# 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.

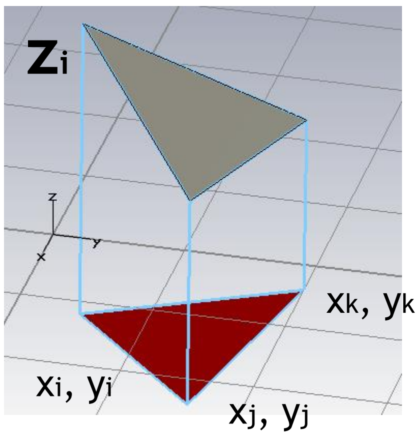
# Outline

- **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

$$k_{m,n} = \iint_{xy} (\varepsilon_x \frac{\partial N_m}{\partial x}\frac{\partial N_n}{\partial x} + \varepsilon_y \frac{\partial N_m}{\partial x}\frac{\partial N_n}{\partial x}) dxdy; m, n = i, j, k$$

[E]: unkowns z

[Q]: Sources

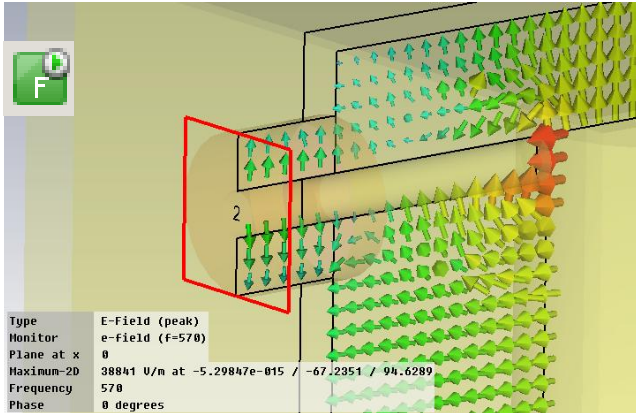
# Introduction to Sensitivity

## 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:

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

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

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

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 Δ*p* :

$$S(x+\Delta p) \approx S(x) + \sum_{p} \frac{\partial S}{\partial p} . \Delta p$$

exact computation of the Sensitivity

(Approximated by 1st order Taylor expansion)

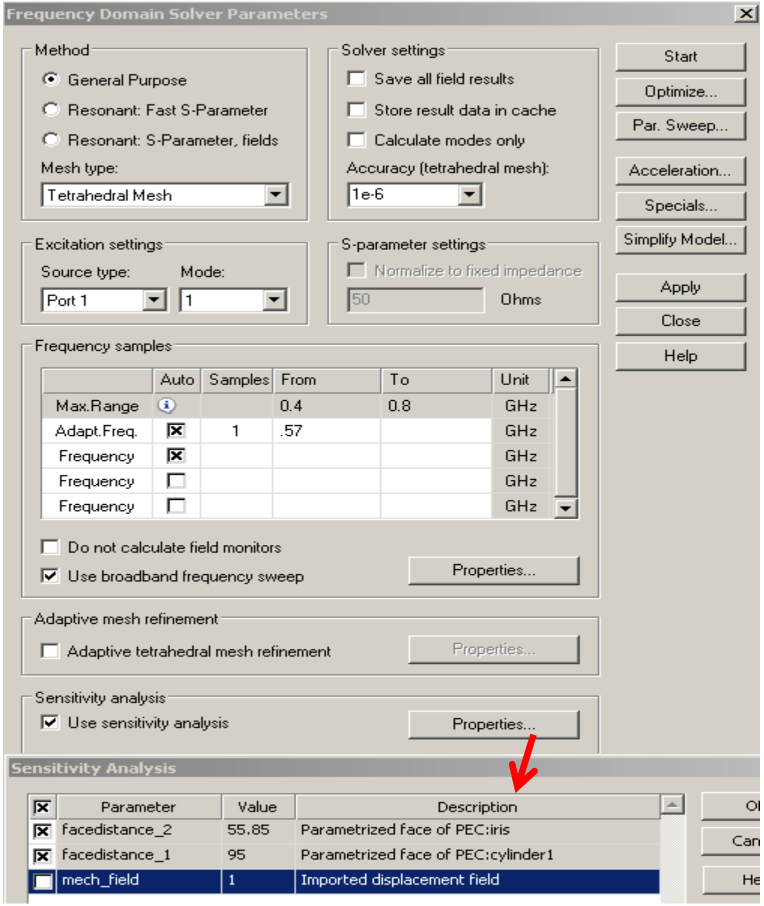
- The various sensitivities are used in an optimizer to solve for Δp as variables to best fit the S-parameter goals.

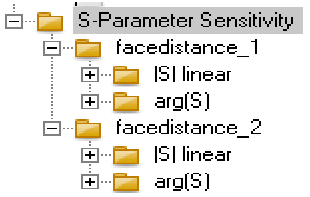
$$S_{nm} \Leftarrow S_{nm(3D-MWS)} + \sum_{p} \frac{\partial S}{\partial p} . \Delta p$$

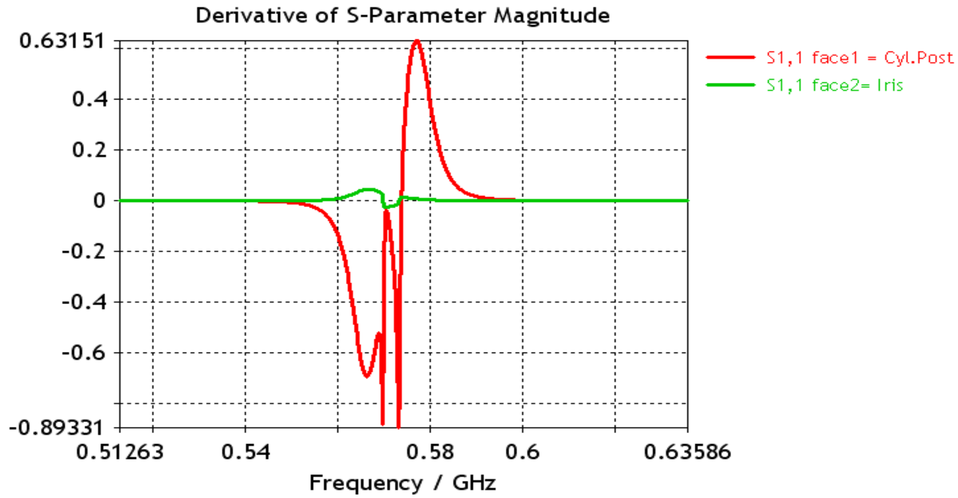
Δp … face constraints

# Introduction to Sensitivity

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



# What is the Yield Analysis

For every product, there are:

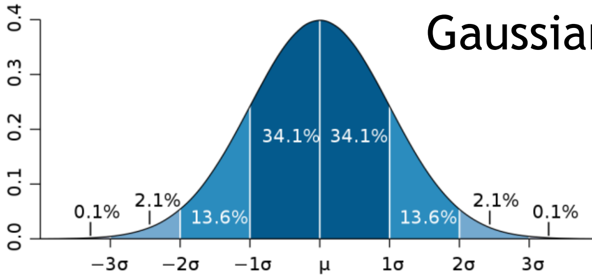
- Technical specifications
- Fabrication tolerances

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

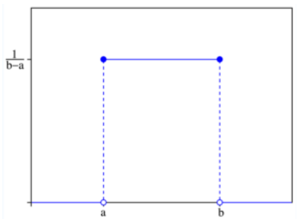
Yield:

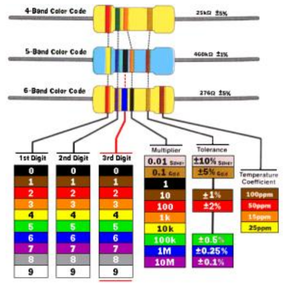
$$yield = \frac{\#Passed}{\#Total}$$

Gaussian




Uniform



# 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 - typicaly hundreds or thousands!!!

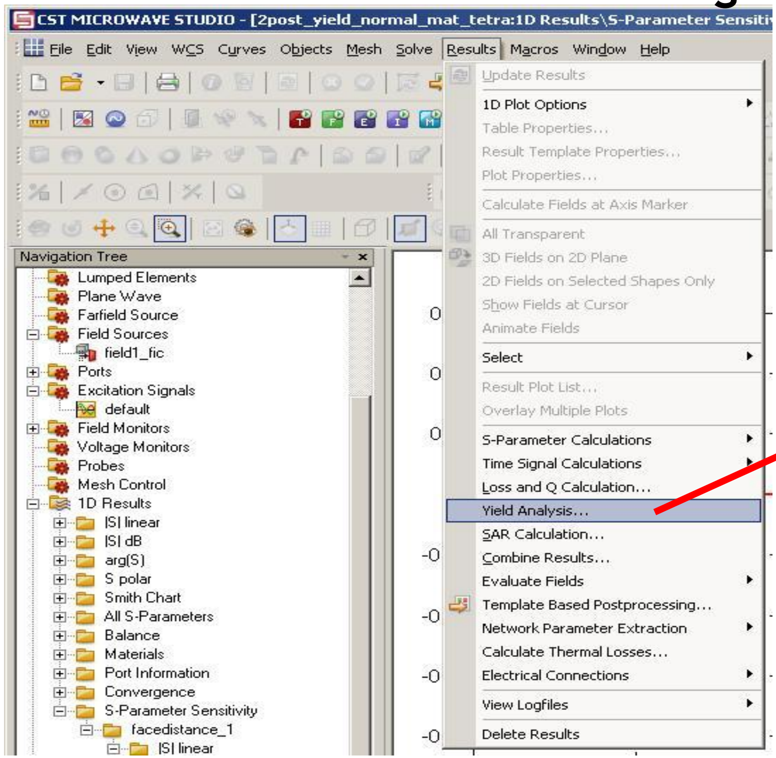
Knowing the sensitivity, there is no need to perform 3D simulations, at least if the parameters vary in a small range.

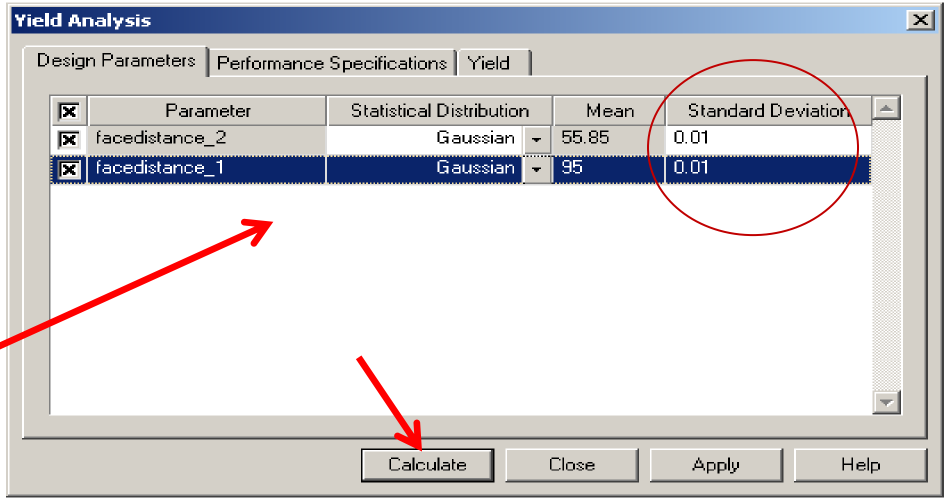
The efficiency of this new sensitivity analysis approach makes Monte-Carlo based yield analysis feasible even for complex multi-parametrical three-dimensional structures

# Introduction to Yield

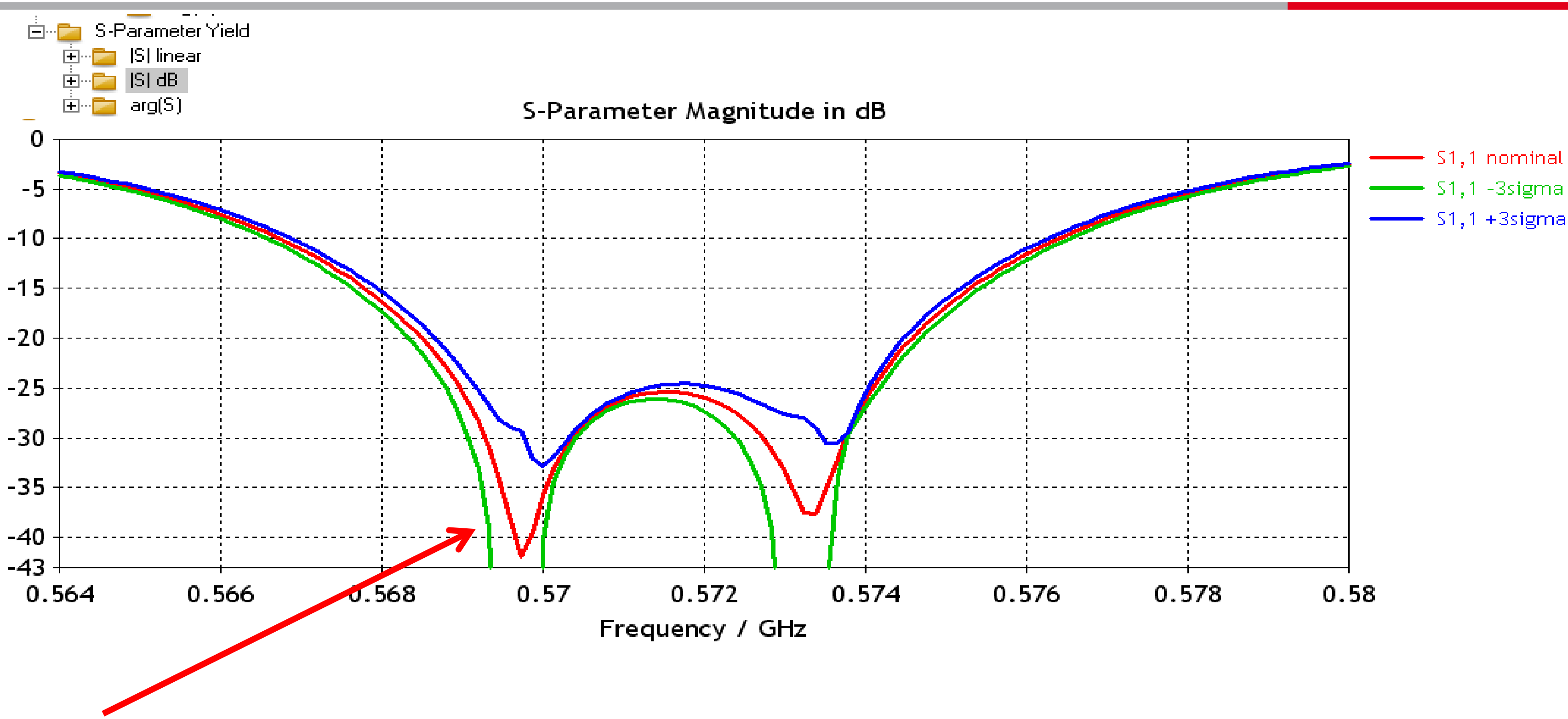
## Define manufacturing tol. of the parameter (statistical values)

## Perform Yield



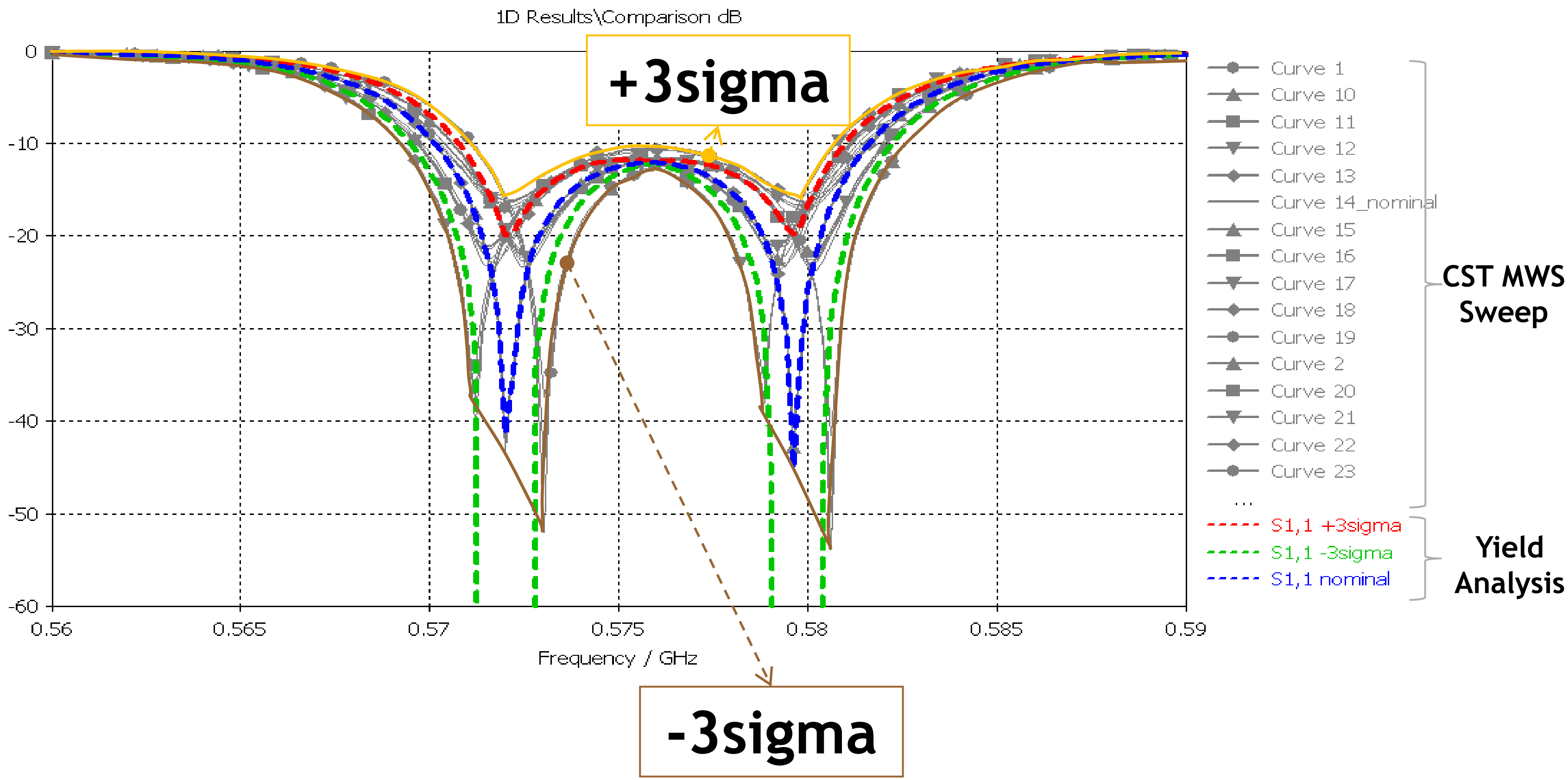



# Introduction to Yield




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

# Yield Analysis vs. Parameter Sweep

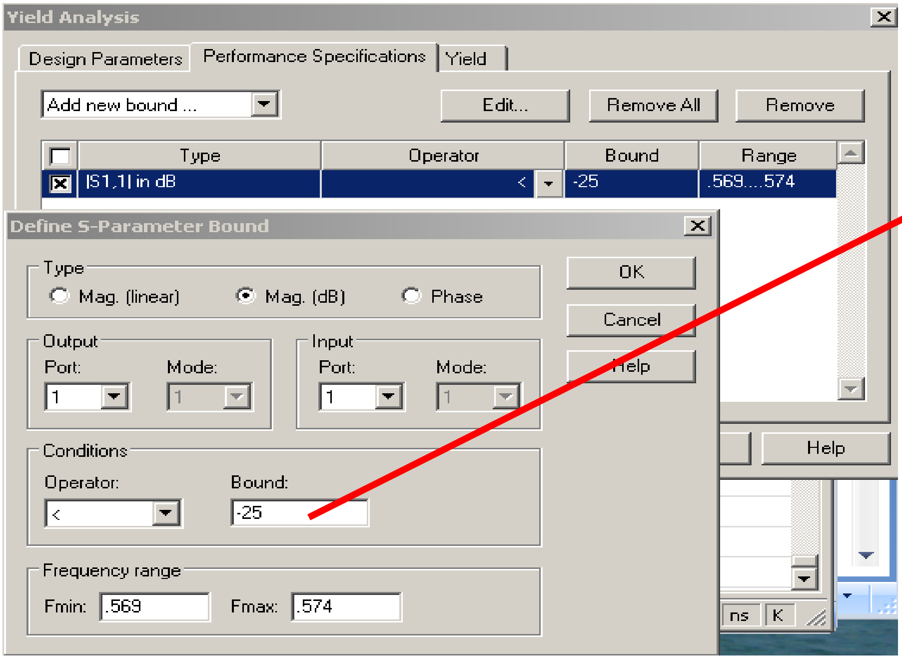


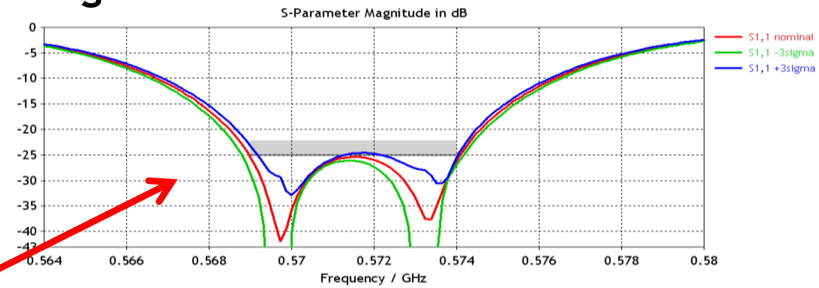
# Introduction to Yield

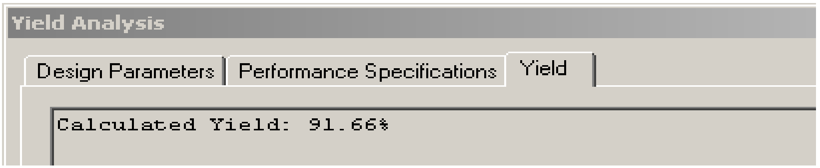
## Yield-Specifications: < -25dB

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

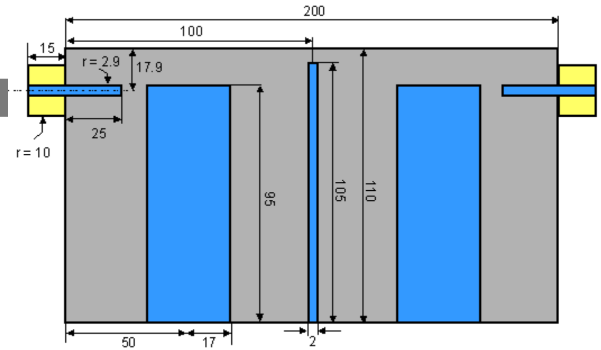
**For this spec, the yield will tell us what percentage of the devices are within this limit of < -25 dB for the given frequency band.**

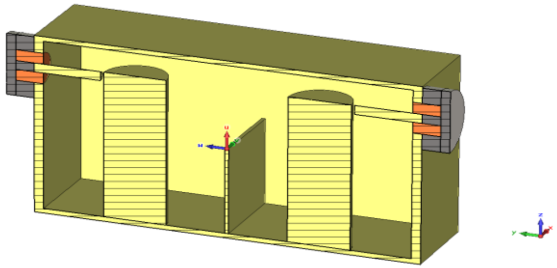


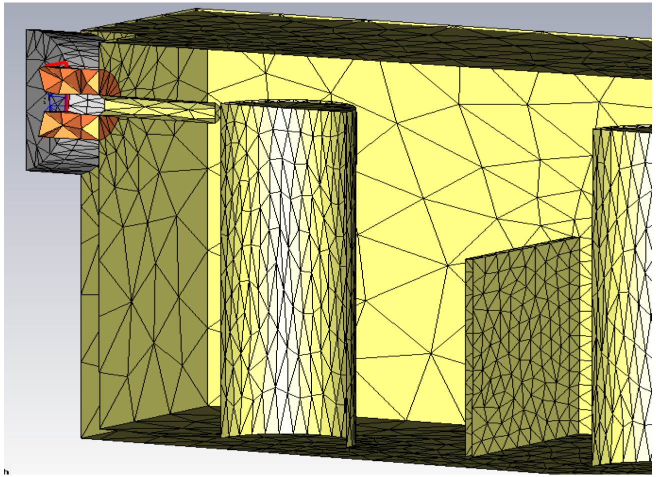



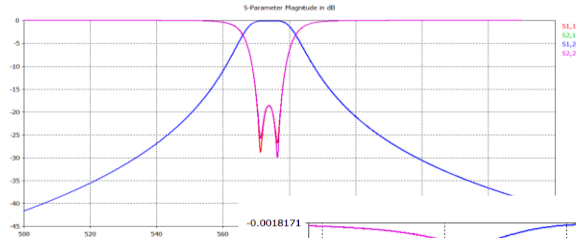



# Example : 2-Post Bandpass Filter

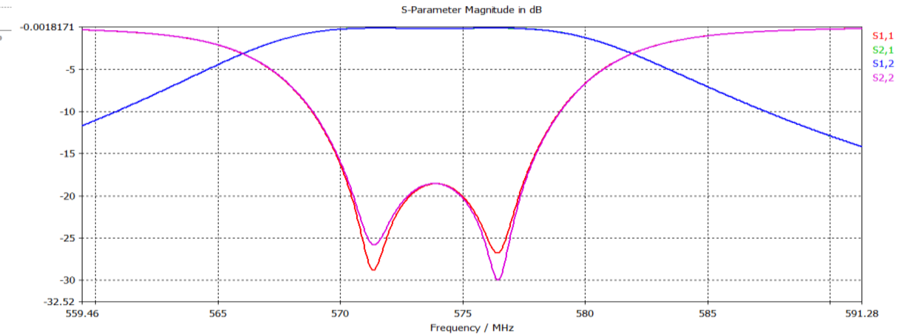



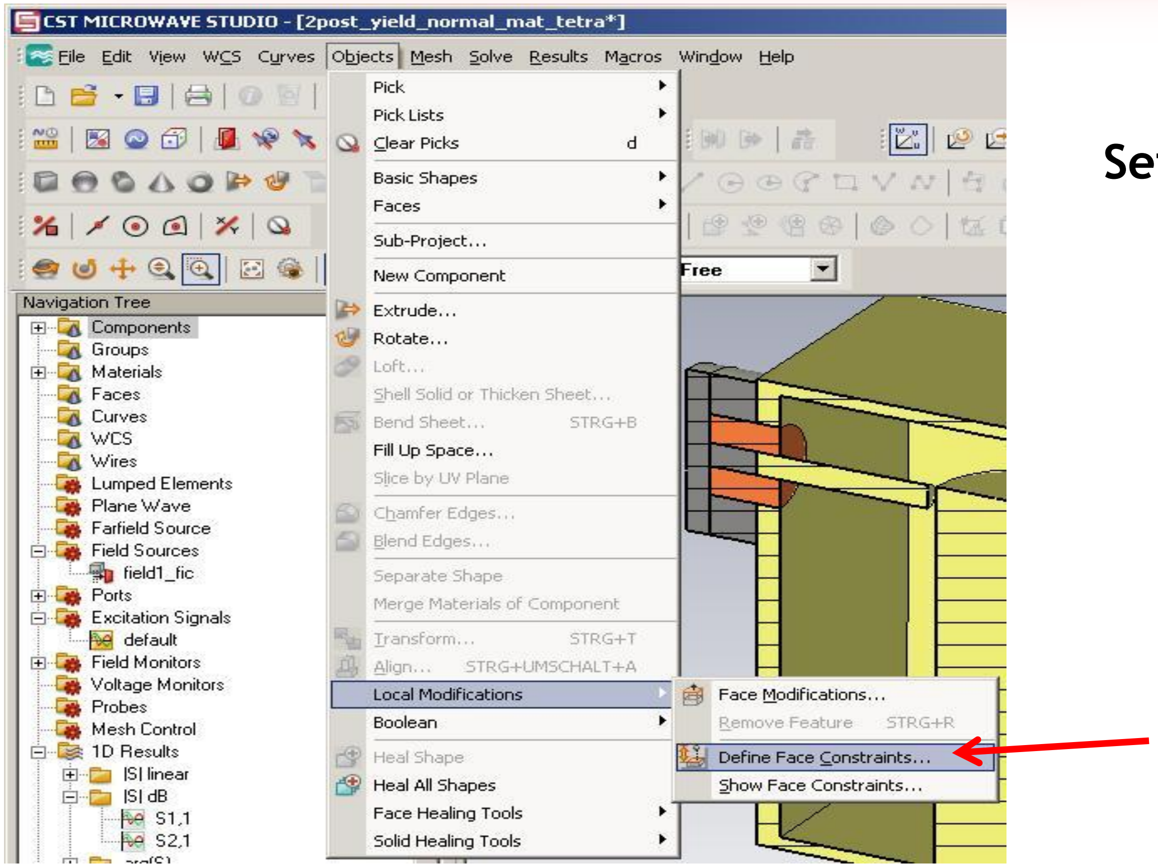





**Rel Bandwidth:0.9 %**



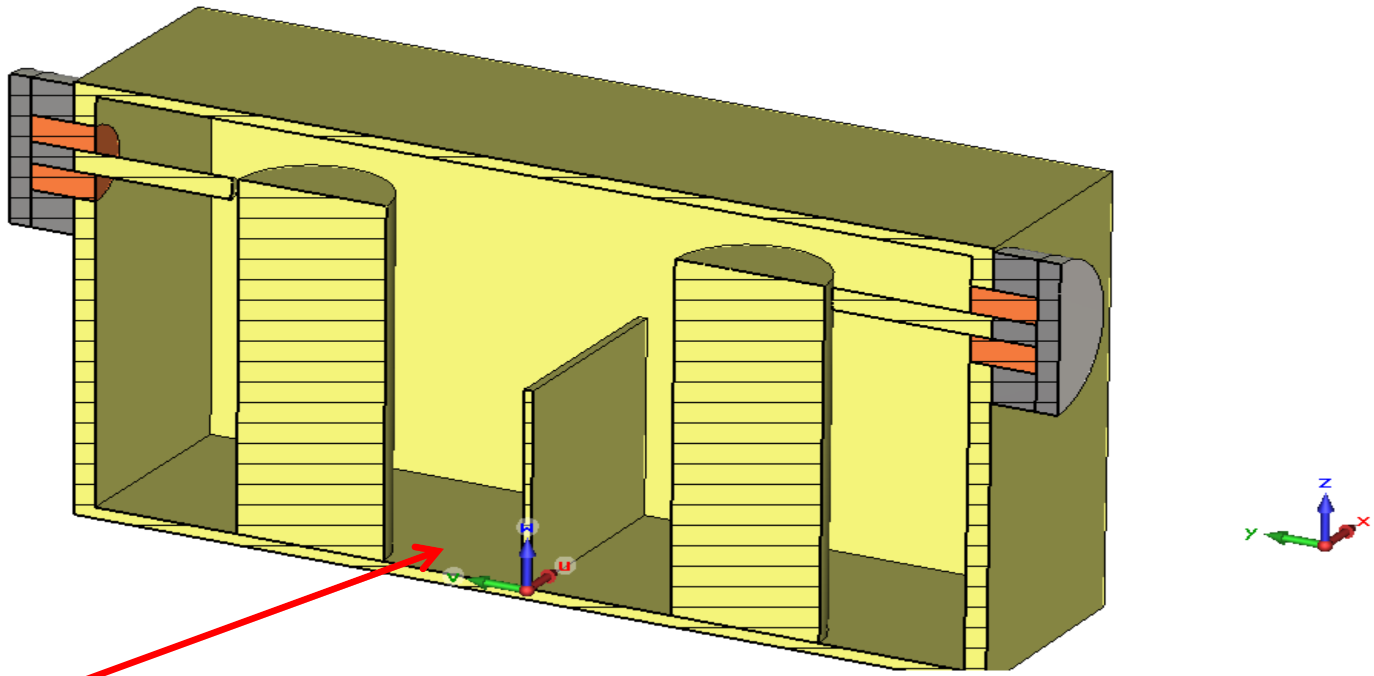
# Sensitivity (based on local modifications)




**Setup Face-Constraints**

# Sensitivity

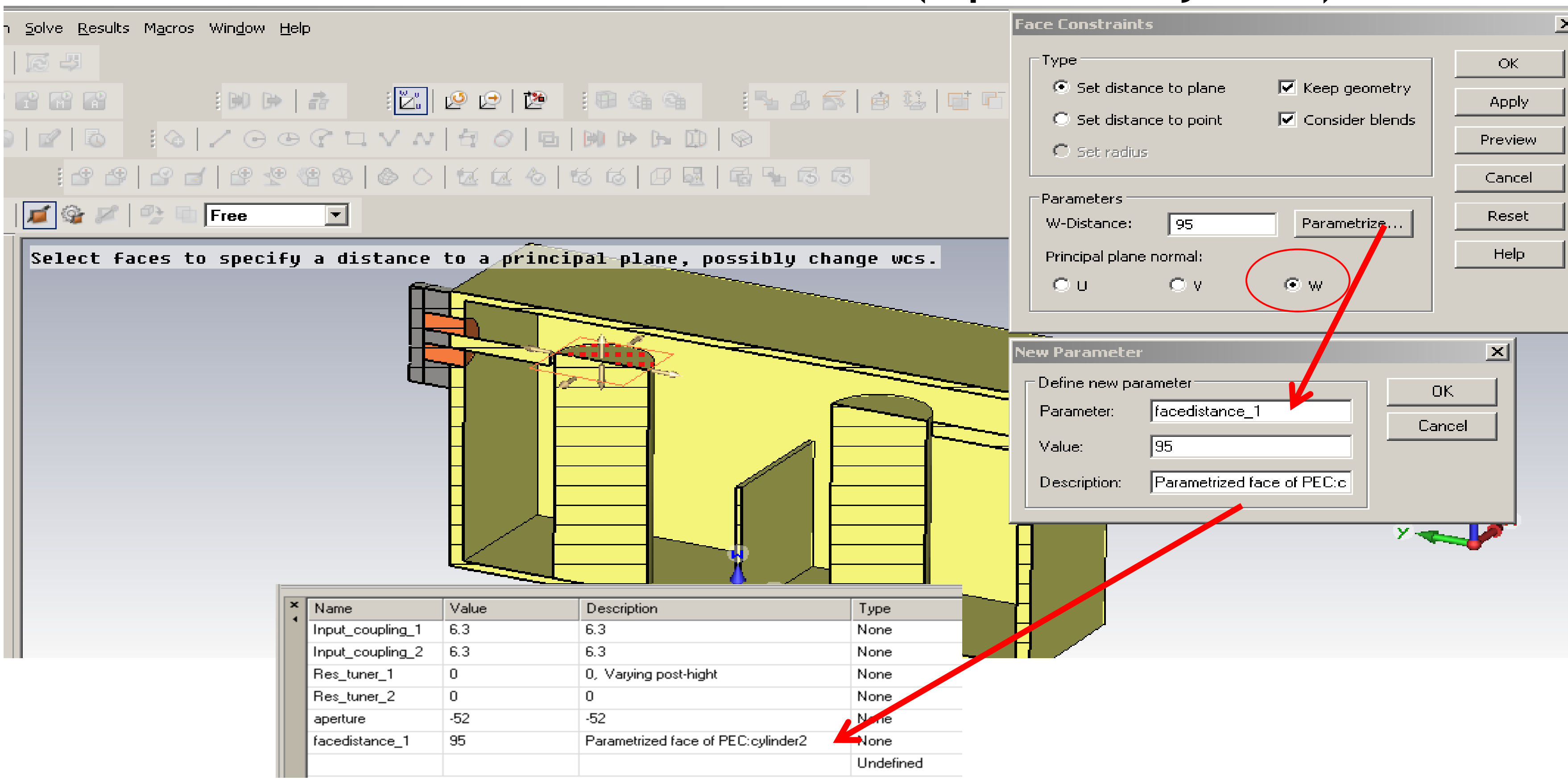
Move WCS to a reference plane (for the mechanically fixed reference)




This face is mech. fixed

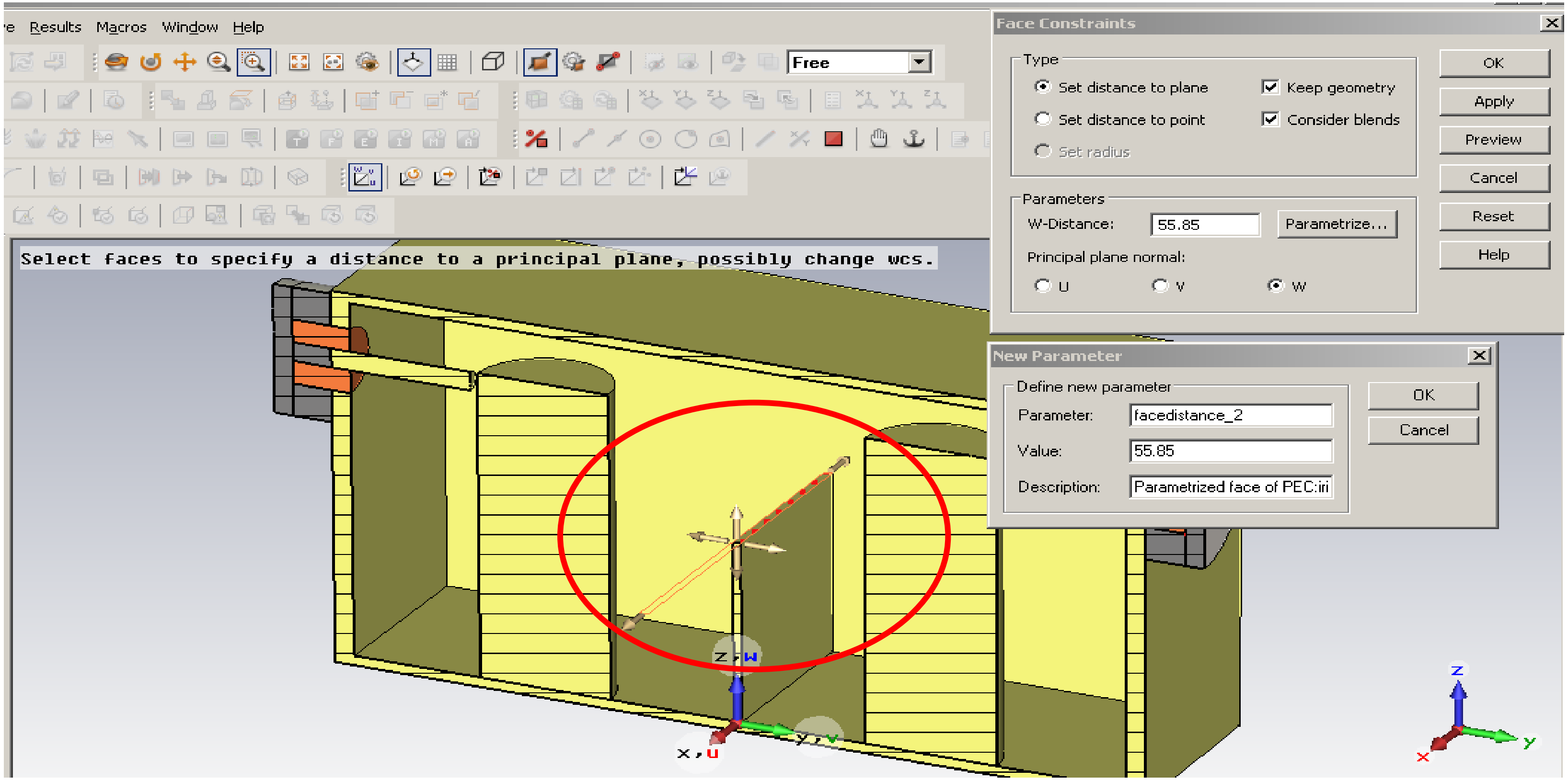
# Sensitivity

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



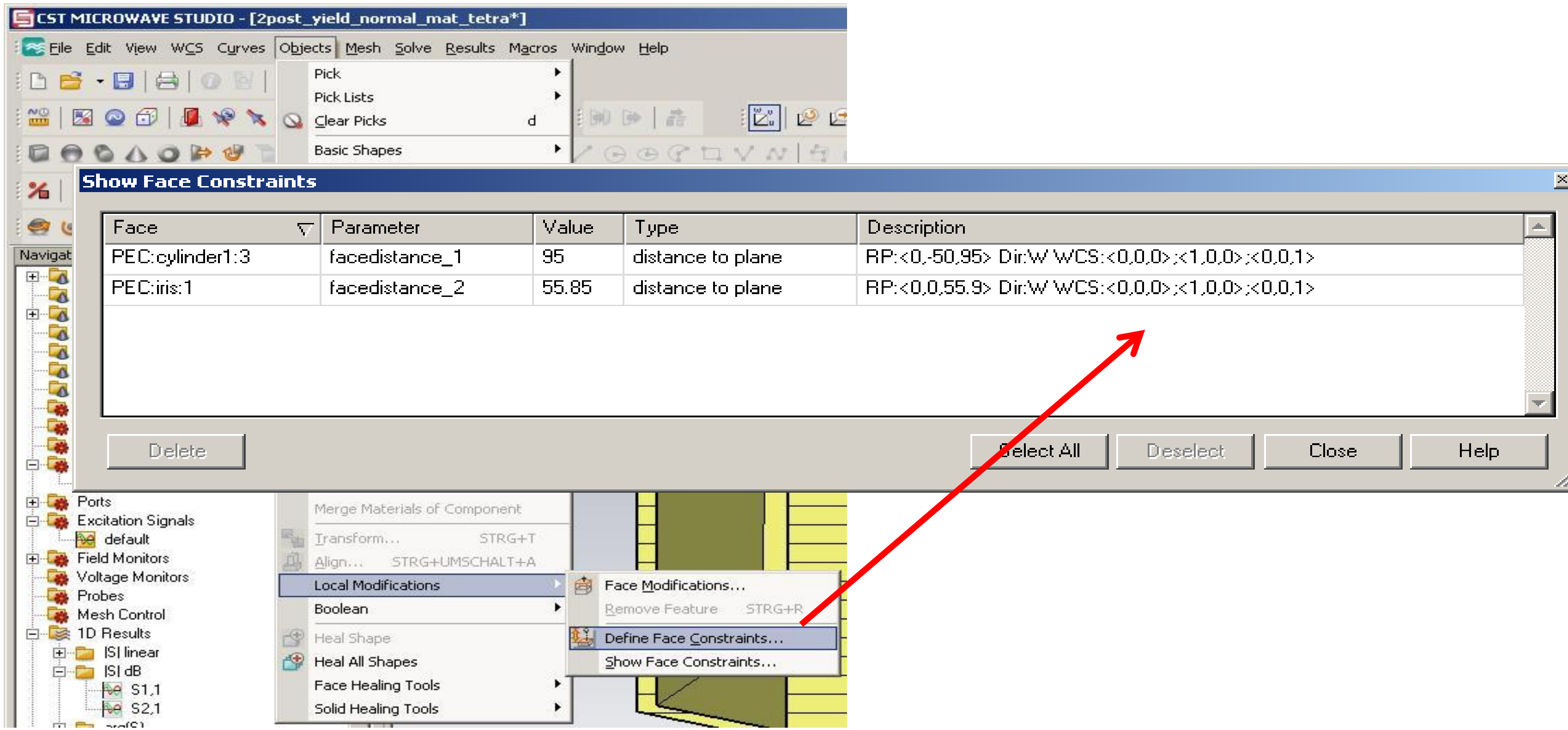
# Sensitivity

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



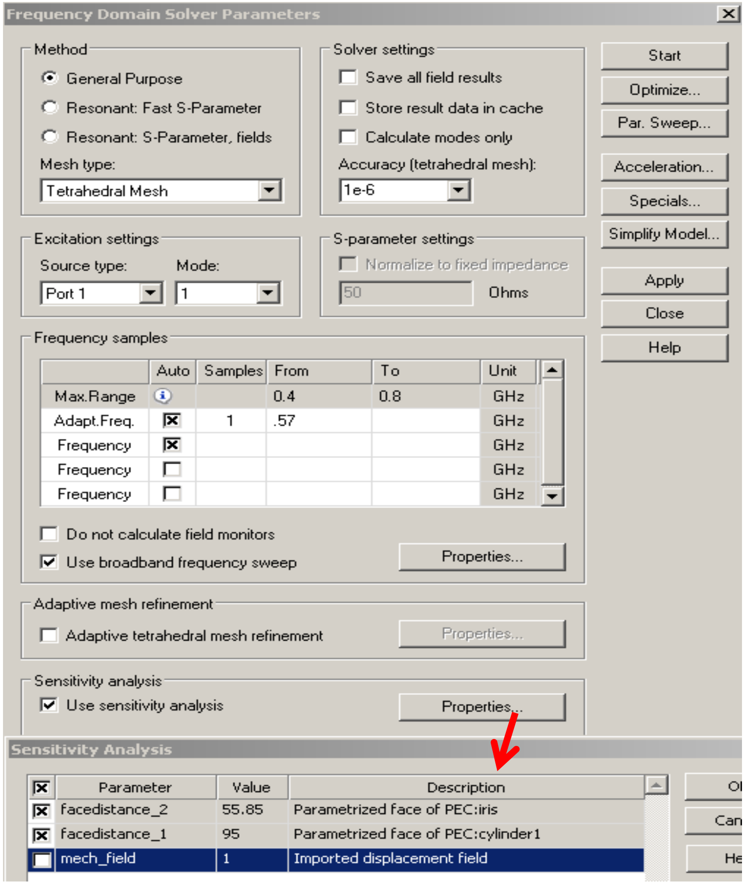
# Sensitivity

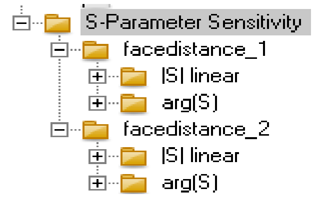
## Show constraints

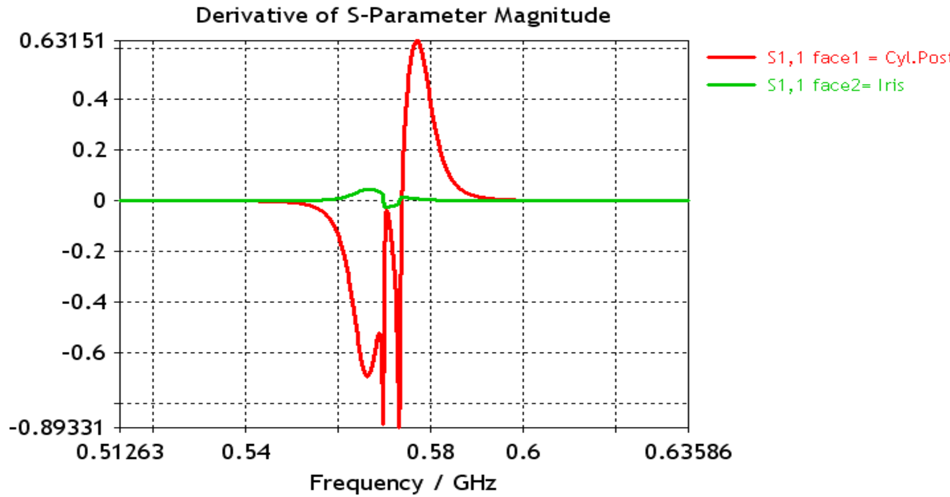


# Sensitivity, Setup FD-Analysis,

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



# Yield

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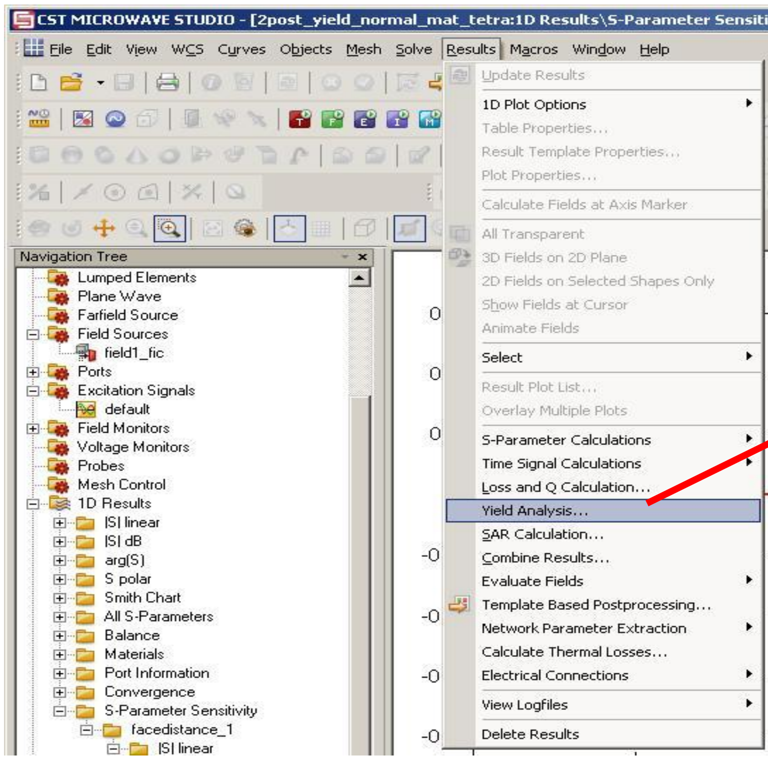
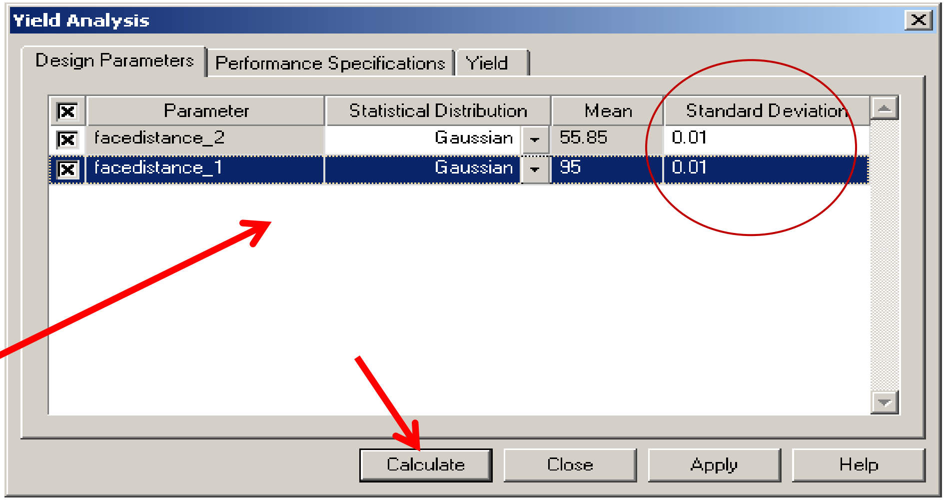
**Perform Yield**



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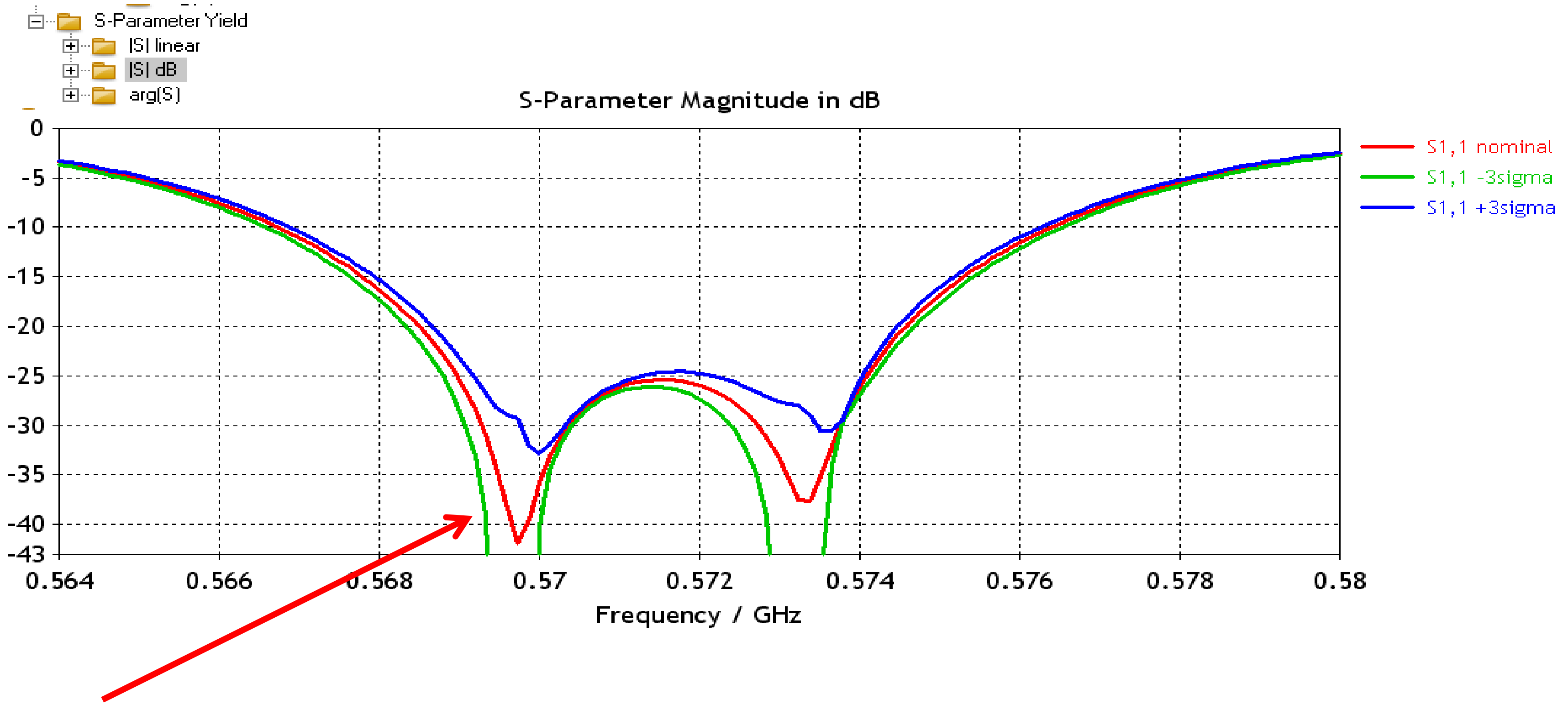


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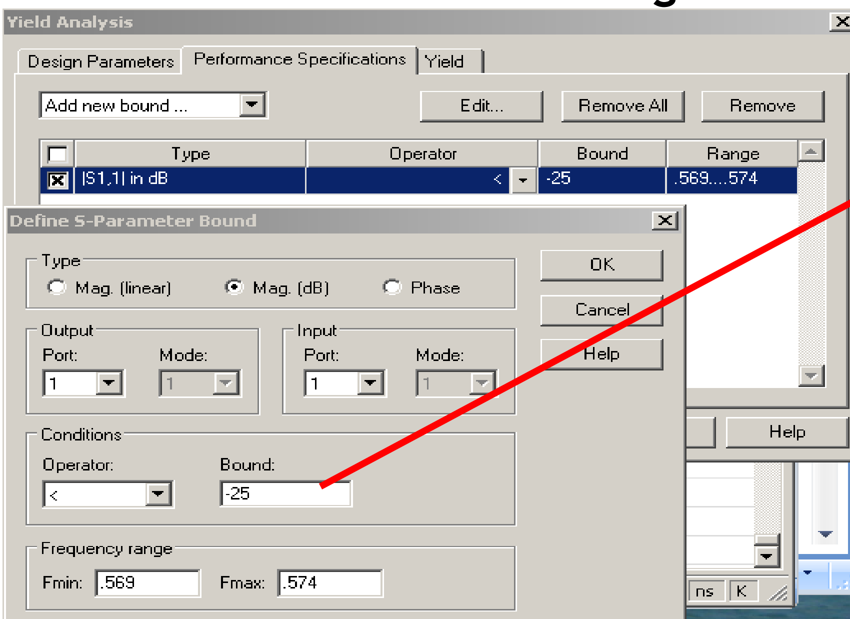


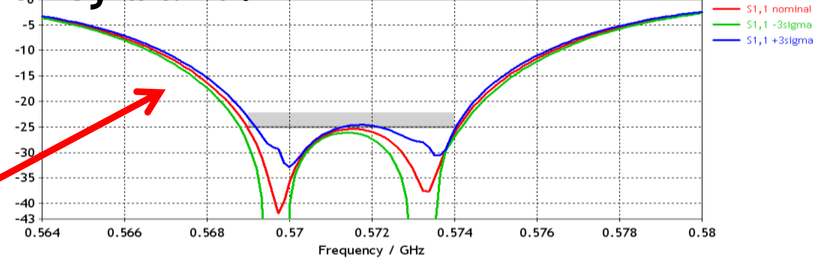


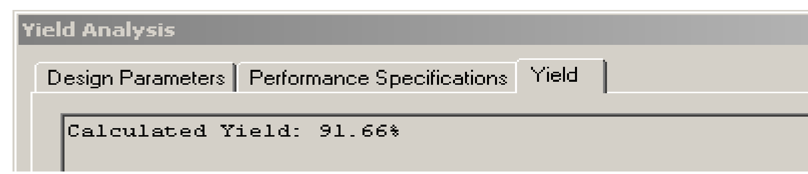

# Yield

**Another yield specification: S11 < -26dB**

**Yield Result: only 0.71%**