# FABRICATION TOLERANCES IN LOW COST ANTENNA SUBSTRATES AT 60 GHZ

## CST European User Conference

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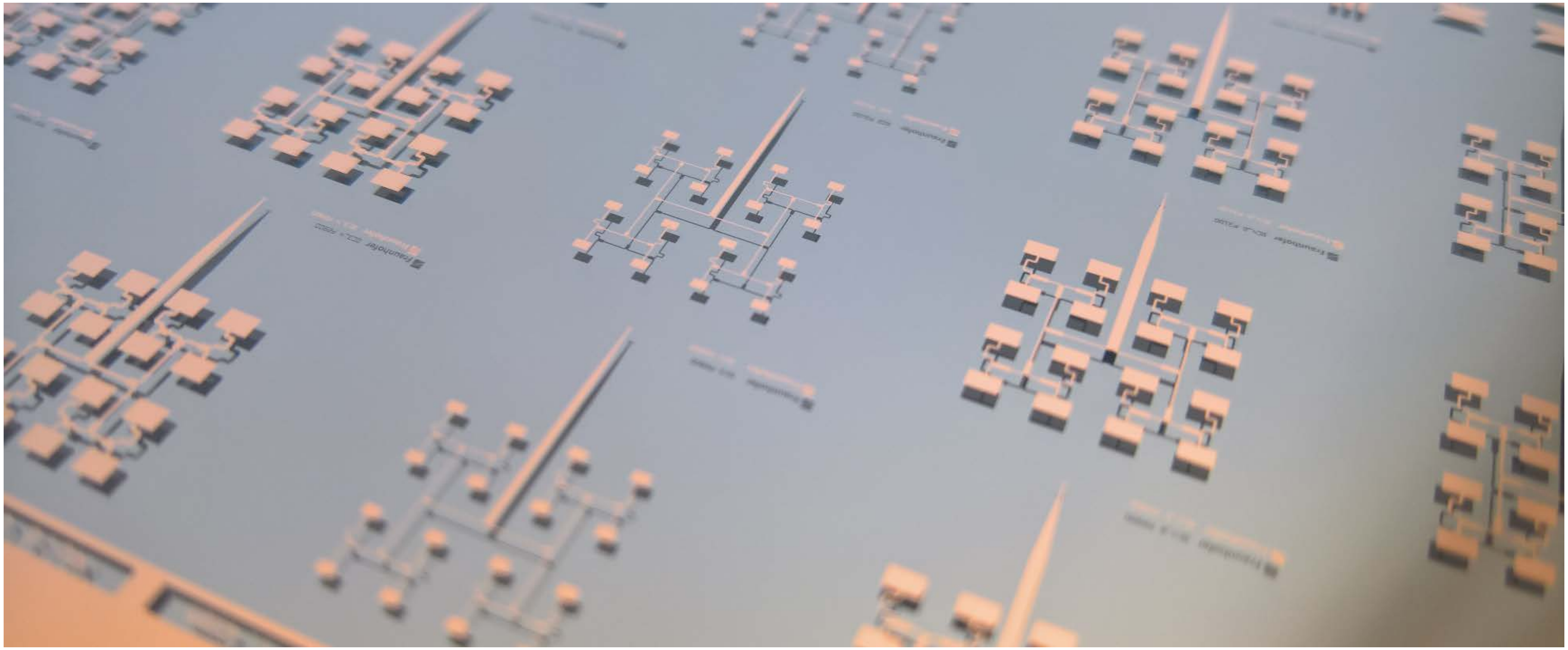



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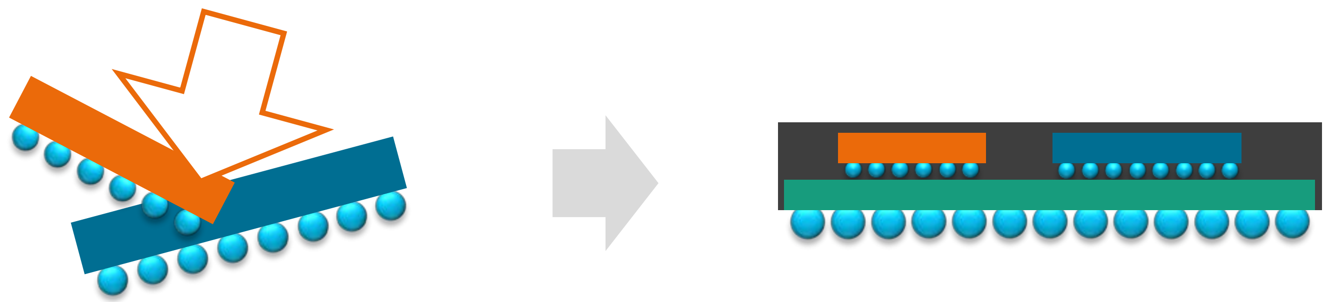
# OUTLINE

- Introduction of Fraunhofer EAS
- Low Cost Antenna Substrates, Package Example
- Fabrication Issues – Examples
  - Inhomogeneous substrate thickness
  - Warpage Modeling
- Simulation Results
- Summary

# Fraunhofer IIS / Division Engineering Adaptive Systems
## Advanced System Integration Group



**Our Mission:**

Customer support for cost effective integration of multiple chips in a single package.

- System concept, design and prototype development
- Path finding
- Production of packages
- Supply chain





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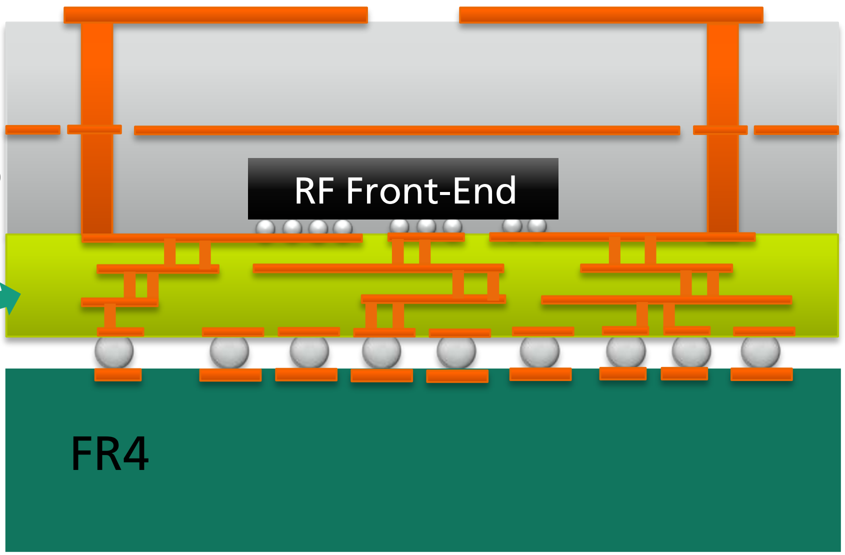
# Low Cost Antenna Substrate

## Low Cost IoT Node for 60 GHz

- Antenna Array
- Antenna Substrate
  - Mold Compound (Nagase R4251)
  - Thickness ≥ 300µm
- Redistribution Layer embedded in Polyimide




Key Parameters:

- 4x4 Antenna Array of Rectangular Patch Antennas
- Package Dimensions: 16 x 16 mm

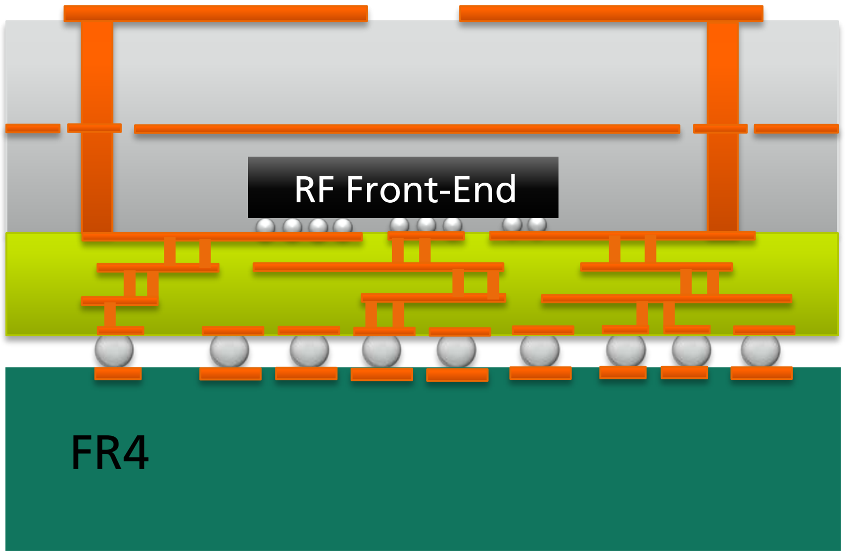
# Low Cost Antenna Substrate

**Issues arise from applying mold materials**

1. Deformation due to fabrication process
2. Less suitable dielectric properties compared to, i.e. Rogers laminates and LTCC

Nagase R4251:

- $\varepsilon_r = 3.65$
- $\tan\delta = 0.0037$

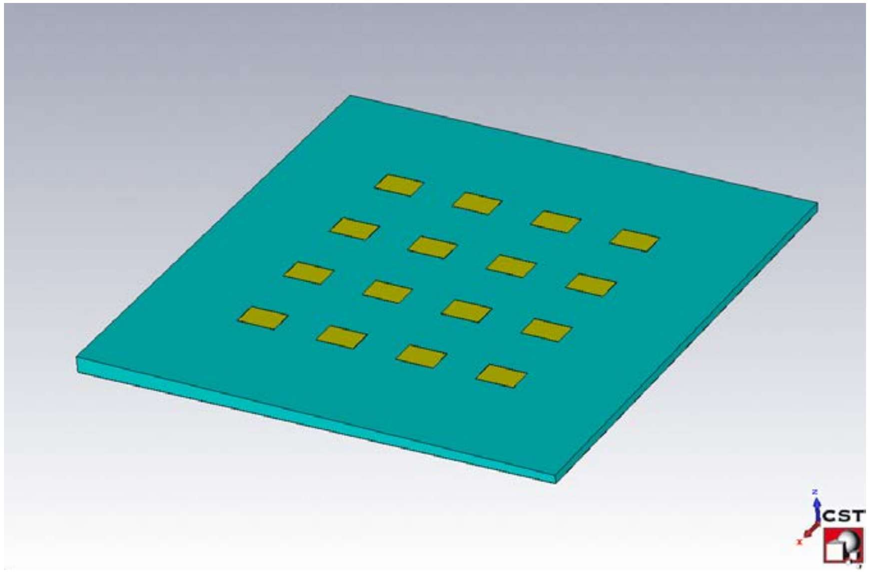


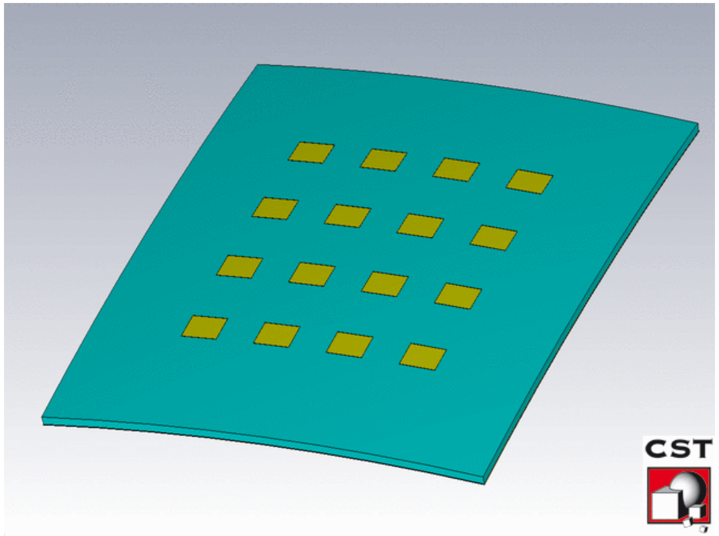

**→ Tolerable range of measurable deformations has to be found**

# Low Cost Antenna Substrate

## Impact of substrate deformations on antenna characteristics

- Variation in antenna impedance
- Decrease of Gain
- Change of main lobe direction



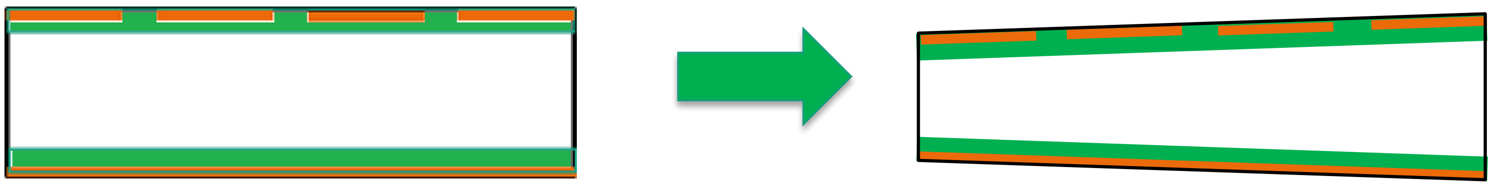




- Increase of the side lobe level
- Increase of  Antenna Crosstalk

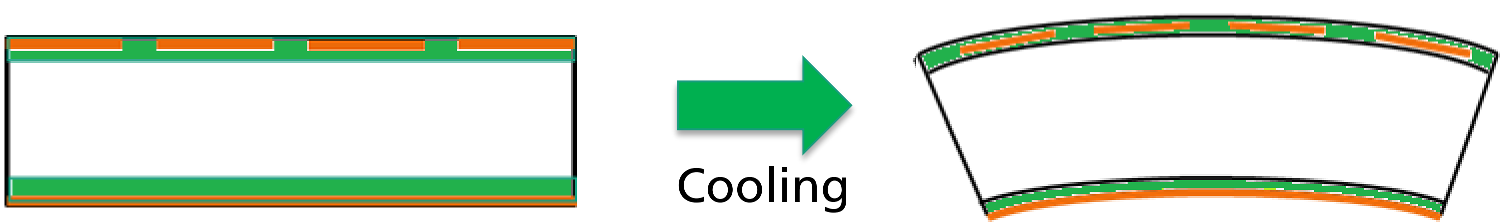
# Low Cost Antenna Substrate

## Substrate Deformation

1. Inhomogeneous substrate thickness



2. Warpage
   - Various layers on top / bottom side (Cu, passivation,..)
   - Inhomogeneous distribution of Cu on top/bottom side





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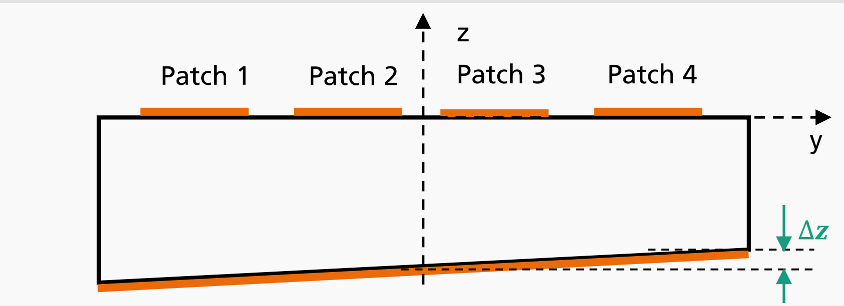
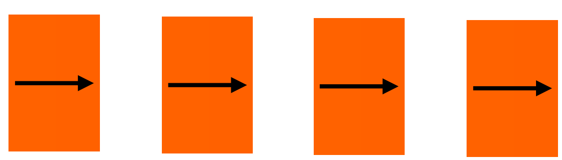
# Modeling

# Modeling Substrate Deformation
# Inhomogeneous substrate thickness

## Case Study with different thickness variation functions

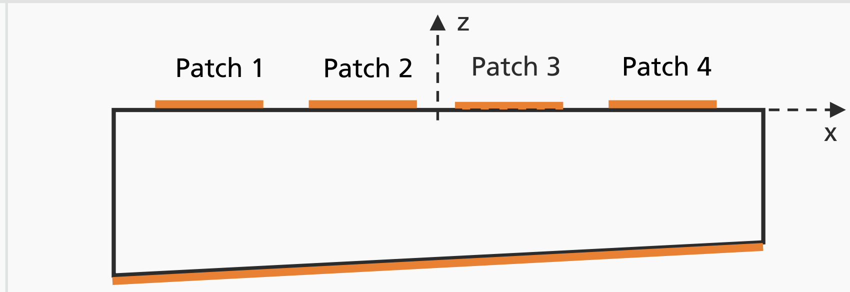
$$t_{sub} = f(y), \qquad \vec{E} = E_y\,\vec{e}_y$$



$$\vec{E} = E_y\vec{e}_y$$

$$t_{sub} = f(x), \qquad \vec{E} = E_y\,\vec{e}_y$$




$$\vec{E} = E_y\vec{e}_y$$

- Thickness variation $\Delta z$ on 8 mm: 0, 25µm, 50µm





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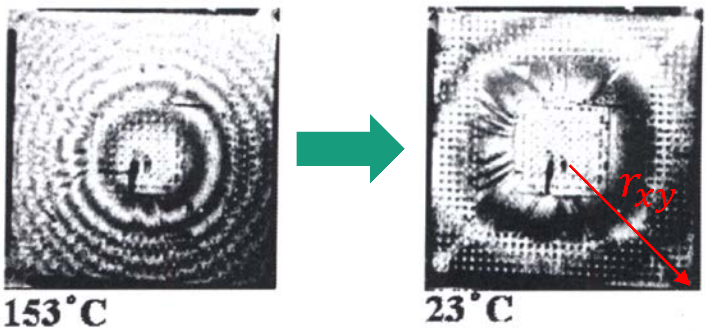
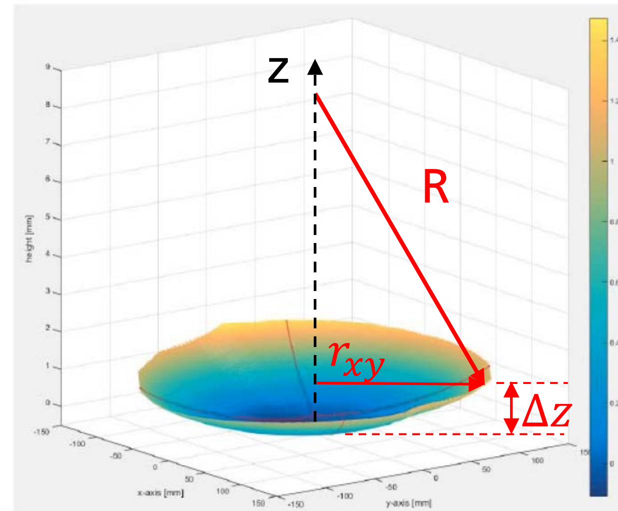
# Modeling Substrate Deformation
# Warpage of substrate materials




[2] – Mold on organic substrate (upper figure)

[3] – Mold on Silicon (right figure)

→ High similarity to sphere cut

Modeling Warpage by the sphere equation: $R^2 = x^2 + y^2 + (z - z_M)^2$

→ $\text{Warpage ratio} = \frac{\Delta z}{r_{xy}} \cdot 100\%$

| Ref. | Block Size mm | Warpage $\Delta z/\mu m$ | Warpage Ratio / % |
|---|---|---|---|
| [1] | 12 | 84 | 0.99 |
| **[2]** | **40** | **60** | **0.11** |
| **[3]** | **300** | **200** | **0.13** |
| [4] | 6 | 50 | 0.59 |

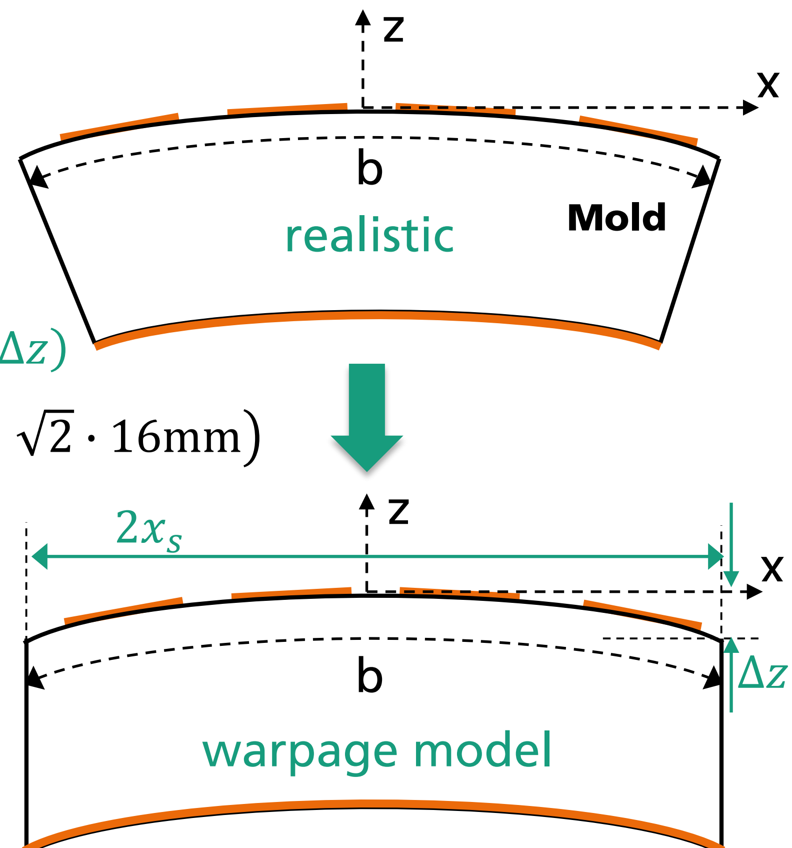
[2] "Characterization of Residual Strains of the EMC in PBGA during Manufacturing and IR Solder Reflow Process", M. Y. Tsai et al.
[3] "Low Warpage Wafer Level Transfer Molding post 3D die to wafer assembly", Francisco Cadacio Jr. et al.

# Modeling Substrate Deformation
# Warpage of substrate materials

## Specification of the warpage model

- Higher Cu density on bottom side
  → convex deformation
- Defining the origin of the coordinate system according to the figure
  → $R^2 = x^2 + y^2 + (z + R)^2$ with $\mathrm{R} = f(b, \Delta z)$
- Arc length b is equal to edge length $\left(b = \sqrt{2} \cdot 16\mathrm{mm}\right)$

| Warpage Ratio / % | $\Delta z$ / mm | R / mm |
|---|---|---|
| 1 | 0.11 | 565.7 |
| 2 | 0.23 | 283.0 |
| 4 | 0.45 | 141.6 |





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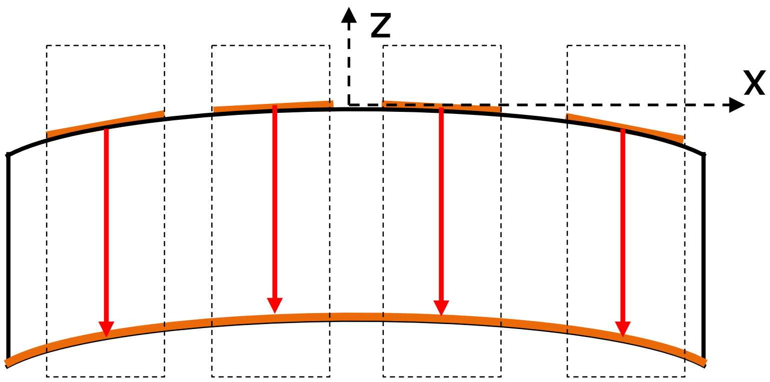
# Modeling Substrate Deformation
# Warpage of substrate materials

### Modeling Progress

Simplified modeling by applying analytical faces

- Substrate, Cu plane on top/bottom side
  - Analytical Face by $R^2 = x^2 + y^2 + (z + R)^2$
  - Copy Face, Pick Inside Faces
  - Loft Function
- Antenna Array
  - Bricks at the antenna positions
  - Boolean Operation → Intersection
- Discrete Edge Port





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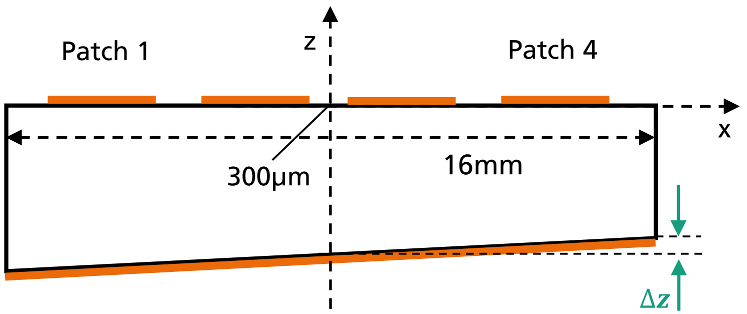
# Simulation Results

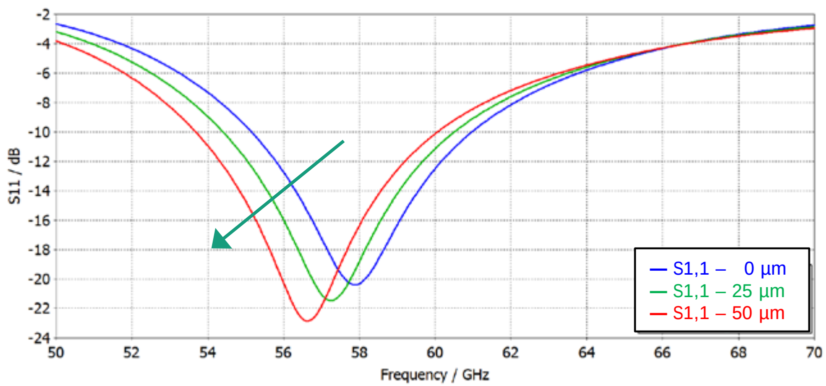
# Inhomogeneous Substrate Thickness

## Simplification to linear antenna array

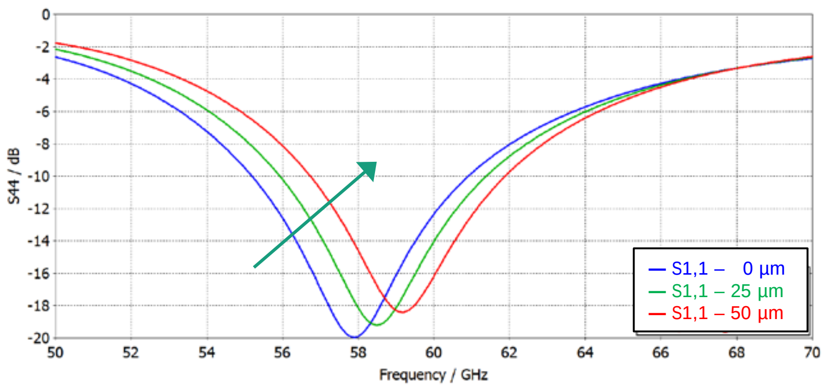
- Thickness variation $\Delta z$:  0, 25µm, 50µm
- Reflection Loss with lowest and highest substrate thickness




Patch 1 (Highest Thickness)




Patch 4 (Lowest Thickness)





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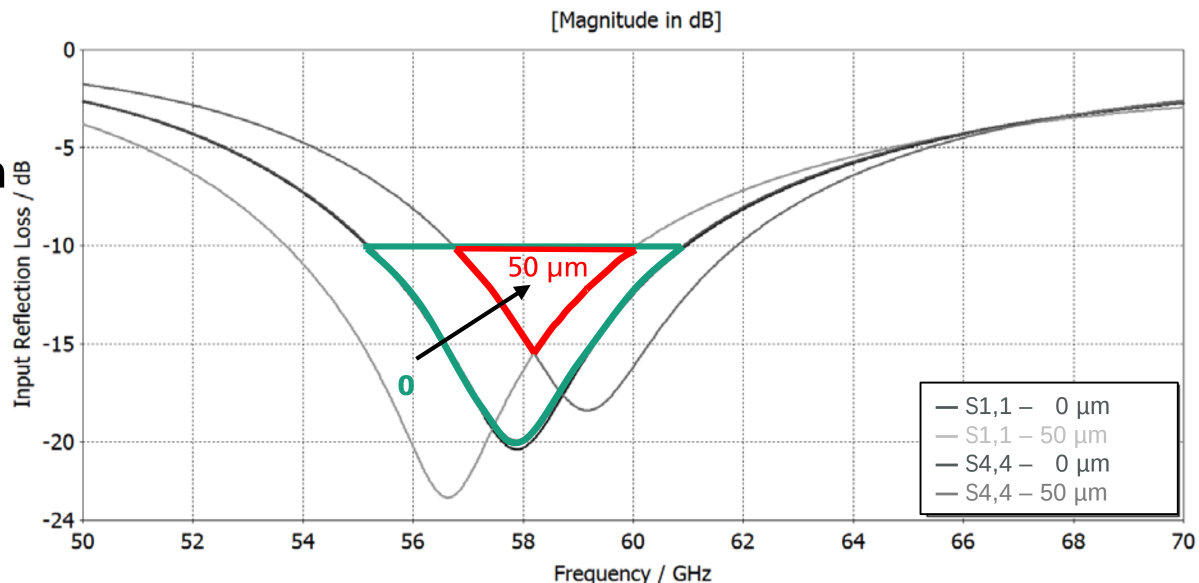
# Inhomogeneous Substrate Thickness

## Combination of S1,1 of Patch 1 and Patch 4

- Strong Reference: -10dB Level
- Common bandwidth of Patch 1 and Patch 4




- Operational Frequency: $\Delta f$ = 1.2 GHz
- Bandwidth variation: $\Delta B$ = 0.58 GHz

→ Decrease in operational bandwidth of 33 %

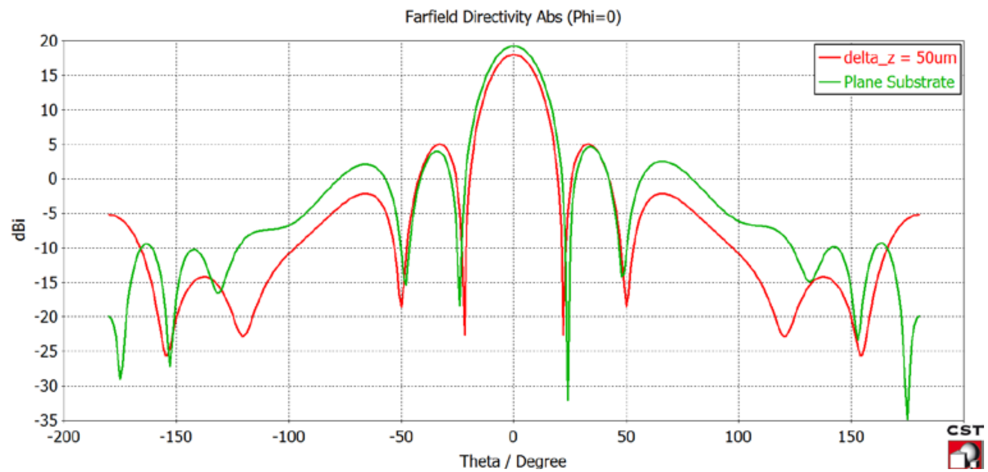
# Simulation Results – Substrate Thickness
# Farfield Plot

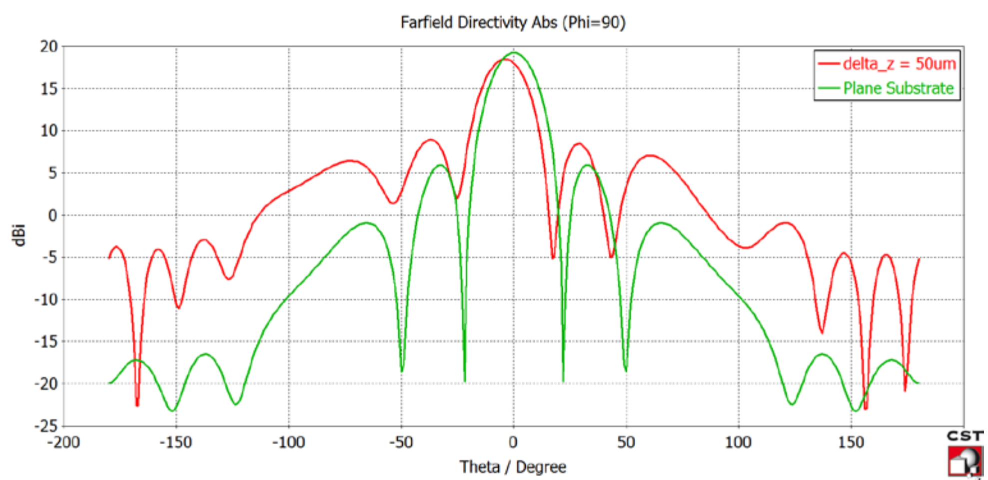
**Thickness** $t_{sub} = f(y)$

- E-field Vector $\vec{E} = E_y$

At 60 GHz:

| **Directivity** | **Plane substrate** | **50µm Variation** |
|---|---|---|
| Main Lobe Gain | 19.3 dBi | 18.5 dBi |
| Main Lobe Direction | 0° | -4° |
| Min. Side Lobe Level | -13.3 dB | -9.5 dB |
| Angular Width (3dB) | 19.2° | 19.3° |





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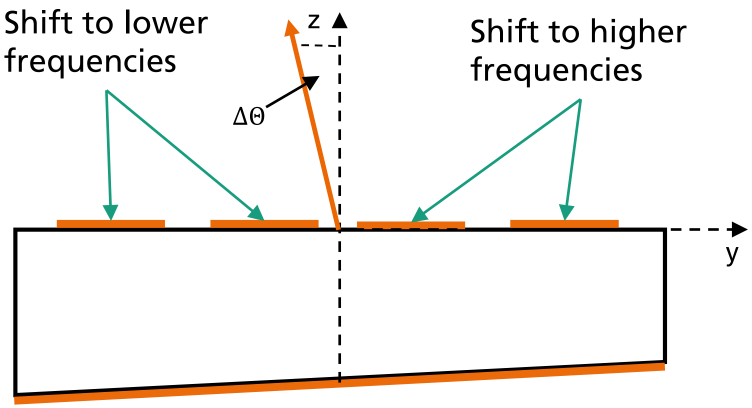
# Summary – Substrate Thickness

## Inhomogeneous substrate thickness

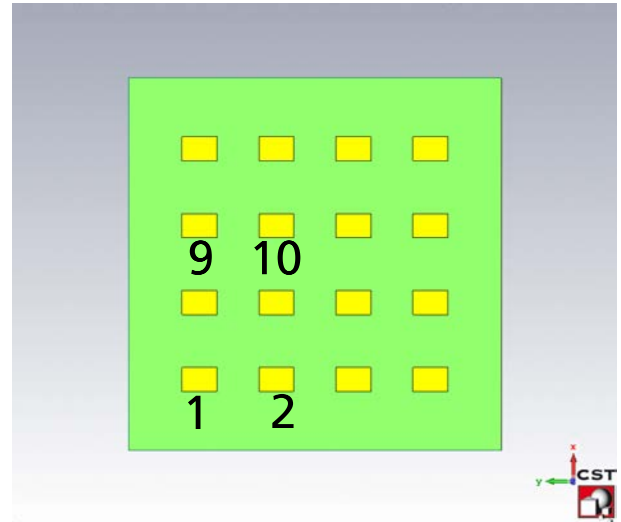
- Shift of self-resonating frequency of each patch → decrease of operational bandwidth
- Variation of Main Lobe direction
- No increase in antenna crosstalk

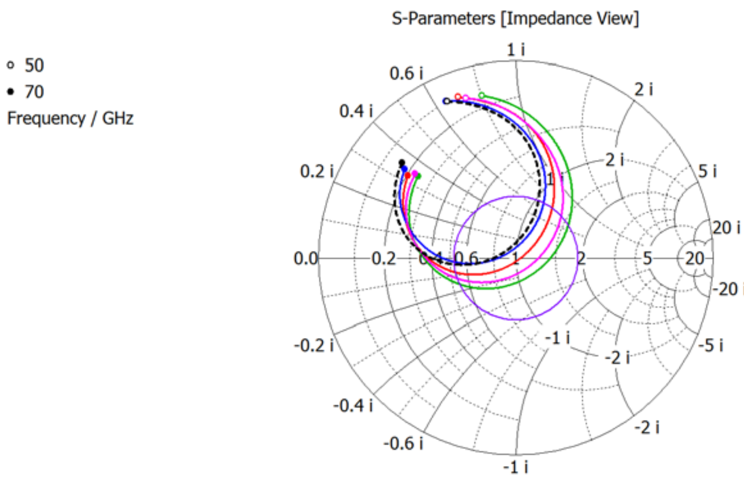


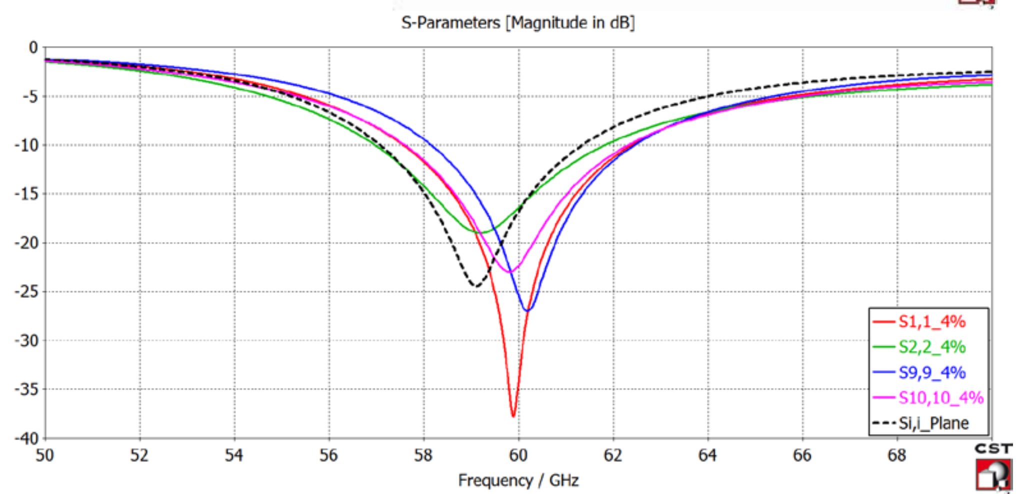
# Simulation Results - Warpage
# Input Reflection Loss

## Reflection Loss

- Operational Frequency to higher frequencies: $\Delta f$ = 1.1 GHz
- Very small bandwidth variation





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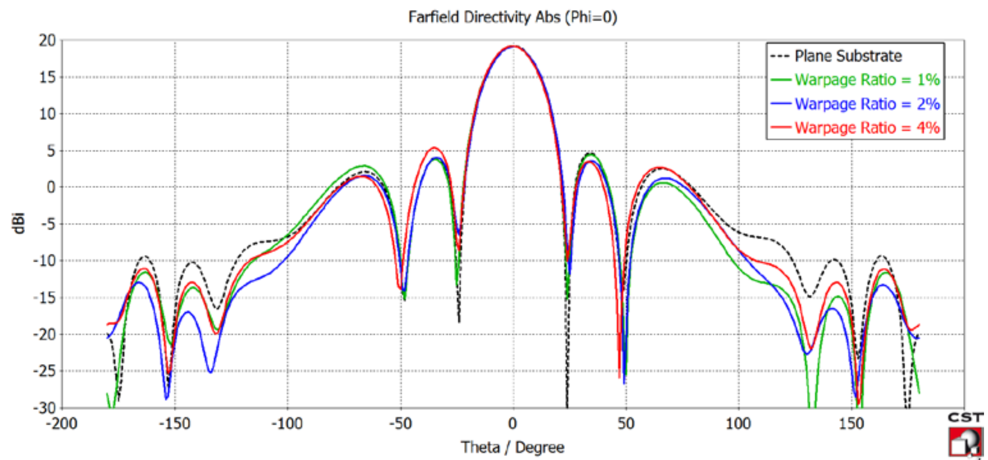
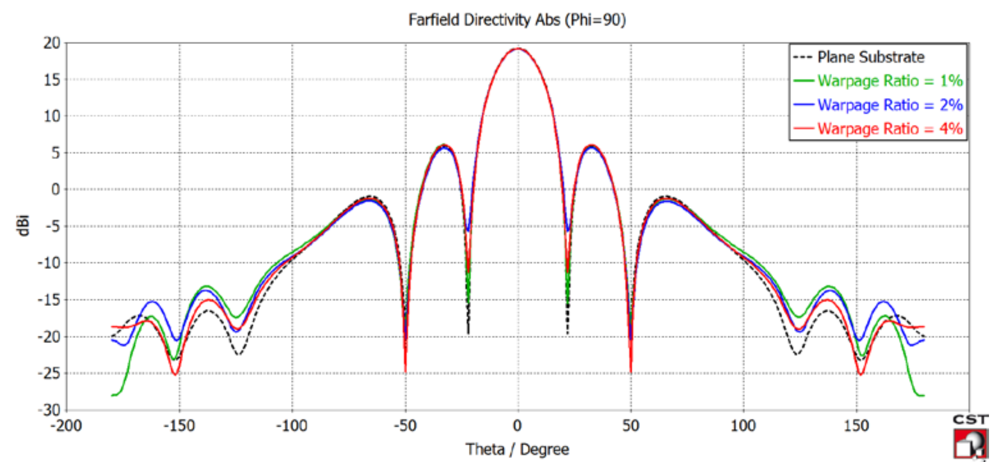
# Simulation Results - Warpage
# Farfield Plot

E-field Vector $\vec{E} = E_x$

At 60 GHz:

| Directivity | Plane substrate | Warpage ratio 4% |
|---|---|---|
| Main Lobe Gain | 19.3 dBi | 19.2 dBi |
| Main Lobe Direction | 0° | 0° |
| Min. Side Lobe Level | -13.3 dB | -13.1 dB |
| Angular Width | 19.2° | 19.1° |





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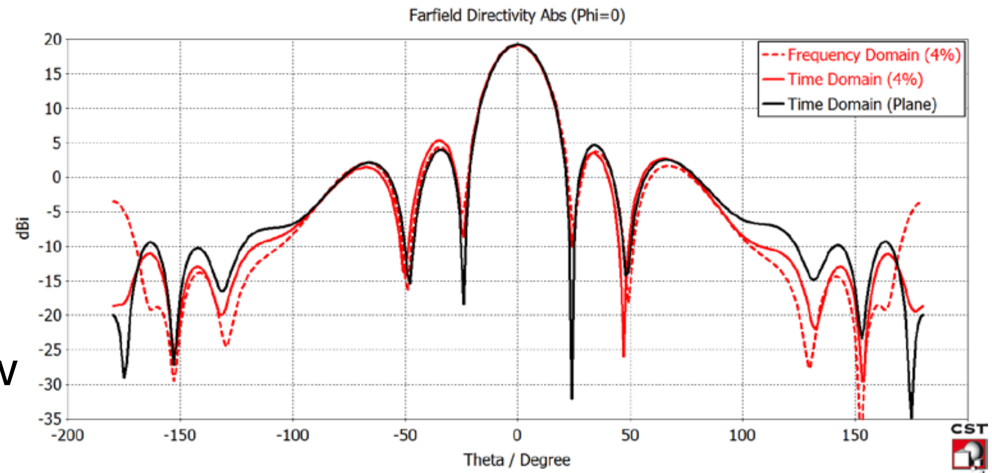
# Simulation Results - Warpage
# Farfield Plot

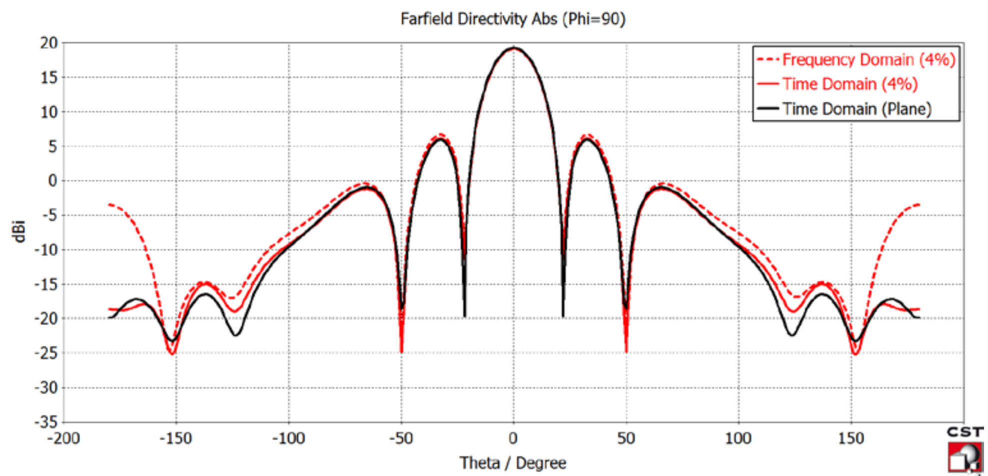
Frequency Domain vs.
Time Domain Simulation

- E-field Vector $\vec{E} = E_x$

- Both simulation do not show
  - Main lobe broadening
  - Side lobe level reduction

- Difference is the FTBR
  - -4dB (Freq Domain)
  - -18dB (Time Domain)





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# Summary

| Properties | Warpage | Substrate Thickness Variation |
|---|---|---|
| Antenna Impedance / Bandwidth | Highest impact<br>→ bandwidth shift of up to +1.1 GHz | High impact<br>→ bandwidth shift of up to ± 1.2 GHz<br>→ Degradation of Total Radiation Efficiency (incl. Reflection Loss) |
| Farfield Properties | Low impact<br>→ Almost unchanged properties | Moderate impact<br>→ Main Lobe Direction (max. 4%, 50µm)<br>→ Decrease in Side Lobe Level (max 4dB, 50µm) |

# Outlook

- Replacement of high accurate substrate models
- Conclusions from small antenna arrays to large arrays

# THANK YOU FOR YOUR ATTENTION

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# BACK-UP SLIDES





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# Time Domain vs. Frequency Domain Simulation
# Warpage Ratio = 4%

| | Time Domain | Frequency Domain |
|---|---|---|
| Peak Memory | 19.42 GB | 58.57 GB |
| Total Solver Time | 46 h, 58 m, 6 s | 34 h, 58 m, 56 s |
| Meshcells | 33,423,096 | 2,574,516 |

- Frequency Domain and Time Domain Solver with Adaptive Mesh Refinement (Maximum delta = 0.02)
- System:
  - Processor: Intel(R) Xeon® CPU E5-1620 v3 @ 3.5GHz (4 Cores)
  - RAM: 128 GB





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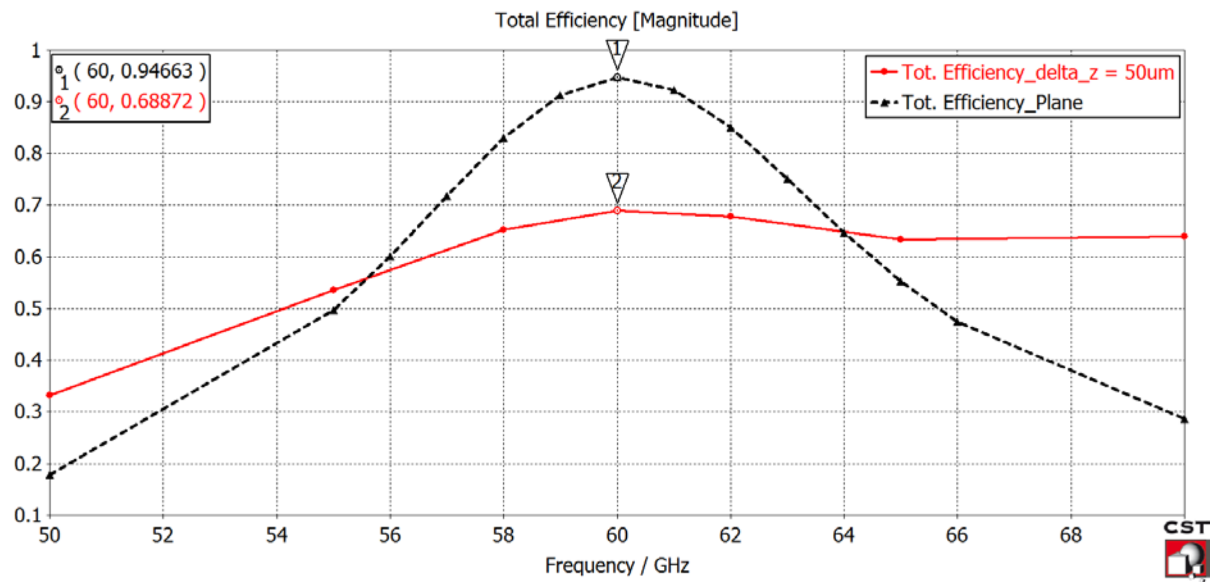
# Substrate Thickness Variation

Total Efficiency including Input Reflection Loss and Material Losses

- Strong degradation of the total radiation efficiency (up to 26%)





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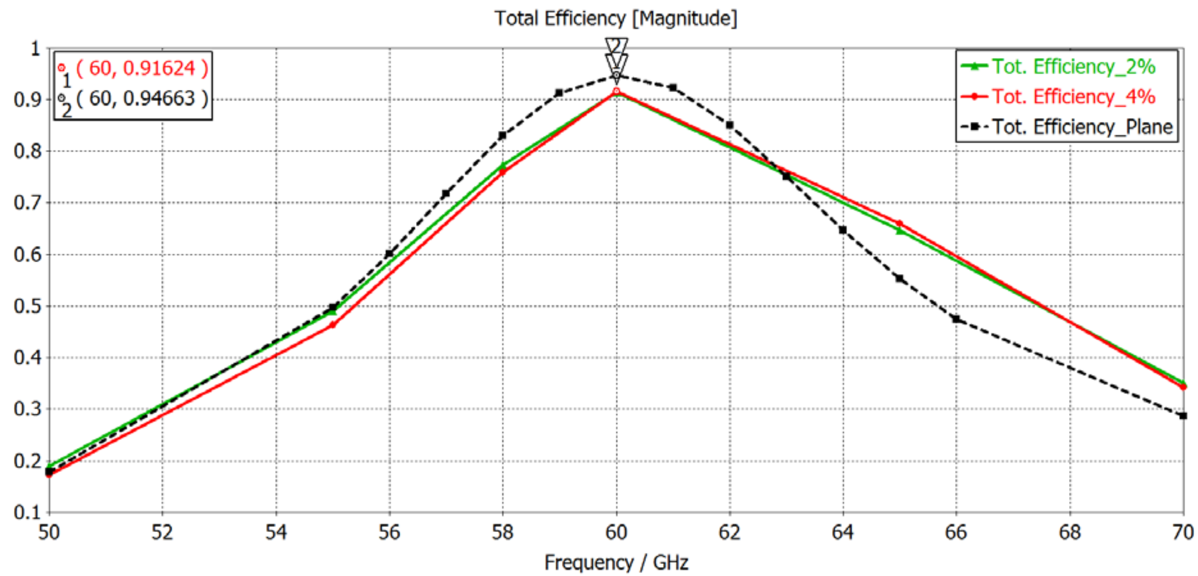
# Warpage

Total Efficiency including Input Reflection Loss and Material Losses

- Possible shift of the Efficiency Maximum to higher frequencies
- Worst case: Reduction of up to 3%





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# Literature


[1] "Mold Compound Properties for Low Warpage Array Packages",
Tanweer Ahsan, Hao Tang, *Electronics Packaging Technology Conference*, 2008 (EPTC 2008)

[2] "Characterization of Residual Strains of the EMC in PBGA during Manufacturing and IR Solder Reflow Process", M. Y. Tsai

[3] "Low Warpage Wafer Level Transfer Molding post 3D die to wafer assembly", Francisco Cadacio Jr. et al., 66th Electronic Components and Technology Conference, 2016

[4] "The Warpage Control Method in Epoxy Molding Compound", Wei Tan et al., *International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP)*, 2009






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