



Filter Tuning using Sensitivity Data

CST MWS features a sensitivity analysis algorithm capable of evaluating the S-parameter dependencies on various model parameters after a single 3D electromagnetic simulation run. Evaluations for different model parameter sets and optimization runs based on sensitivity data can be derived without restarting the full-wave simulation.



Outline



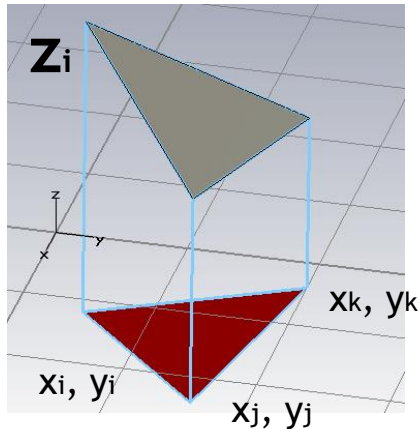
- **Background**
 - What is sensitivity and yield analysis
- **Application example**
 - Two post filter (online)
- **How can sensitivity data be used in an optimization?**
- **Conclusions**

Introduction to Sensitivity

Matrix to solve: $[K]\{E\} = \{Q\}$



$[K]$: symmetric, complex, contains geometry, material, frequency



Example: Linear Shape functions for a 2D element in xy

$$[N] = -\frac{1}{2\Delta} [1, x, y] \begin{bmatrix} a_i & a_j & a_k \\ b_i & b_j & b_k \\ c_i & c_j & c_k \end{bmatrix}; a_{ijk} = x_j y_k - y_j x_k; b_{ijk} = y_j - y_k; c_{ijk} = x_k - x_j$$

$$z = [N_i, N_j, N_k] \begin{Bmatrix} z_i \\ z_j \\ z_k \end{Bmatrix}$$

Example: electrostatic

$$k_{m,n} = \iint_{xy} (\epsilon_x \frac{\partial N_m}{\partial x} \frac{\partial N_n}{\partial x} + \epsilon_y \frac{\partial N_m}{\partial y} \frac{\partial N_n}{\partial y}) dx dy; m, n = i, j, k$$

$[E]$: unknowns z

$[Q]$: Sources

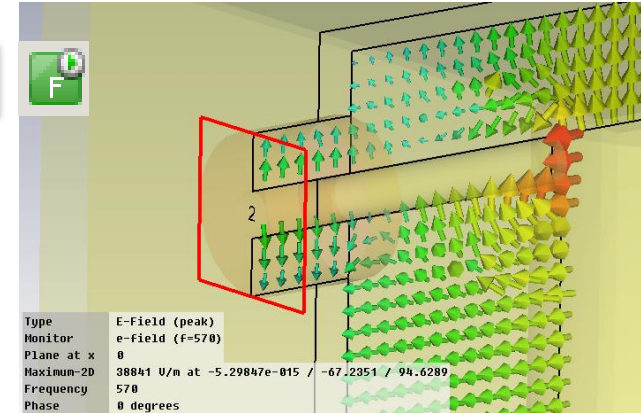
Introduction to Sensitivity

S-Parameters:

3D Fieldsolution

$$S(\omega, p) = \frac{1}{-j\omega\mu_0} E^T(\omega, p) K^T(\omega, p) E(\omega, p)$$

[K] ...left hand side, E (Fields at ports, p... any parameter



Sensitivity of S-parameter vs. parameter change:

$$-j\omega\mu_0 \frac{\partial S}{\partial p} = E^T \left(\frac{\partial K}{\partial p} \right) E$$

Same 3D Fieldsolution

Direct analytical derivation of K-matrix elements via e.g. [N]

Introduction to Sensitivity

Numerical calculation of gradients is expensive and unstable

Here: Sensitivity of S-parameter vs. parameter change

$$-j\omega\mu_0 \frac{\partial S}{\partial p} = E^T \frac{\partial K}{\partial p} E$$

no additional 3D solution required (only another S-Parameter computation)

Very efficient computation of sensitivities

Result: S-parameter ranges for tolerant parameters

Currently available for FD-Tet solver

Introduction to Sensitivity



What is it good for?

- The sensitivity helps estimate „new“ S-parameters due to the (small) change of the parameter, at no extra cost

Suppose the parameter p changes by a quantity Δp :

$$S(x + \Delta p) \approx S(x) + \sum_p \frac{\partial S}{\partial p} \cdot \Delta p$$



(Approximated by 1st order Taylor expansion)

exact computation of the Sensitivity

- The various sensitivities are used in an optimizer to solve for Δp as variables to best fit the S-parameter goals.

$$S_{nm} \Leftarrow S_{nm(3D-MWS)} + \sum_p \frac{\partial S}{\partial p} \cdot \Delta p$$



Δp ... face constraints

Introduction to Sensitivity



As Result: Derivative of S-Parameter vs Parameter and frequency

Frequency Domain Solver Parameters

Method: General Purpose, Resonant: Fast S-Parameter, Resonant: S-Parameter, fields

Mesh type: Tetrahedral Mesh

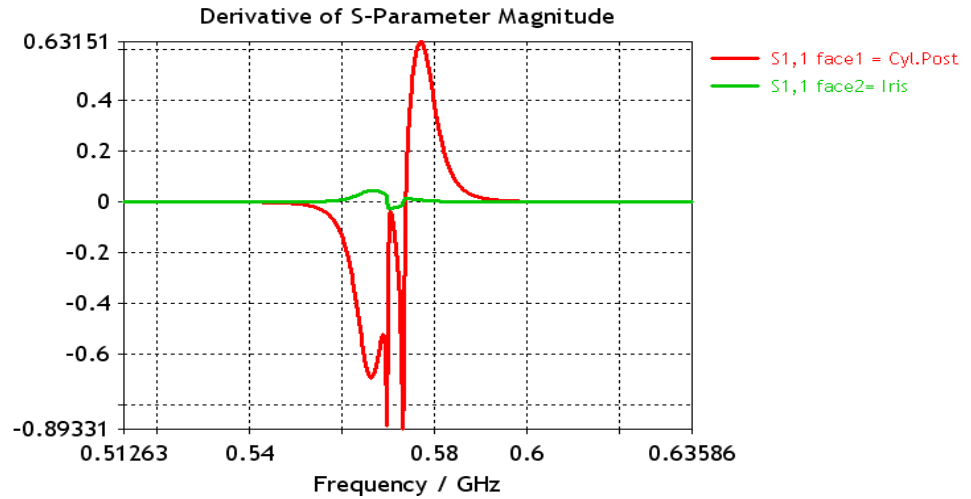
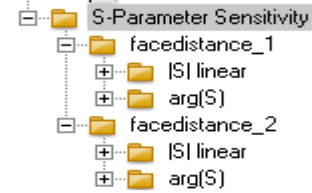
Excitation settings: Source type: Port 1, Mode: 1

Frequency samples: Max. Range: 0.4 to 0.8 GHz, Adapt. Freq. checked, Frequency checked

Sensitivity analysis: Use sensitivity analysis

Sensitivity Analysis Table:

Parameter	Value	Description
face2distance_2	55.85	Parametrized face of PEC:iris
face2distance_1	95	Parametrized face of PEC:cylinder1
mech_field	1	Imported displacement field



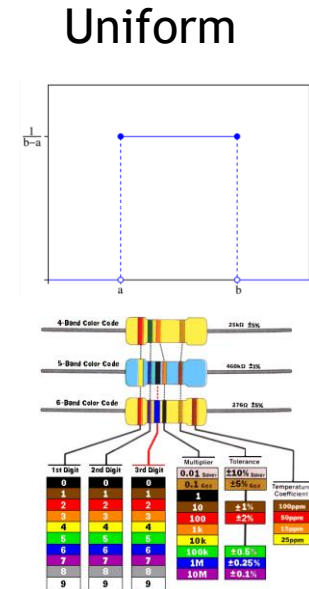
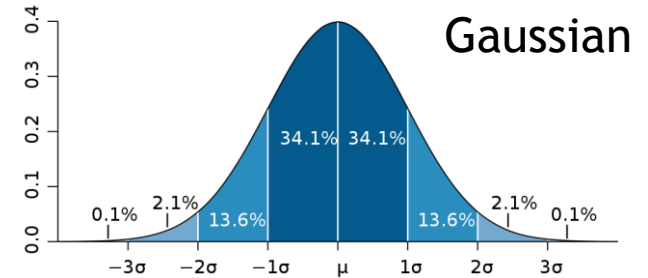
What is the Yield Analysis

For every product, there are:
 Technical specifications
 Fabrication tolerances

The fabrication tolerances will lead to some products not fulfilling the specifications

Yield:

$$yield = \frac{\#Passed}{\#Total}$$



Typical Approach vs. CST Approach



How is yield calculated typically?

Parameters vary according to a known probability curve

Repeat

Change the value of all parameters

Simulate

Check if specification (in our case for S-params.) is met

Until the number of simulations is statistically relevant

This is a large number of EM simulations - typically hundreds or thousands!!!

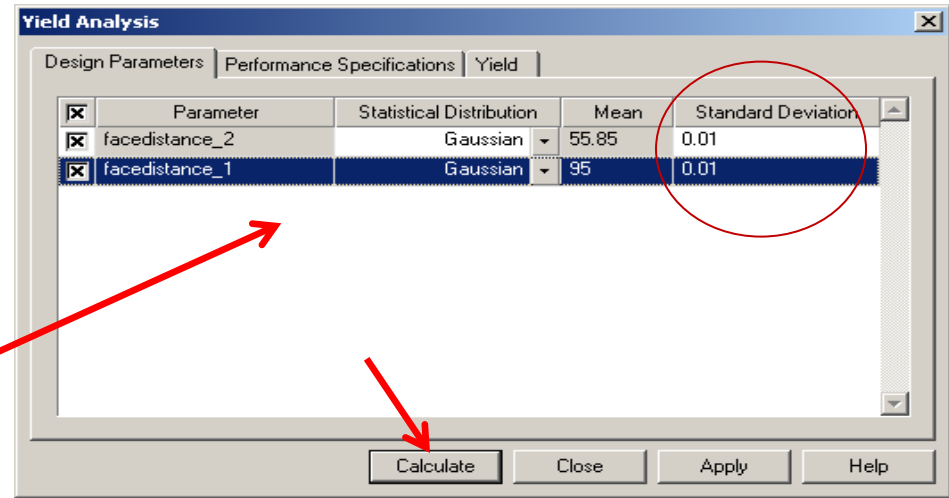
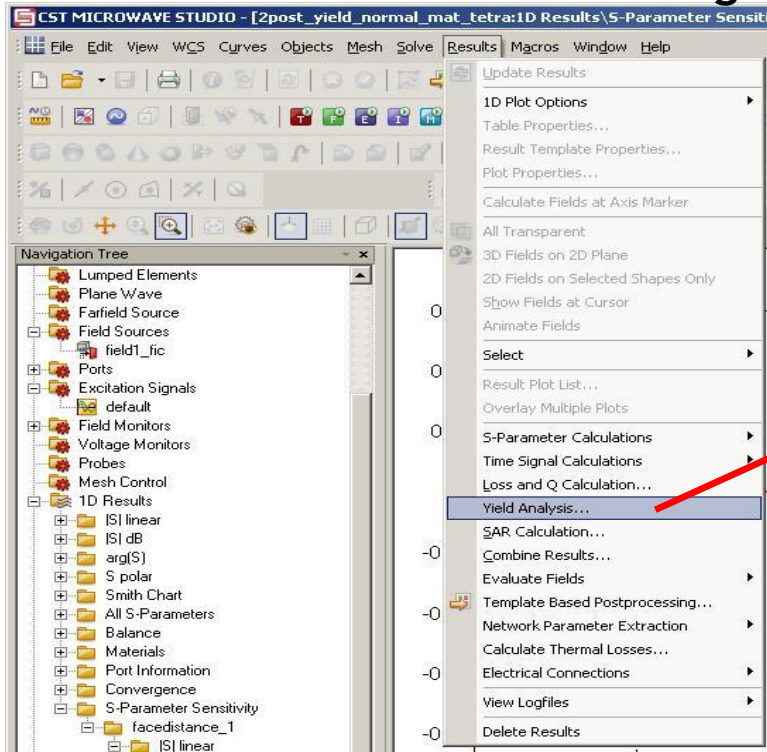
Knowing the sensitivity, there is **no need to perform 3D simulations**, at least if the **parameters vary in a small range**.

The efficiency of this new sensitivity analysis approach makes Monte-Carlo based yield analysis feasible even for complex multi-parametrical three-dimensional structures

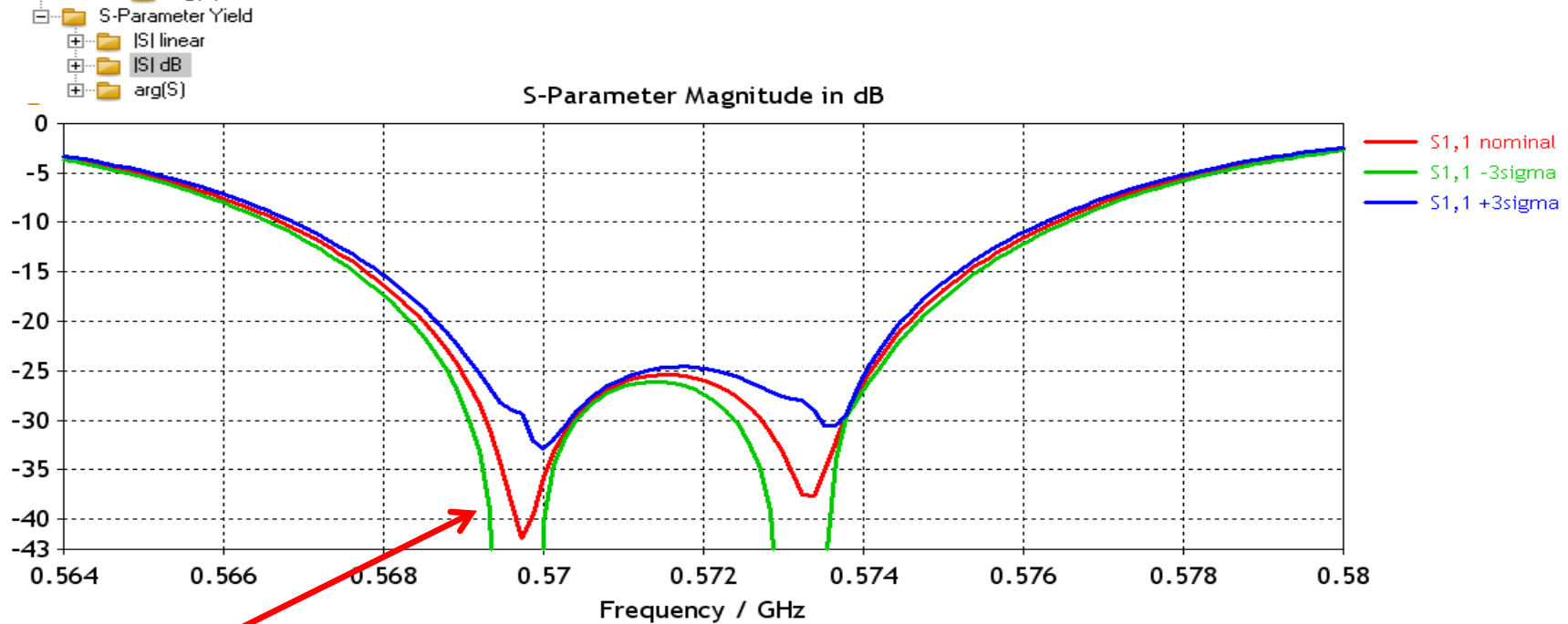
Introduction to Yield

Define manufacturing tol. of the parameter (statistical values)

Perform Yield

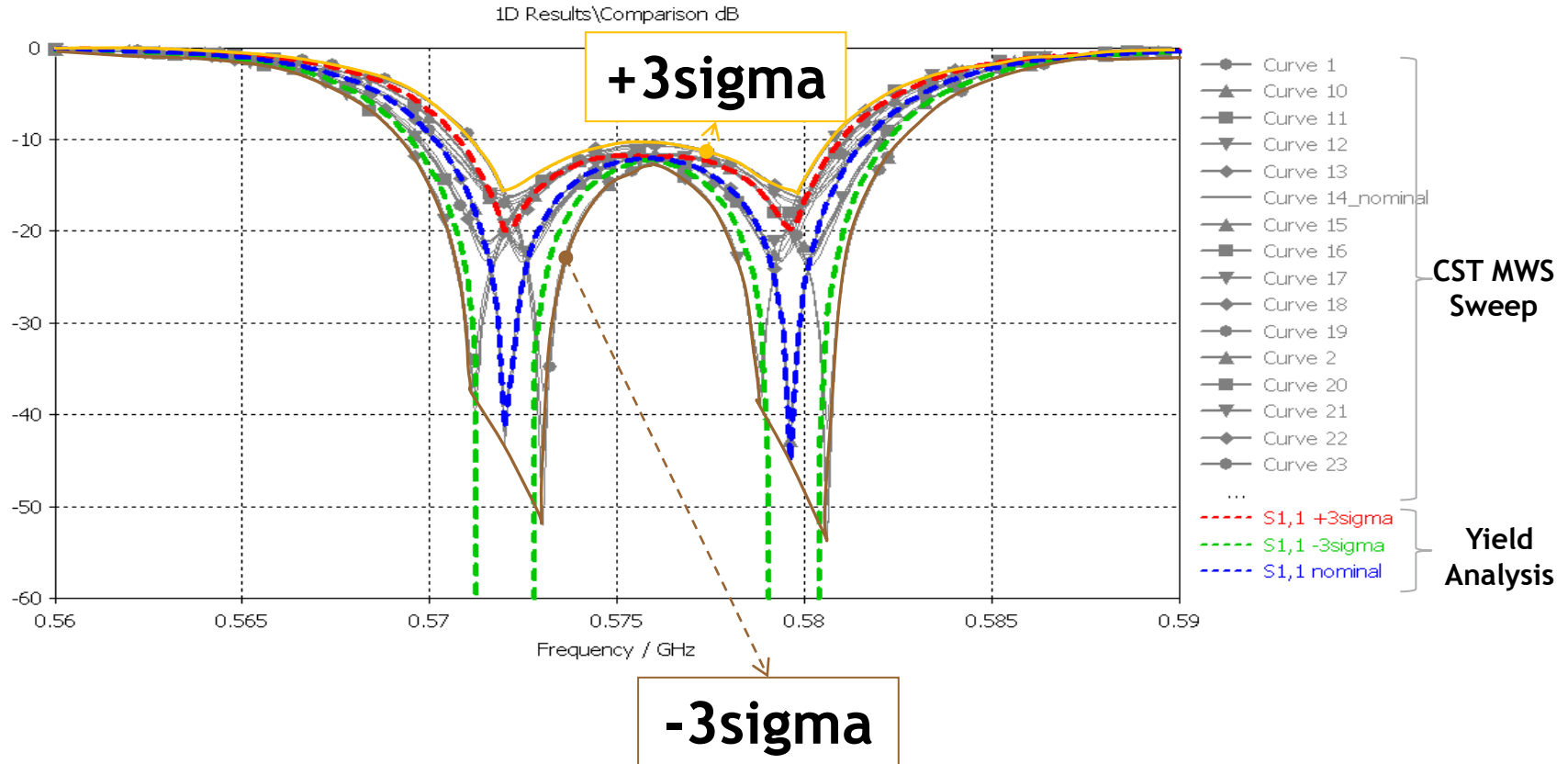


Introduction to Yield



3 sigma: 99.73% of the devices are within this band

Yield Analysis vs. Parameter Sweep



Introduction to Yield

Yield-Specifications: $< -25\text{dB}$

In the range .569 to .574, S11 is under -25dB , the 3-sigma Lines are partially above and below -25dB

For this spec, the yield will tell us what percentage of the devices are within this limit of $< -25\text{ dB}$ for the given frequency band.

Yield Analysis

Design Parameters | Performance Specifications | **Yield**

Add new bound ... Edit... Remove All Remove

Type	Operator	Bound	Range
<input checked="" type="checkbox"/> S1,1 in dB	<	-25	.569...574

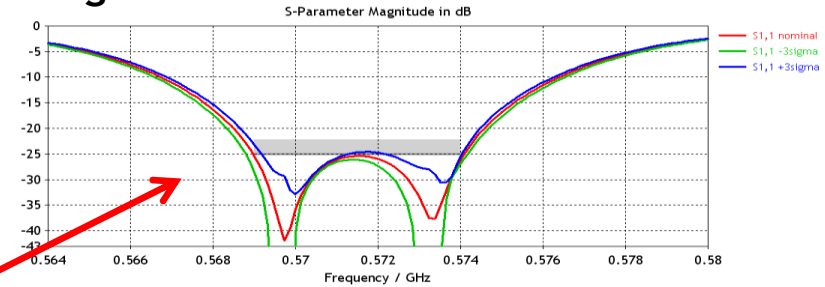
Define S-Parameter Bound

Type: Mag. (linear) Mag. (dB) Phase

Output Port: 1 Mode: 1 Input Port: 1 Mode: 1

Operator: < Bound: -25

Frequency range: Fmin: .569 Fmax: .574



Yield Analysis

Design Parameters | Performance Specifications | **Yield**

Calculated Yield: 91.66%

Example : 2-Post Bandpass Filter

CST MICROWAVE STUDIO®

Filter Tutorial

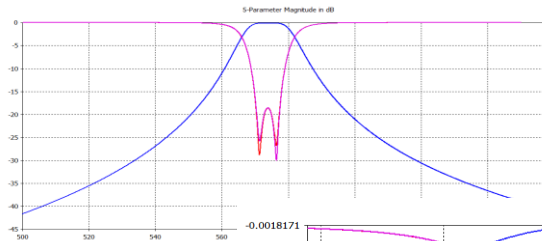
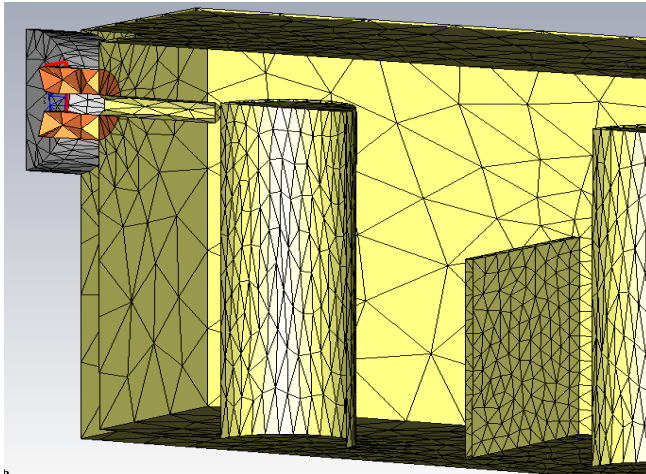
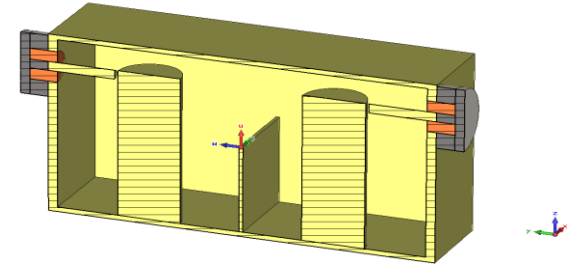
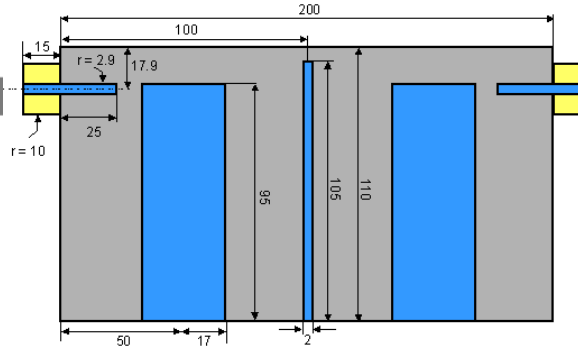
[Tutorials](#)

Frequency Domain Tetrahedral:

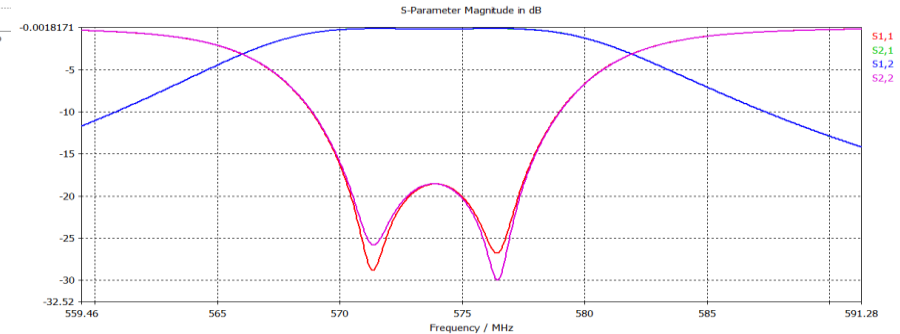
Run Example

Frequency Domain Resonant:

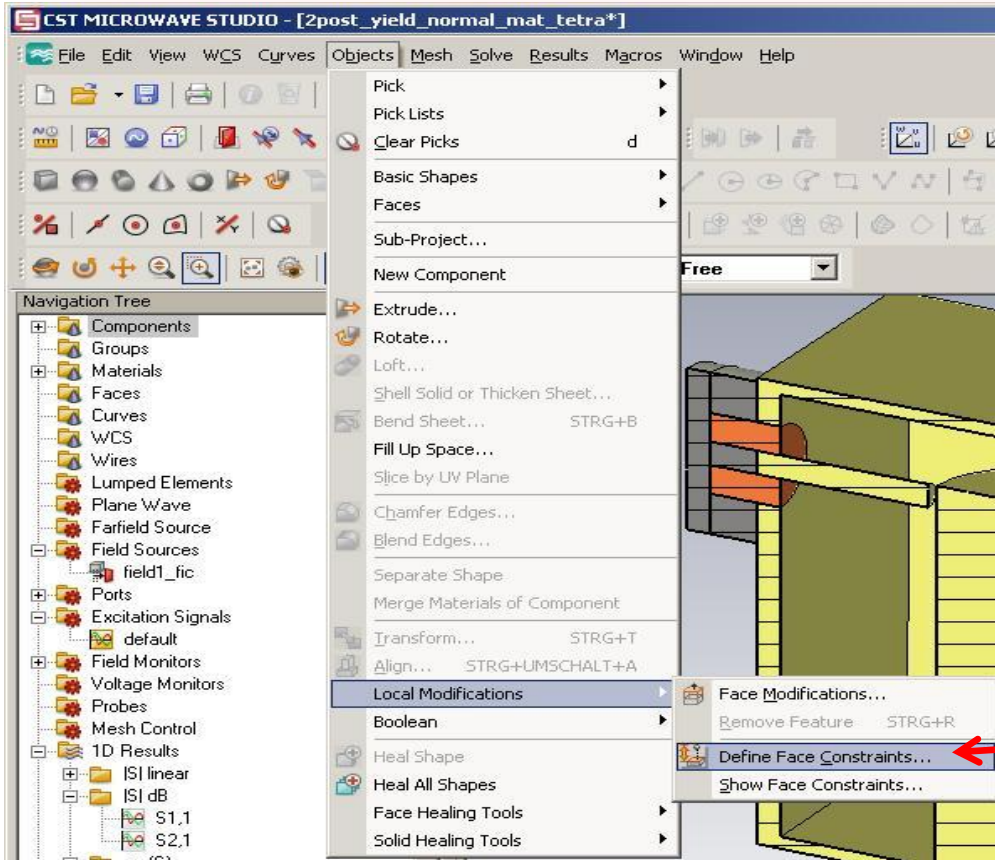
Run Example



Rel Bandwidth: 0.9 %



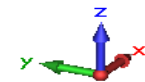
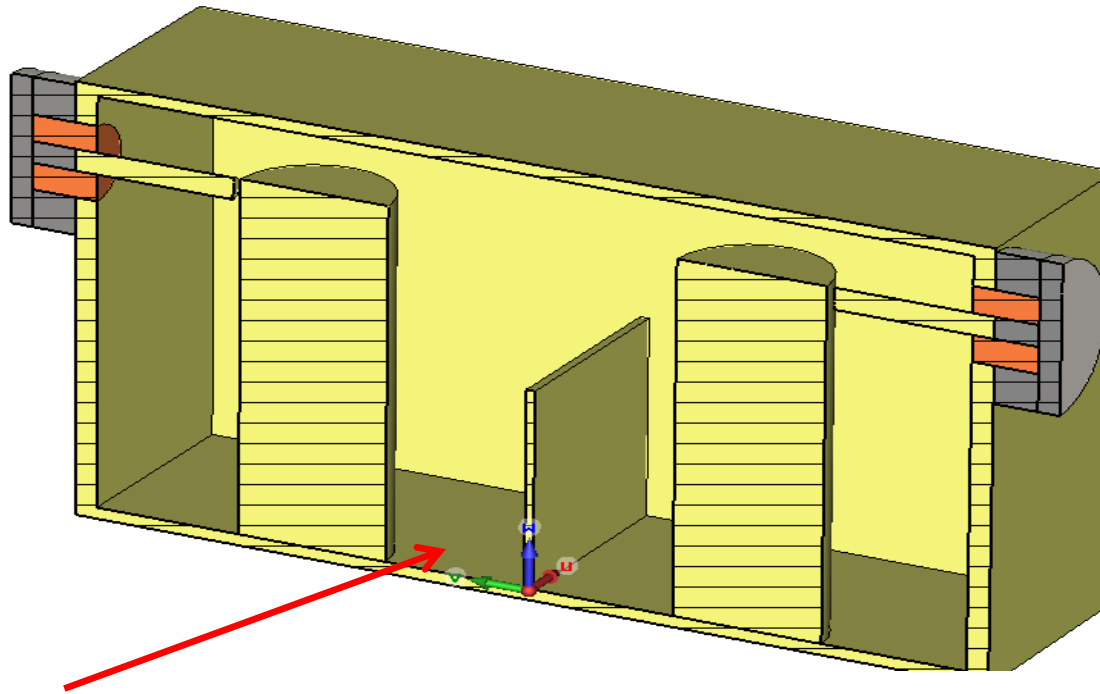
Sensitivity (based on local modifications)



Setup Face-Constraints

Sensitivity

Move WCS to a reference plane (for the mechanically fixed reference)



This face is mech. fixed

Sensitivity



Select a face that should be varied (top face of cylinder)

Select faces to specify a distance to a principal plane, possibly change wcs.

Face Constraints

Type

- Set distance to plane
- Set distance to point
- Set radius

Keep geometry
 Consider blends

Parameters

W-Distance: 95 Parametrize...

Principal plane normal:

- U
- V
- W

New Parameter

Define new parameter

Parameter: facedistance_1

Value: 95

Description: Parametrized face of PEC:cylinder2

Name	Value	Description	Type
Input_coupling_1	6.3	6.3	None
Input_coupling_2	6.3	6.3	None
Res_tuner_1	0	0. Varying post-hight	None
Res_tuner_2	0	0	None
aperture	-52	-52	None
facedistance_1	95	Parametrized face of PEC:cylinder2	None
			Undefined

Sensitivity



Select a face that should be varied (top face of Iris)

Select faces to specify a distance to a principal plane, possibly change wcs.

Face Constraints

Type:

- Set distance to plane
- Set distance to point
- Set radius

Keep geometry

Consider blends

Parameters:

W-Distance: 55.85 Parametrize...

Principal plane normal:

- U
- V
- W

New Parameter

Define new parameter:

Parameter: facedistance_2

Value: 55.85

Description: Parametrized face of PEC:iri

Sensitivity



Show constraints

The screenshot shows the CST Microwave Studio interface. The 'Show Face Constraints' dialog box is open, displaying a table of constraints. The table has five columns: Face, Parameter, Value, Type, and Description. Two constraints are listed:

Face	Parameter	Value	Type	Description
PEC:cylinder1:3	facedistance_1	95	distance to plane	RP:<0,-50,95> Dir:W WCS:<0,0,0>:x1,0,0>:x<0,0,1>
PEC:iris:1	facedistance_2	55.85	distance to plane	RP:<0,0,55.9> Dir:W WCS:<0,0,0>:x1,0,0>:x<0,0,1>

Below the table are buttons for 'Delete', 'Select All', 'Deselect', 'Close', and 'Help'. In the background, a context menu is open over a 3D model, with 'Define Face Constraints...' selected. A red arrow points from this menu option to the 'Show Face Constraints' dialog box.

Sensitivity, Setup FD-Analysis,



As Result: Derivative of S-Parameter vs Parameter and frequency

Frequency Domain Solver Parameters

Method: General Purpose, Resonant: Fast S-Parameter, Resonant: S-Parameter, fields
 Mesh type: Tetrahedral Mesh

Solver settings: Save all field results, Store result data in cache, Calculate modes only
 Accuracy (tetrahedral mesh): 1e-6

Excitation settings: Source type: Port 1, Mode: 1

S-parameter settings: Normalize to fixed impedance, 50 Ohms

Frequency samples:

	Auto	Samples	From	To	Unit
Max.Range	<input checked="" type="checkbox"/>		0.4	0.8	GHz
Adapt.Freq.	<input checked="" type="checkbox"/>	1	.57		GHz
Frequency	<input checked="" type="checkbox"/>				GHz
Frequency	<input type="checkbox"/>				GHz
Frequency	<input type="checkbox"/>				GHz

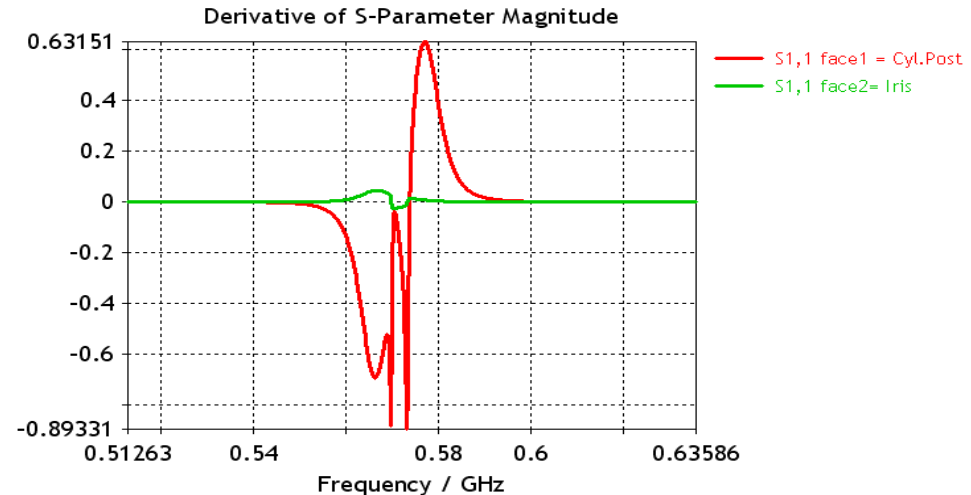
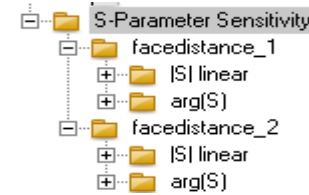
Do not calculate field monitors
 Use broadband frequency sweep

Adaptive mesh refinement: Adaptive tetrahedral mesh refinement

Sensitivity analysis: Use sensitivity analysis

Sensitivity Analysis

<input checked="" type="checkbox"/>	Parameter	Value	Description
<input checked="" type="checkbox"/>	facedistance_2	55.85	Parametrized face of PEC:iris
<input checked="" type="checkbox"/>	facedistance_1	95	Parametrized face of PEC:cylinder1
<input type="checkbox"/>	mech_field	1	Imported displacement field

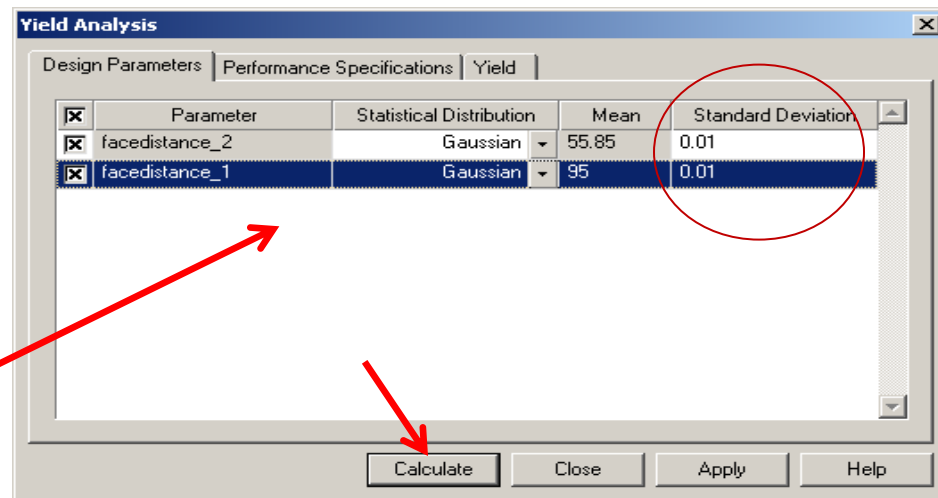
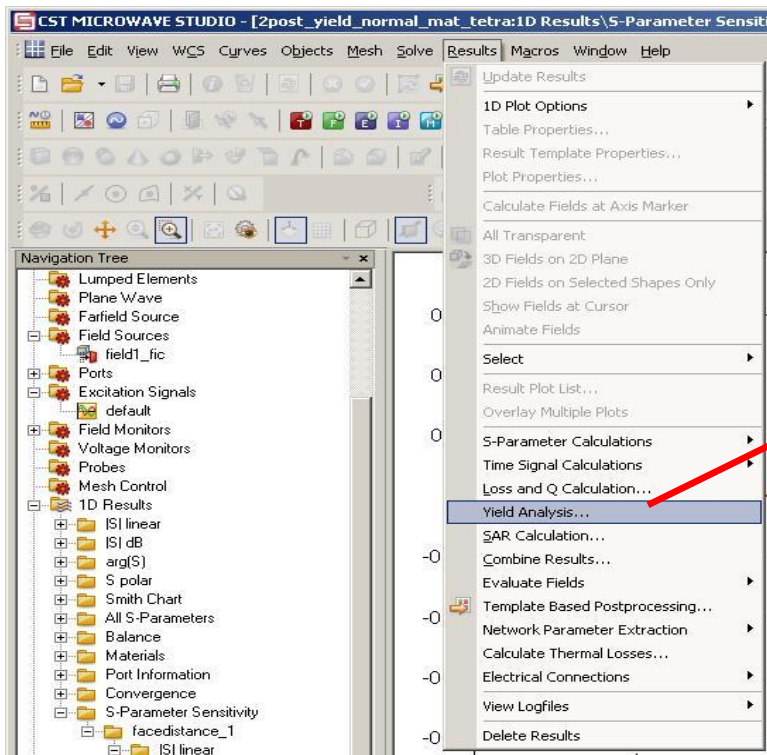


Yield

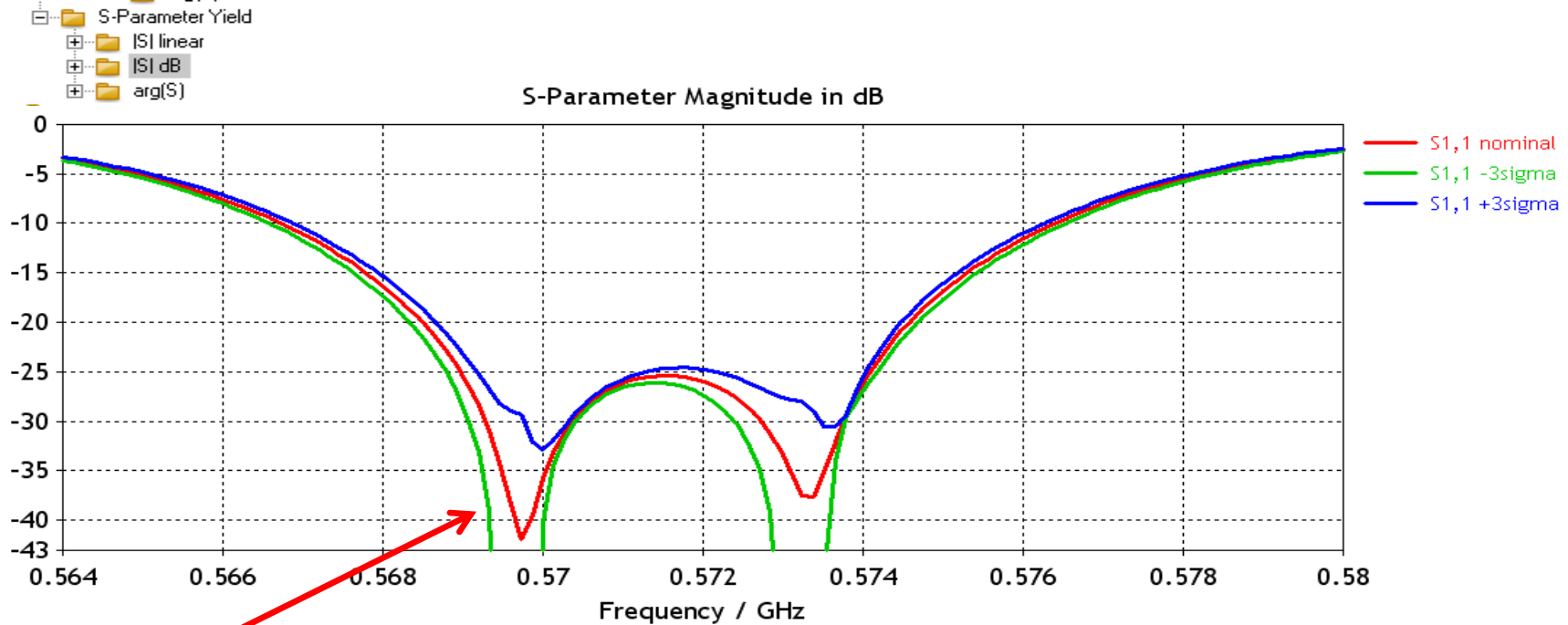


Define manufacturing tol. of the parameter (statistical values)

Perform Yield



Yield



3 sigma: 99.73% of the devices are within this band

Yield



Yield-Specifications: < -25dB

In the range .569 to .574, S11 is under -25dB, the 3-sigma Lines are partially above and below -25dB

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<input checked="" type="checkbox"/> S1,1 in dB	<	-25	.569...574

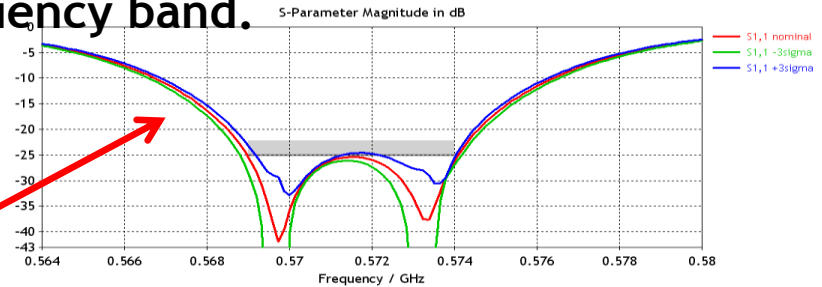
Define S-Parameter Bound

Type: Mag. (linear) Mag. (dB) Phase

Output Port: 1 Mode: 1 Input Port: 1 Mode: 1

Conditions: Operator: < Bound: -25

Frequency range: Fmin: .569 Fmax: .574



Yield Analysis

Design Parameters Performance Specifications Yield

Calculated Yield: 91.66%

Yield

Another yield specification: $S_{11} < -26\text{dB}$
Yield Result: only 0.71%

