Reduced Order MEEC Models for RFIC Design Based on Coupled Electric and Magnetic Circuits

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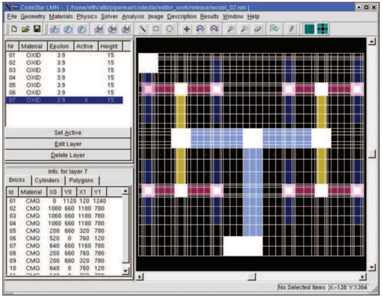
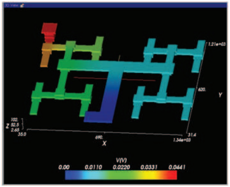
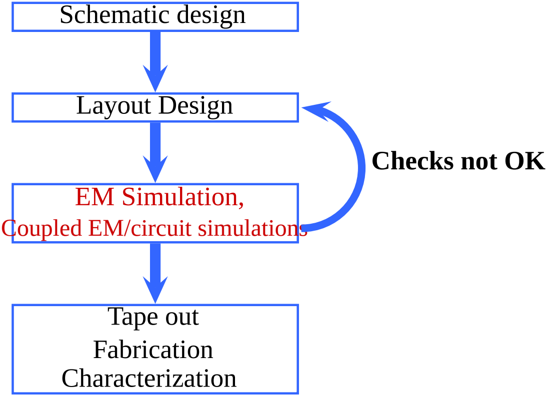
Outline

Bridge from layout to circuit, considering EM couplings







Basic IC design flow.

MEEC models are useful at the EM simulation step.

Context - Inductance Modeling

$$L_{ij} = \frac{\mu_0}{4\pi}\oint_{\Gamma_i}\oint_{\Gamma_j}\frac{\mathbf{dl}_i\cdot\mathbf{dl}_j}{R_{ij}}$$

$$L_{ij} = \frac{\mu_0}{4\pi A_i A_j}\int_{\mathcal{S}_i}\oint_{\Gamma_i}\int_{\mathcal{S}_j}\oint_{\Gamma_j}\frac{\mathrm{d}a_i\mathrm{d}a_j\mathbf{dl}_i\cdot\mathbf{dl}_j}{R_{ij}}$$

$$\begin{aligned}\varphi &= \mathbf{Li}\\ \Gamma &= \mathbf{L}^{-1}\\ \mathbf{i} &= \Gamma\varphi\end{aligned}$$

$$\Gamma_i = \cup_{k=1}^{e_i} C_{i,k} \quad \Gamma_j = \cup_{p=1}^{e_j} C_{j,p}$$

$$L'_{kp} = \frac{\mu_0}{4\pi A_i A_j}\int_{\mathcal{S}_i}\int_{C_{i,k}}\int_{\mathcal{S}_j}\int_{C_{j,p}}\frac{\mathrm{d}a_i\mathrm{d}a_j\mathbf{dl}_i\cdot\mathbf{dl}_j}{R_{ij}}$$

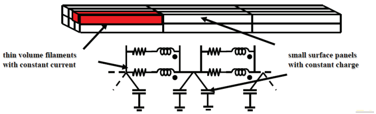
$$L_{ij} = \sum_{k=1}^{e_i}\sum_{p=1}^{e_j}\pm L'_{kp}$$

Partial inductances have no physical meaning because they are non-measurable quantities.

Context - Inductance Modeling

1. PEEC (Partial element equivalent circuit) method [Ruehli74, Nabors91, Kamon94, Silveira95, Phillips97, Kamon98, Daniel01, Daniel04, Marques04, Zhu05, Jiang05, Zhang06]
2. K-method or reluctance method: [Devgan00, Ji01, Zhong03, Li05, Escovar05, Huang03, Krauter95, Beattie01, Chen02]
3. VPEC - Vector Potential Equivalent Circuit: [Pacelli02, Pacelli00, Luryi02, Bhaduri04, Yu03, Yusirf04, Yu05]
4. GPEEC - Generalized partial element equivalent circuit [Yang09]

Context - Inductance Modeling - PEEC



- partition of conductors in segments;
- coupling inductance between any two segments;
- expensive model (full matrix)
- sparsification is not robust
- efficient implementation in *FastHenry* by Kamon et al (the reference program for inductance extraction)

Main concern: theoretical inconsistency - since inductances are properties of closed loops

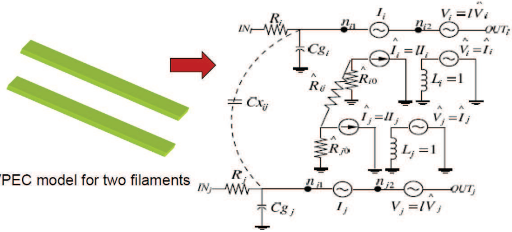
Context - Inductance Modeling - K-method

- use the inverse of the partial inductances matrix:

$$\mathbf{K} = (\mathbf{L}')^{-1}$$

- K matrix has locality and sparsity, in a similar way to the capacitance matrix
- K parameters are not allowed in Spice $\Rightarrow$ double inversion needed
- implemented in a time domain simulator called *Inductwise*.

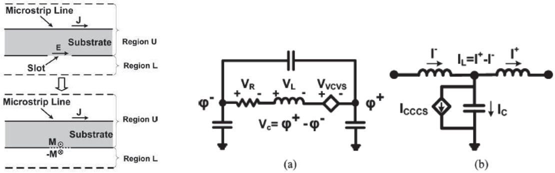
Context - Inductance Modeling - VPEC



VPEC model for two filaments

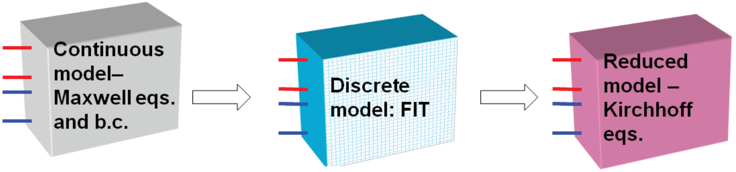
- partition of conductors in segments;
- two complementary discretizations, one for electric quantities, one for magnetic quantities
- the equivalent circuit for inductive effects contains non-physical resistors ("vector potential rezistances", measured in m^{-1}),
- it does not use partial inductances, but, due to the discretization of wire, the stability condition for VPEC is that the matrix of partial inductances be positive defined.

Context - Inductance Modeling - GPEEC



- generalized PEEC for planar circuits (multilayered circuits with slotted grounds);
- an equivalent "magnetic current" is used to represent the tangential electric field on the slots
- the model consists of two circuits, one electric and one magnetic, coupled by means of controlled sources
- Green′s functions in the spatial domain are used to derive the parameters of the coupled circuits

From Maxwell to Kirchhoff



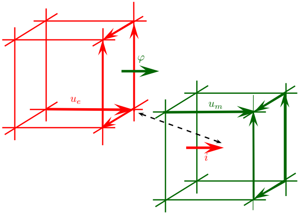
PDE $\Rightarrow$ DAE $\Rightarrow$ ODE

From Maxwell to Kirchhoff

Discretization by Finite Integrals Technique (FIT)

- numerical method to solve field problems, based on spatial discretization without shape functions [Th. Weiland et al. since 1977];
- dual staggered orthogonal grids, (Yee type = "complex of dual Cartesian cells"), suitable for Manhattan geometries;
- global variables as DoFs: voltages and fluxes on grid elements, and not local field components;
- global form of field equations (neither differential form - FDM, nor weak-variational form - FEM, nor integral equations - BEM/VIE).

From Maxwell to Kirchhoff



FIT for discretization of Maxwell's equation:

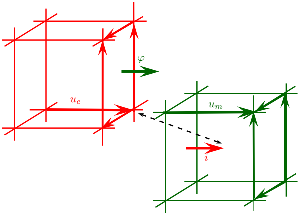
- **1)** Faraday's law (FL)

$$\mathrm{curl}\,\vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \Rightarrow \quad \mathbf{C}\mathbf{u}_e = -\frac{\mathrm{d}\varphi}{\mathrm{d}t}, \quad (1)$$

- **2)** Ampere's law (AL)

$$\mathrm{curl}\,\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad \Rightarrow \quad \mathbf{C}'\mathbf{u}_m = \mathbf{i}_\sigma + \frac{\mathrm{d}\psi}{\mathrm{d}t}, \quad (2)$$

From Maxwell to Kirchhoff



FIT for discretization of Maxwell's equation:

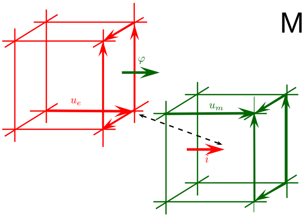
- **3)** Magnetic flux law (MFL)

$$\operatorname{div} \vec{B} = 0 \quad \Rightarrow \quad \mathbf{D}'\varphi = \mathbf{0}, \tag{3}$$

- **4)** Electric flux law (EFL)

$$\operatorname{div} \vec{D} = \rho \quad \Rightarrow \quad \mathbf{D}\psi = \mathbf{q}, \tag{4}$$

From Maxwell to Kirchhoff



FIT for discretization of Maxwell's equation:

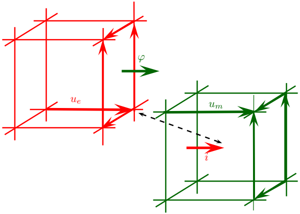
- **5)** Current conservation law (CCL)

$$\operatorname{div}\vec{J} = -\frac{\partial \rho}{\partial t} \quad \Rightarrow \quad \mathbf{Di}_\sigma = -\frac{\mathbf{dq}}{\mathrm{d}t}, \tag{5}$$

Combined with Hodge operators that describe the material behaviour.

- **1)** $\vec{B} = \mu\vec{H} \quad \Rightarrow \quad \varphi = \mathbf{M}_\mu \mathbf{u}_m$
- **2)** $\vec{J} = \sigma\vec{E} \quad \Rightarrow \quad \mathbf{i}_\sigma = \mathbf{M}_\sigma \mathbf{u}_e,$
- **3)** $\vec{D} = \varepsilon\vec{E} \quad \Rightarrow \quad \psi = \mathbf{M}_\varepsilon \mathbf{u}_e.$

From Maxwell to Kirchhoff



- (FL) $\mathbf{C}\mathbf{u}_e = -\frac{\mathrm{d}\varphi}{\mathrm{d}t}$
- (AL) $\mathbf{C}'\mathbf{u}_m = \mathbf{i}_\sigma + \frac{\mathrm{d}\psi}{\mathrm{d}t}$
- (MFL) $\mathbf{D}'\varphi = \mathbf{0}$
- (EFL) $\mathbf{D}\psi = \mathbf{q}$
- (CCL) $\mathbf{D}\mathbf{i}_\sigma = -\frac{\mathrm{d}\mathbf{q}}{\mathrm{d}t}$,
- $\varphi = \mathbf{M}_\mu \mathbf{u}_m$
- $\mathbf{i}_\sigma = \mathbf{M}_\sigma \mathbf{u}_e$,
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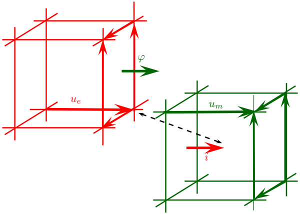
From Maxwell to Kirchhoff



- (FL) $\mathbf{B}\mathbf{u}_e = -\dfrac{\mathrm{d}\varphi}{\mathrm{d}t}$
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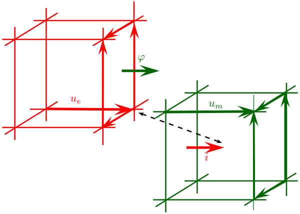
From Maxwell to Kirchhoff



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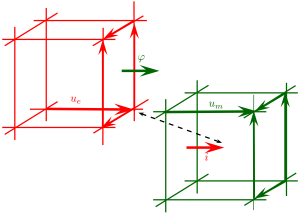

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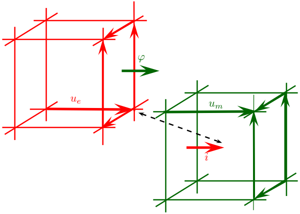

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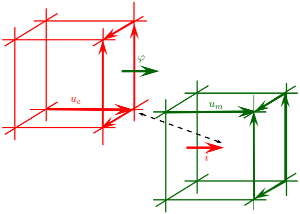
From Maxwell to Kirchhoff



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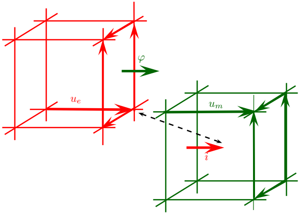
From Maxwell to Kirchhoff



- (FL) $\mathbf{B}\mathbf{u}_e = -\frac{\mathrm{d}\varphi}{\mathrm{d}t}$
- (AL,ε) $\mathbf{B}'\mathbf{u}_m = \mathbf{i}$, $\quad \mathbf{i} = \mathbf{i}_\sigma + \mathbf{i}_\varepsilon$,
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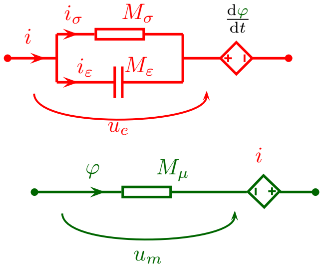
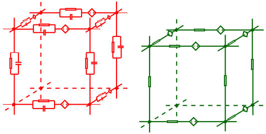
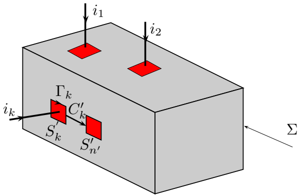
From Maxwell to Kirchhoff

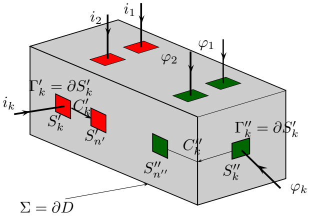
- $\mathbf{B}\mathbf{u}_e = -\frac{\mathrm{d}\varphi}{\mathrm{d}t}$
- $\mathbf{B}'\mathbf{u}_m = \mathbf{i}$
- $\mathbf{A}'\varphi = \mathbf{0}$
- $\mathbf{A}\mathbf{i} = \mathbf{0}$,
- $\varphi = \mathbf{M}_\mu \mathbf{u}_m$
- $\mathbf{i}_\sigma = \mathbf{M}_\sigma \mathbf{u}_e$,
- $\mathbf{i} = \mathbf{i}_\sigma + \mathbf{i}_\varepsilon$,
- $\mathbf{i}_\varepsilon = \mathbf{M}_\varepsilon \frac{\mathrm{d}\mathbf{u}_e}{\mathrm{d}t}$.





Boundary Conditions: Hooks - ECE





Electric Circuit Element (ECE) (left):

$$\vec{n} \cdot \operatorname{curl} \vec{E}(P,t) = 0 \quad \text{for } (\forall)\, P \in \Sigma, \tag{6}$$

$$\vec{n} \cdot \operatorname{curl} \vec{H}(P,t) = 0 \quad \text{for } (\forall)\, P \in \Sigma - \cup S'_k, \tag{7}$$

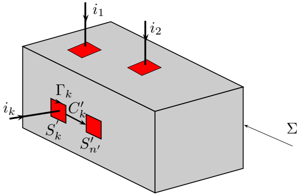
$$\vec{n} \times \vec{E}(P,t) = \vec{0} \quad \text{for } (\forall)\, P \in \cup S'_k, \tag{8}$$

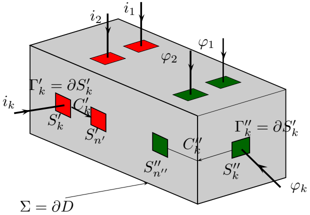
$$i_k(t) = \oint_{\Gamma_k} \vec{H} \cdot \mathrm{d}\vec{r}, \quad \Gamma_k = \partial S'_k,$$

$$v_k(t) = \int_{C_k} \vec{E} \cdot \mathrm{d}\vec{r},$$

$$P = -\oint_{\Sigma} (\vec{E} \times \vec{H}) \cdot d\vec{A} = \sum_{k=1}^{n'-1} v_k i_k .$$

Boundary Conditions: Hooks - EMCE





Electro-Magnetic Circuit Element (EMCE) (right):

$$\vec{n} \cdot \mathrm{curl}\, \vec{E}(P,t) = 0 \quad \text{for } (\forall)\, P \in \Sigma - \cup S''_k, \tag{9}$$

$$\vec{n} \cdot \mathrm{curl}\, \vec{H}(P,t) = 0 \quad \text{for } (\forall)\, P \in \Sigma - \cup S'_k, \tag{10}$$

$$\vec{n} \times \vec{E}(P,t) = \vec{0} \quad \text{for } (\forall)\, P \in \cup S'_k, \tag{11}$$

$$\vec{n} \times \vec{H}(P,t) = \vec{0} \quad \text{for } (\forall)\, P \in \cup S''_k, \tag{12}$$

$$\frac{\mathrm{d}\varphi_k(t)}{\mathrm{d}t} = \oint_{\Gamma_k} \vec{E} \cdot \mathrm{d}\vec{r},$$

$$u_{m,k}(t) = \int_{C_k} \vec{H} \cdot \mathrm{d}\vec{r}$$

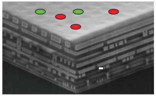
$$P = -\oint_{\Sigma} (\vec{E} \times \vec{H}) \cdot d\vec{A} = \sum_{k=1}^{n'-1} v_k i_k + \sum_{k=1}^{n''-1} u_{m,k} \frac{\mathrm{d}\varphi_k(t)}{\mathrm{d}t}.$$

Notes on EMCE boundary conditions

- An electric terminal = superconducting spot on the boundary, through which the magnetic field is not allowed to pass; it is equipotential from the electric point of view;
- A magnetic terminal = equipotential from the magnetic point of view, through which the electric current (conduction or displacement) is not allowed to pass;
- At the limint, when a hook is a node, the interface is transparent for the EM field $\Rightarrow$ unacceptable from the computational point of view $\Rightarrow$ The number of hooks must be small!

Even if the number of hooks is small, the space size of the discretized system is high (order = no. of FIT cells) $\Rightarrow$ further reduction is needed (e.g. sparsefied circuits).

Domain Partitioning

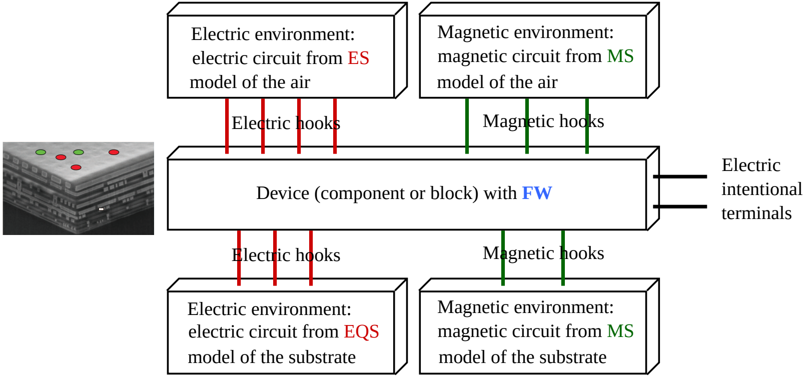


Air:
ES + MS (open boundary)

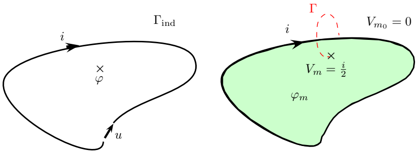
SiO_2 including the device and the non-homogeneous part of the substrate:
FW or horizontally partitioned

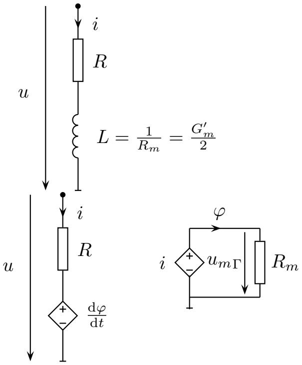
Si including the homogeneous part of the substrate:
EQS + MS

Domain Partitioning



Most simple MEEC model (1 filamentary coil, 1 turn)

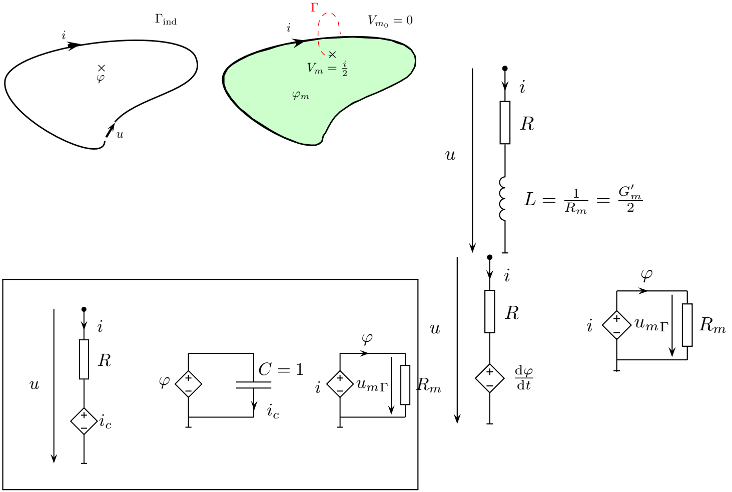




$$
\begin{aligned}
L &= \varphi / i, \\
Ri - u &= -\frac{\mathrm{d}\varphi}{\mathrm{d}t}.
\end{aligned}
$$

$$
\begin{aligned}
u_{m_\Gamma} &= i, \\
u_{m_\Gamma} &= R_m \varphi_m, \\
\varphi_m &= \varphi
\end{aligned}
$$

Most simple MEEC model (1 filamentary coil, 1 turn)



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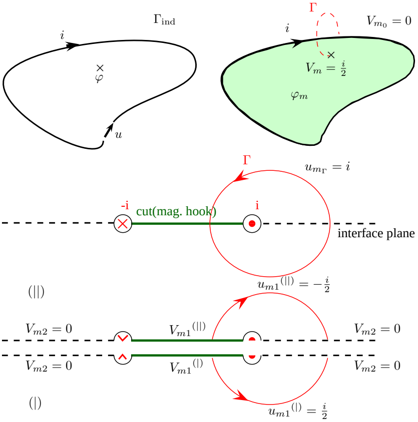


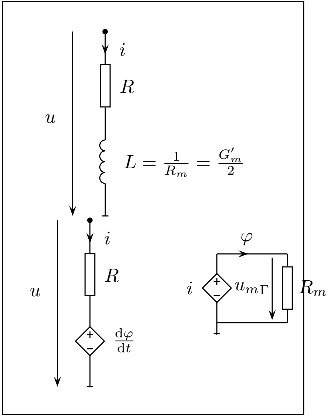
$$\begin{aligned} \operatorname{curl} \vec{H} &= \mathbf{0}, \\ \operatorname{div} \vec{B} &= 0, \\ \vec{B} &= \mu_0 \vec{H} \end{aligned}$$

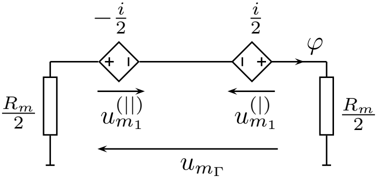
$$\operatorname{curl} \vec{H} = -\operatorname{grad} V_m.$$

$$\triangle V_m = 0$$

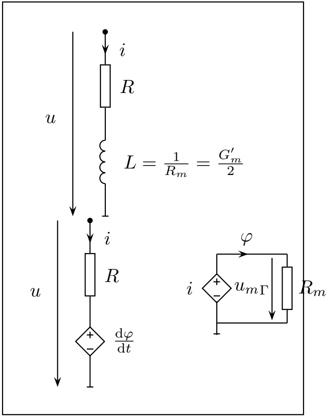
$$\begin{aligned} G'_m &= 1/R'_m = 2/R_m = 2L \\ L &= G'_m/2 \end{aligned}$$

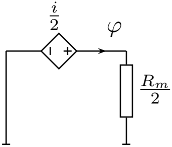
Most simple MEEC model (1 filamentary coil, 1 turn)

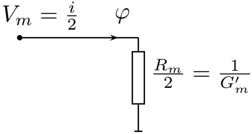




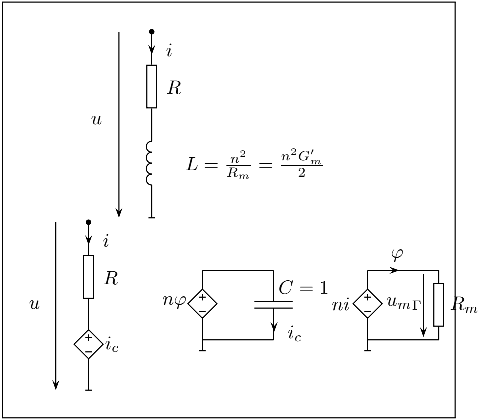
Most simple MEEC model (1 filamentary coil, 1 turn)





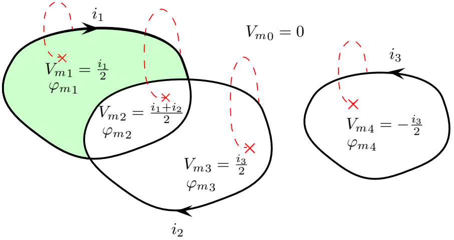


Most Simple MEEC model (1 filamentary coil, n turns)



$$L = \varphi/i = n\varphi_m/i = nG'_m/2.$$

MEEC Models for Planar Inductors



$$V_{m_k} = \sum \pm i_j/2$$

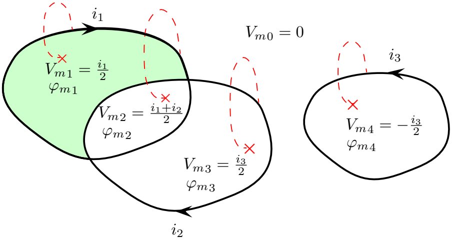
$$\mathbf{V}_m = \frac{1}{2}\mathbf{S}_{me}\mathbf{i}$$

$$\mathbf{S}_{me} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\begin{aligned} \varphi_m &= \mathbf{G}'_m \mathbf{V}_m \\ \varphi &= \mathbf{L}\mathbf{i} \\ \varphi &= \mathbf{S}_{em}\varphi_m \end{aligned}$$

$$\mathbf{S}_{em} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

MEEC Models for Planar Inductors



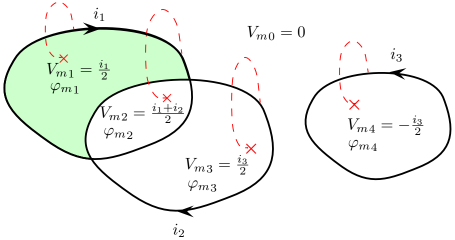
$$\begin{aligned}
\mathbf{V}_m &= \frac{1}{2}\mathbf{S}_{me}\mathbf{i} \\
\varphi_m &= \mathbf{G}'_m\mathbf{V}_m \\
\varphi &= \mathbf{L}\mathbf{i} \\
\varphi &= \mathbf{S}_{em}\varphi_m
\end{aligned}$$

$$\mathbf{S}_{em} = \mathbf{S}, \quad \mathbf{S}_{me} = \mathbf{S}^T$$

$$\varphi = \mathbf{S}\varphi_m = \mathbf{S}\mathbf{G}'_m\mathbf{V}_m = \frac{1}{2}\mathbf{S}\mathbf{G}'_m\mathbf{S}^T\mathbf{i}$$

$$\mathbf{L} = \frac{1}{2}\mathbf{S}\mathbf{G}'_m\mathbf{S}^T$$

MEEC Models for Planar Inductors



$$\mathbf{L} = \frac{1}{2}\mathbf{S}\mathbf{G}_m'\mathbf{S}^T$$

S = relationships between the magnetic fluxes through the surfaces generated by closed conducting paths and the magnetic fluxes that flow through the magnetic hooks. E.g.

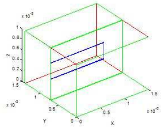
- if ind.no.1 has 3 turns and ind.no.3 has 2 turns

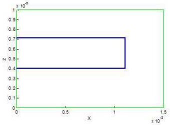
$$\mathbf{S} = \begin{bmatrix} 3 & 3 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & -2 \end{bmatrix}$$

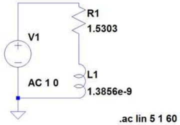
- if, furthermore, ind.no.1 and ind.no.2 series connected

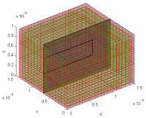
$$\mathbf{S} = \begin{bmatrix} 3 & 4 & 1 & 0 \\ 0 & 0 & 0 & -2 \end{bmatrix}$$

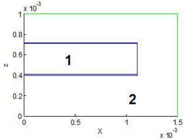
Idea illustrated on simple cases - Example 1

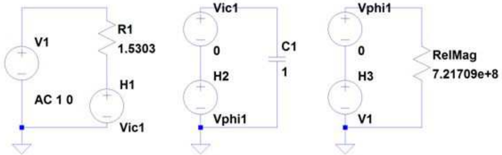






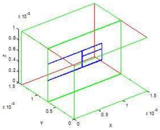


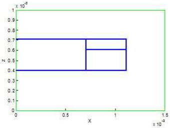


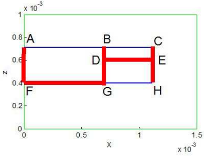


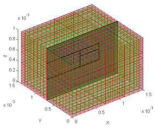
L_{ref} $\qquad L = \frac{G_{\mathrm{mag}}^{(nodal)}}{2}$ $\qquad \mathrm{Relmag} = \frac{1}{L}$ $\qquad$ er = 0.37 % .ac lin 5 1 60

Idea illustrated on simple cases - Example 2

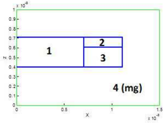




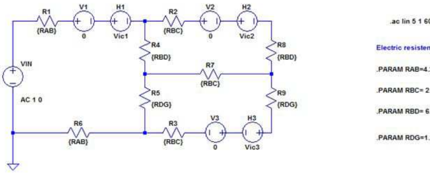




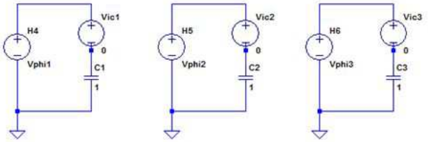
Z_{ref}



$\mathbf{G}_{\mathrm{mag}}^{(nodal)} \in \mathbb{R}^{3\times 3}$

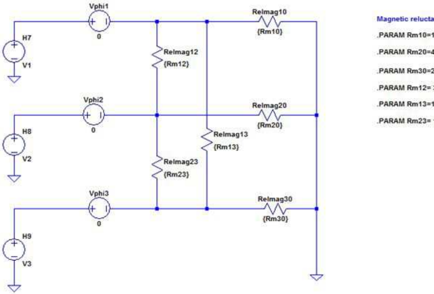


Idea illustrated on simple cases - Example 2



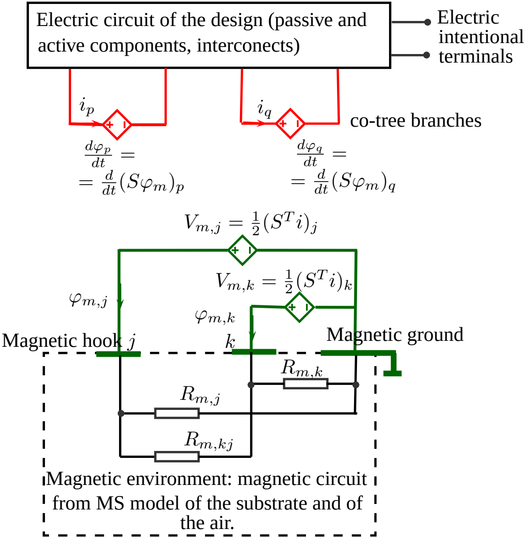
$$\mathrm{Relmag}_{ij} = -\frac{2}{Gmag_{\mathrm{ij}}^{(nodal)}}$$

$$\mathrm{Relmag}_{i0} = \frac{2}{\sum_{k=1}^{3} Gmag_{\mathrm{ki}}^{(nodal)}}$$



er = 0.6 %

MEEC Models for Inductive Effects in RF Blocks



Implementation

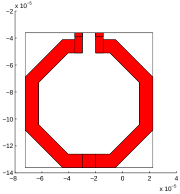
1. Layout oriented step:
   - Extract magnetic hooks from the layout;
   - Do MS simulation by solving the Laplace's equation in a semi-space with the magnetic hooks above as terminals.
   - Compute terminal magnetic conductances $\mathbf{G}'_m$.
2. Netlist oriented step:
   - Extract a tree that leaves in the co-tree all the existent inductors.
3. Geometric netlist oriented step:
   - Derive the link between the loops generated by the tree in the electric netlist and the magnetic hooks **S**.
4. Correction of the initial netlist:
   - Insert in the co-tree branches coupled inductors having the values computed according to

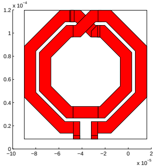
$$\mathbf{L} = \frac{1}{2}\mathbf{S}\mathbf{G}'_m\mathbf{S}^T.$$

Planar Inductors

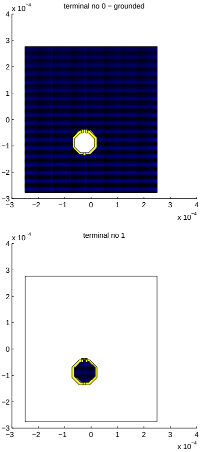
Coils used in the LNA design.

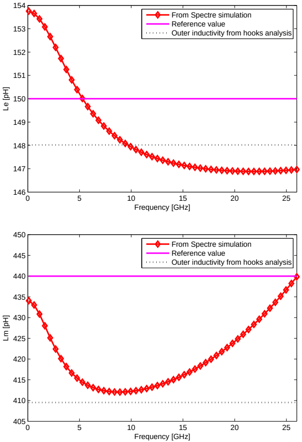
Inductor	Description	L (Spectre simulation)
Le	Q4gLsimwosh din=75 n=1 w=10 s=3.0 lc=5.0 wc=5.5 sc=10 es=3.0 ec=1.0 wb=10.0 nvia=1 cpin=0	150 pH
Lm	Q4gLsimwosh din=60 n=2 w=10 s=3.0 lc=5.0 wc=5.5 sc=10 es=3.0 ec=8.45 wb=10.0 nvia=9 cpin=0	440 pH





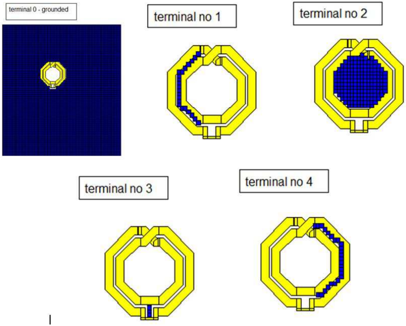
Planar Inductors



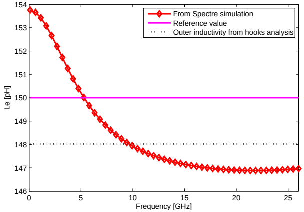


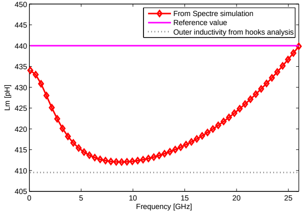
$$\mathbf{S}_{Le} = \begin{bmatrix} 1 \end{bmatrix}$$

Planar Inductors

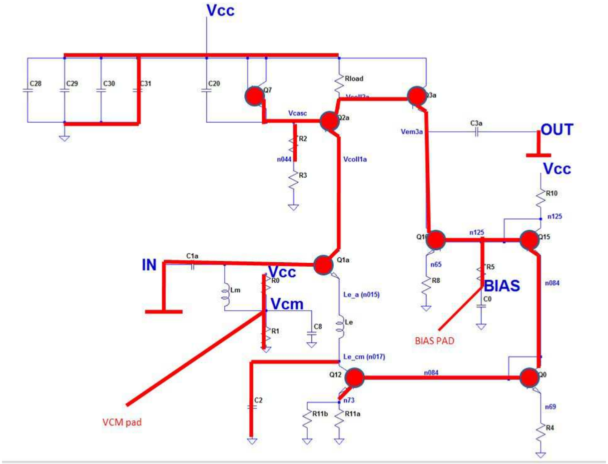


$$\mathbf{S}_{Lm} = \begin{bmatrix} 1 & 2 & 1 & 1 \end{bmatrix}$$

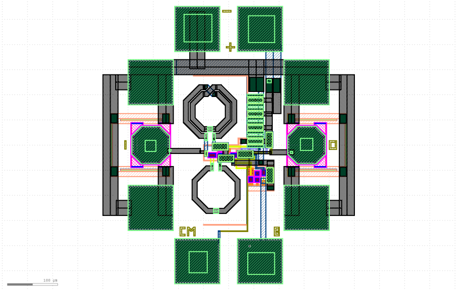


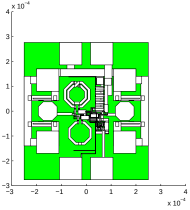


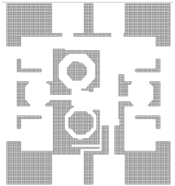
LNA - electric schematic and chosen tree



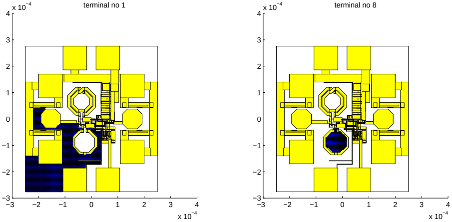
LNA - layout and magnetic hooks

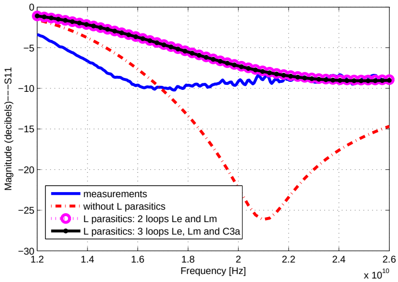


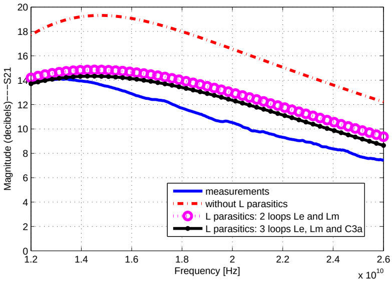




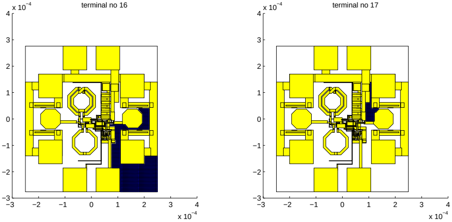
LNA - magnetic hooks touching the Le co-tree branch

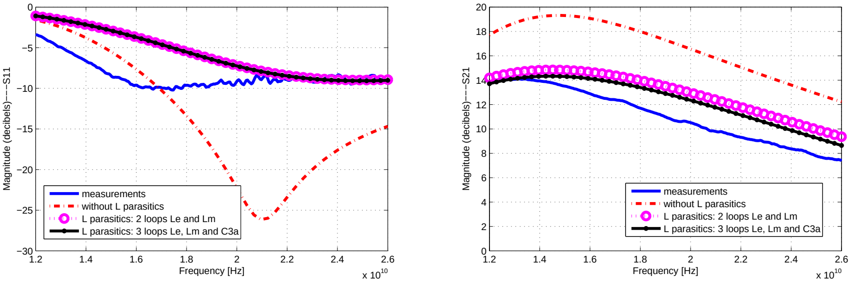




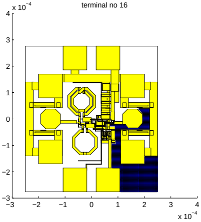


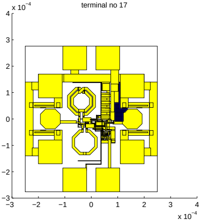
LNA - magnetic hooks touching the Ca co-tree branch

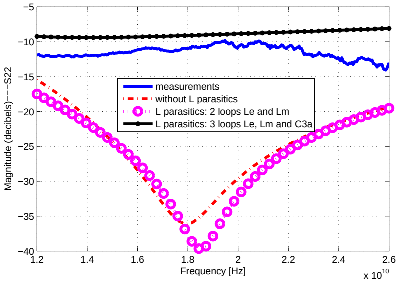


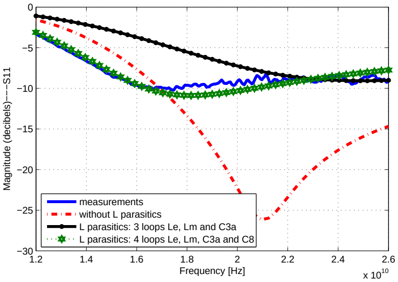


LNA - magnetic hooks touching the C3a branch









Notes on the Computational Effort

- Magnetic hook identification = almost instantaneously (planar domain minus the projections of the conducting bricks).
- Computation of magnetic reluctances = with *FastCap* and similitude with ES, reults $\times \mu_0/\varepsilon_0$. (6327 conducting panels *FastCap*, time $\leq$ 4 seconds on an Intel(R) i7 CPU, 2.20 GHz, 8GB RAM.)
- Steps 2, 3 and 4 of the algorithm were done by inspection.

For an automatic procedure, step 3 is the most difficult part (i.e computation of matrix **S**) has to be derived.
For this, it is necessary to enhance the electric netlist with geometric information about the nodes and branches.

Qualitative comparison with VPEC

Similar - both VPEC and MEEC

- focus on long-range inductive interactions between large conductors and use a MS formulation in order to estimate the magnetic field effects.
- derive two connected equivalent circuits, one for the electric part and one for the magnetic part, that are linked together by means of controlled sources.

Qualitative comparison with VPEC

Different:

- In VPEC the equivalent circuit contains non-physical resistors (called vector potential resistances and having as unit m^{-1}), whereas in MEEC there are only physical magnetic reluctances.
- In VPEC needs discretization into cells that surround single wire segments and thus, even if no partial inductances are computed as in PEEC, its stability is similar to PEEC stability, whereas MEEC does not need to discretize conducting paths, $\Rightarrow$ less computational effort and an unconditional stability (the extracted magnetic reluctance matrix is always positive defined, irrespective of the number of hooks used).

Qualitative comparison with GPEEC

- Similar: there are two separate circuit representations of the electric and magnetic parts, the couplings being carried out by means of controlled sources.
- Different, but an equivalence might exists: GPEEC uses equivalent magnetic currents, whereas MEEC uses the concept of magnetic hooks (special boundary conditions).
- Different: GPEEC relies on Green's functions, whereas MEEC refers to the EM problem formulation, and does not assume a specific solving method.

Conclusions

- MEEC relies on the use of coupled electric and magnetic circuits for the modeling of inductive effects in RF components or blocks.
- It is an alternative to existing methods relying on wires segmentation and on the computation of partial inductivities, such as VPEC.
- Is built on a solid theoretical foundation and it does not suffer from such numerical instabilities because the current distribution is considered as a sum of virtual mesh currents, through closed fundamental loops.
- It is based on domain partitioning instead of conductor segmentation, and use of special boundary conditions, called hooks, on the interfaces between the subparts in which the computational domain is decomposed.

Conclusions

- Avoiding the wire segmentation, the size of the model is drastically reduced and the extracted model is more robust and easy to be reduced by geometric and algebraic sparsification.
- The surfaces of these loops are the magnetic hooks, which allow the modeling of intentional or parasitic coupling between subdomains, by means of a finite number of quantities assigned to them.
- The success of the correct extraction of inductive effects relies on the correct placement of magnetic hooks on the interfaces.

Conclusions

- The output of the MEEC approach consists of two circuits, one electric and one magnetic, that are coupled together in a natural way.
- A new concept is proposed and used - the geometric netlist = classical netlist enhanced with geometric attributes of nodes and branches (not only the topology is important but also the geometric placement of components and their interconnections).
- The shape and placement of magnetic hooks used in MEEC is automatically found from the IC layout, the magnetic hooks being mapped to its holes.

Conclusions

- The size of the extracted model is low and needs a small effort since there is no need to compute any components of the **L** or **K** matrices, *nor to invert these matrices*. (suitable for large scale problems).
- Sparsification can be carried out in an effective and robust manner, the passivity being kept. Sparsification of MEEC means = ignoring the existence of certain magnetic hooks based on algebraic or/and geometric reasons.
- Drawbacks:
  1. MEEC is not suitable for conductors with arbitrary 3D shape, where VPEC can be applied easily.
  2. Parasitic capacitors are allowed only at the local level (inside the partitioned sub-domains) and not at the global level.

Acknowledgment

Note: the extensive content of this presentation has been published in the paper
Gabriela Ciuprina, Daniel Ioan, Rick Janssen, and Edwin van der Heijden, MEEC Models for RFIC Design Based on Coupled Electric and Magnetic Circuits, IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 34(3), pp. 395-408, 2015, ISSN:0278-0070, DOI: 10.1109/TCAD.2014.2387863, available at

http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7003979

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3. Dr. Edwin van der Heijden - NXP Semiconductors.

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