EM Simulation of a Low-Pass Filter Based on a Microstrip Defected Ground Structure Using COMSOL

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Abstract: We perform EM simulations of a low-pass microstrip filter consisting of a cross-junction open stub and two unit sections implemented as defected ground structures (DGS). The defect introduced by unit sections corresponds to an etched lattice on the copper backside ground plane. The filter presents wide and deep attenuation characteristics in the stopband. Different model implementations were carried out with the aim at evaluating the computational costs versus accuracy. Simulations of a high-fidelity model are in good agreement with experimental data reported in a previous paper. COMSOL simulation settings, enclosing box, computational costs, and simulation times for the considered models are provided.

Keywords: microstrip structure, defected ground structure, radiation loss, fine model, coarse model, COMSOL, low-pass filter.

1. Introduction

The defected ground structure (DGS) belongs to a class of electromagnetic bandgap structures that enables the construction of high-performance microwave filters. The defect consists of etches on the backside ground plane that modifies the EM fields of a microstrip section, creating bandpass and stopband characteristics over certain frequency intervals. The structure to be considered herein was first proposed in [1] as a low-pass filter with improved characteristics such as wide and deep stopband and low insertion losses.

In this paper, we develop fine and coarse model implementations of the low-pass filter based on a defected ground structure using the EM module of COMSOL[1]. A fine model is referred herein to an implementation based on simulation items that allow predicting the filter performance with high accuracy; whereas the coarse model uses less-accurate items with the aim at reducing the computational cost hence simulation time.

The fine model of the aforementioned filter presents an excellent agreement with measured data reported in [1]. The coarse model, on the other hand, provides fairly good predictions of the filter responses over a frequency range of interest, with a simulation time much smaller than that of the fine model. A trade-off between computational costs and accuracy is then reached. Filter performance, accuracy and computational costs are evaluated.

The paper is organized as follows. First, a description of the low-pass filter and the circuit equivalence of the structure are provided. Then, details on COMSOL implementations of coarse and fine models are given. Lumped ports are used for coarse model implementation and numeric ports for the fine model. Since the defected structure produce large radiation losses creating potential resonances with the enclosing box, a proper selection of the box size and boundary conditions is realized. Finally, coarse and fine model responses are compared against results reported in the open literature.

2. Description of the Low-Pass Filter

Figure 1 shows the geometrical structure of the low-pass filter based on two DGS units. Each DGS unit section consists of two rectangular etches of area $a \times b$ connected through a narrow etched aperture of area $W \times g$. Etches are in the backside metallic ground plane with thickness t, equal to that of the metal conductor. The filter design parameters are the gap distance of the aperture, g, the lattice area defined by a and b, and the width and length of the cross-junction open stub, W_c and P_c, respectively (see Figure 1).

[1] COMSOL Multiphysics version 4.2 2012, COMSOL AB, Tagnérgatan 23, SE-111 40 Stockholm, Sweden.

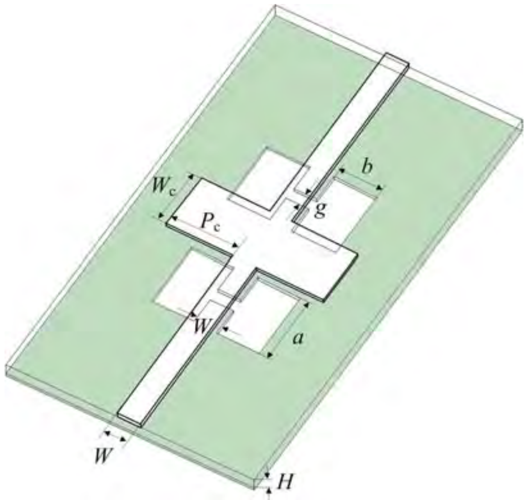

Figure 1. Geometrical structure of the low-pass filter with two-DGS unit sections using cross-junction opened stub.

The feeding microstrip line has a width, W, and was designed as a 50-Ω line at least in the low-frequency range.

A distinct feature of the defected ground structure is the ability to increase the effective inductance and capacitance of the microstrip transmission line without varying the microstrip width [1]. This avoids parasitics associated with discontinuities while attaining deeper attenuation at high frequencies.

Table 1 lists the filter parameter values as reported in [1], which are also used in this work. The laminate used is RT/Duroid 5880[2]. The dielectric substrate has a relative permittivity ε_r = 2.94 and a loss tangent $\tan\delta$ = 0.0009 at 10 GHz. The substrate thickness, H, is equal to 20 mils and metal thickness, t, is equal to 0.65 mils (half-once copper).

Table 1. Design parameters of the low-pass filter.

Parameter	Value
g	0.5 mm
W	2.4 mm
a	5 mm
b	5 mm
W_c	5 mm
P_c	6 mm

[2]Advanced Circuit Materials, RT/duroid® 5870/5880/5880LZ High Frequency Laminates.

The performance of the filter can be approached by the lumped circuit representation of Figure 2 [1]. Such circuit equivalence helps to explain the bandgap effect of the DGS through a simple parallel LC circuit connected in series, while the cross-junction is modeled by the parallel capacitance.

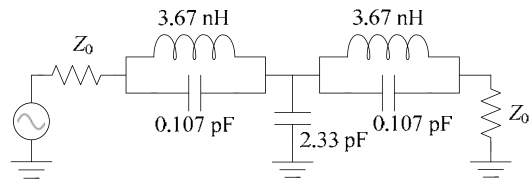

Figure 2. Schematic of the low-pass filter with two-DGS unit sections using cross-junction opened stub.

As shown later, this circuital equivalence provides a rough approximation of the microwave filter responses in the low-frequency range, however, it does not capture the radiation losses effects that take place at high frequencies in the stop band. Therefore, the microwave filter based on DGS units calls for a full-wave EM analysis.

3. COMSOL Implementations

3.1 Fine and Coarse Model Implementation

The implementation of the fine model for the low-pass filter includes items that increase accuracy. It is based on numeric ports, high mesh resolution, lossy ground plane and microstrip signal traces in the form of hollow lines with impedance boundary condition and lossy dielectric with a loss tangent.

The coarse model version of the low-pass filter is implemented with lumped ports, ground plane and microstrip signal trace in the form of infinitesimally thin perfect electric conductor (PEC), low mesh resolution and a lossless dielectric model. All those items introduce a low computational cost.

Both models need for a careful implementation of the copper void that form etches on the backside ground plane. These are filled by air in the form of a 'boundary condition' for the coarse model and as a 'domain' for the fine model.

3.2 Ports and Boundary Conditions

Figure 3 illustrates COMSOL filter implementations, the enclosing boxes for the fine and coarse models and their physical variables.

The enclosing box for fine and coarse models is made of two air layers surrounding the filter structure, being H_{air1} the thickness of the upper air layer and H_{air2} the thickness of the bottom air layer. The distance between the microstrip end of the stub section and the box wall, y_{gap}, is another parameter that should not influence filter performance (see Figure 3).

Given the potential resonances with an electrically enclosed bounding box (made of perfect electric material, PEC), scattering boundary conditions were set on the top and bottom box covers. This selection matches with conditions at which measurements were performed [1]. By using the enclosing box with the above characteristics, simulations were carried out without resonances.

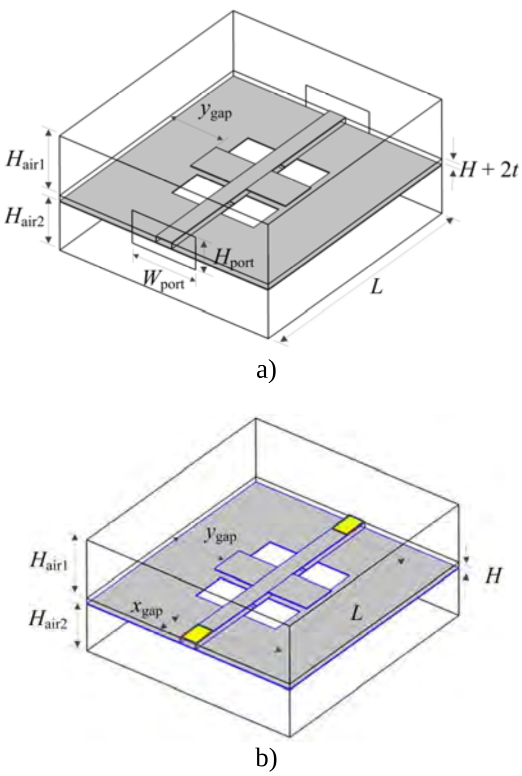

Figure 3. 3D-perspective of COMSOL model implementations: a) fine model uses numeric ports and metals with thickness t; and b) coarse model uses horizontal lumped ports and infinitesimally thin metals.

We found the values for the physical variables of the bounding box at which the filter performance becomes very insensitive to the boundaries. This was achieved by doing a sweep analysis for each parameter, obtaining the values listed on Table 2.

Table 2. Parameters of COMSOL enclosing box.

Box parameter	Expression	Size
y_{gap}	$6W$	14.4 mm
H_{air1}	$10H$	7.87 mm
H_{air2}	$10H$	7.87 mm
L	$W_c + 2a + 8W$	34.2 mm

Numeric ports in Figure 3a accounts for the spatial distribution of field excitation. These were implemented as two surfaces of width, W_{port}, equal to $6W$ and height, H_{port}, equal to $8H$. This port size allows dominant mode field excitation with a low influence of the enclosing box walls.

For the coarse model, the lumped ports are defined horizontally instead of vertically, making ground to the frontal metallic walls, as shown in Figure 3b. The port length, x_{gap}, is the distance between the microstrip trace and the frontal walls. This port configuration allows the selection of small port lengths (a fraction of the microstrip line width W) thereby reducing the ports' domain while improving the lumped port approximation[1].

Nonetheless, for non-resonant structures, such as a microstrip line, we have found that there are values of x_{gap} that can give accurate results but the use of a proper meshing scheme becomes crucial in obtaining reliable results [2]. In contrast, for resonant circuits such as a bandpass filter, S-parameters are less impacted by the selection of x_{gap} [3]. For this low-pass filter based on defected ground structures, we found that the reflection parameter $|S_{11}|$ is sensitive to the selection of x_{gap} at low frequencies; however it has a lower effect at medium and high frequencies. We choose an x_{gap} equal to $0.9W$ using the low-mesh resolution shown in the following section. At that value the responses of the coarse model tend to approximate those of the fine model over a large frequency range.

4. Meshing

4.1 Coarse Model Meshing

The development of coarse and fine models requires a careful mesh discretization. For reliable simulations, the minimal element size of the mesh must be smaller than the objects pertaining to the filter geometry.

A low mesh resolution is considered here to achieve fast simulations. Air and substrate domains are discretized by considering the highest frequency simulated, f_{max} = 10 GHz. Using the corresponding formulas for the wavelengths, we obtain a wavelength on the air, λ_a, equal to 30 mm, and the wavelength around the microstrip metallic traces, $\lambda_m = v_p/f_{max}$ = 25.66 mm, where $v_p = c/(\varepsilon_e)^{½}$ is the corresponding propagation velocity, c is the speed of light in free-space, and ε_e = 1.366 is the effective dielectric constant obtained from classical formulas [4].

We set the maximal element size on the substrate, $\delta_{max\text{-}sub} = \lambda_m/15$ and the minimal element size $\delta_{min\text{-}sub} = \lambda_m/150$, being $\delta_{min\text{-}sub}$ smaller than H and W. The meshing for the air section is set by $\delta_{max\text{-}air} = \lambda_a/3$ and $\delta_{min\text{-}air} = \lambda_a/30$. Using this mesh resolution, reasonable accuracy is obtained at relatively low computational cost. This model is referred below as to Coarse 1.

The mesh of the whole structure using this box has 9,262 elements and the simulation of the whole structure using the above parameters consumes 2 minutes and 47 seconds using 50 frequency points from 0.1 to 10 GHz.

An even cheaper model was developed with the aim at comparing accuracy and computational resources. Mesh resolution is decreased in air and substrate domains by using a new combination of mesh discretization parameters. We choose the parameters $\delta_{max\text{-}air} = \lambda_a/2$ and $\delta_{max\text{-}sub} = \lambda_m/4$ as they do not represent any problem for the COMSOL solver. By doing so, the minimal element size in the mesh is still smaller than the geometrical objects pertaining to the geometry, maintaining a level of accuracy in the responses. Using these mesh discretization parameters, the simulation time reduces to 53 seconds and the mesh comprises 3,269 elements. In the following, this model is referred to as Coarse 2.

These parameters are itemized in Table 3.

Table 3. Computational costs of the cheapest coarse model (Coarse 2).

Parameter	Value
$\delta_{max\text{-}air}$, $\delta_{max\text{-}sub}$	$\lambda_a/2$, $\lambda_m/4$
$\delta_{min\text{-}air}$, $\delta_{min\text{-}sub}$	$\lambda_a/20$, $\lambda_m/40$
Elements in mesh	3,269
Degrees of freedom	21,922
Frequency points	50
Simulation time	53s

Figure 4 shows the S-parameters of the structure using both coarse models and allows contrasting with the fine model responses, whose corresponding meshing is described in the following sub-section. It is seen that the prediction of the scattering reflection parameter of both coarse models becomes inaccurate at low and high frequencies. However, both coarse models predict a scattering transmission parameter with good accuracy at low and medium frequencies. Overall, both coarse models make a good approximation for the fine model from 2 to 8 GHz.

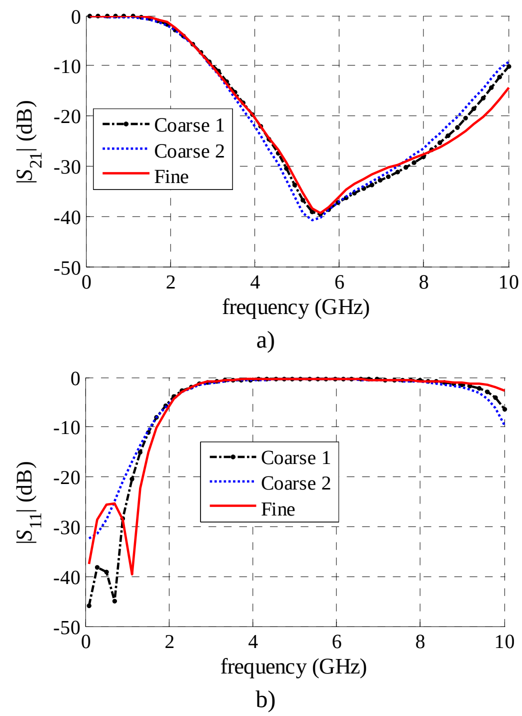

Figure 4. Responses of the fine model and both coarse models: a) insertion loss, and b) return loss.

4.2 Fine Model Meshing

The use of numeric ports requires meshing the area inside and around the ports with a high resolution, yielding a much higher number of elements than that one used for the coarse models.

For the maximal element size, we use $\delta_{max\text{-}air} = \lambda_a/5$ and $\delta_{max\text{-}sub} = \lambda_m/20$. This selection does not increase greatly mesh resolution and do not represent any problem for the COMSOL solver. In addition, the results obtained with this resolution are in good agreement with measured data reported in [1].

The simulation time for a 100-frequency point simulation is 57 minutes and 24 seconds. The number of elements in the mesh for this model is equal to 48,542. Table 4 summarizes the parameters used for this model.

Table 4. Computational costs of the fine model.

Parameter	Value
$\delta_{max\text{-}air}$, $\delta_{max\text{-}sub}$	$\lambda_a/5$, $\lambda_m/20$
$\delta_{min\text{-}air}$, $\delta_{min\text{-}sub}$	$\lambda_a/50$, $\lambda_m/200$
Elements in mesh	48,542
Degrees of freedom	398,890
Frequency points	100
Simulation time	57min 24s

All simulations reported in this article were run on the same computer platform Dell XPS8300 Intel Core i7-2600 at 3.4 GHz, 16 GB RAM and Windows 7 with 64 bits.

5. Results Comparison

In reference [1] it is shown measurement data and simulation results of the filter based on a cross-junction-type open stub illustrated in Figure 1. A good agreement between the EM results and measured data at low and medium frequencies is reported in [1].

Figure 5 shows the simulation results of our fine model using COMSOL, as well as the results of the equivalent lumped circuit in Figure 2. By comparing results in [1] and with those of our fine model responses in Figure 5, it is confirmed that COMSOL results are in excellent agreement with measured and EM simulated data reported in [1]. Also, simulation results of the lumped circuit in Figure 5 show very significant differences with respect to EM results starting at 6 GHz, where radiation losses become large, as commented before.

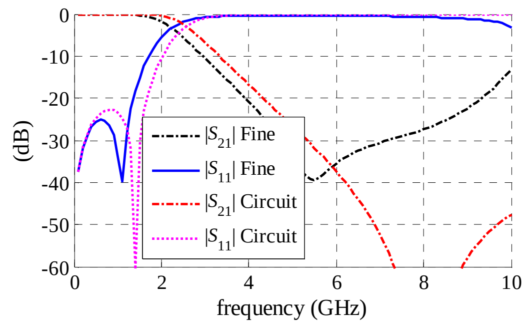

Figure 5. COMSOL results of the fine model implementation.

The low-pass filter presents a good insertion-loss characteristic and a 3-dB cut-off frequency of 2.2 GHz. The return loss is higher than 25.2 dB within 0 to 1 GHz and the second frequency null of $|S_{11}|$ is at 1.1 GHz. In the stop band, the minimum transmission parameter is –39 dB at 5.5 GHz. As shown in Figure 5, the attenuation is deteriorated as $|S_{21}|$ increases with frequency, reaching –13.1 dB at 10 GHz. Similarly, it is interesting to notice a small but steady reduction with frequency of the scattering reflection parameter within the stopband. This is a consequence of the large radiation losses that take place at the DGS units at high frequencies, which are not capture by the equivalent lumped circuit. The radiation loss predictions for both models are displayed in Figure 6. It is seen that the radiation losses reduces the rejection band. At frequencies approaching 10 GHz, Coarse 2 model predicts higher radiation losses than the fine model.

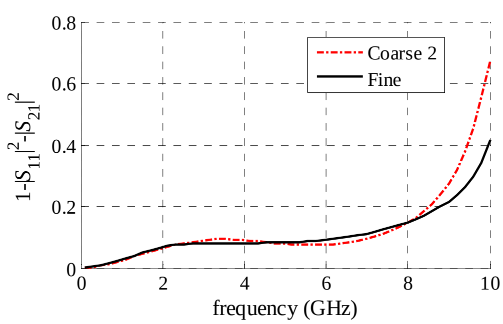

Figure 6. Power loss predicted by fine model and coarse 2 model.

It is interesting to notice that, since Coarse 2 model is lossless, Figure 6 indicates that radiation losses are dominant over dielectric and metallic losses for this particular filter.

As mentioned before, Table 3 and Table 4 summarize our results regarding the computational costs of the coarse and fine models, respectively.

6. Conclusions

We described the implementation of fine and coarse models of a low-pass filter based on defected ground unit sections using COMSOL. The simulation process of the fine model is validated by showing excellent agreement between the results obtained by COMSOL and results reported in a paper pertaining to this same structure. A version of the coarse model that reduces greatly the mesh resolution and simulation time was developed. It is seen that a coarse model based on less-accurate items and low mesh resolution becomes a good representation for the fine model over certain frequency range. The radiation losses of the structure reduce the rejection band and set the upper frequency of the filter S-parameter specification.

7. References

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