Impact of 3D EM Model Configuration on the Direct Optimization of Microstrip Structures

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Abstract: We apply the classical Nelder-Mead optimization algorithm to a low fidelity EM model, using different mesh and bounding-box configurations. We demonstrate that the interaction of the coarse mesh with the bounding box size can determine whether the optimization is successful or not.

Keywords: Microstrip, model configuration, EM simulation, direct optimization.

1. Introduction

Setup of 3D electromagnetic (EM) models, specifically the selection of proper boundary conditions, size of the simulation box, kind-and-size of port excitations, and meshing scheme for a given structure are especially important for reliable EM simulations. It is desired to rapidly explore the solution space by using a low fidelity EM model and a way to do it is through optimization algorithms so that insight can be gained before moving on to the design and fabrication process.

Microstrip circuits and other planar structures are particularly sensitive to these configuration parameters, since, a too small simulation box might alter the results due to unintended EM interaction between the simulated structure and the box walls [1]. Usually, this problem is empirically solved by selecting a sufficiently large simulation box; however, we demonstrate that the effective size of the box is dependent upon the mesh size and therefore, a sufficiently large box can become insufficient when changing the size of the mesh. Extremely large simulation boxes do not suffer this problem, but force larger simulation times.

We calibrate a simulation box by finding the box size at which the structure responses are practically unchanged when small perturbations to the box dimensions are applied for a particular mesh size and then modify the mesh size. We present two different results obtained when performing direct EM optimization of a classical microstrip band-pass filter [2] for two different mesh and box sizes.

2. Structure under Study

The filter model under study is illustrated in Fig. 1. We keep separations y_{gap}, x_{gap}, and H_{air} from the filter to the bounding walls (see Fig. 1). The horizontal lumped ports length is l_{port}. All walls of the enclosing box are scattering boundary conditions, excepting the bottom cover which is defined as impedance boundary condition to account for the ground plane losses. Infinitesimally thin metals, using a transition boundary condition, are employed for the conductors. We include metallic and dielectric losses and the model uses “free-tetrahedral” meshing for all domains.

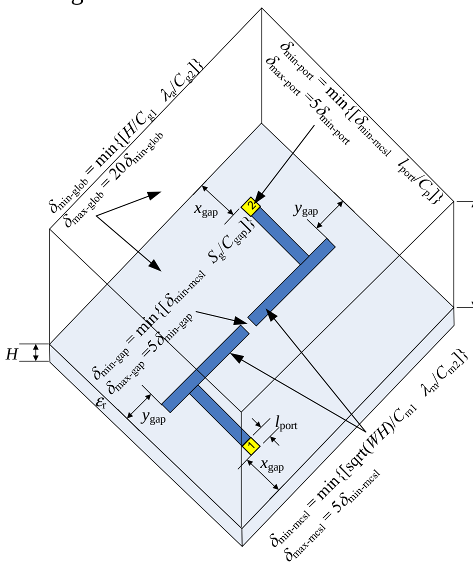


Figure 1. Bounding box dimensions and minimum/maximum element sizes of meshing scheme for a microstrip band-pass filter in COMSOL.

The meshing scheme considers not only the wavelength on different domains, but also the physical size of the different model regions. Different meshing resolutions are assigned for microstrip trace regions, ports, gap, and the global structure, by defining minimum and maximum element sizes (δ_{min}, δ_{max}), as illustrated in Fig. 1.

All the simulations in this paper use default solver settings for COMSOL[1] 4.3a (build 161) configured with asymptotic waveform evaluation (AWE) extension using the expression *abs(emw.S11)* and Padé approximation of order 5. We use a PC Intel Core i7-2600 at 3.4 GHz and 16 GB RAM and Windows 7 with 64 bits.

The length of the lumped port l_{port} was selected reasonably small to achieve a good quasi-static approximation. Using a low-resolution mesh, $C_g = [1 \;\; 10]$, $C_m = [4 \;\; 10]$, $C_p = 3$ and $C_{gap} = 3$ (see Fig. 1), we select a large simulation box size ($H_{air} = 20H$, $y_{gap} = 20H$, $x_{gap} = 20H$) such that small perturbations on box dimensions do not change filter responses, as shown in Fig. 2. Fig. 3 shows the band-pass filter model configuration in COMSOL.

3. Formulation of the Optimization Problem

Let $\boldsymbol{x} \in X \subseteq \Re^n$ represent the n optimization variables of the structure to be optimized. In general, the optimization variables are restricted to a region X of valid design parameters. The circuit responses are denoted by $\boldsymbol{R} \in \Re^r$, where r is the number of responses to be optimized. Vector $\boldsymbol{R}$ depends on the optimization variables $\boldsymbol{x}$, some pre-assigned parameters contained in vector $\boldsymbol{z}$, and the simulated frequencies contained in vector $\boldsymbol{f} \in \Re^p$. However, from the optimization perspective, the responses of interest can be treated as a multidimensional vector function dependent only on the optimization variables, $\boldsymbol{R}(\boldsymbol{x})$: $X \rightarrow \Re^r$.
We want to solve the following optimization problem,

$$\boldsymbol{x}^* = \arg \min_{\boldsymbol{x} \in X} U(\boldsymbol{R}(\boldsymbol{x})) \qquad (1)$$

where U: $\Re^n \rightarrow \Re$ is the objective function expressed in terms of the design specifications, and vector $\boldsymbol{x}^*$ contains the optimal model design.

[1] COMSOL Multiphysics version 4.3a 2012, COMSOL AB, Tegnérgatan 23, SE-111 40 Stockholm, Sweden.

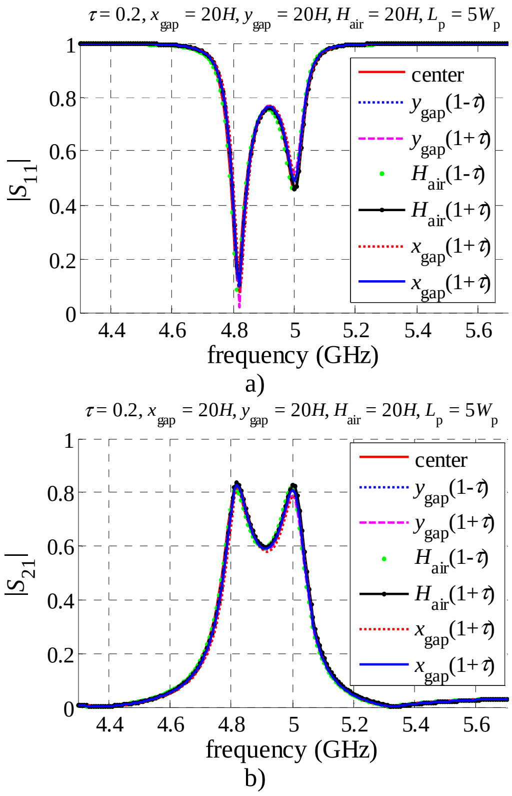


Figure 2. Filter responses within small perturbations on box dimensions a) reflection parameter, b) transmission parameter.

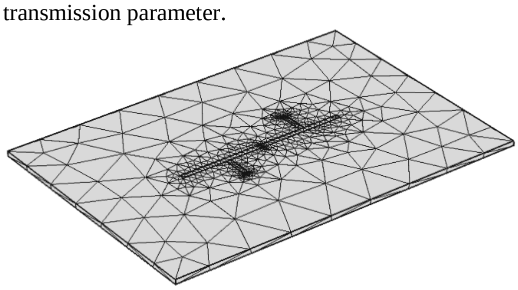


Figure 3. Band-pass filter model configuration in COMSOL using a low-resolution mesh, $C_g = [1 \;\; 10]^T$, $C_m = [4 \;\; 10]^T$, $C_p = 3$ and $C_{gap} = 3$; and the box size, $H_{air} = 20H$, $y_{gap} = 20H$, $x_{gap} = 20H$.

For the objective function employed in (1) we use a minimax formulation,

$$U(\boldsymbol{R}(\boldsymbol{x})) = \max\{\ldots e_k(\boldsymbol{x}) \ldots\} \qquad (2)$$

where a negative value in the k-th error function, $e_k(\boldsymbol{x})$, implies that the corresponding design specification is satisfied, otherwise it is violated.
For the structure under study, the following design specifications are defined,

$$|S_{21}| > 0.8 \text{ for } 4.9 \text{ GHz} \leq f \leq 5.1 \text{ GHz} \qquad (3a)$$

$$|S_{21}| < 0.1 \text{ for } 5.5 \text{ GHz} \leq f \leq 4.5 \text{ GHz} \quad (3b)$$
$$|S_{11}| < 0.2 \text{ for } 4.92 \text{ GHz} \leq f \leq 5.08 \text{ GHz} \quad (3c)$$

We use as optimization variables $\boldsymbol{x} = [L_1 \;\; L_2 \;\; L_3 \;\; L_4 \;\; S_g]^T$, keeping fixed during optimization the pre-assigned parameters $\boldsymbol{z} = [H \;\; \varepsilon_r \;\; W_p \;\; L_p]^T$ (see Fig. 4). In this case, vector $\boldsymbol{R}$ contains the filter transmission and reflection magnitudes at all the simulated frequencies.

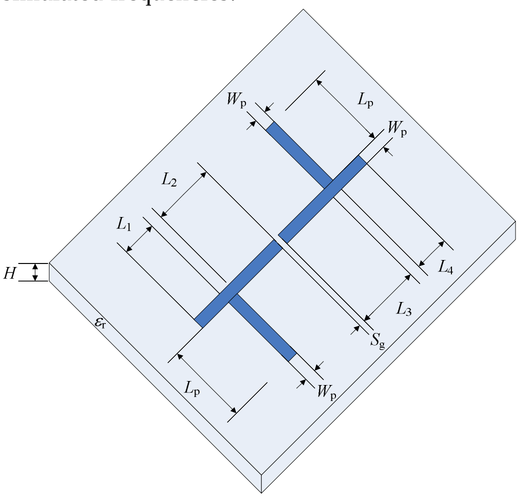
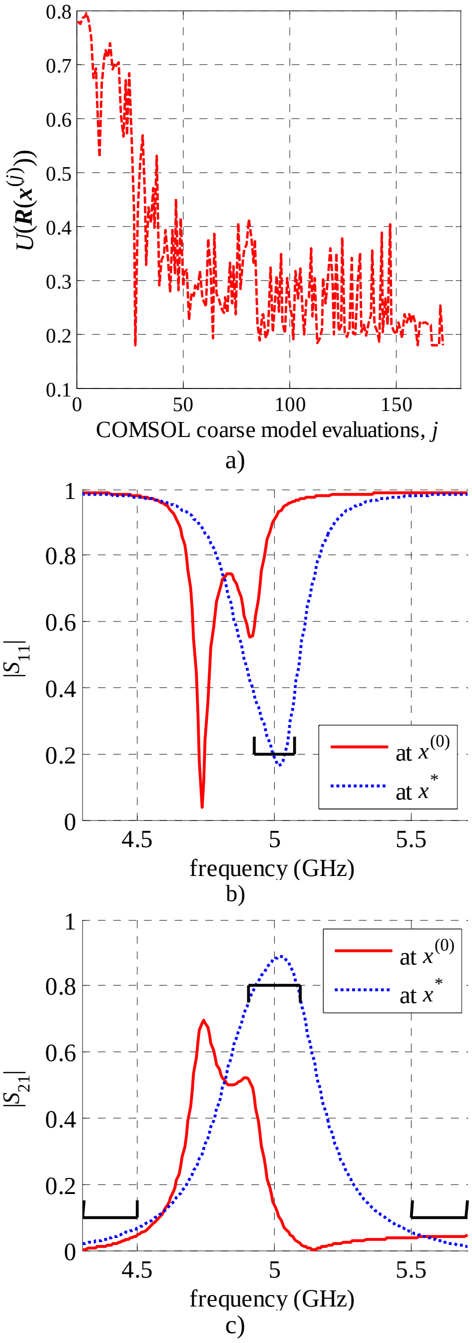


Figure 4. Band-pass filter dimensions.

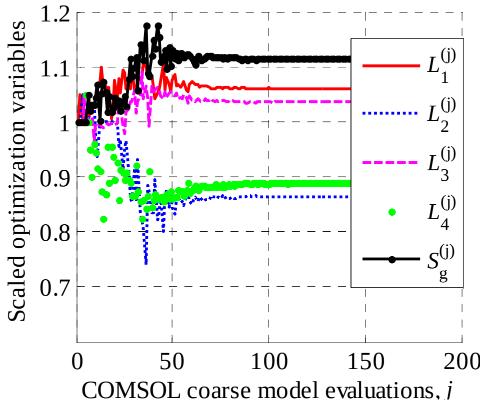
4. Optimization Results

The filter is optimized using the Nelder-Mead optimization method. The starting point for optimization is $\boldsymbol{x}^{(0)} = [L_1^{(0)} \;\; L_2^{(0)} \;\; L_3^{(0)} \;\; L_4^{(0)} \;\; S_g^{(0)}]^T = [6.275 \quad 4.75 \quad 5.9 \quad 5 \quad 0.15]^T$ (mm). The Nelder-Mead method [3,4] employs a direct search strategy (no gradients are calculated). It only uses function evaluations following a simplex, which is a special point distribution (polytope) with $n + 1$ vertices. The Nelder-mead algorithm [5] is widely used in engineering fields due to its good performance with highly nonlinear, discontinuous, non-differentiable, and noisy objective functions. The Matlab[2] command of the unconstrained Nelder-Mead method, also known as the simplex search method, is fminsearch.

Using the model configuration described in section 2, the optimization results are shown in Fig. 5. It is seen (Fig. 5a) that the objective function $U(\boldsymbol{R}(\boldsymbol{x}))$ does not become negative, indicating that the optimization process fails to fulfill the design specifications, as confirmed in Figs. 5b and 5c. Fig. 5d shows the evolution of the normalized optimization variables. These undesired optimization results are due to an improper model configuration, as demonstrated next.



[2] Matlab R2012a, Version 7.14.0.739, The MathWorks, Inc., 3 Apple Hill Drive, Natick MA 01760-2098, 2012.



d)

Figure 5. Optimization results using an improper model configuration in COMSOL: a) objective function $U(\boldsymbol{R}(\boldsymbol{x}))$, b) reflection parameter at initial and optimal designs, c) transmission parameter at initial and optimal designs, d) scaled optimization variables.

We repeat the same optimization procedure but now using a larger bounding box, $H_{\text{air}} = 25H$, $y_{\text{gap}} = 25H$, $x_{\text{gap}} = 25H$ and a better resolution $C_g = [1 \quad 10]$, $C_m = [8 \quad 10]$, $C_p = 4$ and $C_{\text{gap}} = 4$ which decreased the minimum and maximum element sizes ($\delta_{\min}$, $\delta_{\max}$), see Fig. 1. Fig. 6 shows the band-pass filter model configuration in COMSOL.

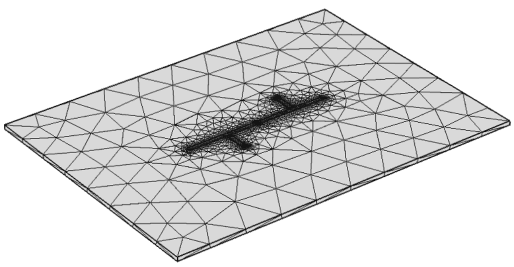
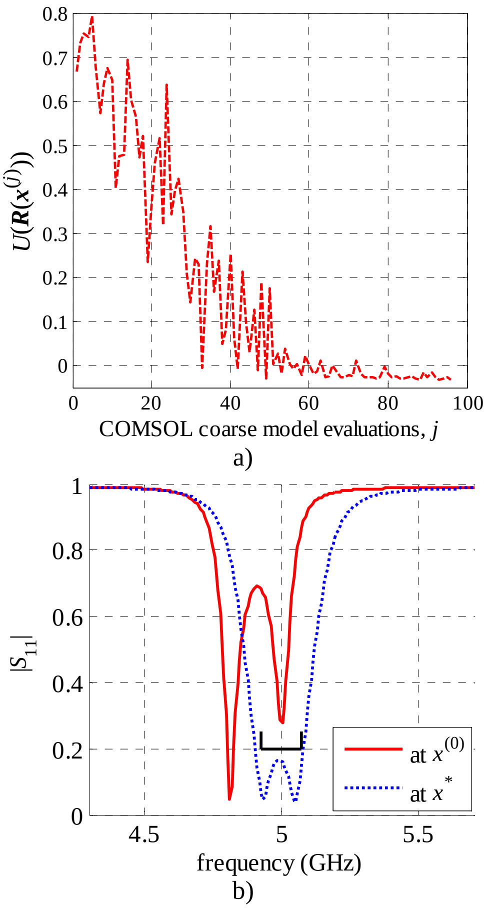


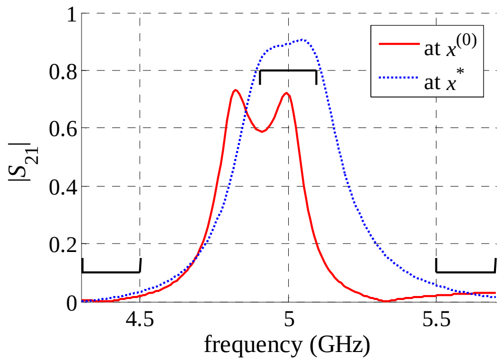
Figure 6. Band-pass filter model configuration in COMSOL using a better resolution mesh, $C_g = [1 \quad 10]$, $C_m = [8 \quad 10]$, $C_p = 4$ and $C_{\text{gap}} = 4$; and a larger bounding box, $H_{\text{air}} = 25H$, $y_{\text{gap}} = 25H$, $x_{\text{gap}} = 25H$.

It is seen in Fig. 7a that the objective function $U(\boldsymbol{R}(\boldsymbol{x}))$ becomes negative, requiring a much smaller number of simulations to fulfill the design specifications, as shown in Figs. 7b and 7c. Fig. 7d shows that the normalized optimization variables have very small changes at the end of the optimization process showing that the model configuration is much more suitable in this case. The optimal design found is $\boldsymbol{x}^* = [L_1^* \quad L_2^* \quad L_3^* \quad L_4^* \quad S_g^*]^T = [6.4123 \quad 4.4192 \quad 6.1825 \quad 4.4776 \quad 0.15101]^T$ (mm). These results confirm that selecting an appropriate 3D EM model configuration is critical to achieving optimization goals.

In summary, our approach to find an appropriate 3D EM model configuration, assuming that the structure to be designed is capable to satisfy the specifications, follows these steps:

a. Select a reasonably small length for the lumped port, using a low-resolution mesh with a large simulation box size such that small perturbations on box dimensions do not change filter responses.
b. Optimize the structure.
c. If the optimization process fails to fulfill the design specifications, it is necessary to change the model configuration by using a larger bounding box, and a better resolution.
d. Launch the same optimization procedure.
e. Repeat steps c and d until the objective function becomes negative.





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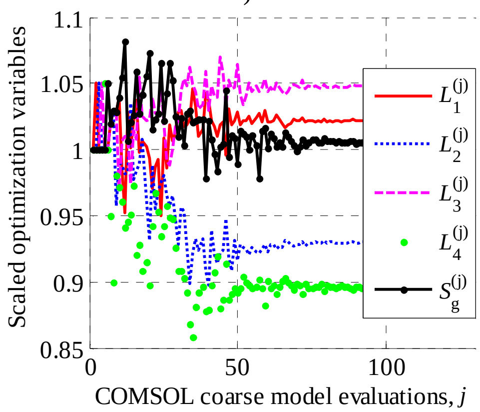

d)

Figure 7. Optimization results using a suitable model configuration in COMSOL: a) objective function $U(\boldsymbol{R}(\boldsymbol{x}))$, b) reflection parameter at initial and optimal designs, c) transmission parameter at initial and optimal designs, d) scaled optimization variable.

5. Conclusions

The EM optimization of a coarsely discretized model of a microstrip band-pass filter implemented in COMSOL was realized using two different model configurations. We presented a systematic methodology to find an appropriate 3D EM model configuration on a direct EM optimization of a low fidelity models. It was confirmed that the direct EM optimization of coarse models in COMSOL could be dramatically enhanced by an appropriate bounding box size as well as by the lumped port length and a suitable meshing scheme.

6. References

[1] J. E. Rayas-Sánchez, Z. Brito-Brito, J. C. Cervantez-González and C. A. López "Systematic configuration of coarsely discretized 3D EM solvers for reliable and fast simulation of high-frequency planar structure" *IEEE Latin American Symposium on Circuits and Systems*, Cuzco, Peru, Feb. 2013, pp. 1-4.

[2] V. Gutiérrez-Ayala and J. E. Rayas-Sánchez, "Neural input space mapping optimization based on nonlinear two-layer perceptrons with optimized nonlinearity," *Int. J. RF and Microwave CAE*, vol. 20, pp. 512-526, Sep. 2010.

[3] J. A. Nelder and R. Mead, "A simplex method for function minimization," *Computer J.*, vol. 7, pp. 308-313, 1965.

[4] J. C. Lagarias, J. A. Reeds, M. H. Wright and P. E. Wright, "Convergence properties of the Nelder-Mead simplex method in low dimensions," *SIAM J. of Optimization*, vol. 9, num. 1, pp. 112-147, 1998.

[5] A. Ravindran, K. M. Ragsdell and G. V. Reklaitis, *Engineering Optimization: Methods and Applications*. Hoboken, NJ: Wiley, 2006.