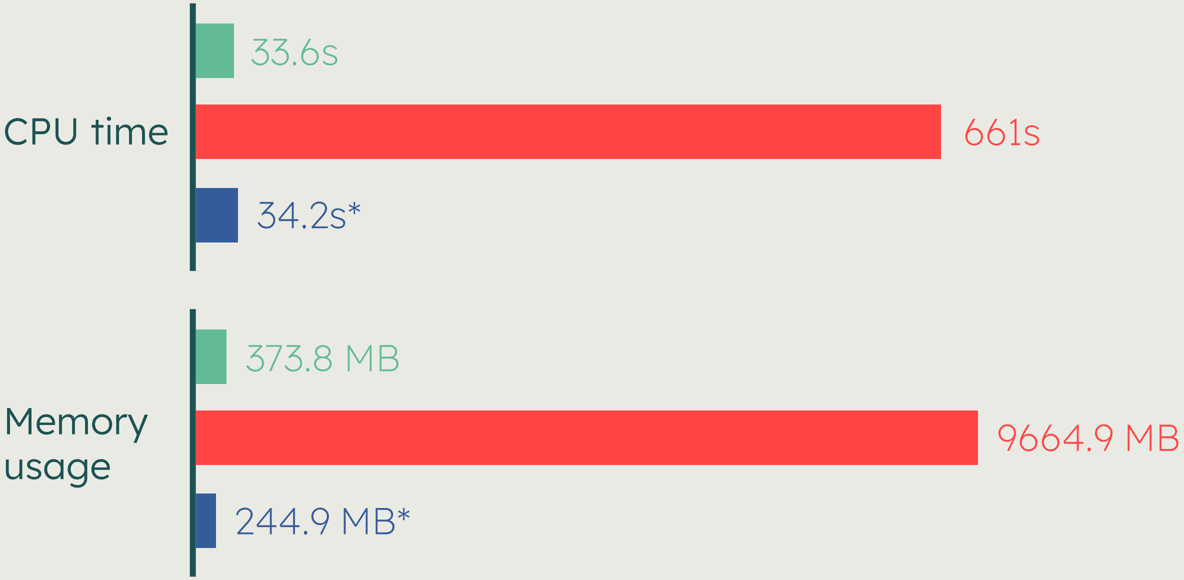
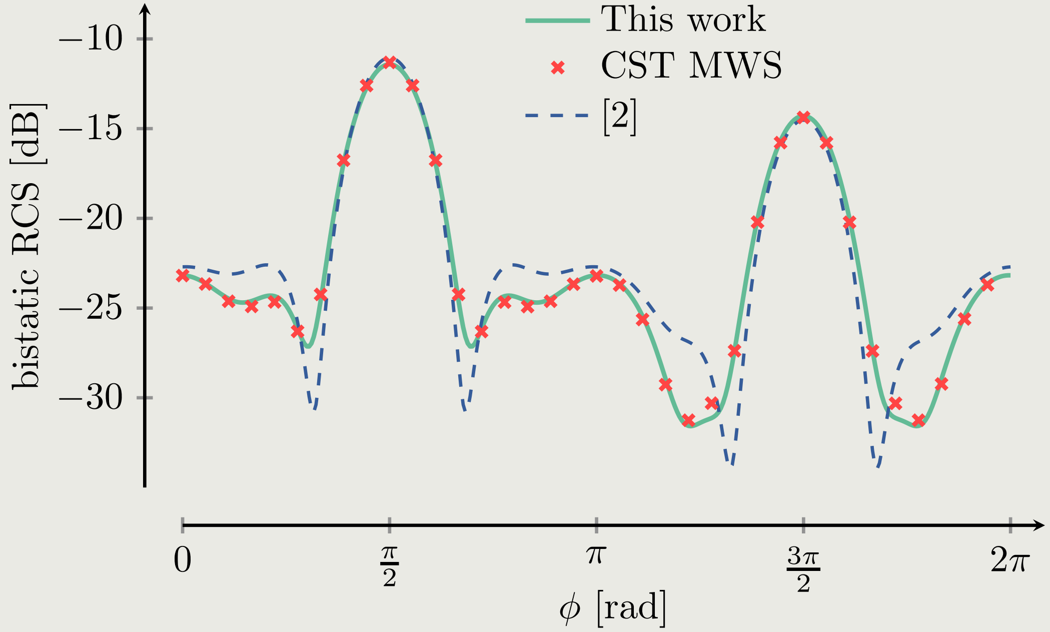


Significant improvement in computational efficiency





*Does not yield accurate results

[2] M. Huynen et al., IEEE Trans. Microw. Theory Techn., vol. 68, no. 4, pp. 1217–1233, 2020.

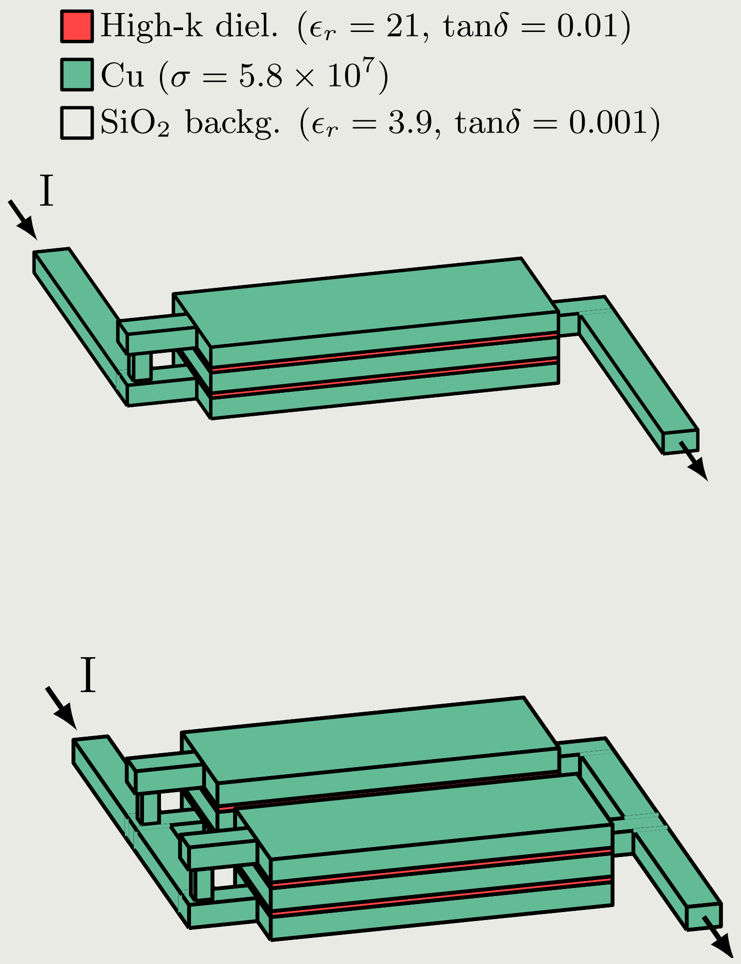
Numerical results

Interdigital on-chip capacitor structures

Single and double element capacitor structures

Material choices reflect typical on-chip integration practices

Unit current is injected into both structures, allowing to determine the **impedance response**

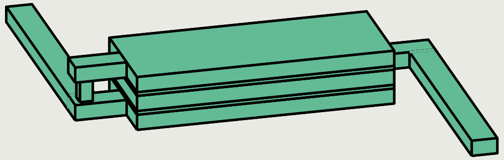


Numerical results

Interdigital on-chip capacitor structures

Validation with:

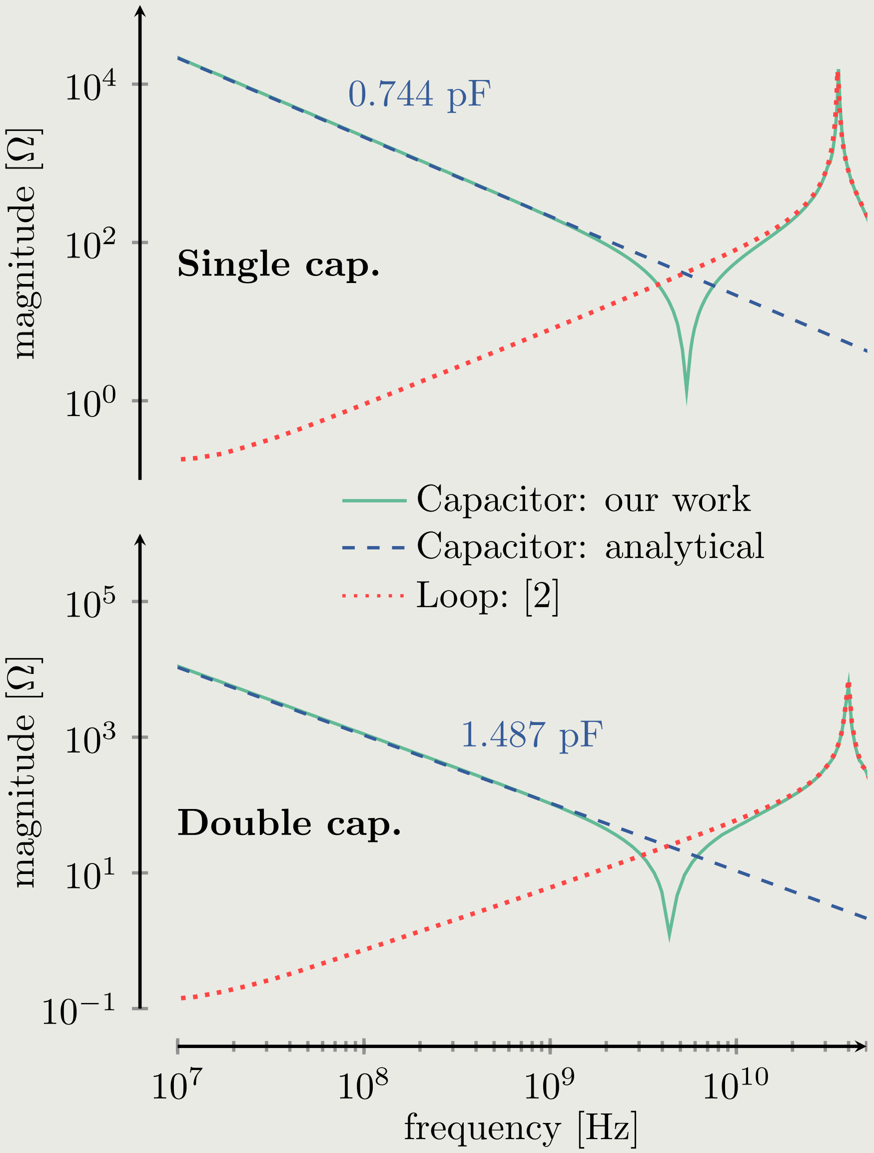
1. Analytical capacitor impedance
2. Loop impedance by shorting dielectric [2]



Very good agreement with both reference solutions across a broad frequency range

15% reduction in number of unknowns

CST MWS was unable to produce reliable results



[2] M. Huynen et al., IEEE Trans. Microw. Theory Techn., vol. 68, no. 4, pp. 1217–1233, 2020.

Conclusions

Increasing integration density and circuit speed requires accurate and efficient full-wave modeling

Leveraged analytical properties of EDBFs to derive a PS operator for piecewise homogeneous volumes

Novel DSA operator was constructed using these PS operators and subsequently combined with the aEFIE

Demonstrated that new formalism accurately models material interfaces while reducing the number of unknowns quest. Quantum Mechanical & Electromagnetic Systems Modelling Lab

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