Reduced-Basis Method for Maxwell's Equations: Understanding Electromagnetics via Circuit Theory

Valentin de la Rubia

Departamento de Matematica Aplicada
Universidad Politecnica de Madrid
(UPM)

e-mail: valentin.delarubia@upm.es

Bucharest 2015

Outline

Índice

Motivation

- Full-wave design of microwave circuits.
- We had a ROM for fast frequency sweep that no one used for design.
- It worked but you never knew the frequency band of convergence.
- You never knew how many moments you have to solve for in the circuit you were dealing with.
- In the end, only a well-trained expert could make it worthy for FFS.

Goals

- Reliable reduced-order model.
- Efficient model order reduction process.
- No expertise help be required.

Motivation

- Full-wave design of microwave circuits.
- We had a ROM for fast frequency sweep that no one used for design.
- It worked but you never knew the frequency band of convergence.
- You never knew how many moments you have to solve for in the circuit you were dealing with.
- In the end, only a well-trained expert could make it worthy for FFS.

Goals

- Reliable reduced-order model.
- Efficient model order reduction process.
- No expertise help be required.

Time-Harmonic Maxwell's Equations. Weak formulation

Continuous problem

Find $\overline{H} \in \mathcal{X}$ such that

$$\int\limits_{\Omega} \left(\frac{1}{\varepsilon_r} \nabla \times \overline{H} \cdot \nabla \times \overline{W} - k^2 \mu_r \overline{H} \cdot \overline{W} \right) dv = -\frac{jk}{\eta_0} \int\limits_{\partial\Omega} \overline{\Psi} \cdot \overline{W} ds \quad \forall \overline{W} \in \mathcal{X}.$$

$\mathcal{X}$ is $H(curl;\Omega)$.

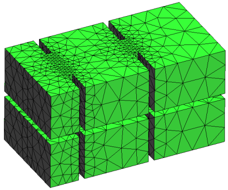
Finite Element formulation

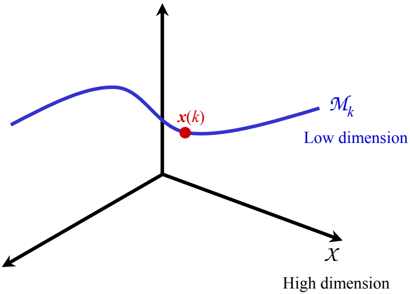
Find $\overline{H} \in \mathcal{X}^{\mathcal{N}}$ such that

$$\int\limits_{\Omega} \left(\frac{1}{\varepsilon_r} \nabla \times \overline{H} \cdot \nabla \times \overline{W} - k^2 \mu_r \overline{H} \cdot \overline{W} \right) dv = -\frac{jk}{\eta_0} \int\limits_{\partial\Omega} \overline{\Psi} \cdot \overline{W} ds \quad \forall \overline{W} \in \mathcal{X}^{\mathcal{N}}.$$

$\mathcal{X}^{\mathcal{N}}$ is Nédélec finite elements.

Reduced basis space





CEM

We tend to approximate the field solution itself $\Longrightarrow$ Large approximation space $\mathcal{X}$

BUT...

The field does NOT arbitrarily vary. It evolves on reduced manifold $\mathcal{M}_k$

WHY NOT?

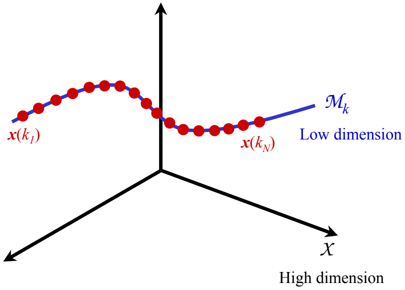
Try a hand at approximating this low-dimensional manifold instead? Reduced-basis space.

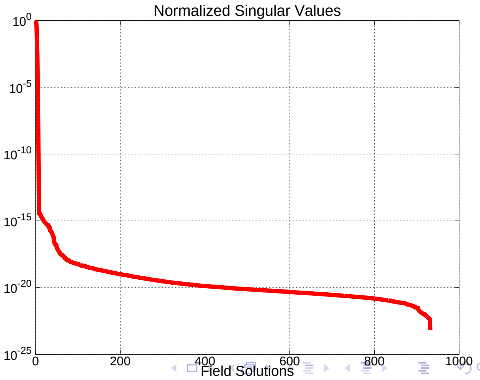
Reduced basis space. Proper Orthogonal Decomposition

Proper orthogonal decomposition

1. Fine sampling of the field solutions in the parameter space.
2. Throw away all linearly dependency in the field solutions via SVD.

Canonical waveguide filter

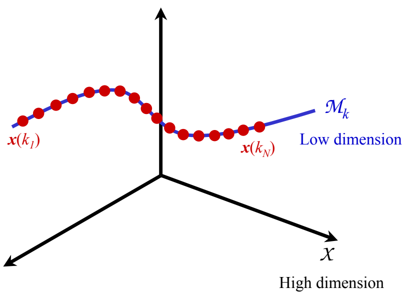


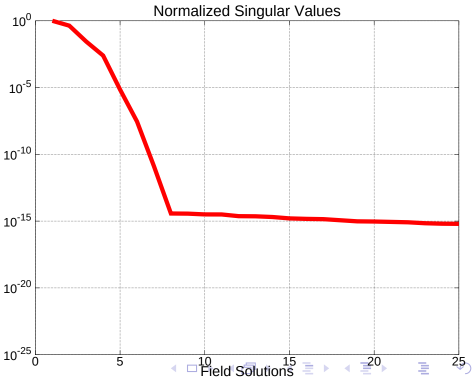


Proper orthogonal decomposition

1. Fine sampling of the field solutions in the parameter space.
2. Throw away all linearly dependency in the field solutions via SVD.

Canonical waveguide filter





Problem statement

Original problem. Dimension $M, M \gg 1$

Find $\mathbf{x}(k)$ such that:

$$\mathbf{A}(k)\mathbf{x}(k) = \mathbf{b}(k) \qquad \forall k \in [k_1, k_2]$$

Reduced-order model. Dimension $n, n \ll M$

Find $\widetilde{\mathbf{x}}(k)$ such that:

$$\mathbf{V}^T\mathbf{A}(k)\mathbf{V}\widetilde{\mathbf{x}}(k) = \mathbf{V}^T\mathbf{b}(k) \quad \mathbf{V} = cols\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$$

$$\widetilde{\mathbf{A}}(k)\widetilde{\mathbf{x}}(k) = \widetilde{\mathbf{b}}(k) \qquad \forall k \in [k_1, k_2]$$

Affine parameter dependence

$$\mathbf{A}(k) = \mathbf{S} - k^2\mathbf{T}$$
$$\mathbf{b}(k) = f(k)\mathbf{b}$$

Derived parameter dependence

$$\widetilde{\mathbf{A}}(k) = \widetilde{\mathbf{S}} - k^2\widetilde{\mathbf{T}}$$
$$\widetilde{\mathbf{b}}(k) = f(k)\widetilde{\mathbf{b}}$$
$$\widetilde{\mathbf{S}} = \mathbf{V}^T\mathbf{S}\mathbf{V},\ \widetilde{\mathbf{T}} = \mathbf{V}^T\mathbf{T}\mathbf{V},\ \widetilde{\mathbf{b}} = \mathbf{V}^T\mathbf{b}$$

Problem statement

Original problem. Dimension $M, M \gg 1$

Find $\mathbf{x}(k)$ such that:

$$\mathbf{A}(k)\mathbf{x}(k) = \mathbf{b}(k) \qquad \forall k \in [k_1, k_2]$$

Reduced-order model. Dimension $n, n \ll M$

Find $\widetilde{\mathbf{x}}(k)$ such that:

$$\mathbf{V}^T\mathbf{A}(k)\mathbf{V}\widetilde{\mathbf{x}}(k) = \mathbf{V}^T\mathbf{b}(k) \quad \mathbf{V} = cols\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$$

$$\widetilde{\mathbf{A}}(k)\widetilde{\mathbf{x}}(k) = \widetilde{\mathbf{b}}(k) \qquad \forall k \in [k_1, k_2]$$

Affine parameter dependence

$$\mathbf{A}(k) = \mathbf{S} - k^2\mathbf{T}$$
$$\mathbf{b}(k) = f(k)\mathbf{b}$$

Derived parameter dependence

$$\widetilde{\mathbf{A}}(k) = \widetilde{\mathbf{S}} - k^2\widetilde{\mathbf{T}}$$
$$\widetilde{\mathbf{b}}(k) = f(k)\widetilde{\mathbf{b}}$$
$$\widetilde{\mathbf{S}} = \mathbf{V}^T\mathbf{S}\mathbf{V},\ \widetilde{\mathbf{T}} = \mathbf{V}^T\mathbf{T}\mathbf{V},\ \widetilde{\mathbf{b}} = \mathbf{V}^T\mathbf{b}$$

Problem statement

Original problem. Dimension $M, M \gg 1$

Find $\mathbf{x}(k)$ such that:

$$\mathbf{A}(k)\mathbf{x}(k) = \mathbf{b}(k) \qquad \forall k \in [k_1, k_2]$$

Reduced-order model. Dimension $n, n \ll M$

Find $\widetilde{\mathbf{x}}(k)$ such that:

$$\mathbf{V}^T\mathbf{A}(k)\mathbf{V}\widetilde{\mathbf{x}}(k) = \mathbf{V}^T\mathbf{b}(k) \quad \mathbf{V} = cols\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$$

$$\widetilde{\mathbf{A}}(k)\widetilde{\mathbf{x}}(k) = \widetilde{\mathbf{b}}(k) \qquad \forall k \in [k_1, k_2]$$

Affine parameter dependence

$$\mathbf{A}(k) = \mathbf{S} - k^2\mathbf{T}$$
$$\mathbf{b}(k) = f(k)\mathbf{b}$$

Derived parameter dependence

$$\widetilde{\mathbf{A}}(k) = \widetilde{\mathbf{S}} - k^2\widetilde{\mathbf{T}}$$
$$\widetilde{\mathbf{b}}(k) = f(k)\widetilde{\mathbf{b}}$$
$$\widetilde{\mathbf{S}} = \mathbf{V}^T\mathbf{S}\mathbf{V},\ \widetilde{\mathbf{T}} = \mathbf{V}^T\mathbf{T}\mathbf{V},\ \widetilde{\mathbf{b}} = \mathbf{V}^T\mathbf{b}$$

A posteriori error estimation

$$\widetilde{\mathbf{A}}(k)\widetilde{\mathbf{x}}(k) = \widetilde{\mathbf{b}}(k) \qquad \mathbf{x}(k) \simeq \mathbf{V}\widetilde{\mathbf{x}}(k) = \sum_i \widetilde{x}_i(k)\mathbf{v}_i$$

Residual

$$\mathbf{R}(\widetilde{\mathbf{x}}(k);k) = \mathbf{b}(k) - \mathbf{A}(k)\mathbf{V}\widetilde{\mathbf{x}}(k) = \mathbf{b}(k) - \sum_i \widetilde{x}_i(k)\mathbf{A}(k)\mathbf{v}_i$$

Affine parameter dependence

$$\mathbf{R}(\widetilde{\mathbf{x}}(k);k) = f(k)\mathbf{b} - \sum_i \widetilde{x}_i(k)\mathbf{S}\mathbf{v}_i + k^2 \sum_i \widetilde{x}_i(k)\mathbf{T}\mathbf{v}_i$$

$\|\mathbf{R}(\widetilde{\mathbf{x}}(k);k)\|^2 = (\mathbf{R}(\widetilde{\mathbf{x}}(k);k), \mathbf{R}(\widetilde{\mathbf{x}}(k);k))$

$$(\mathbf{b},\mathbf{b}), \quad (\mathbf{b},\mathbf{S}\mathbf{v}_i), \quad (\mathbf{b},\mathbf{T}\mathbf{v}_i), \quad (\mathbf{S}\mathbf{v}_i,\mathbf{S}\mathbf{v}_j), \quad (\mathbf{T}\mathbf{v}_i,\mathbf{T}\mathbf{v}_j), \quad (\mathbf{S}\mathbf{v}_i,\mathbf{T}\mathbf{v}_j)$$

A posteriori error estimation

$$\widetilde{\mathbf{A}}(k)\widetilde{\mathbf{x}}(k) = \widetilde{\mathbf{b}}(k) \qquad \mathbf{x}(k) \simeq \mathbf{V}\widetilde{\mathbf{x}}(k) = \sum_i \widetilde{x}_i(k)\mathbf{v}_i$$

Residual

$$\mathbf{R}(\widetilde{\mathbf{x}}(k);k) = \mathbf{b}(k) - \mathbf{A}(k)\mathbf{V}\widetilde{\mathbf{x}}(k) = \mathbf{b}(k) - \sum_i \widetilde{x}_i(k)\mathbf{A}(k)\mathbf{v}_i$$

Affine parameter dependence

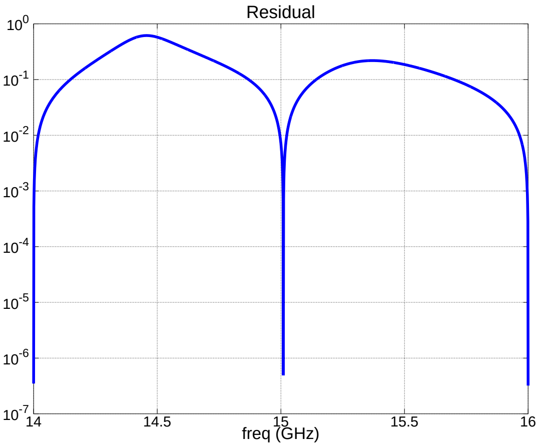
$$\mathbf{R}(\widetilde{\mathbf{x}}(k);k) = f(k)\mathbf{b} - \sum_i \widetilde{x}_i(k)\mathbf{S}\mathbf{v}_i + k^2 \sum_i \widetilde{x}_i(k)\mathbf{T}\mathbf{v}_i$$

$\|\mathbf{R}(\widetilde{\mathbf{x}}(k);k)\|^2 = (\mathbf{R}(\widetilde{\mathbf{x}}(k);k), \mathbf{R}(\widetilde{\mathbf{x}}(k);k))$

$$(\mathbf{b},\mathbf{b}),\ (\mathbf{b},\mathbf{S}\mathbf{v}_i),\ (\mathbf{b},\mathbf{T}\mathbf{v}_i),\ (\mathbf{S}\mathbf{v}_i,\mathbf{S}\mathbf{v}_j),\ (\mathbf{T}\mathbf{v}_i,\mathbf{T}\mathbf{v}_j),\ (\mathbf{S}\mathbf{v}_i,\mathbf{T}\mathbf{v}_j)$$

Reduced basis space. Constructive algorithm

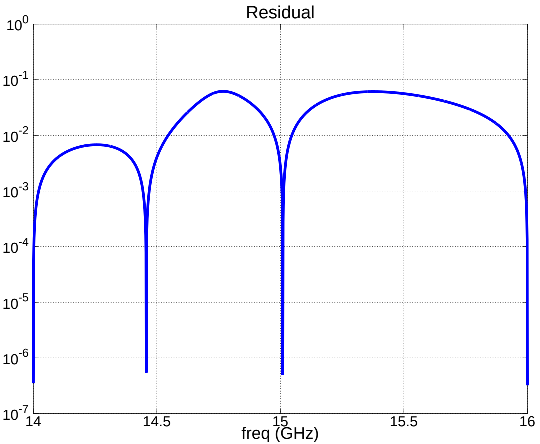
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

Reduced basis space. Constructive algorithm

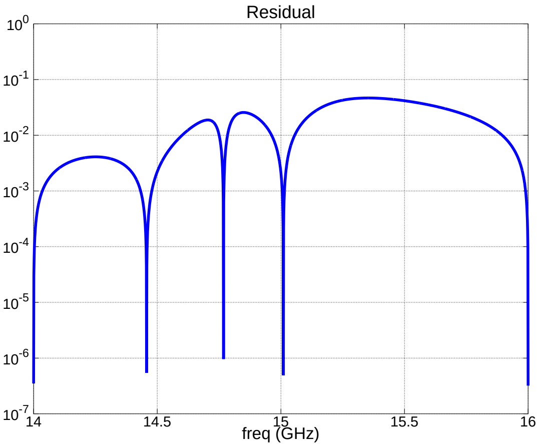
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

Reduced basis space. Constructive algorithm

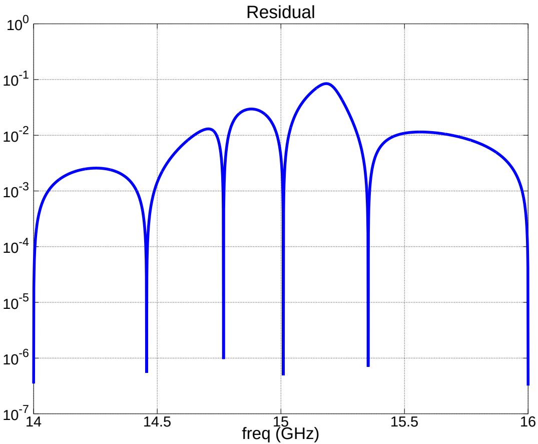
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

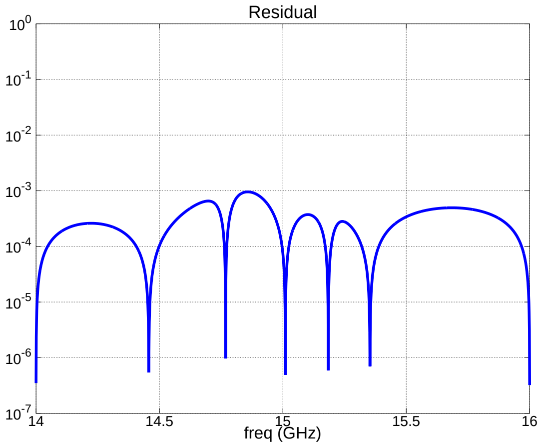
Reduced basis space. Constructive algorithm

Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

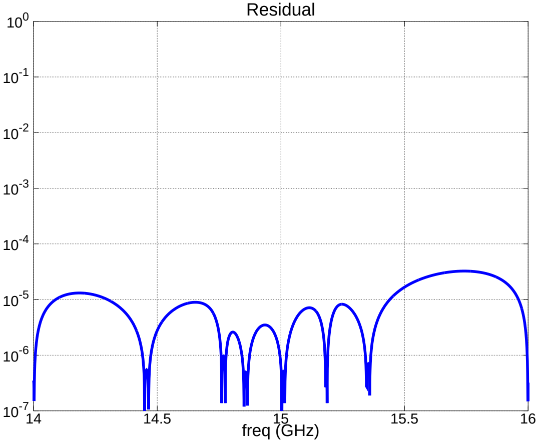
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. **ROM of dimension 7**
6. ROM of dimension 8
7. ROM dim = 9

Reduced basis space. Constructive algorithm

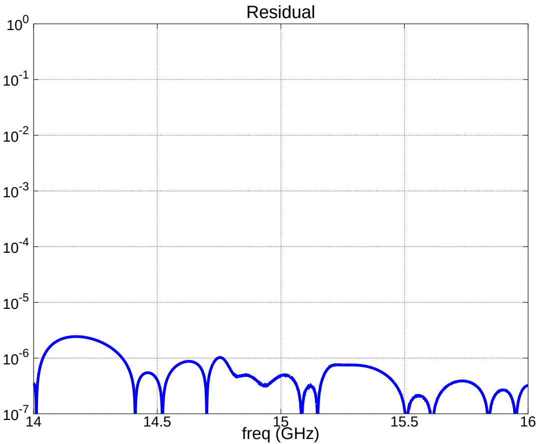
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

Reduced basis space. Constructive algorithm

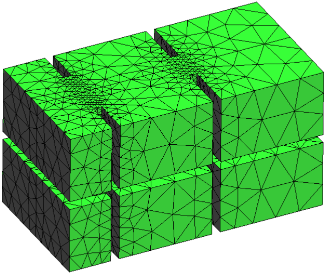
Canonical waveguide filter. Frequency band = **14 - 16 GHz**



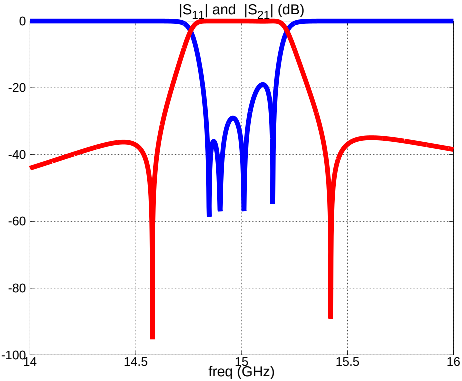
1. ROM of dimension 3
2. ROM of dimension 4
3. ROM of dimension 5
4. ROM of dimension 6
5. ROM of dimension 7
6. ROM of dimension 8
7. ROM dim = 9

Canonical waveguide filter

Frequency band = **14 - 16 GHz**. **Reduced basis dimension =** **9**

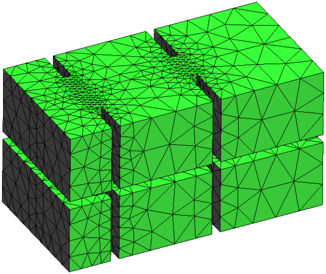


RBM

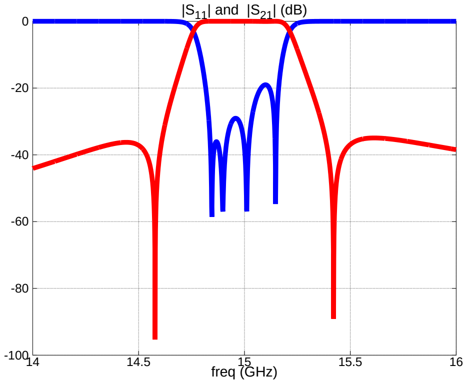


Canonical waveguide filter

Frequency band = **14 - 16 GHz**. **Reduced basis dimension =** **9**

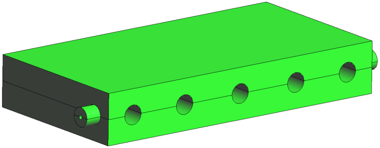


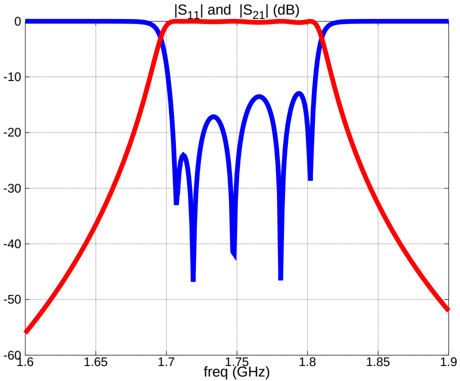
FEM



Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension = 10**

RBM

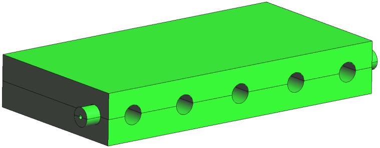


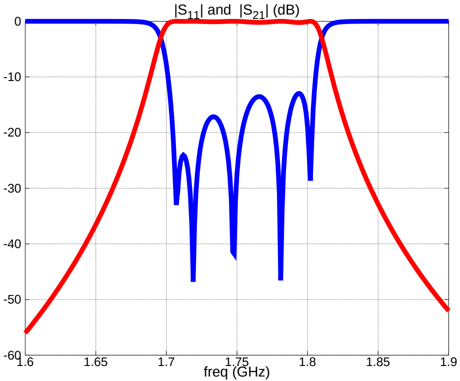


Combline filter

Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension =** **10**

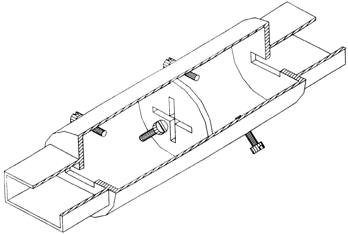
FEM

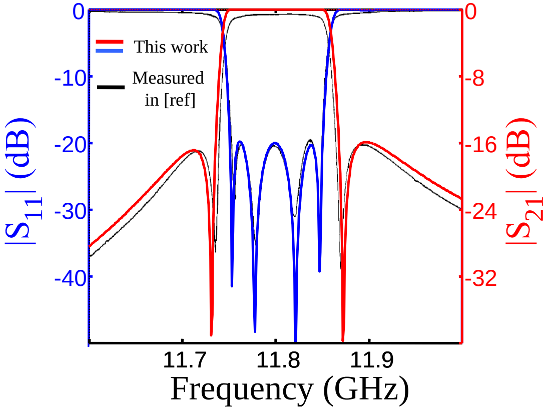




Dual-mode waveguide filter

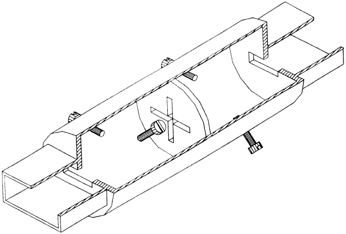
Frequency band = **11.6 - 12 GHz**. **Reduced basis dimension = 5**

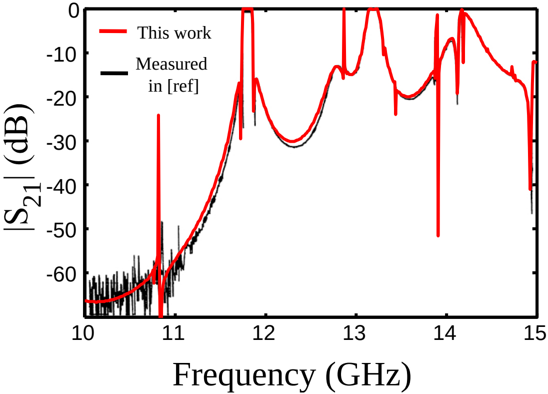




[ref] J. R. Montejo-Garai and J. Zapata, "Full-wave design and realization of multicoupled dual-mode circular waveguide filters," IEEE Trans. Microw. Theory Tech., vol. 43, no. 6, pp. 1290-1297, Jun. 1995.

Frequency band = **10 - 15 GHz**. **Reduced basis dimension =** **14**

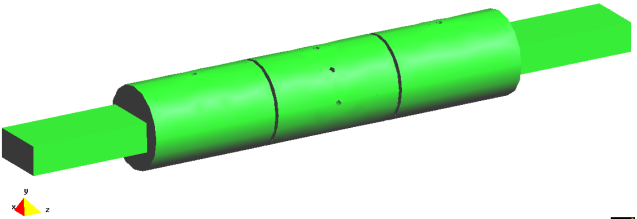


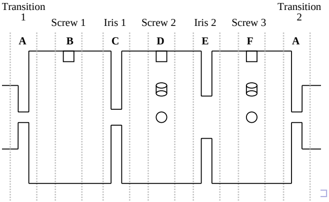


[ref] J. R. Montejo-Garai and J. Zapata, "Full-wave design and realization of multicoupled dual-mode circular waveguide filters," IEEE Trans. Microw. Theory Tech., vol. 43, no. 6, pp. 1290-1297, Jun. 1995.

5-poles waveguide filter. DDM

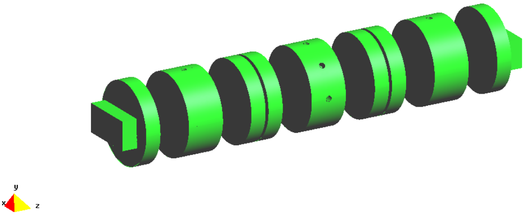
[ref] J. Rubio, J. Arroyo, and J. Zapata, "Analysis of passive microwave circuits by using a hybrid 2-D and 3-D finite-element mode-matching method," IEEE Trans. Microw. Theory Tech., vol. 47, no. 9, pp. 1746-1749, Sept. 1999.

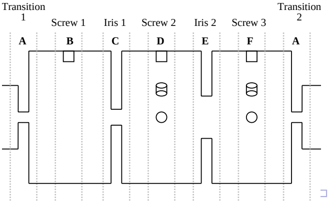




5-poles waveguide filter. DDM

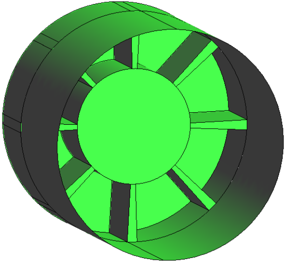
[ref] J. Rubio, J. Arroyo, and J. Zapata, "Analysis of passive microwave circuits by using a hybrid 2-D and 3-D finite-element mode-matching method," IEEE Trans. Microw. Theory Tech., vol. 47, no. 9, pp. 1746-1749, Sept. 1999.

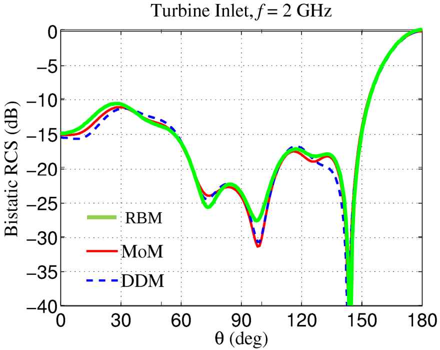




Turbine inlet

4λ **diameter sphere**

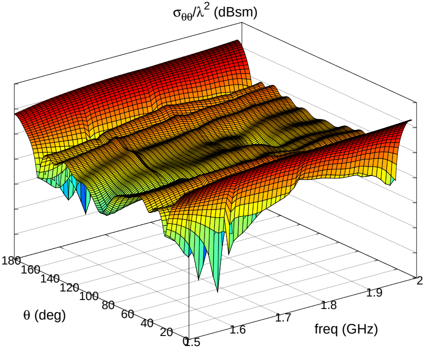


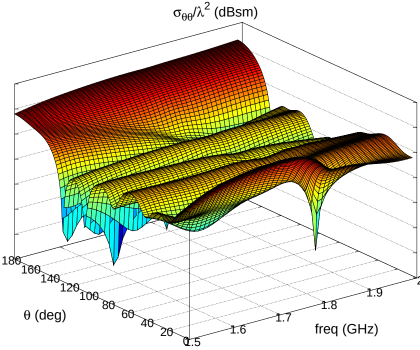


K. Zhao, "A domain decomposition method for solving electrically large electromagnetic problems," PhD Thesis, The Ohio State University, 2007.

Frequency band = **1.5 - 2 GHz**. **Reduced basis dimension =** **21**

Monostatic RCS **Bistatic RCS**

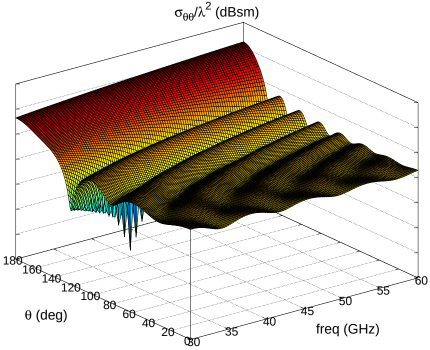




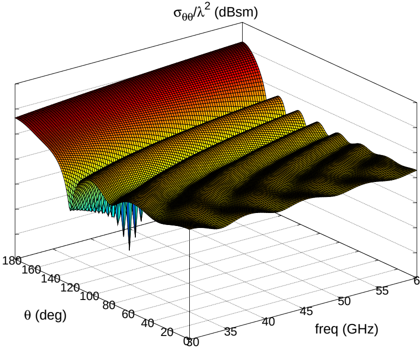
PEC sphere. 1.5λ - 3λ diameter sphere

Frequency band = **30 - 60 GHz**. **Reduced basis dimension = 11**

Bistatic RCS Mie series



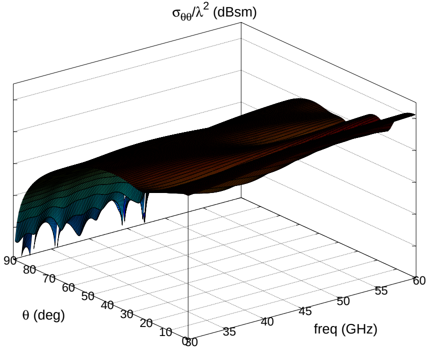
Bistatic RCS RBM



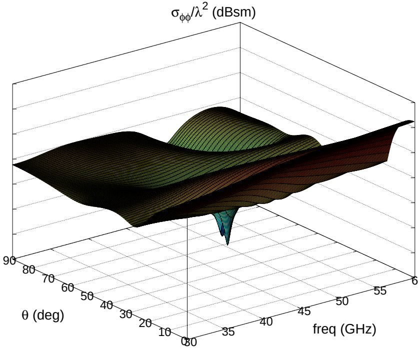
PEC plate. $\lambda \times \lambda$ - $2\lambda \times 2\lambda$ plate

Frequency band = **30 - 60 GHz**. **Reduced basis dimension = 15**

Monostatic RCS $\theta\theta$

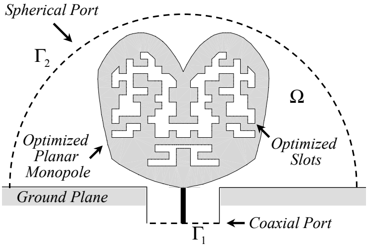


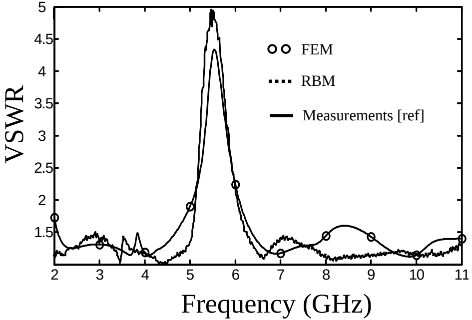
Monostatic RCS $\phi\phi$



Band notched UWB monopole antenna

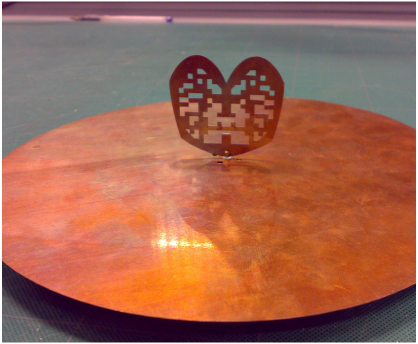
Frequency band = **2 - 11 GHz**. **Reduced basis dimension = 23**

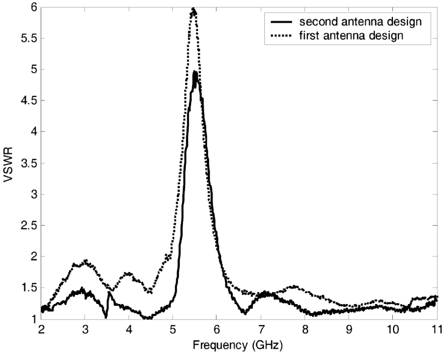




[ref] J. Martínez-Fernández, V. de la Rubia, J. M. Gil, and J. Zapata, "Frequency notched UWB planar monopole antenna optimization using a finite element method-based approach," IEEE Trans. Antennas Propag., vol. 56, no. 9, pp. 2884-2893, Sep. 2008.

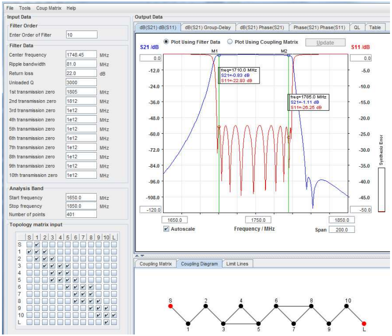
Band notched UWB monopole antenna

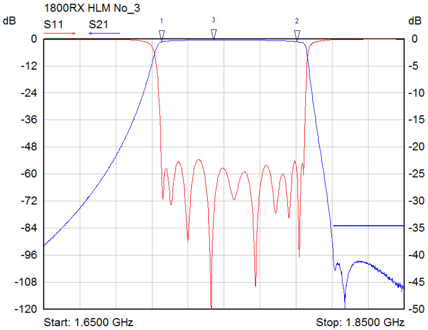


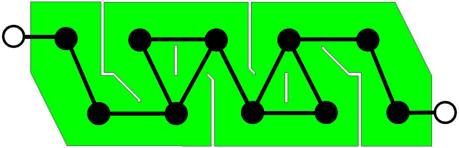


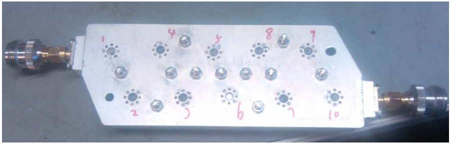
[ref] J. Martinez-Fernandez, V. de la Rubia, J. M. Gil and J. Zapata, Frequency notched UWB planar monopole antenna optimization using a finite element method-based approach, IEEE Trans. Antennas Propagat., vol. 56, no. 9, pp.2884-2893, Sep. 2008.

Dielectric resonator filter. Circuit synthesis

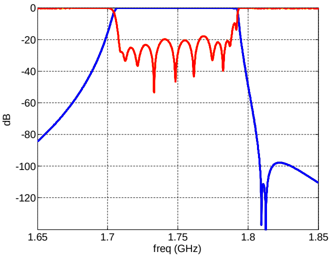


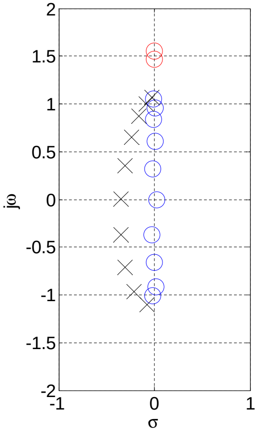






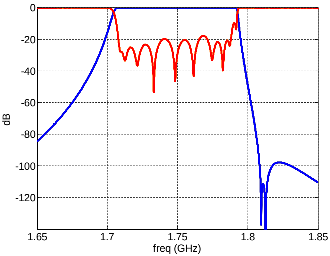
Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension = 10+4**

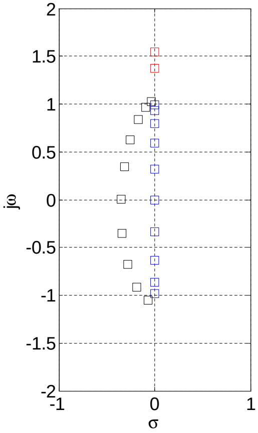




Dielectric resonator filter. Zero-pole diagram

Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension = 10+4**





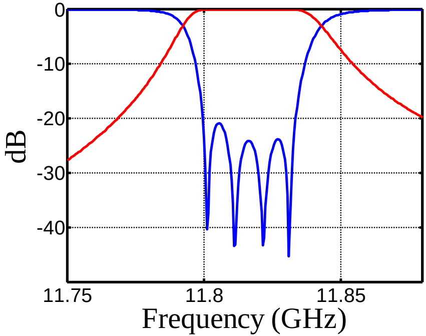
Zero-pole diagram based workflow

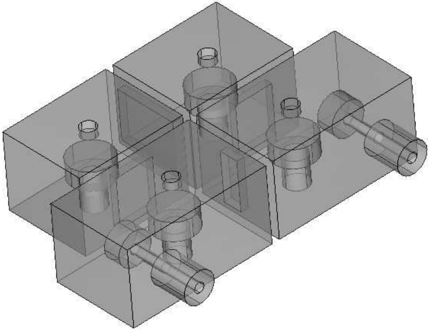
1. Initial prototype
2. Full-wave Simulation. Realible reduced-order model.
3. Get the zero-pole diagram and compare to circuit model.
4. Aceptable error?
5. If not, change geometry and go to step 2.
6. If error is OK, we are done!

[ref] P. Kozakowski and M. Mrozowski, ¨Automated CAD of coupled resonator filters," IEEE Microwave Wireless Compon. Lett., Dec. 2002.

Fourth-order dielectric resonator filter

Frequency band = 11.75 - 11.95 GHz.

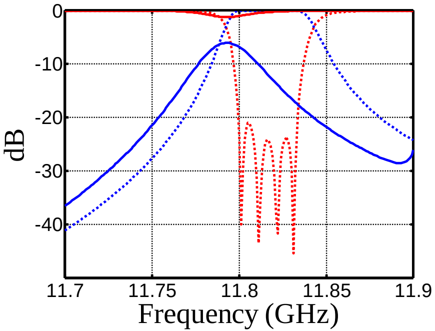


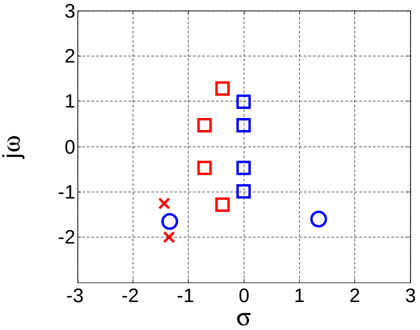


[ref] J. García, J. Rubio, J. R. Montejo-Garai and J. Zapata, ¨CAD of cylindrical dielectric resonator filters by a 3-D finite-element segmentation method," Microwave Opt. Technol. Lett., vol. 31, no. 1, pp 71-75, Oct. 2001.

Fourth-order dielectric resonator filter

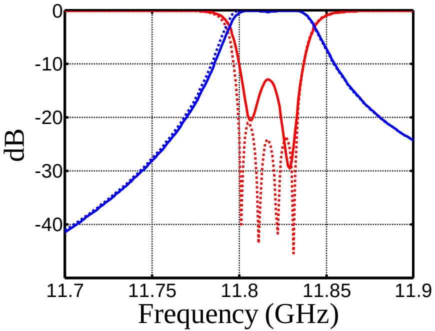
Frequency band = 11.75 - 11.95 GHz. **Iteration 0**

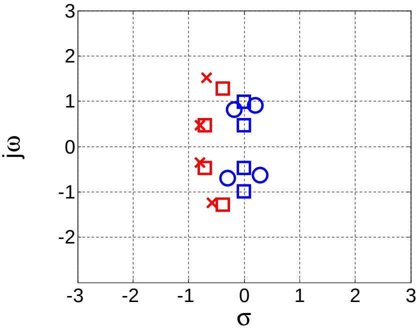




Fourth-order dielectric resonator filter

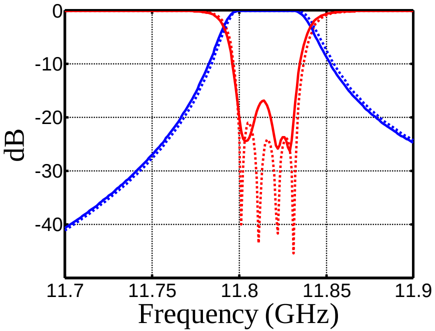
Frequency band = 11.75 - 11.95 GHz. **Iteration 50**

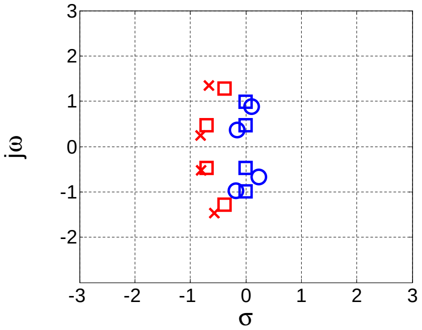




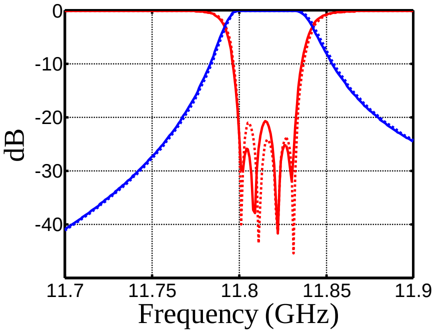
Fourth-order dielectric resonator filter

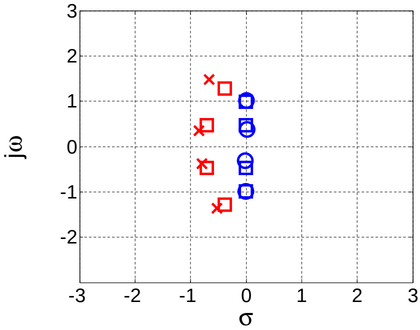
Frequency band = 11.75 - 11.95 GHz. **Iteration 100**





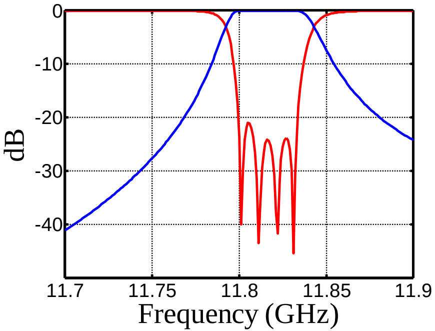
Frequency band = 11.75 - 11.95 GHz. **Iteration 150**

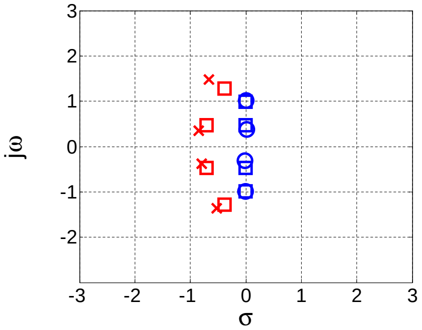




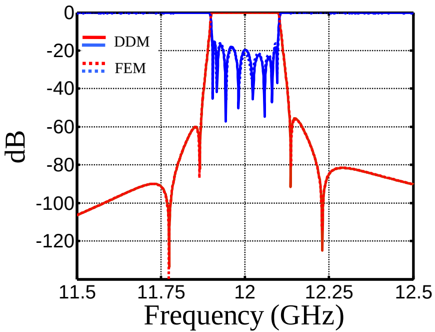
Fourth-order dielectric resonator filter

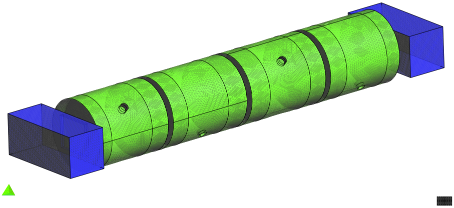
Frequency band = 11.75 - 11.95 GHz. **Iteration 200**





Frequency band = 11.5 - 12.5 GHz.

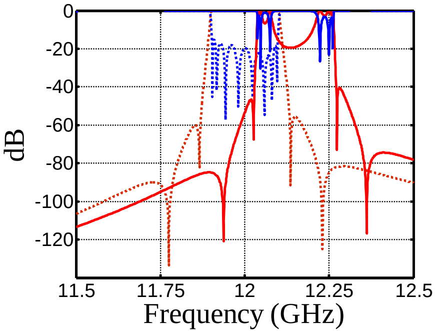


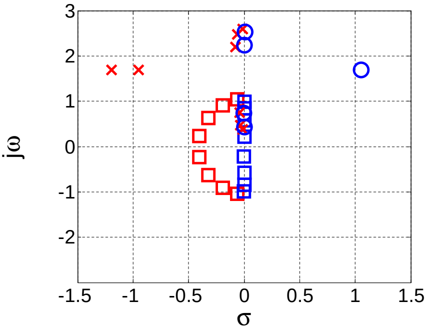


[ref] V. de la Rubia, ¨Reliable reduced-order model for fast frequency sweep in microwave circuits," Electromagnetics, vol. 34, pp 161-170, April 2014.

8-pole dual-mode waveguide filter

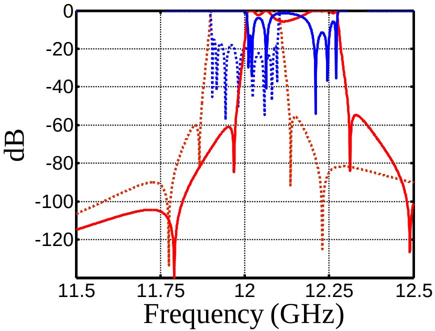
Frequency band = 11.5 - 12.5 GHz. **Iteration 0**

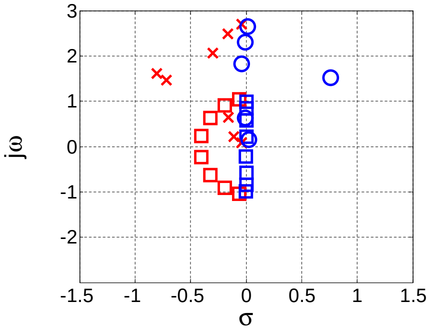




8-pole dual-mode waveguide filter

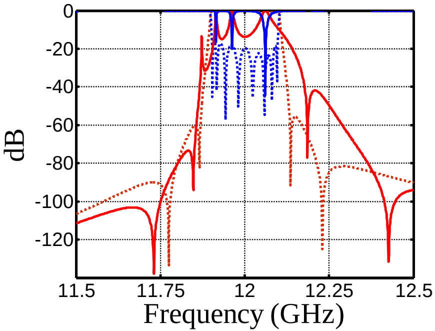
Frequency band = 11.5 - 12.5 GHz. **Iteration 50**

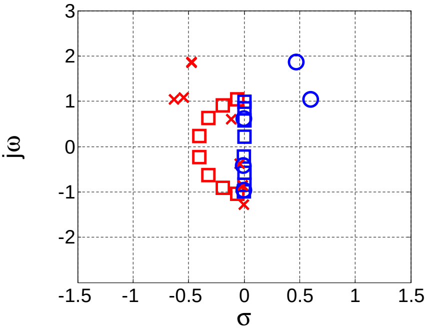




8-pole dual-mode waveguide filter

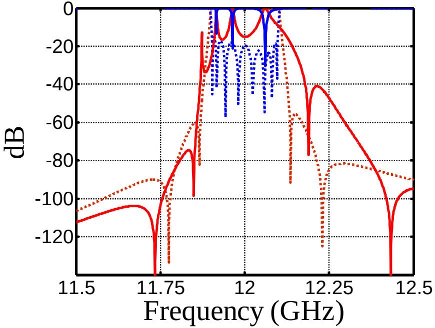
Frequency band = 11.5 - 12.5 GHz. **Iteration 100**

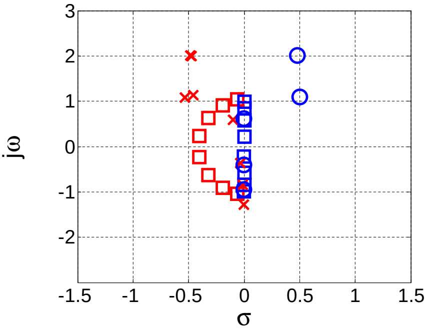




8-pole dual-mode waveguide filter

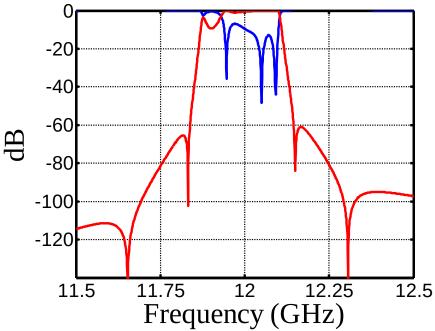
Frequency band = 11.5 - 12.5 GHz. **Iteration 150**

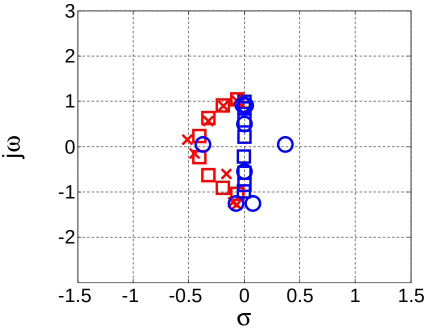




8-pole dual-mode waveguide filter

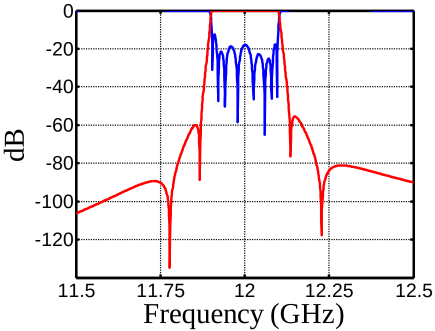
Frequency band = 11.5 - 12.5 GHz. **Iteration 200**

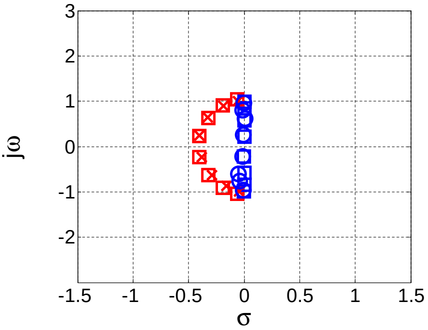




8-pole dual-mode waveguide filter

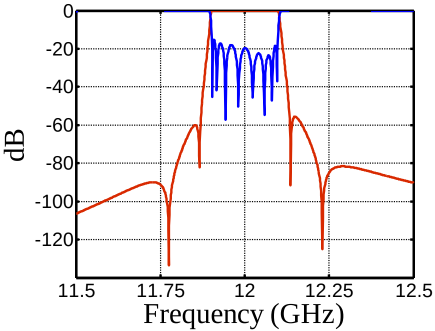
Frequency band = 11.5 - 12.5 GHz. **Iteration 250**

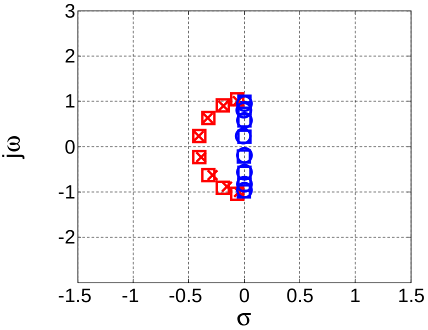




8-pole dual-mode waveguide filter

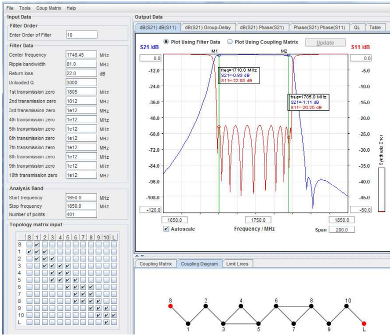
Frequency band = 11.5 - 12.5 GHz. **Iteration 300**

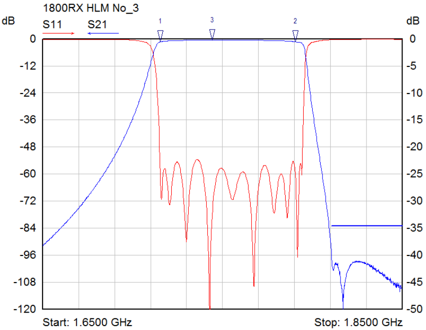


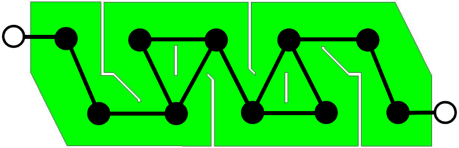


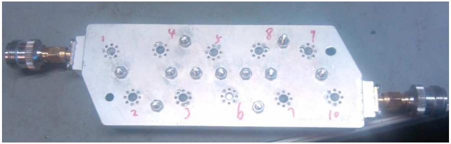
Índice

Circuit synthesis









Philosophy

Can we have a better understanding of Electromagnetics?

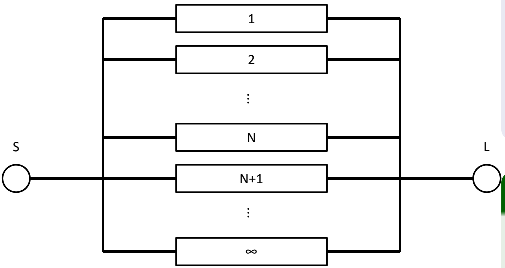
- Try to get a full-wave coupling matrix from Electromagnetics.
- This coupling matrix is different from the one in filter synthesis. Eletromagnetic phenomena should be taken into account.
- Full-wave coupling matrix can ultimately assist the design process.

Full-wave coupling matrix

How do we do this?

- Try to understand how Electromagnetics behaves.
- We may think each tuning screw has a localized tuning effect on the filter response. Not true.
- Each tuning screw has a global influence. It actually modifies neighbouring couplings!
- We do not have local resonators, namely dielectric resonators. What we actually have are global resonances. But from the circuit theory point of view we'd like to transform them into local resonators.

Full-wave coupling matrix



Global eigenmodes

Electromagnetics in the filter can be represented by N+P eigenmodes. N dominant eigenmodes. N = filter order.

P higher order eigenmodes

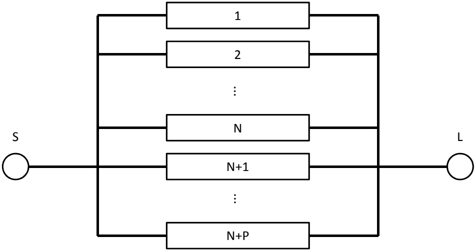
Stand for parasitic electromagnetic behaviour.

As a result

A full-wave transversal network arises [ref].

[ref] R. J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters," IEEE Trans. Microw. Theory Tech., vol. 51, no. 1, pp. 1-10, Jan. 2003.

Full-wave coupling matrix



Global eigenmodes

Electromagnetics in the filter can be represented by N+P eigenmodes. N dominant eigenmodes. N = filter order.

P higher order eigenmodes

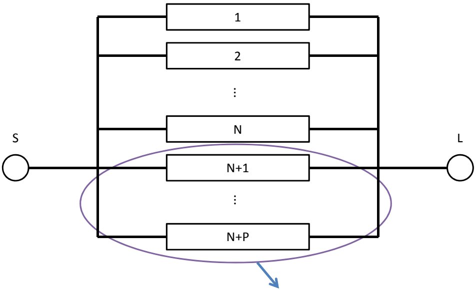
Stand for parasitic electromagnetic behaviour.

As a result

A full-wave transversal network arises [ref].

[ref] R. J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters," IEEE Trans. Microw. Theory Tech., vol. 51, no. 1, pp. 1-10, Jan. 2003.

Full-wave coupling matrix



Global eigenmodes

Electromagnetics in the filter can be represented by N+P eigenmodes. N dominant eigenmodes. N = filter order.

P higher order eigenmodes

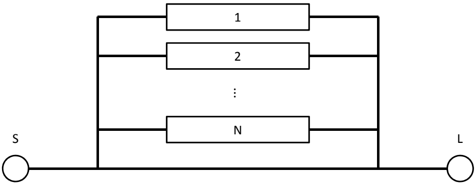
Stand for parasitic electromagnetic behaviour.

As a result

A full-wave transversal network arises [ref].

[ref] R. J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters," IEEE Trans. Microw. Theory Tech., vol. 51, no. 1, pp. 1-10, Jan. 2003.

Full-wave coupling matrix



Global eigenmodes

Electromagnetics in the filter can be represented by N+P eigenmodes. N dominant eigenmodes. N = filter order.

P higher order eigenmodes

Stand for parasitic electromagnetic behaviour.

As a result

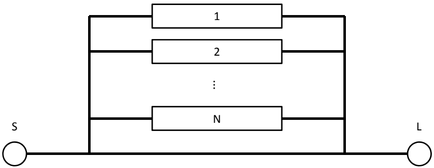
A full-wave transversal network arises [ref].

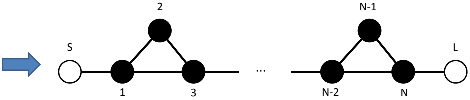
[ref] R. J. Cameron, "Advanced coupling matrix synthesis techniques for microwave filters," IEEE Trans. Microw. Theory Tech., vol. 51, no. 1, pp. 1-10, Jan. 2003.

Full-wave coupling matrix

Filter topology full-wave coupling matrix

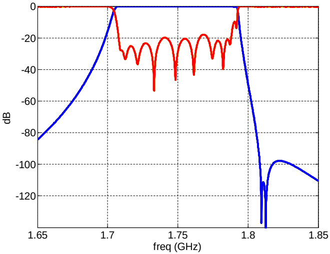
- Rotations are applied to the transversal coupling matrix.
- Additional electromagnetic couplings appear.
- As a result, the coupling route in the actual filter layout arises.
- Global resonances are mapped back to the local resonantors in the filter.
- This is the information we need for CAD.

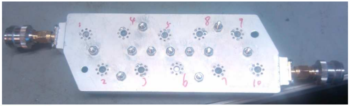


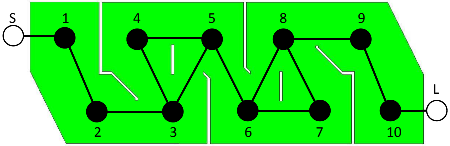


Dielectric resonator filter. Full-wave coupling matrix

Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension = 10+4**

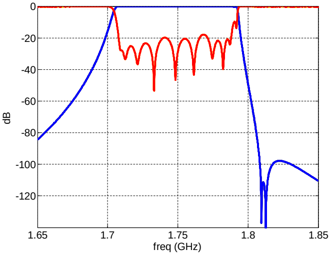


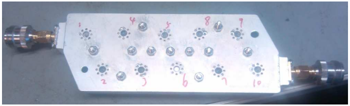


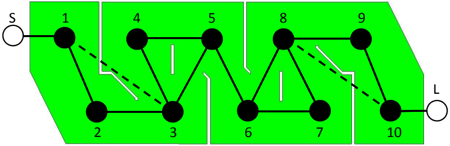


$$\begin{pmatrix}
0.85 & 1.02 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1.02 & -0.11 & 0.85 & 0.06 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.85 & 0.01 & 0.60 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.06 & 0.60 & 0.01 & 0.51 & 0.23 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.51 & -0.43 & 0.50 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.23 & 0.50 & 0.01 & 0.54 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.54 & 0.01 & 0.50 & 0.25 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.50 & -0.49 & 0.50 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0.50 & 0.03 & 0.62 & 0.05 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.62 & 0.16 & 0.79 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.05 & 0.79 & 0.38 & 1.00 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.00 & 0.85
\end{pmatrix}$$

Frequency band = **1.6 - 1.9 GHz**. **Reduced basis dimension =** **10+4**





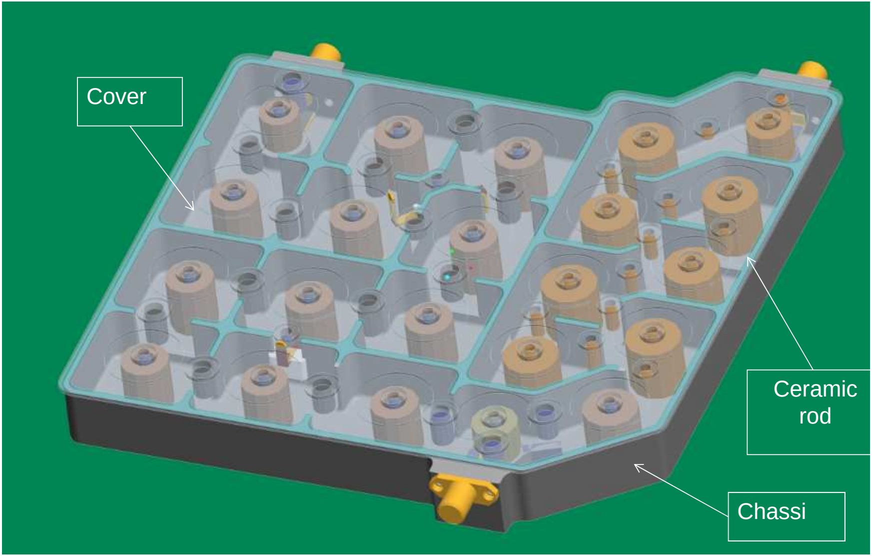


$$\begin{pmatrix}
0.85 & 1.02 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
1.02 & -0.11 & 0.85 & \color{red}{0.06} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0.85 & 0.01 & 0.60 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \color{red}{0.06} & 0.60 & 0.01 & 0.51 & 0.23 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0.51 & -0.43 & 0.50 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0.23 & 0.50 & 0.01 & 0.54 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0.54 & 0.01 & 0.50 & 0.25 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0.50 & -0.49 & 0.50 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0.25 & 0.50 & 0.03 & 0.62 & \color{red}{0.05} & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.62 & 0.16 & 0.79 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \color{red}{0.05} & 0.79 & 0.38 & 1.00\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1.00 & 0.85
\end{pmatrix}$$

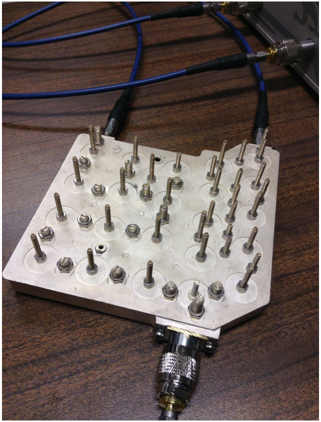
Coupling matrix based workflow

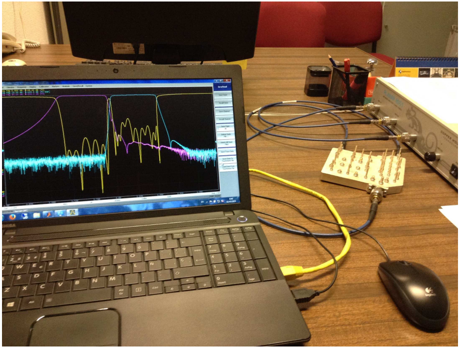
1. Initial prototype
2. Full-wave Simulation. Realible reduced-order model.
3. Coupling matrix comparison. Get full-wave circuit model and compare to synthesis design.
4. Aceptable error?
5. If not, change geometry according to coupling matrix and go step 2.
6. If error is OK, we are done!

Diplexers

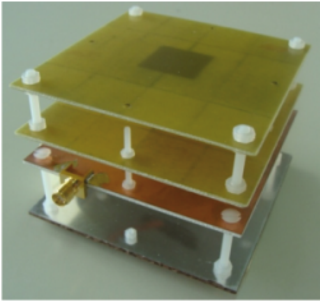


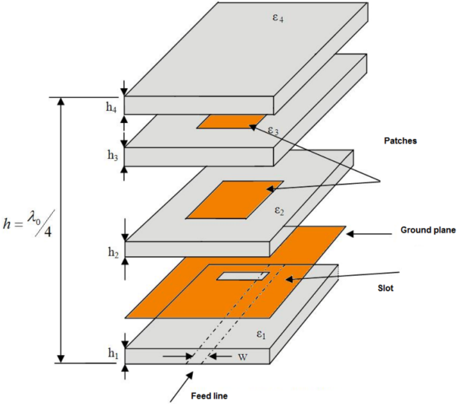
Diplexers



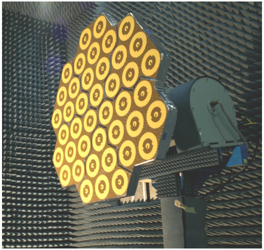


Antennas

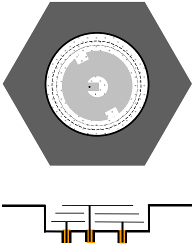


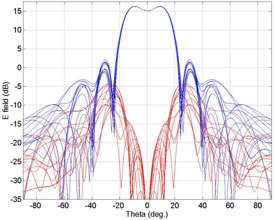

ε_4
h_4
ε_3
h_3
Patches
ε_2
$h = \lambda_0/4$
h_2
Ground plane
Slot
ε_1
h_1
W
Feed line

Antenna Arrays

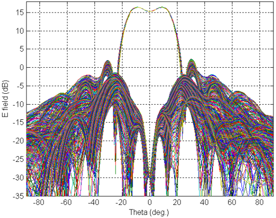


GALILEO system navigation antenna developed at EADS-CASA





Directivity of the Array simulated at 1.228 GHz



Directivity of the Array measured at 1.228 GHz

Índice

Conclusions

1. A fully automated and reliable reduced-order model for fast frequency sweep has been shown.
2. A full-wave circuit model for Electromagnetics has been presented.
3. Full-wave Zero-Pole diagram and/or full-wave Coupling Matrix CAD approaches have been proposed.
4. A better understanding of Electromagnetics is achieved by means of circuit theory.