Highly integrated KA-Band Tx frontend module including 8x8 antenna array

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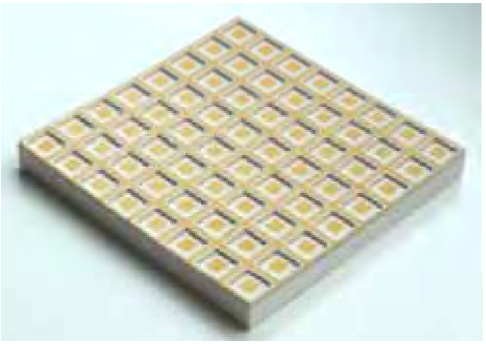
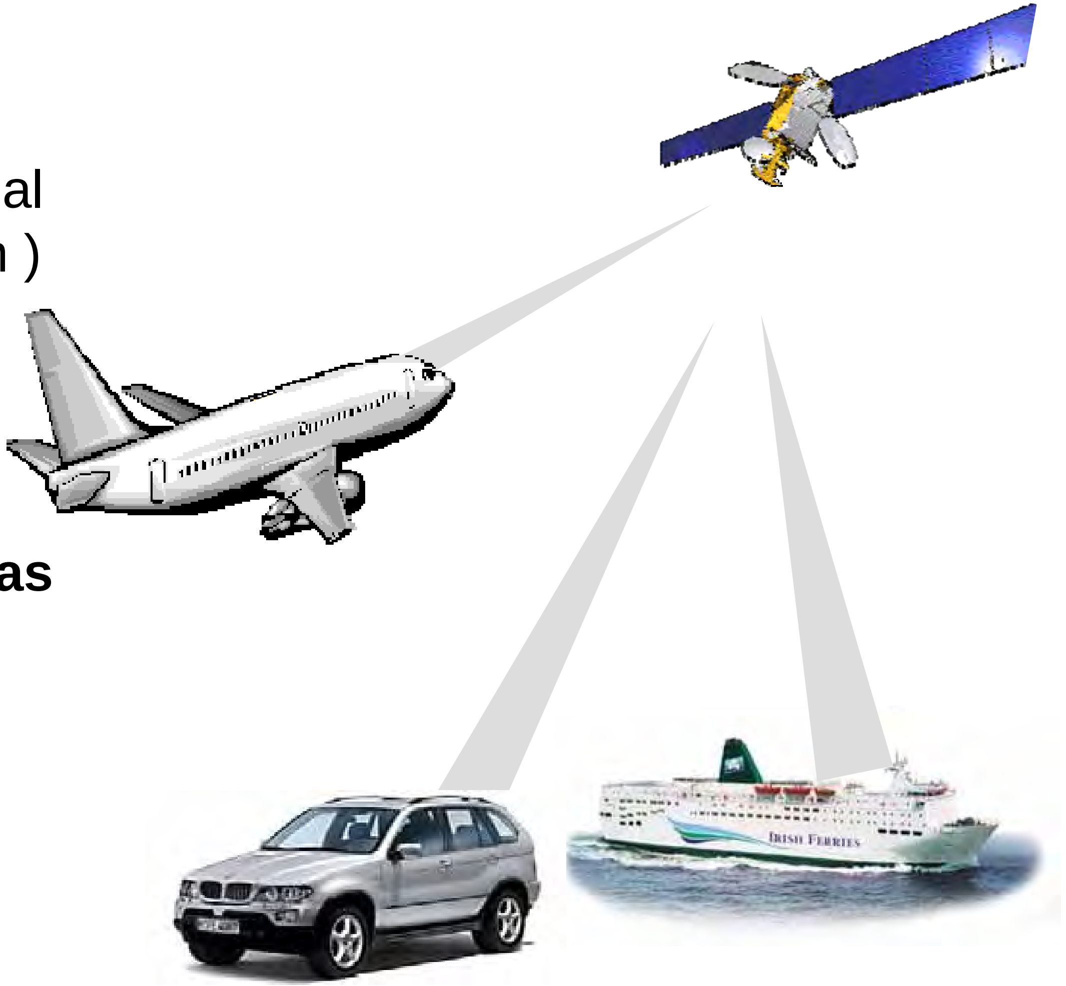
Outline

- Introduction
- EM analysis
- TX module overview
- Integrated array antenna
- RF circuits
- Simulation
- LTCC Technique
- LTCC module manufacturing
- Measurements
- Conclusion



Introduction: Background

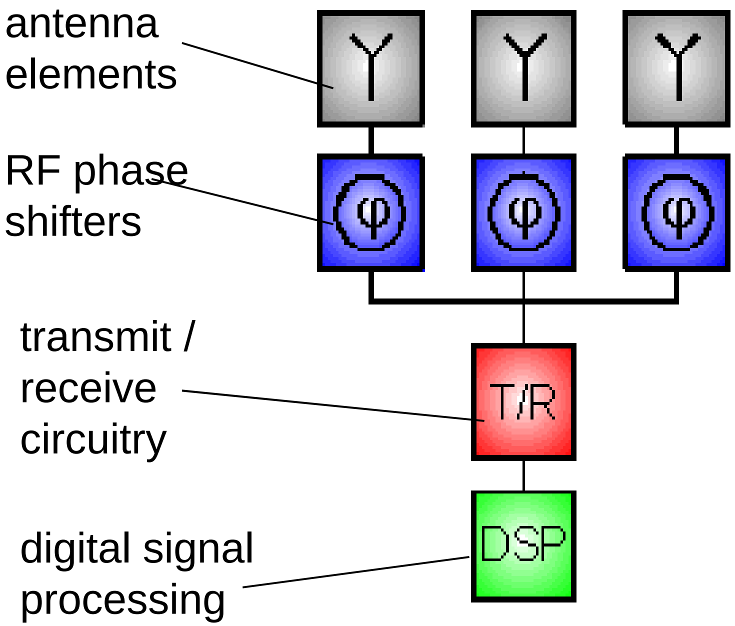
Large and growing request for steerable antennas for commercial applications (e.g. mobile SatCom)



Electronically Steerable Antennas

+ No mechanically moving parts
+ Low abrasion, long lifetime
+ Robust design possible
+ Reduced size height
+ Integration into surfaces
- High complexity, high development effort

Introduction: Electronical Beam Steering



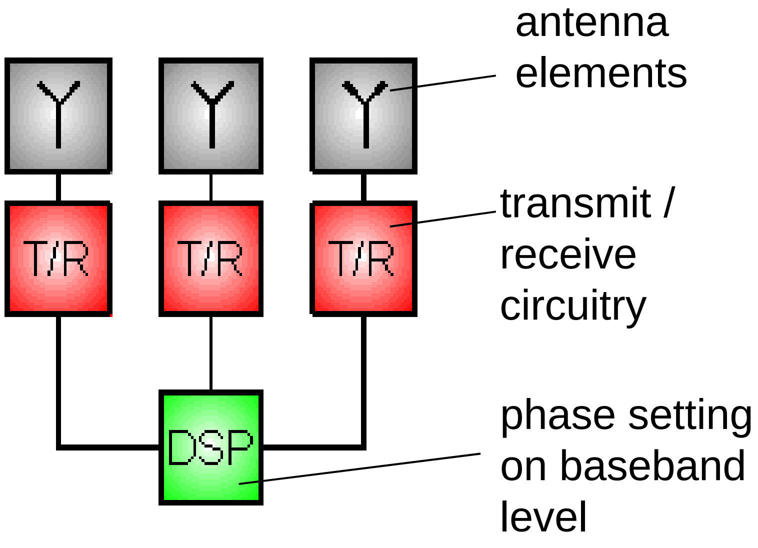
antenna elements

RF phase shifters

transmit / receive circuitry

digital signal processing

classical phased array



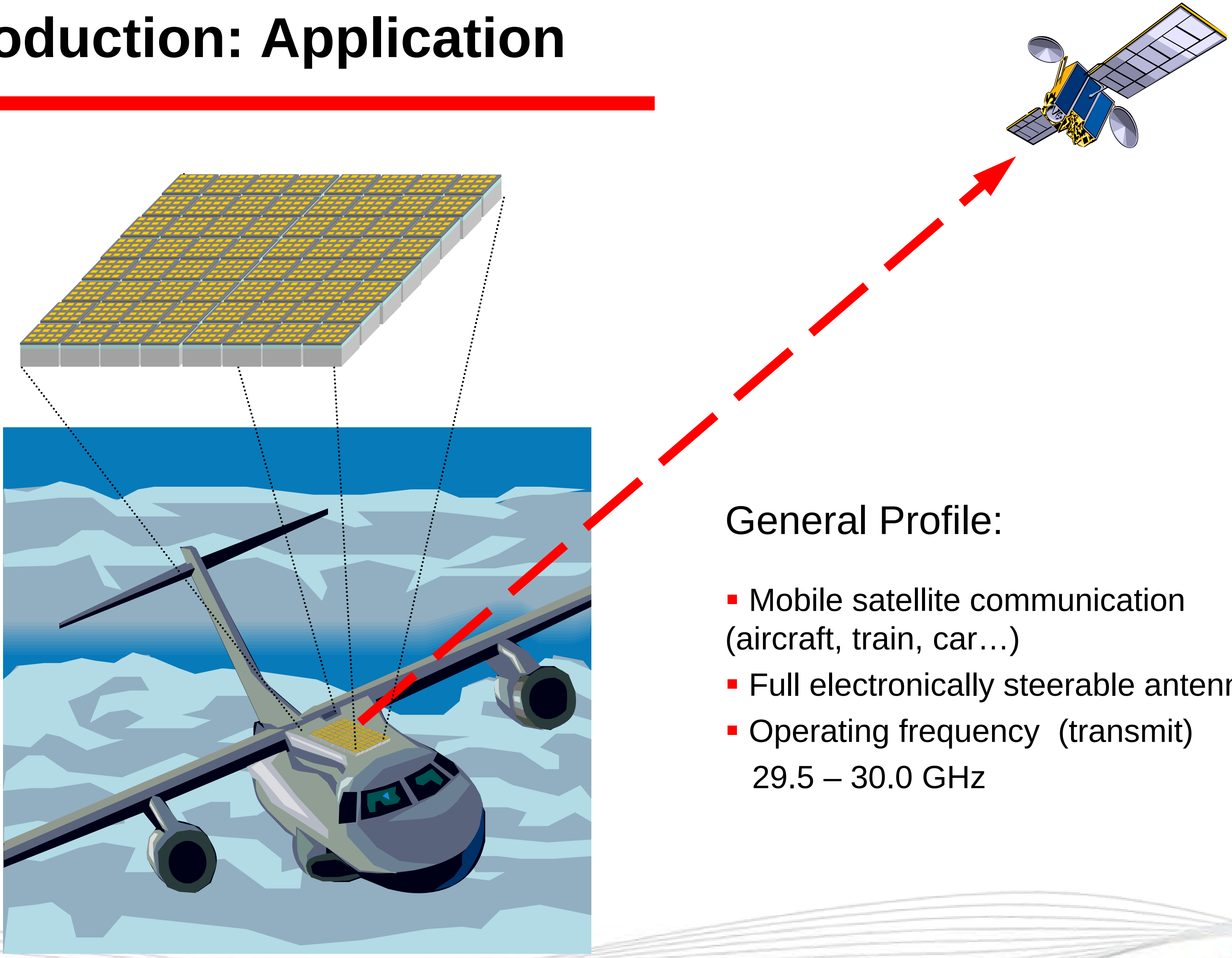
antenna elements

transmit / receive circuitry

phase setting on baseband level

Digital BeamForming (DBF)

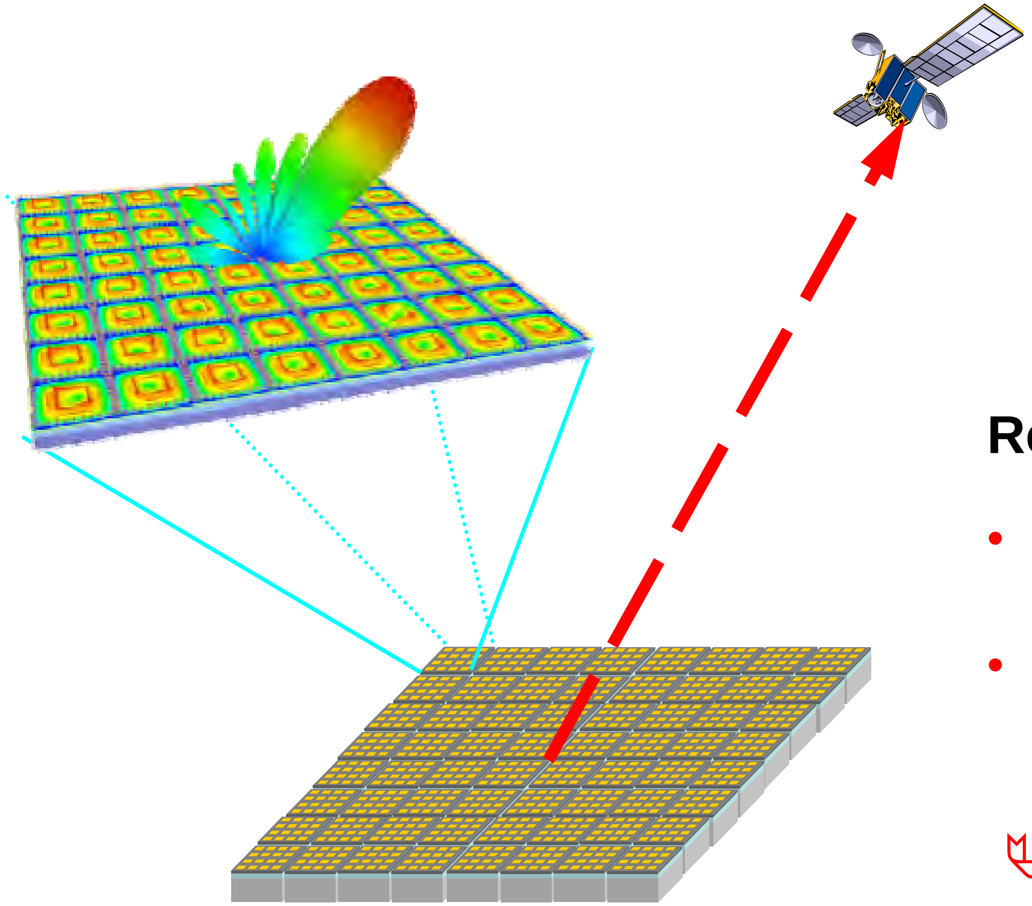
Introduction: Application



General Profile:

- Mobile satellite communication (aircraft, train, car…)
- Full electronically steerable antenna
- Operating frequency (transmit)
  29.5 – 30.0 GHz

Introduction: Modular Design



Flexibility in building up arrays of different sizes

General Profile:

- 8x8 antenna array
- Building block for large arrays
- Mobile satellite communication to GEOs
- Digital beam forming (DBF, high flexibility in steering)

Realization:

- antenna spacing of 0.5 λ forces high integration density
- different RF circuits must be integrated in a multilayer design to stay within size limits

➪ Use of LTCC technology

Advanced Numerical Modelling

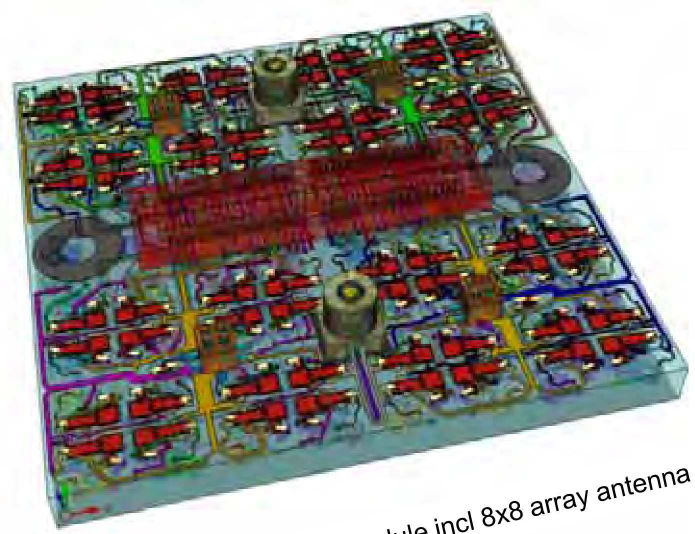
Design Challenges:

- Design Complexity
- Effects of advanced packages
- Varying dimensions / aspect ratios
- Tight Coupling between electronics

⬇

- Accurate and powerful tools for numerical modeling needed

- Which is the best modeling method ?



30 GHz LTCC font end module incl 8x8 array antenna

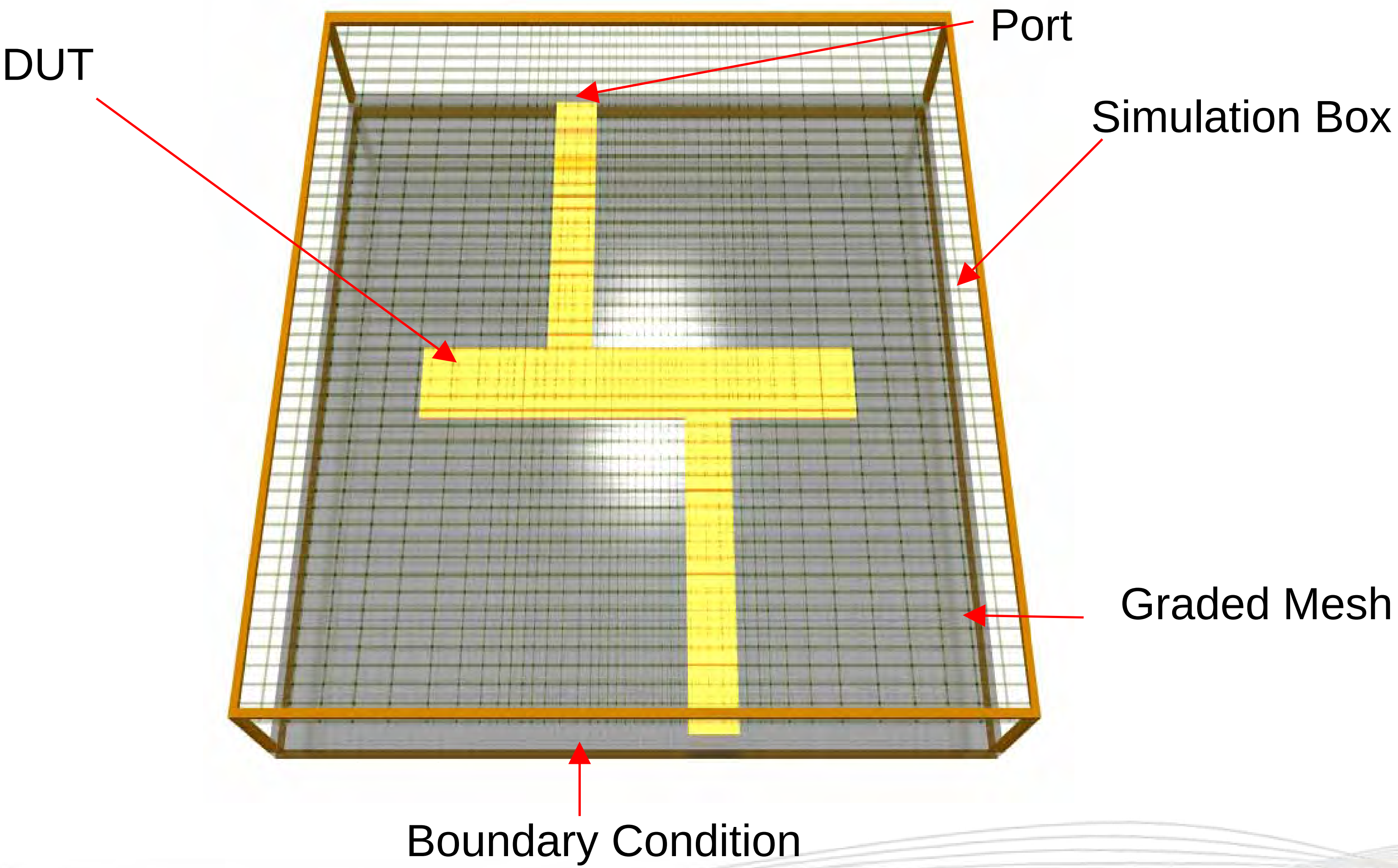
Comparison of the Methods

	MoM	FEM	FDTD
Diskretization Method	Wires, Surfaces	Polyeder (Tetraeder)	Voxel (Cubes)
Discretization Effort	Only Objects	Entire computational domain	Entire computational domain
Boundary Conditions	„built-in“	ABC	ABC
Method	Frequency Domain Linear Equations (Full Matrix)	Frequency Domain Linear Equations (Band Structure)	Time Domain Iterative Calculation in Space and Time
Numerical Effort	$\sim n^3$	$\sim n^2$	$\sim n$

Comparison of the Methods

	MoM	FEM	FDTD
Well suited for:	Wires, Metal Surfaces, Coupling between spaced antennas, Arbitrary shapes, Single or few frequencies	Arbitrary shapes, Arbitrary Materials, Single or few frequencies High Q structures	Shape preferable orthogonal, Arbitrary material distributions, Broadband investigations, Complex Structures
Less suited for:	Dielectric Materials (possible with advanced MoM), Inhomogeneous material distributions, Broadband investigations,	Coupling between spaced antennas, Broadband investigations, Complex Structures (Matrix-Size)	Coupling between spaced antennas, Non orthogonal shaped objects will be approximated by staircased representation, High-Q structures (possible with prediction extension),

Spatial FDTD Principle



FDTD Basics:Spatial Discretisation

Maxwell´s Equations

$$\mu \frac{\partial}{\partial t}\vec{H} = -\nabla \times \vec{E}$$

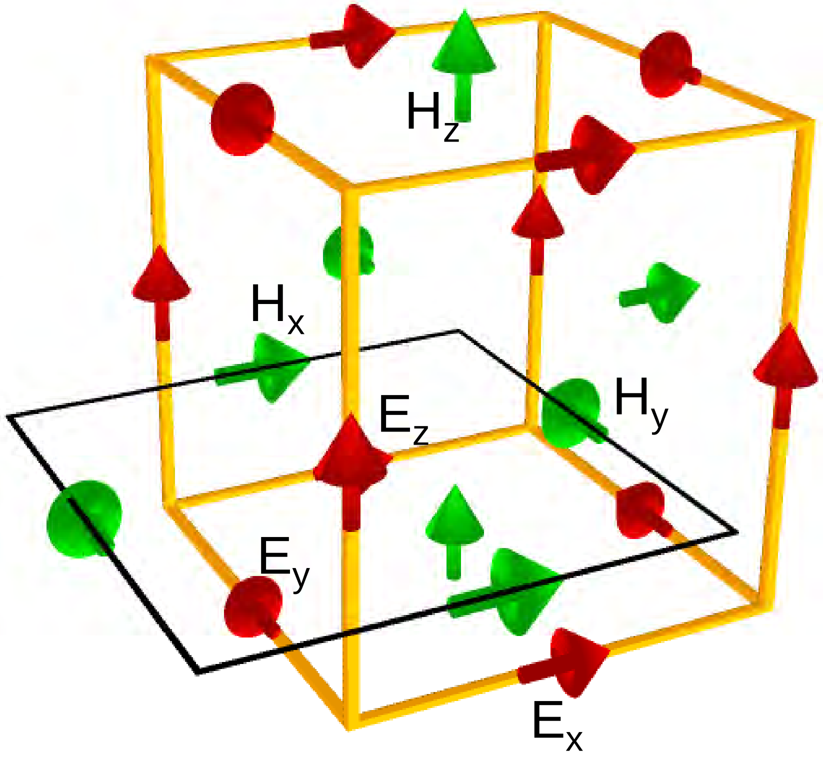
$$\varepsilon \frac{\partial}{\partial t}\vec{E} = \nabla \times \vec{H} - \vec{J}$$

Spatial discretization

$$\mu \frac{\partial}{\partial t}\vec{H} = -\frac{1}{\Delta_x}\sum_{\circlearrowleft}\vec{E}$$

$$\varepsilon \frac{\partial}{\partial t}\vec{E} = \frac{1}{\Delta_x}\sum_{\circlearrowleft}\vec{H} - \vec{J}$$

Yee cell

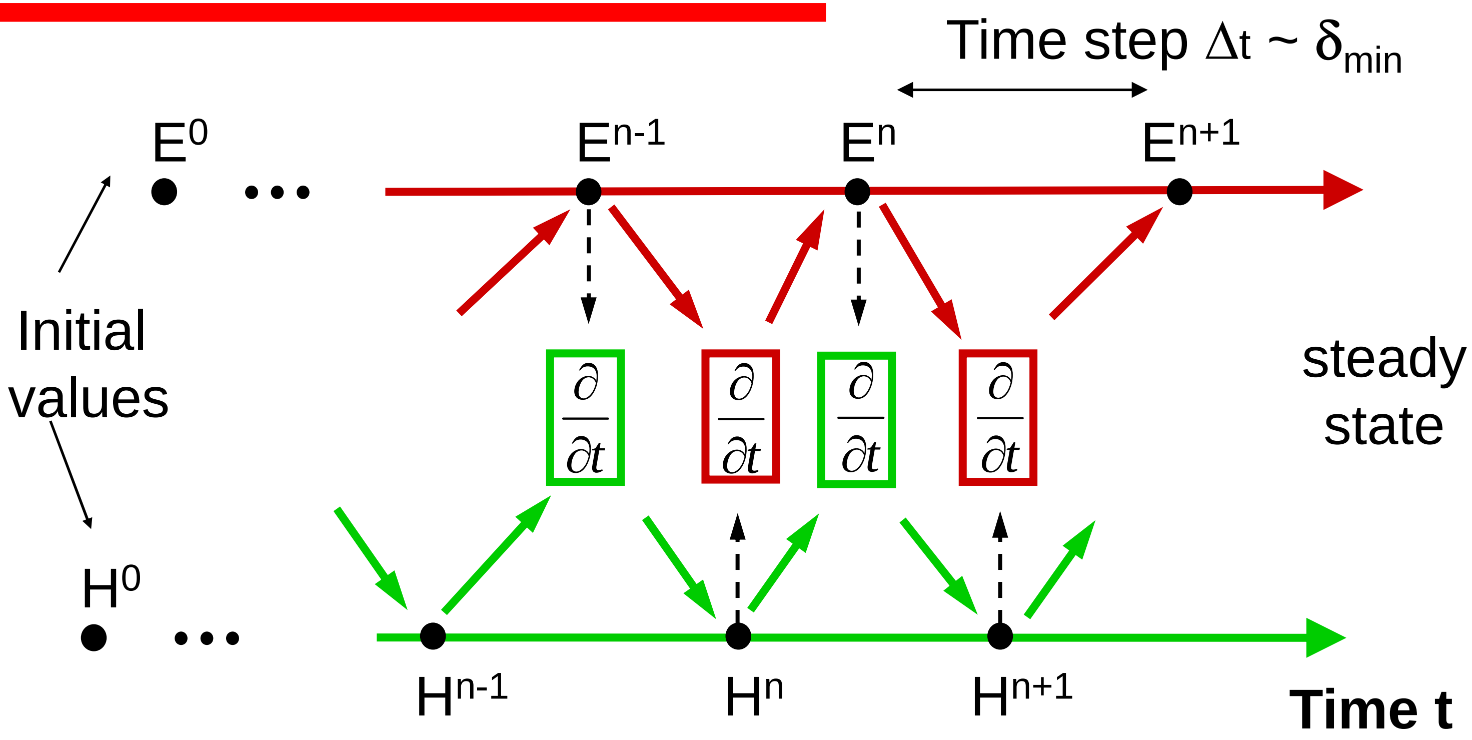


6 Field components per cell

Ex, Ey, Ez, Hx, Hy, Hz

➯ Mem = 24 Byte / cell

Time discretisation for FDTD

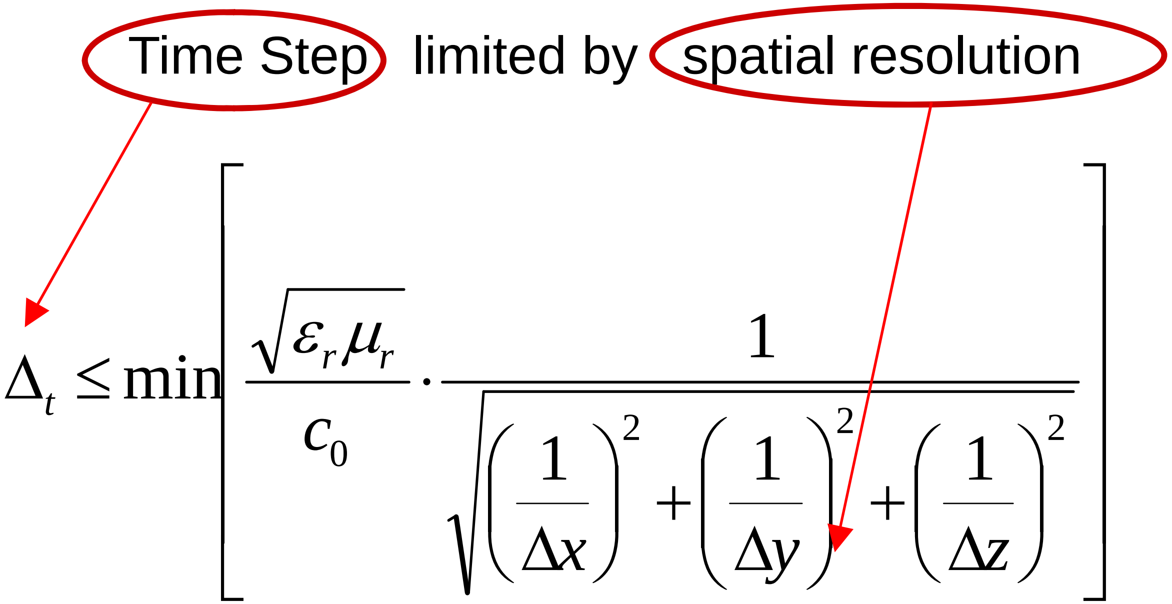


$$Ex'^{n}_{k} = Ex'^{n-1}_{k} + c_k d_k \left(\Delta Hz'^{n-\frac{1}{2}}_{k} + \Delta Hy'^{n-\frac{1}{2}}_{k} \right)$$

Update equation for Ex

- Old values are overwritten each time step
- only one E-field and one H-field array must be stored

FDTD Time step

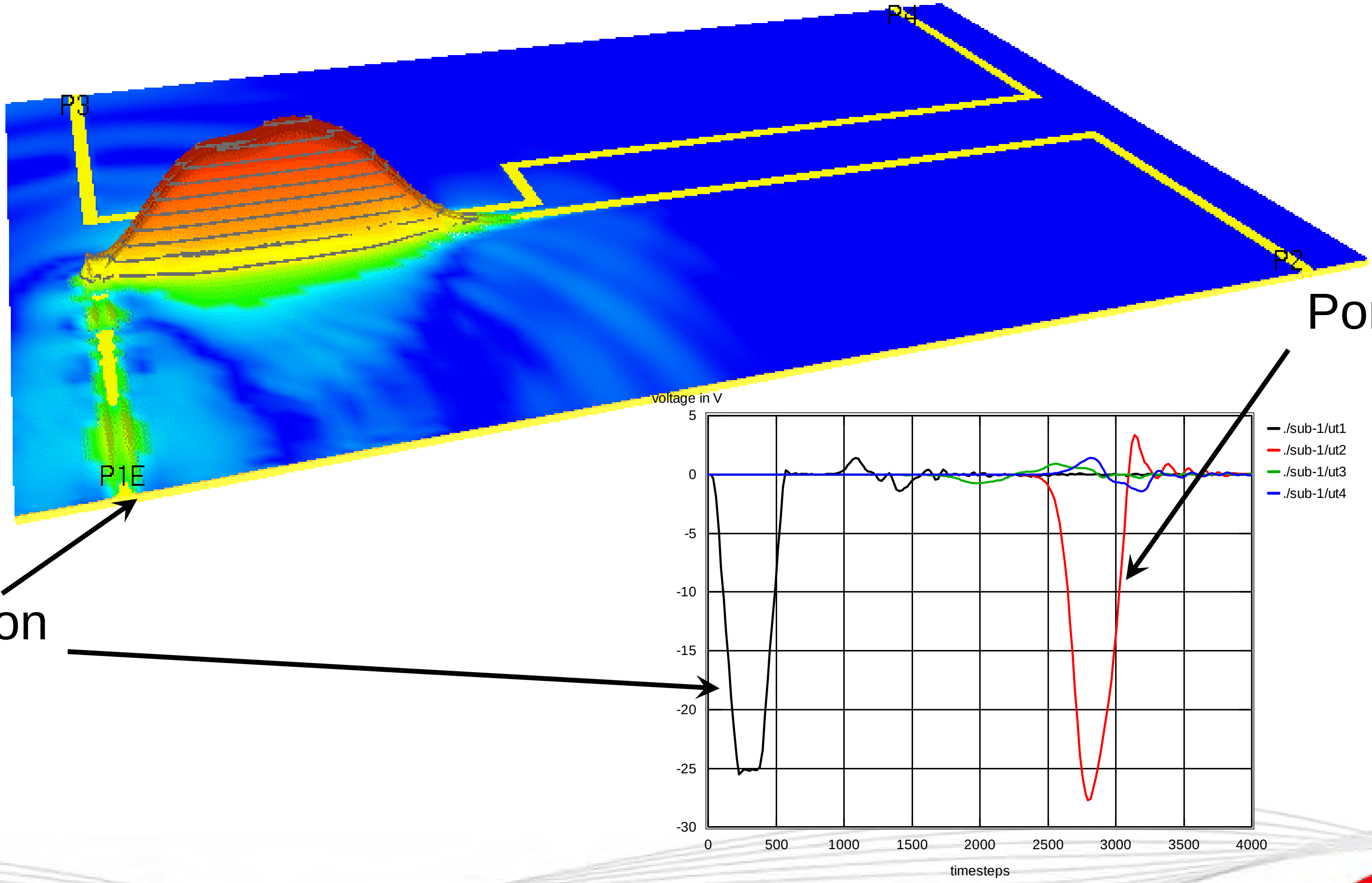


Time Step limited by spatial resolution

$$\Delta_t \le \min\left[\frac{\sqrt{\varepsilon_r \mu_r}}{c_0} \cdot \frac{1}{\sqrt{\left(\frac{1}{\Delta x}\right)^2 + \left(\frac{1}{\Delta y}\right)^2 + \left(\frac{1}{\Delta z}\right)^2}}\right]$$

- Mesh resolution $\Delta \le \lambda / 10$
- Classical FDTD stability criterion
- Small details: long simulation time

Time Domain Simulation: Digital Pulse



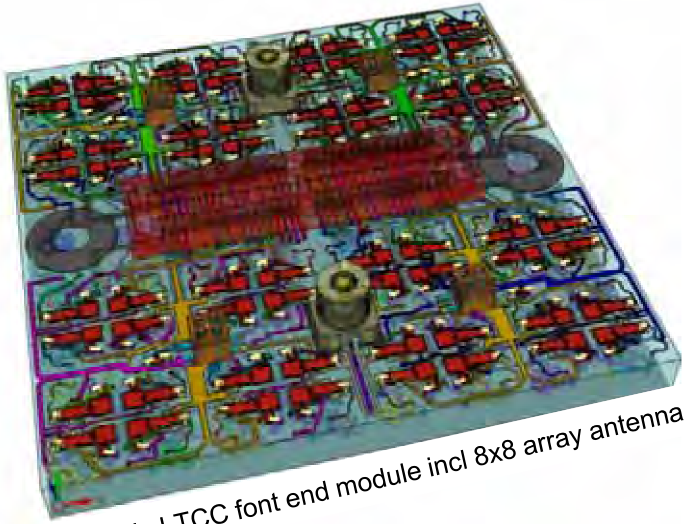
Port 2

Excitation
@Port1

Animation ⇒ http://www.empire.de/media/img/ganim/FDTD-pulse.gif

Advanced Numerical Modelling

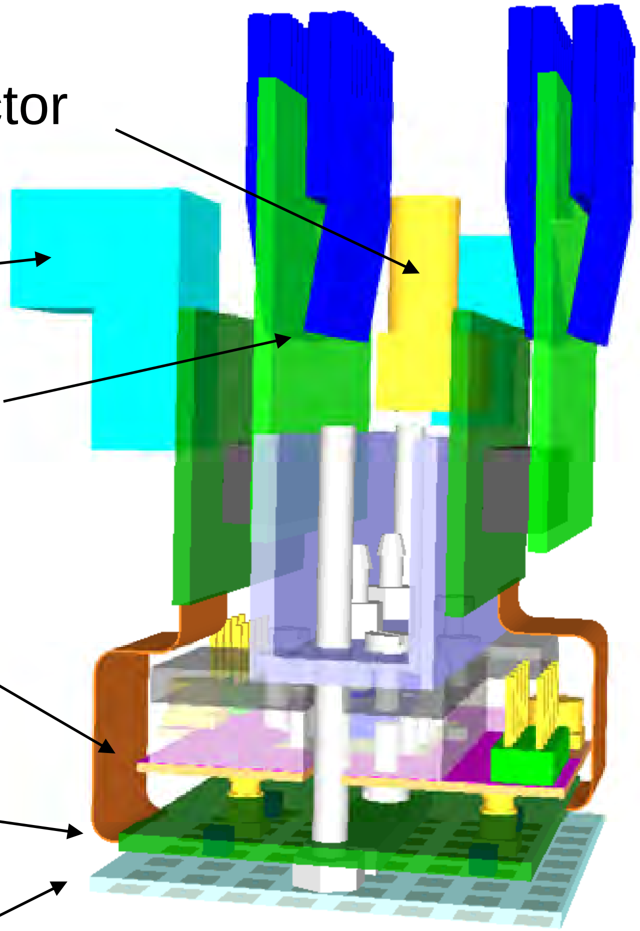
FDTD technique is best suited for modeling complex multilayer modules with thousands of objects



30 GHz LTCC font end module incl 8x8 array antenna

EMPIRE XCcel is based on FDTD method and has been chosen as simulation tool for this project. Due to EMPIRE XCcel's unique adaptive on-the-fly code generation it exhibits the fastest simulation engine known today. With this highly accelerated kernel complex full-wave EM-simulation problems can now be solved in minutes.
For more details visit www.empire.de

KA-Band TX frontend



IF-cable and connector calibration

DC-connector

IF-cabel und connector TX

RF-LO-Board
(incl. watercooling)

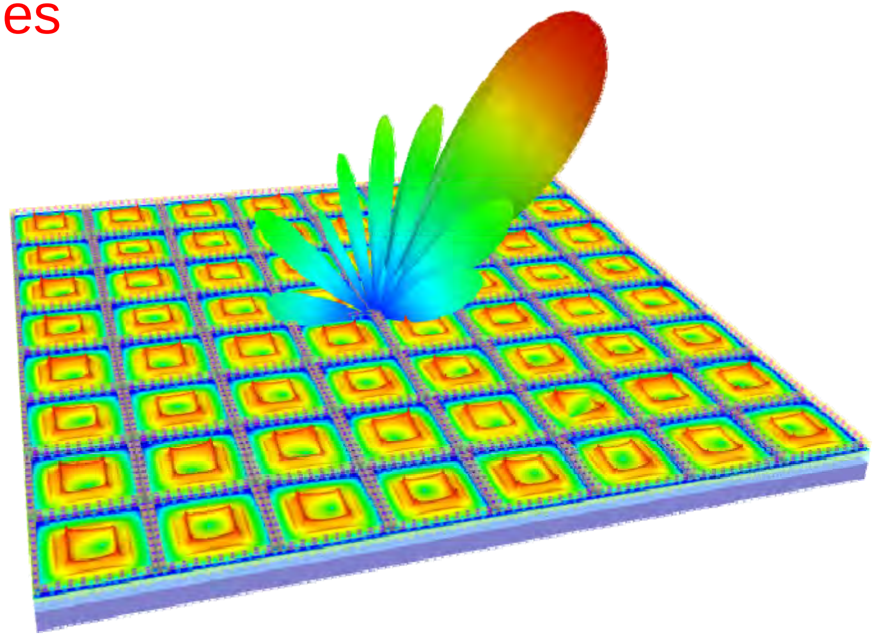
IF-distribution and LTCC power supply

LTCC
(incl. watercooling)

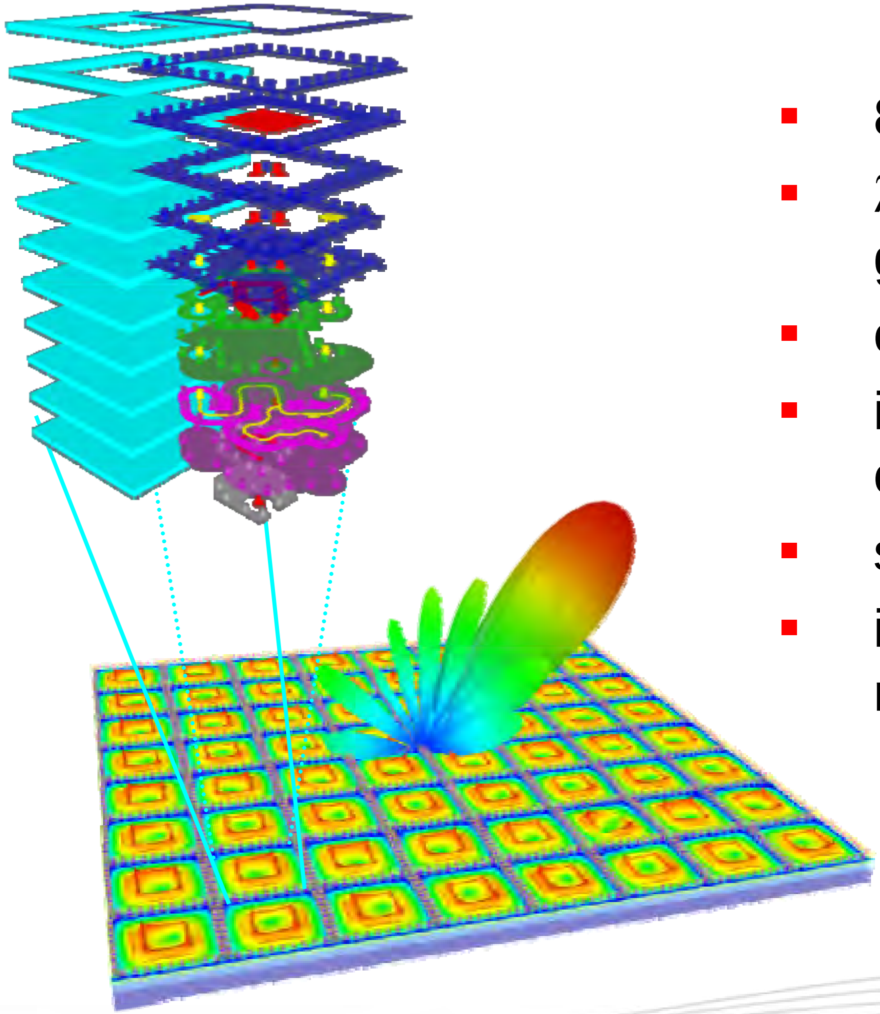
LTCC frontend: System functional elements

Antenna circuitries

- 8x8 antenna elements
- incl. hybrid ring feeds
- calibration network
- active RF circuitries
- LO distribution networks
- IF feeding network
- power and DC supply
- liquid cooling system



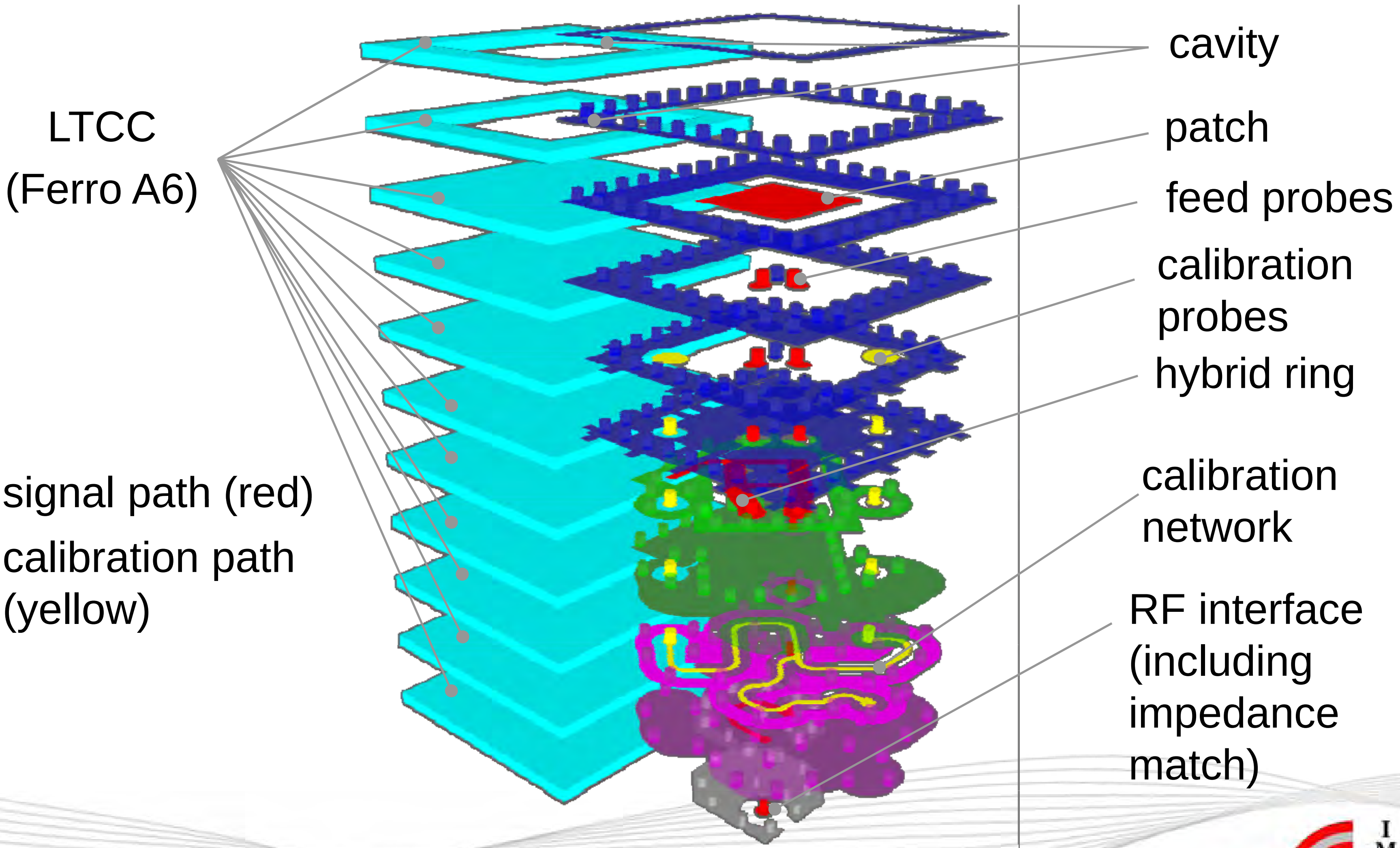
LTCC frontend: antenna circuitries



- 8x8 array
- λ/2 element spacing for good scanning behavior
- circular polarization
- integrated hybrid ring coupler
- sequential rotation
- integrated calibration network

LTCC frontend: antenna circuitry architecture

Exploded view from one antenna element

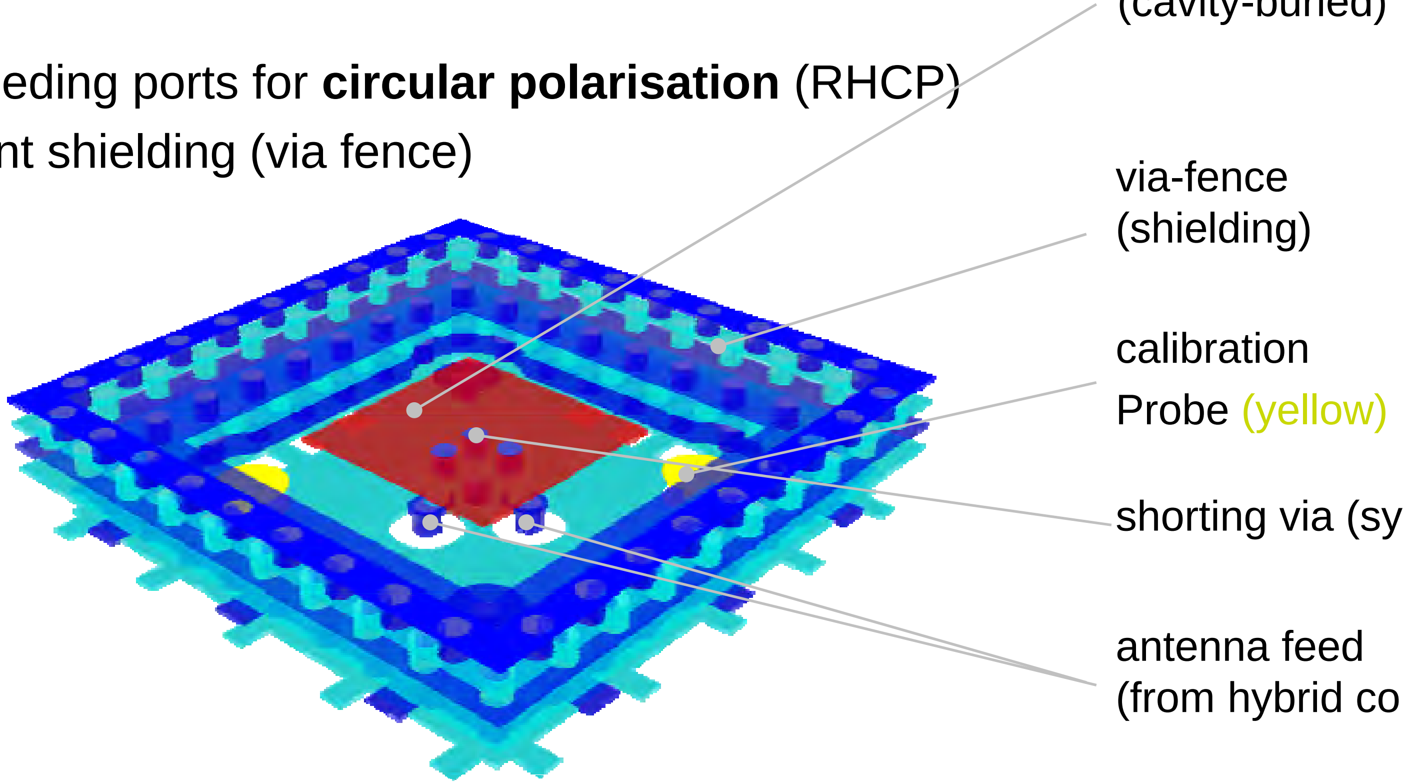


- signal path (red)
- calibration path (yellow)

LTCC frontend: patch element architecture

Antenna element

- Two feeding ports for **circular polarisation** (RHCP)
- Element shielding (via fence)



patch
(cavity-buried)

via-fence
(shielding)

calibration
Probe (yellow)

shorting via (symmetry)

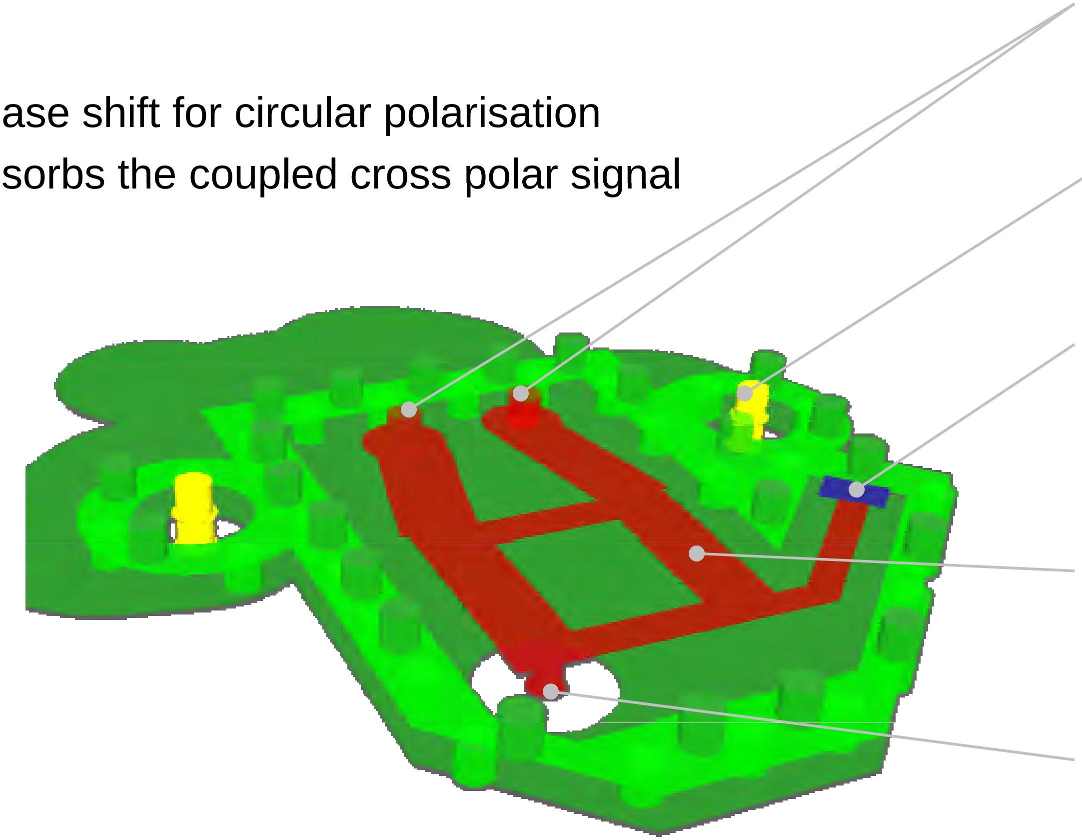
antenna feed
(from hybrid coupler)

- patch element placed in cavity to reduce coupling between elements

LTCC frontend: hybrid ring architecture

Hybrid ring coupler

- phase shift for circular polarisation
- absorbs the coupled cross polar signal



feeding lines
(to antenna)

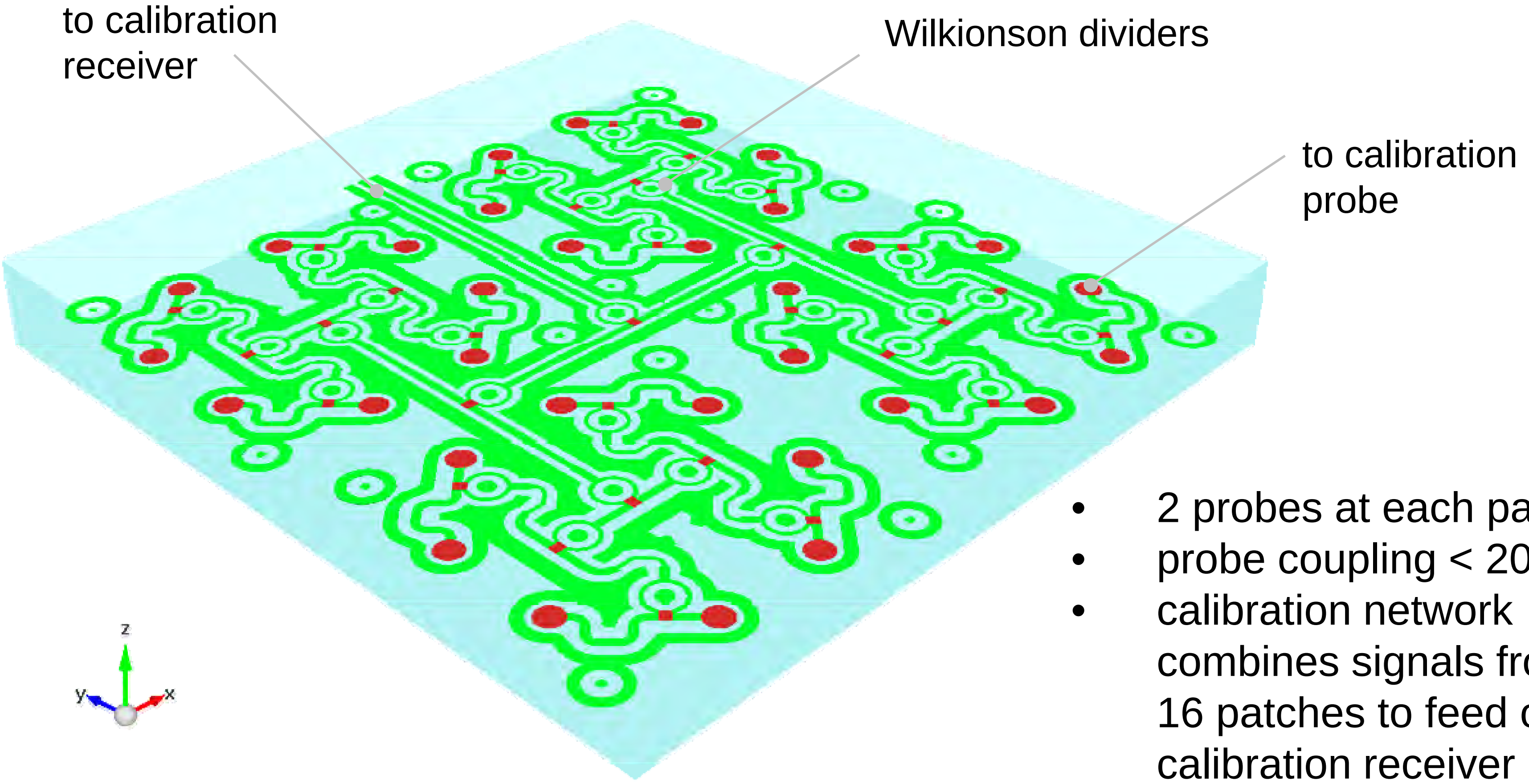
feed through
(calibration network)

load (matched port)

hybrid ring coupler

transmission line
(from RF Interface)

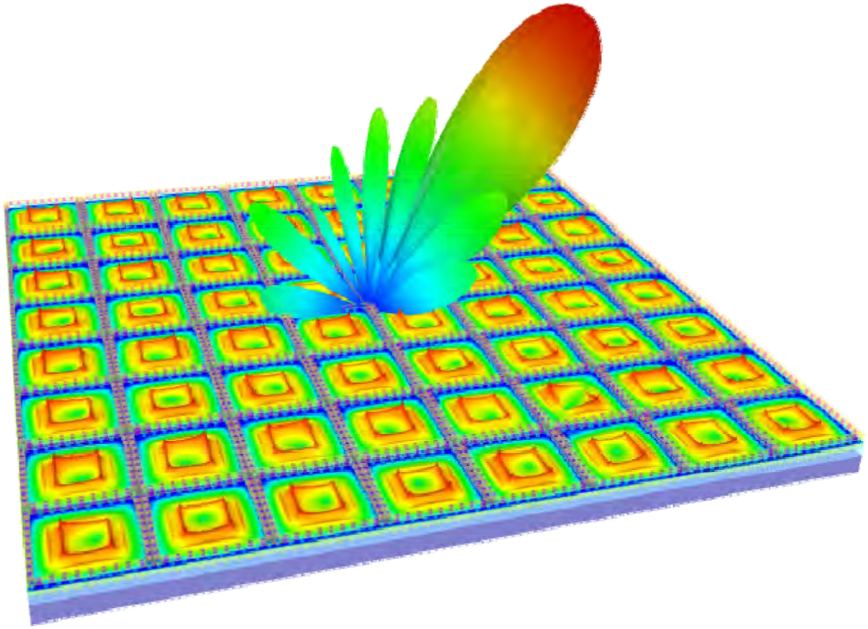
LTCC frontend: calibration network architecture



- 2 probes at each patch
- probe coupling < 20db
- calibration network combines signals from 16 patches to feed one calibration receiver

LTCC frontend: System functional elements

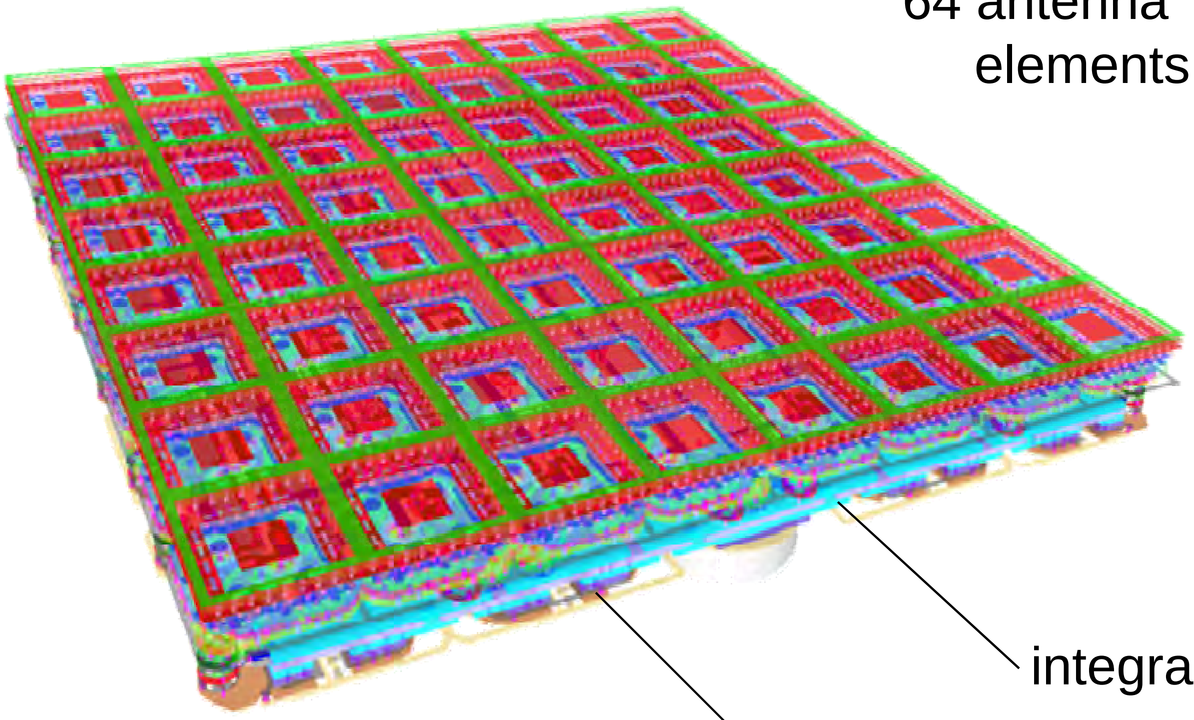
- 8x8 antenna elements
- incl. hybrid ring feeds
- calibration network
- active RF circuitries
- LO distribution networks
- IF feeding network
- power and DC supply
- liquid cooling system



RF circuitries, supply lines and cooling

LTCC frontend: RF circuitry architecture

top view



64 antenna elements

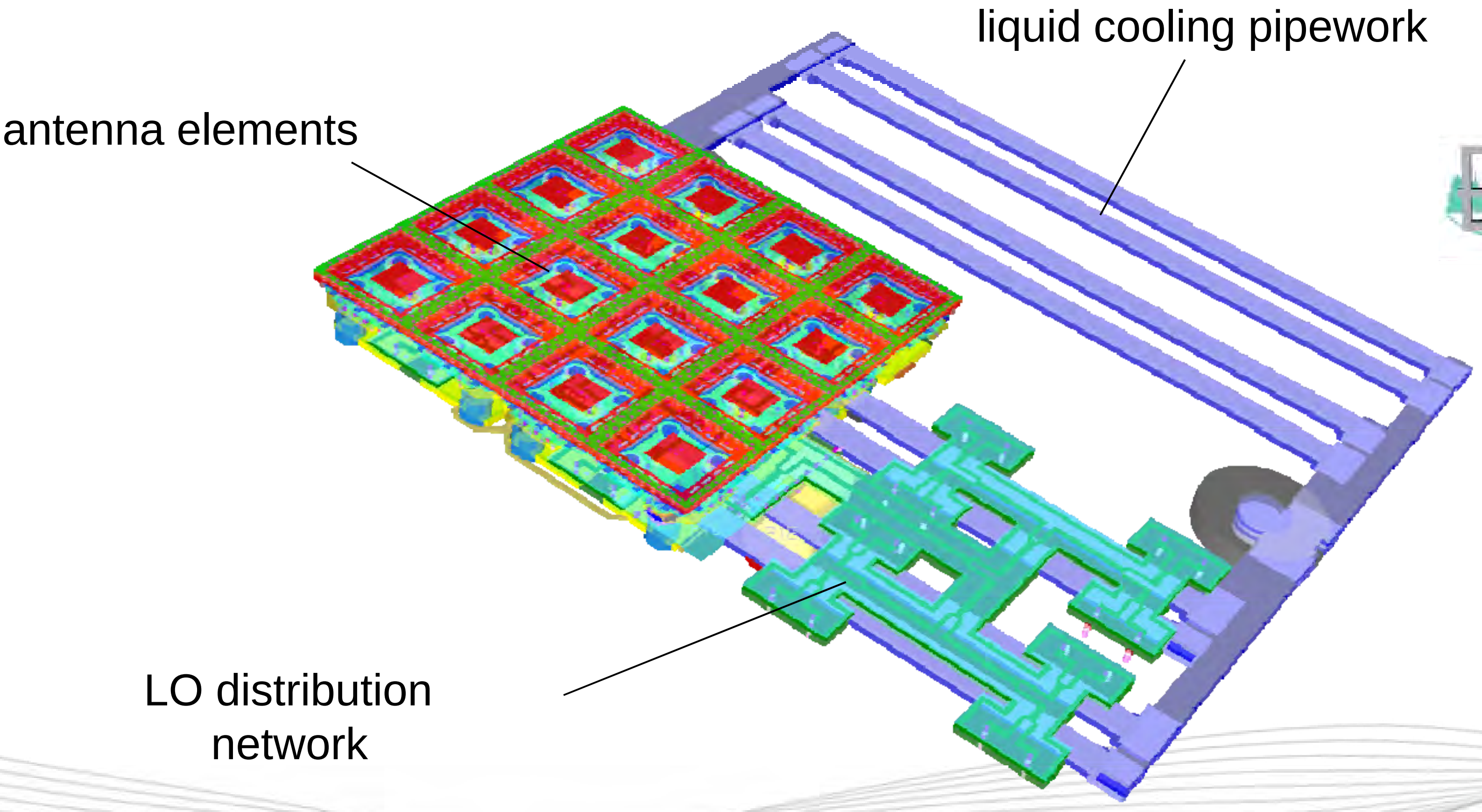
17 layers

integrated liquid cooling

integrated RF circuitry

LTCC frontend: RF circuitry architecture

- top view, partly deconstructed for insight in inner layers
- ¾ of antenna parts removed
- ½ of LO network removed



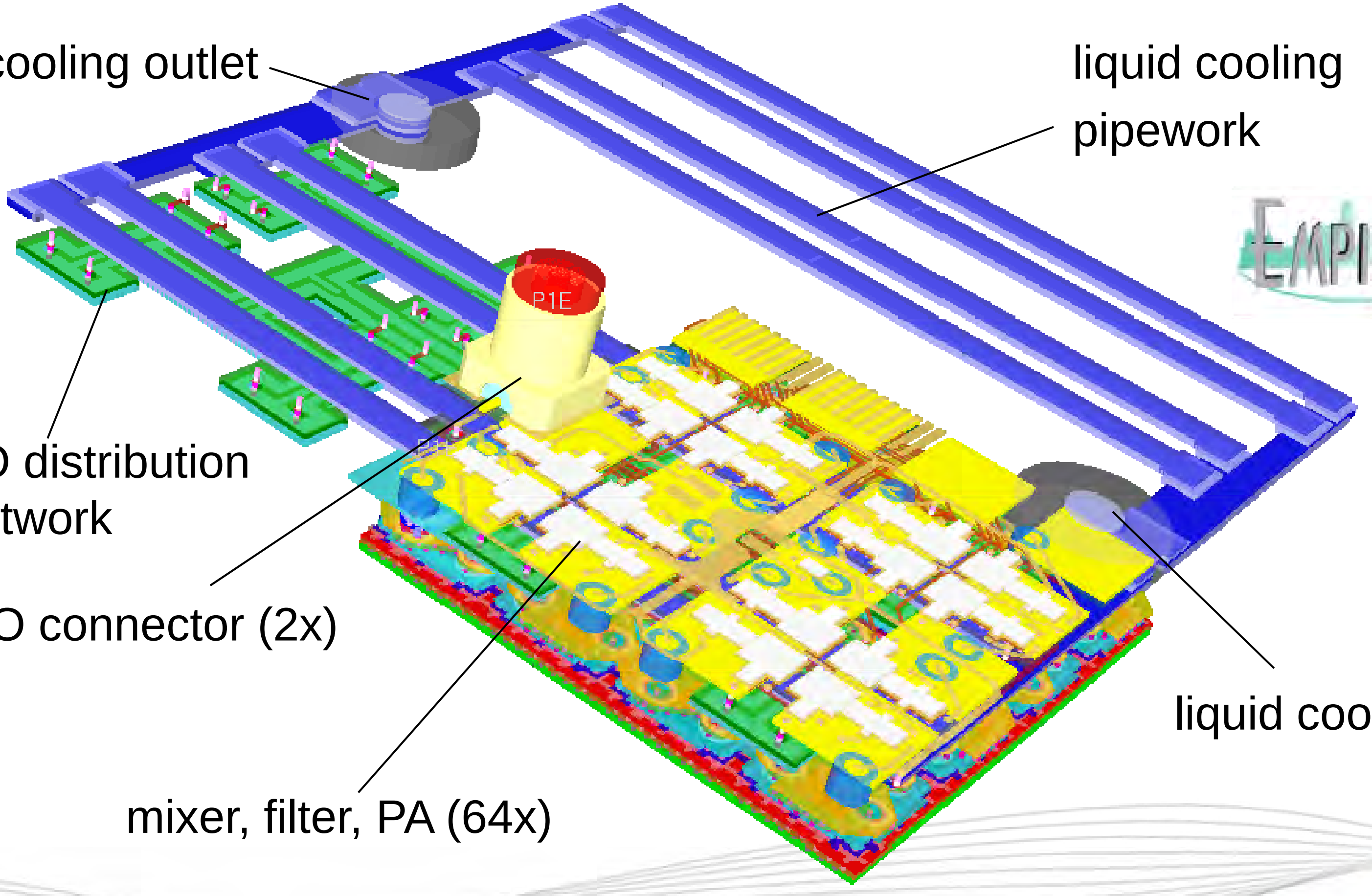
liquid cooling pipework

antenna elements

LO distribution network

LTCC frontend: RF circuitry architecture

- back view / partly deconstructed for insight into inner layers
- ¾ of RF chipsets removed



liquid cooling outlet

liquid cooling pipework

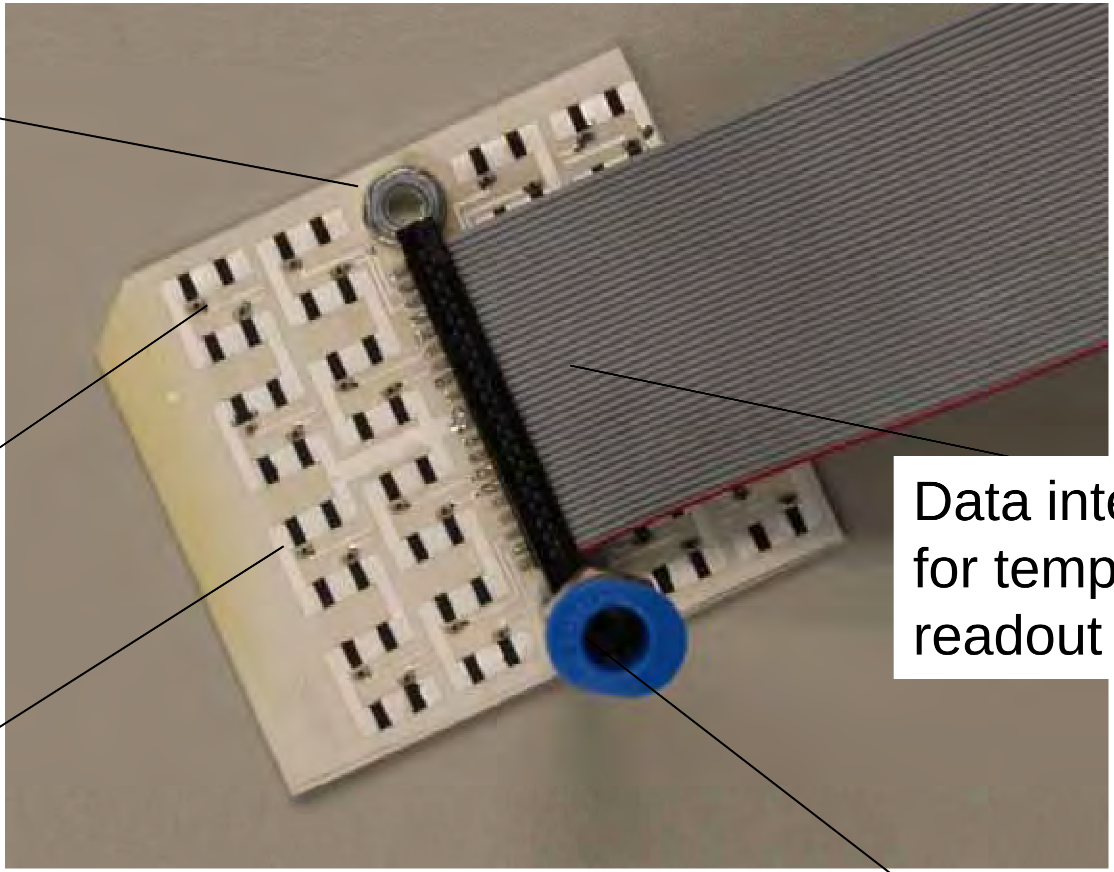
LO distribution network

LO connector (2x)

mixer, filter, PA (64x)

liquid cooling inlet

LTCC frontend: Cool system measurement



LTCC test tile with cooling channels

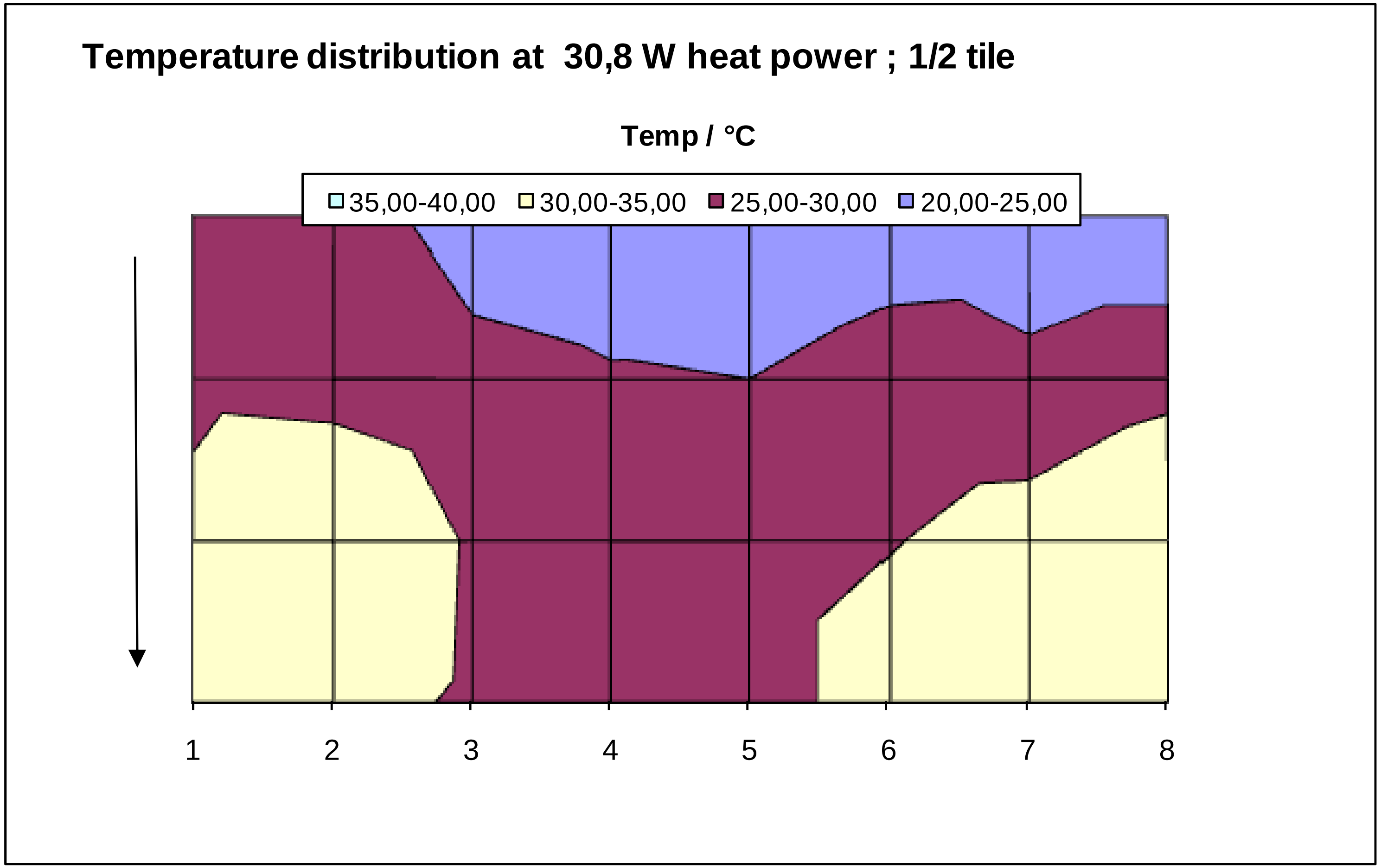
NTC (temerature dependent resistance)

Data interface for temperature readout

Resistor paste to create heat

Connection to cool system

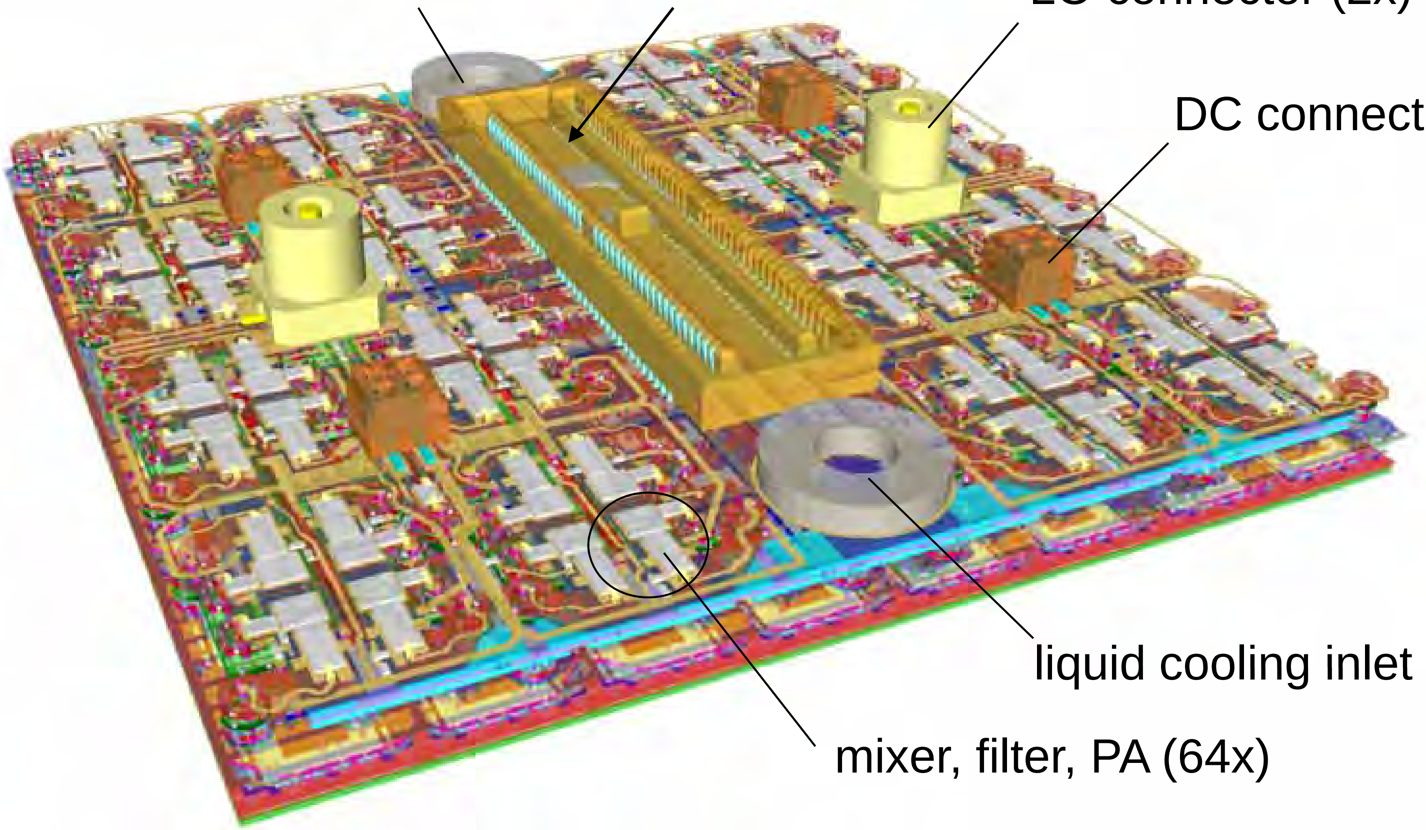
LTCC frontend: Cool system measurement



- Temperature raise in flow direction
- Better cooling inside (shorter connection)
- With 130 ml / min water flow enough cooling capacity

LTCC frontend: RF circuitry architecture

back view, completely assembled



liquid cooling outlet

IF connector

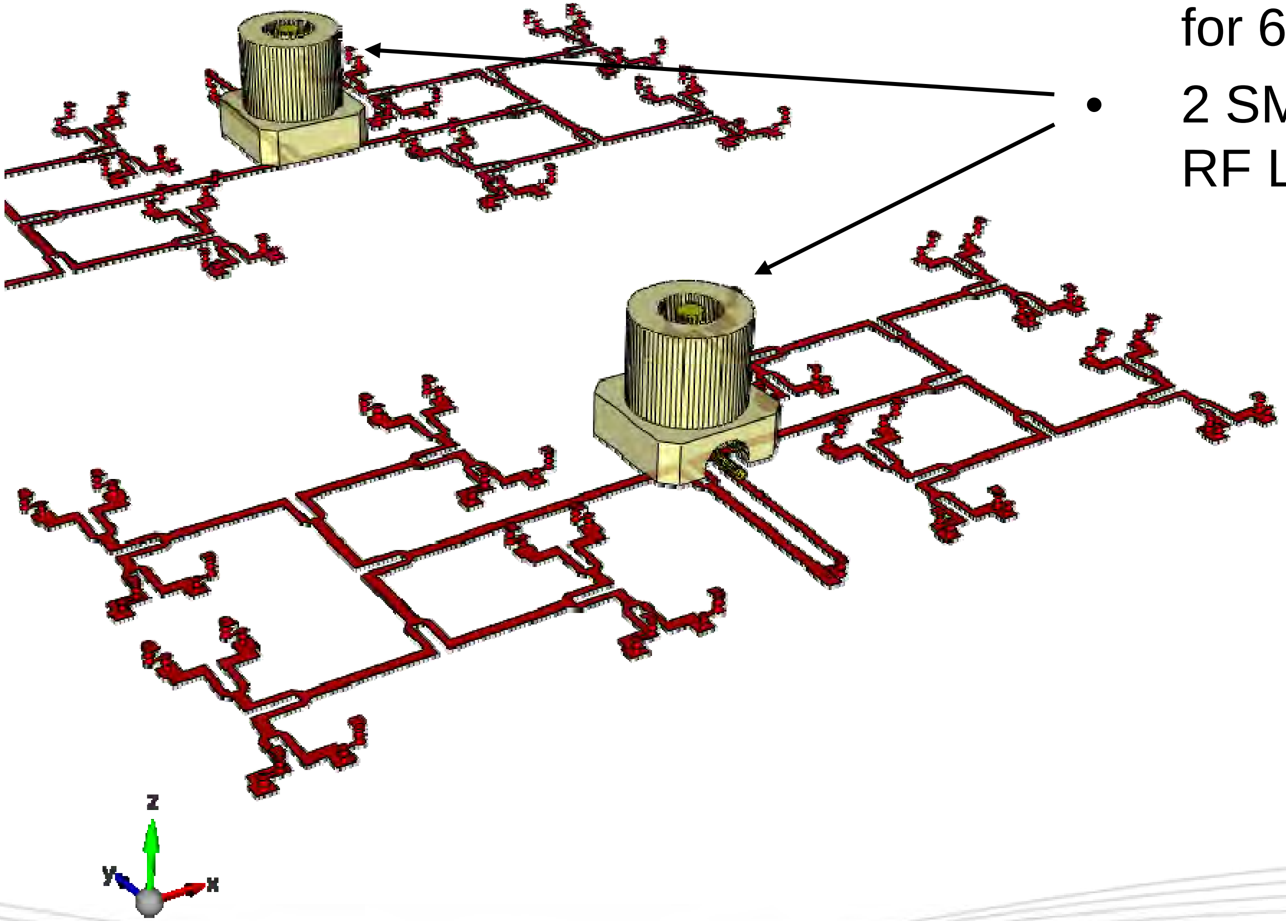
LO connector (2x)

DC connector (4x)

liquid cooling inlet

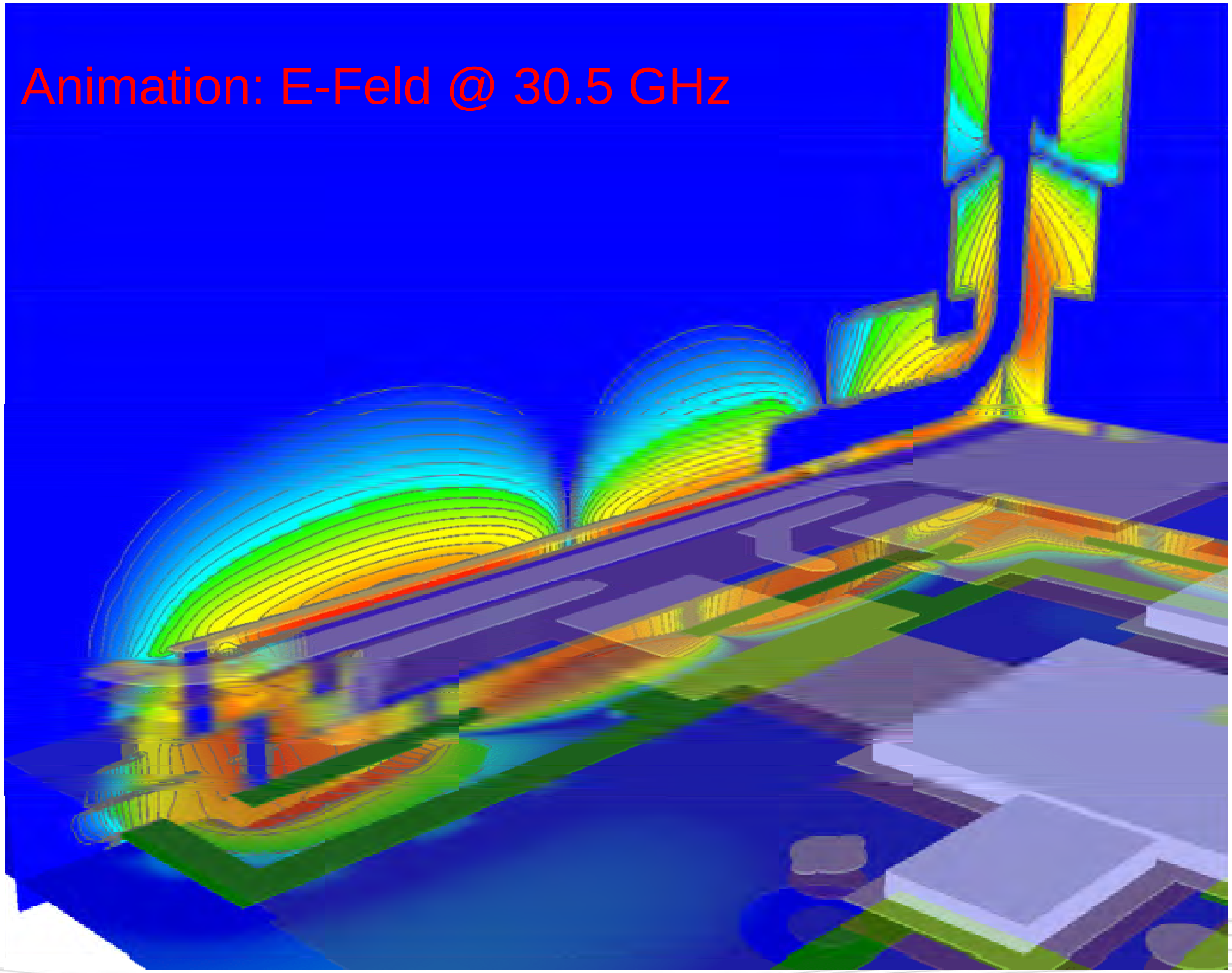
mixer, filter, PA (64x)

LTCC frontend: LO network architecture



- LO frequency: 30.62 GHz
- 2 1:32 LO feed networks for 64 chipsets
- 2 SMP connections to RF LO board

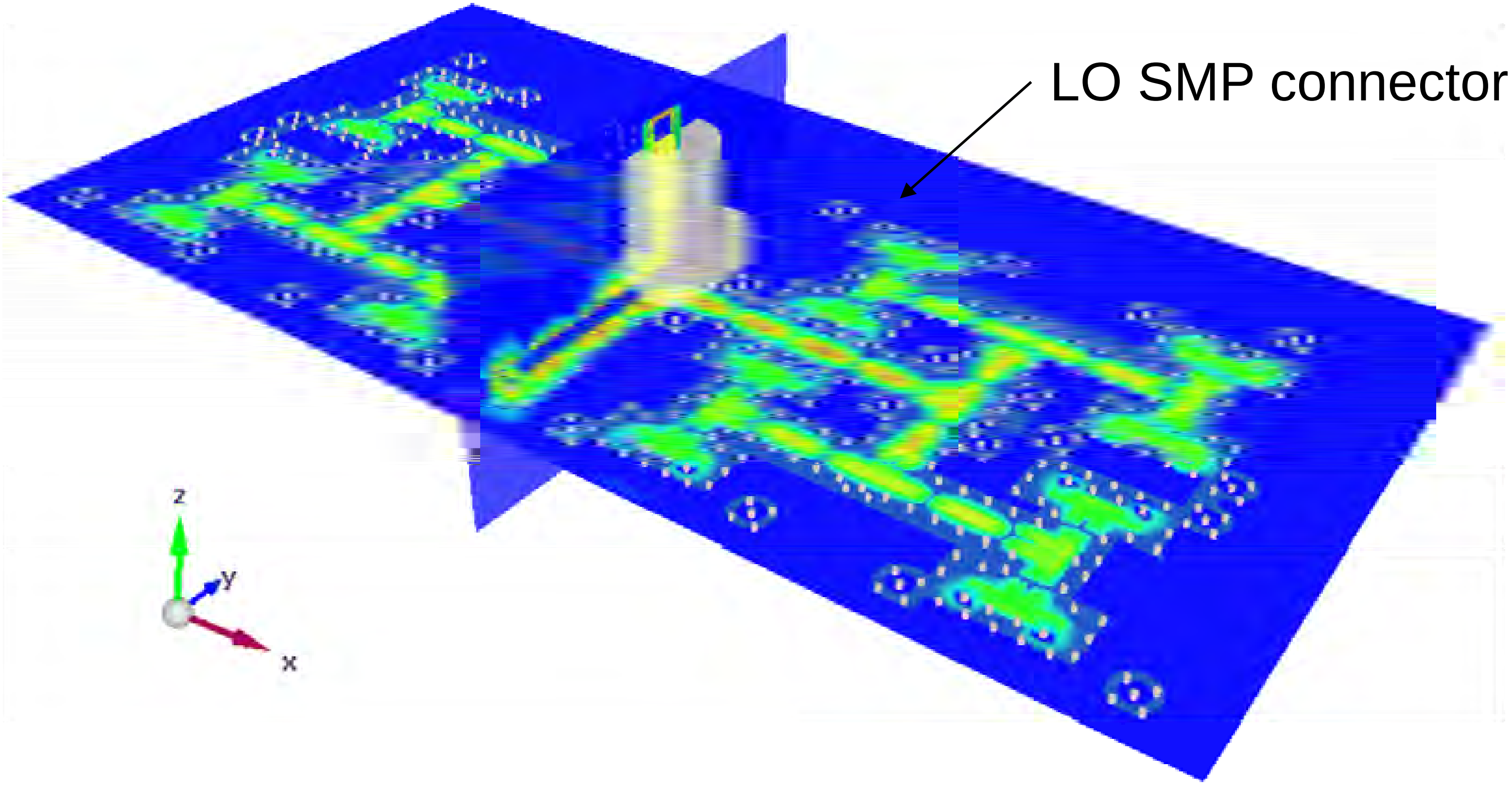
LO feed: SMP connector to Stripline transition



Animation ⇒ http://www.empire.de/media/img/ganim/LO_SMP-Trans.gif

LTCC frontend: LO network architecture

LO Network 1:34

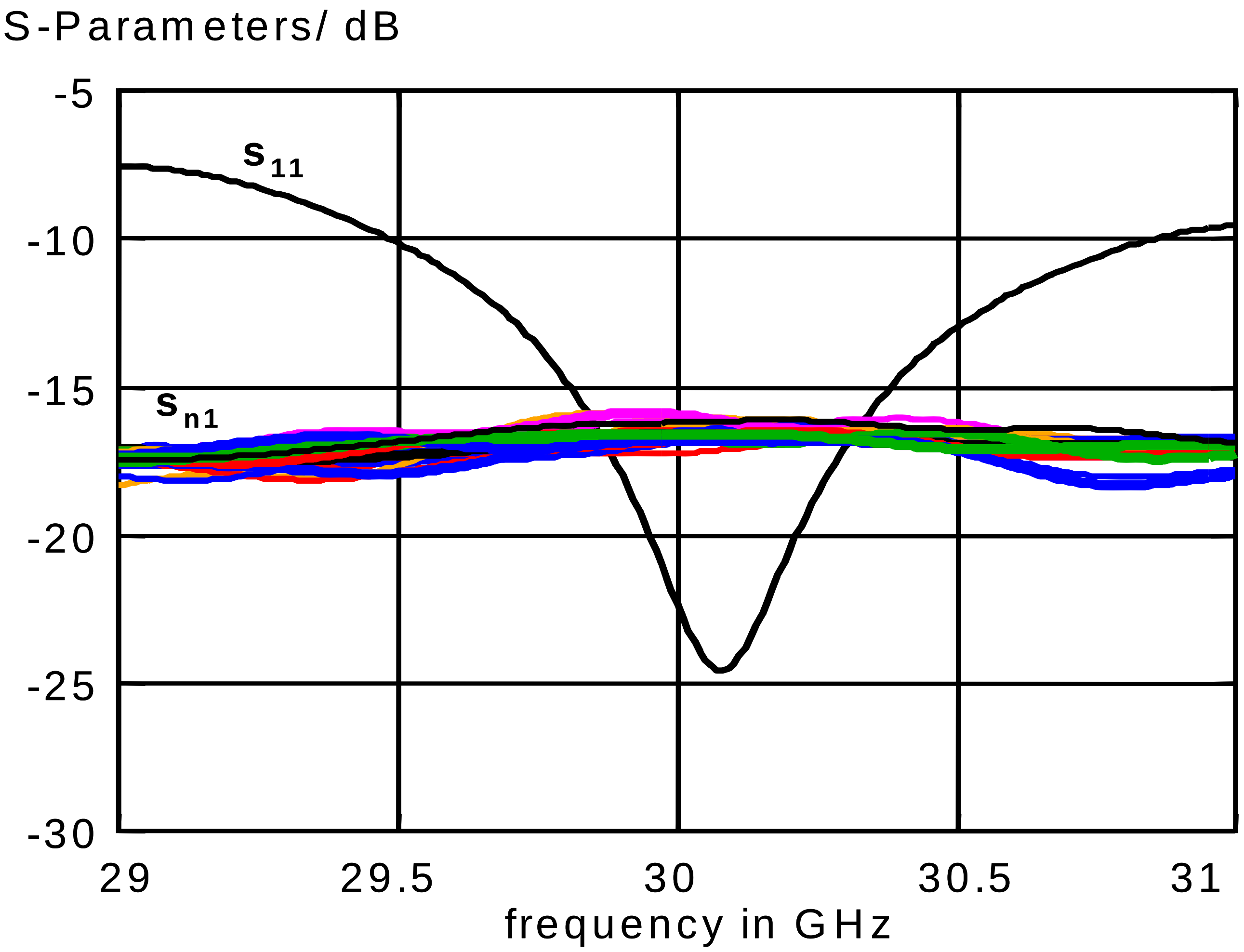


LO SMP connector

Animation: E-Feld @ 30.5 GHz

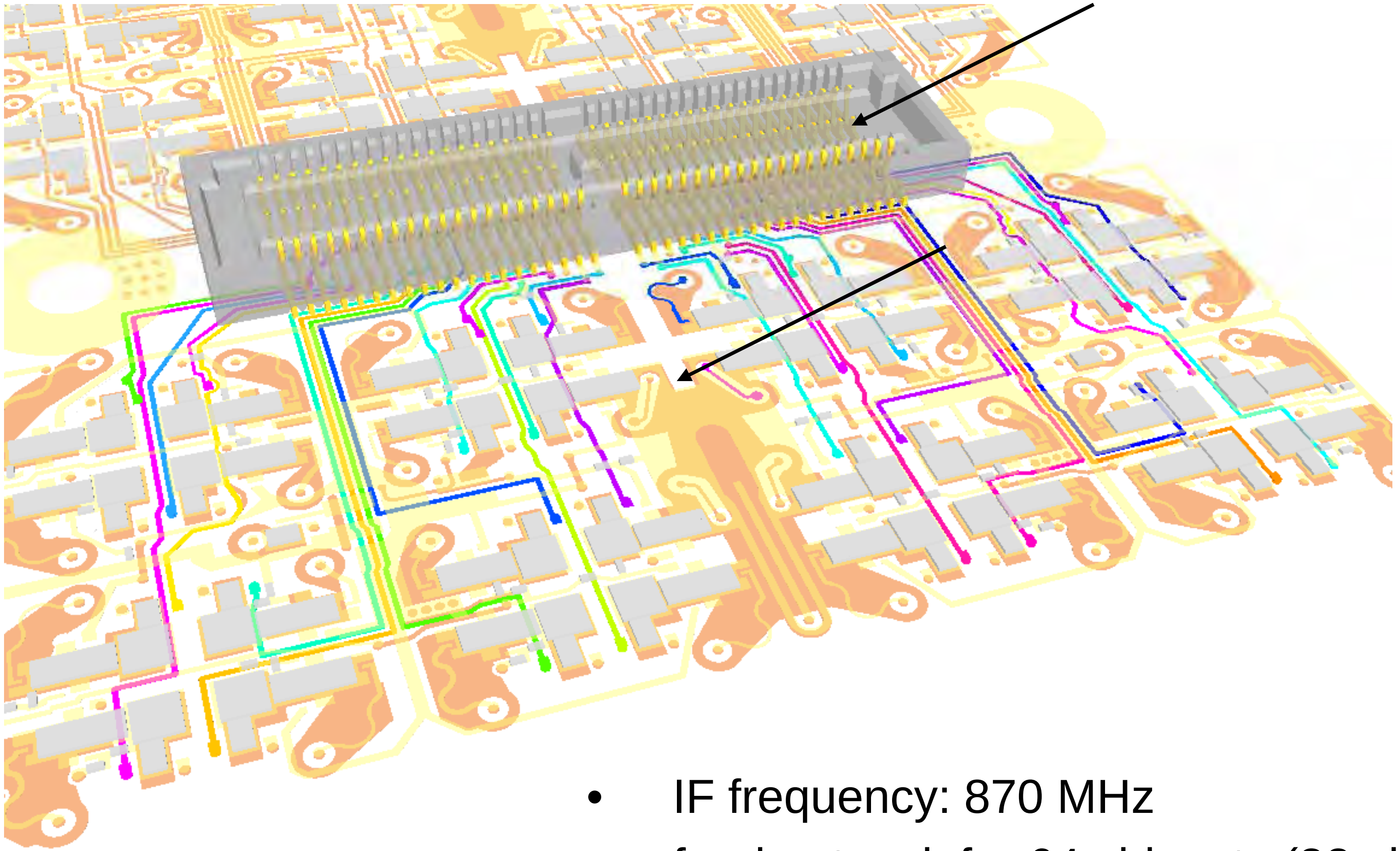
Animation ⇒ http://www.empire.de/media/img/ganim/LO_1x32.gif

LTCC frontend: LO distribution network



Matching at LO input, transmission to mixer ports (32x LO, 2 x calibration receiver

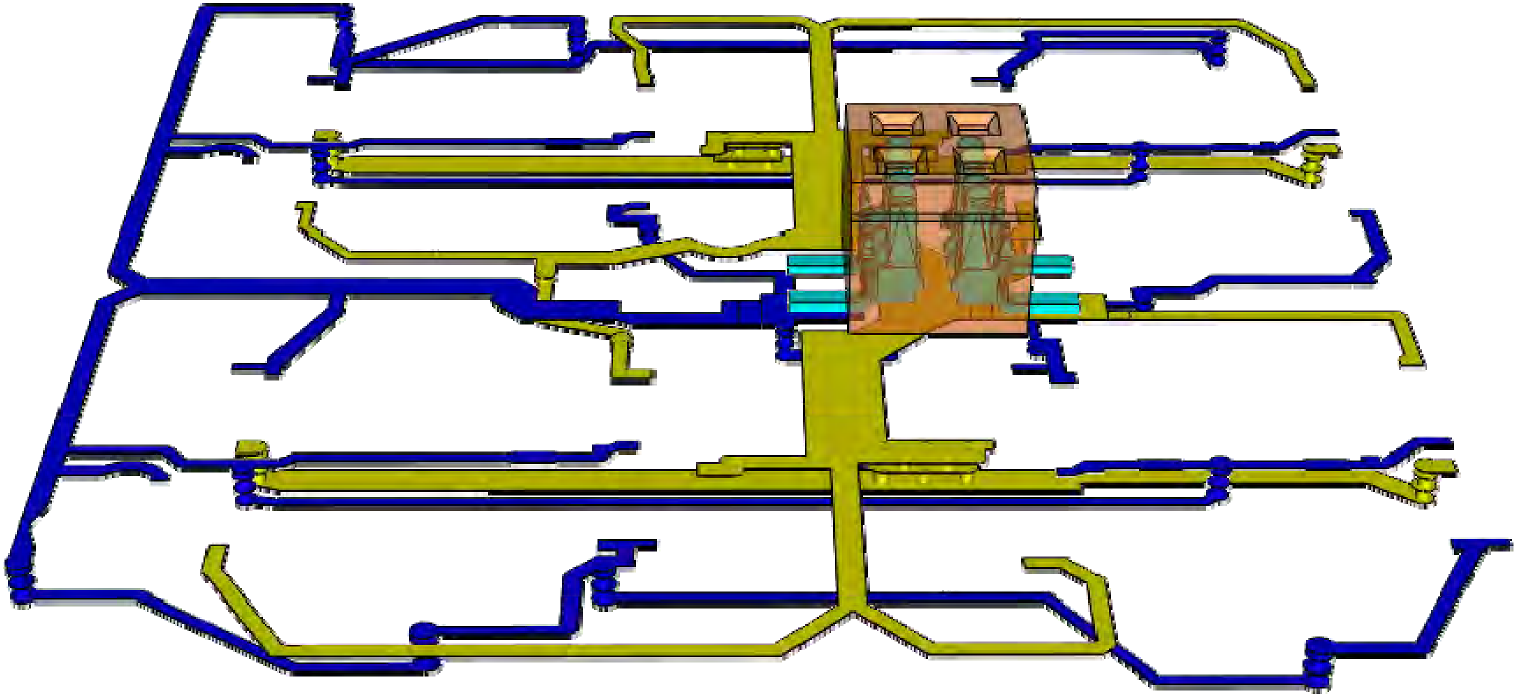
LTCC frontend: IF feed network



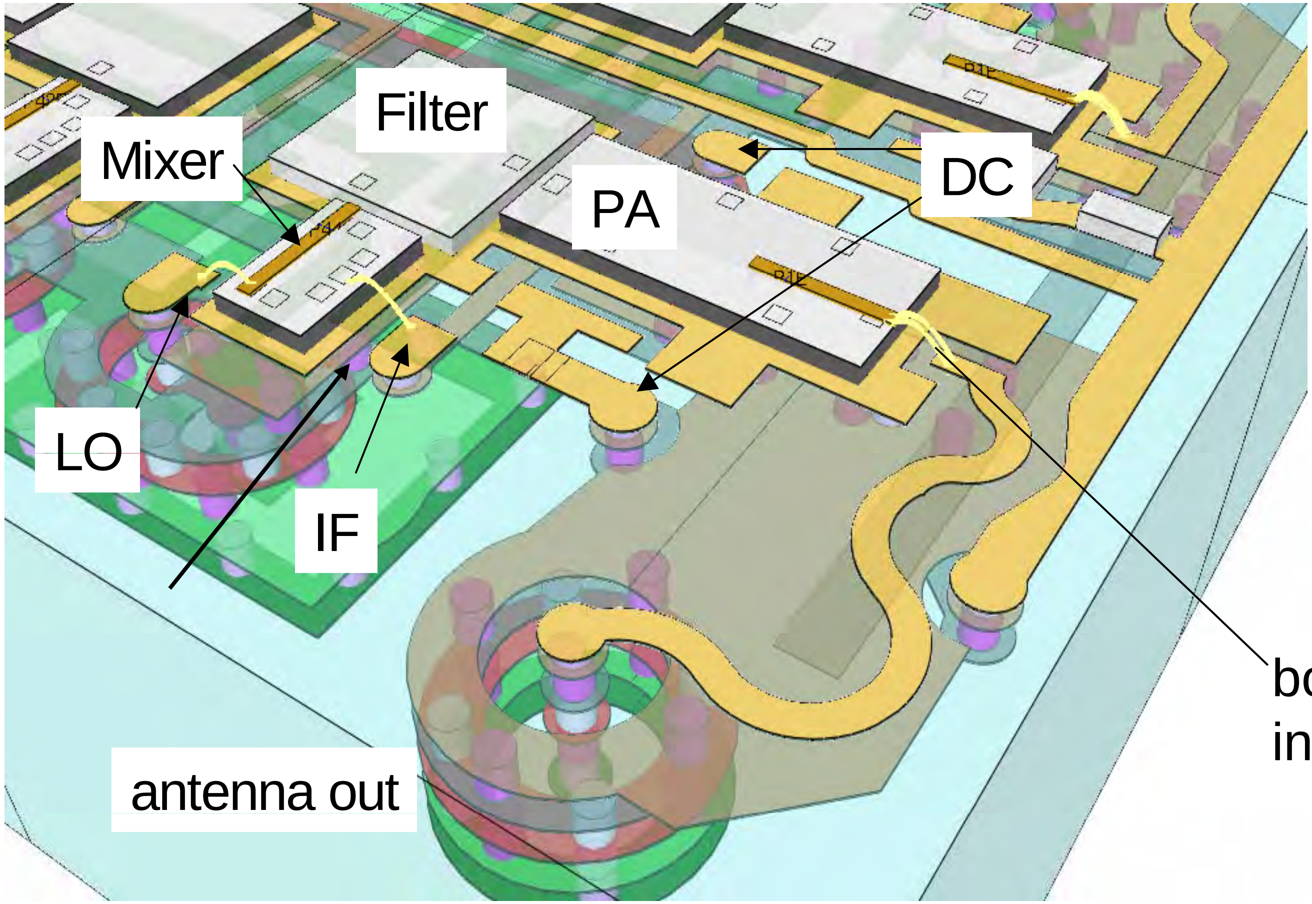
- IF frequency: 870 MHz
- feed network for 64 chipsets (32 shown)

LTCC frontend : DC network

- DC network for 16 elements
- Seperate DC networks for gate and drain supply for PA



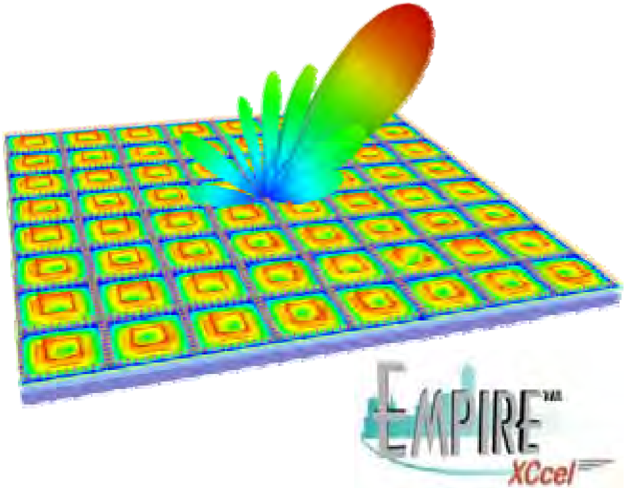
LTCC frontend: RF chipset



bond wires
included in simulation

- **mixer combines 870 MHz IF and 30.6 GHz LO**
- **PA Output power ~ 10 dBm**

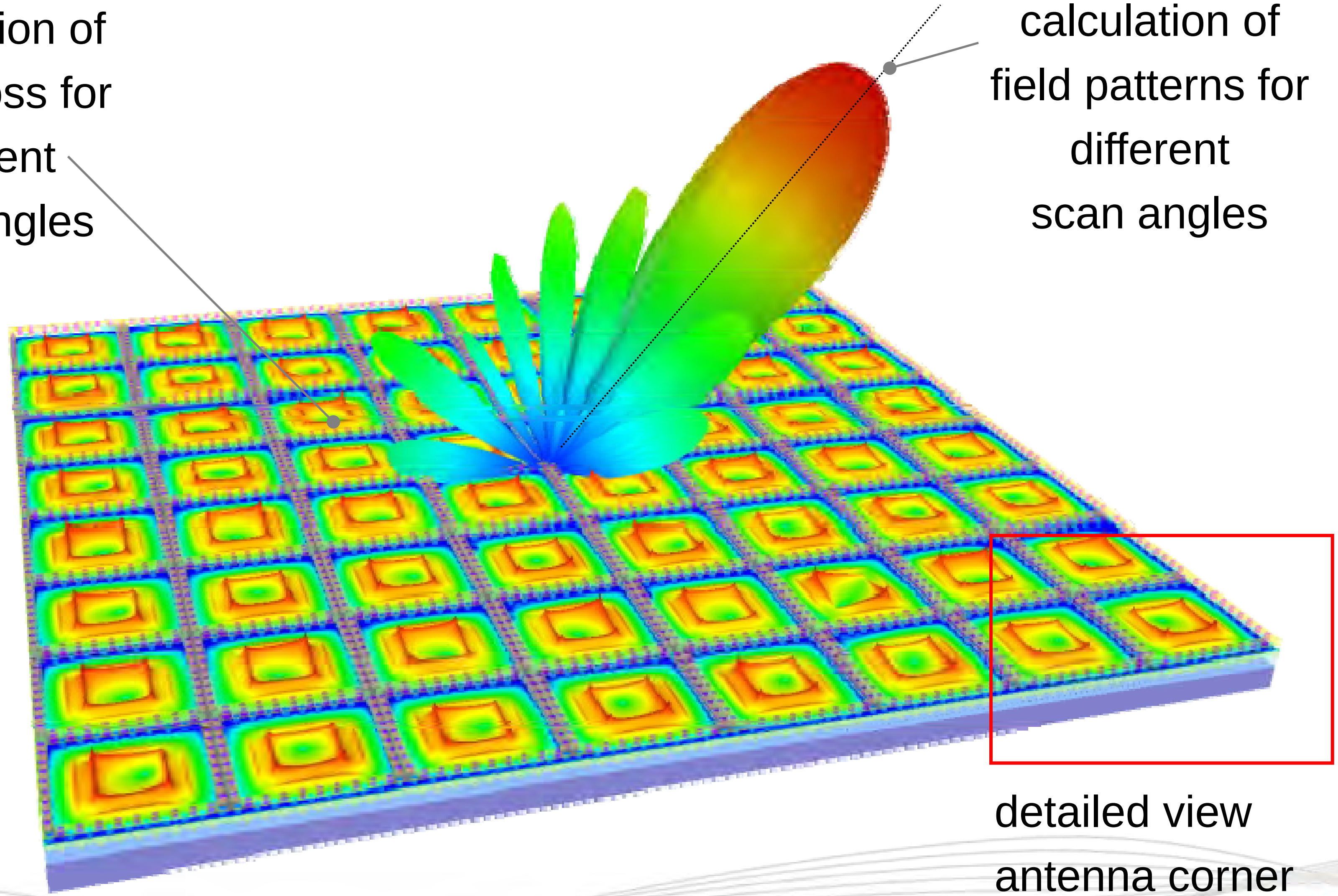
LTCC frontend: Simulation & Design



- initial simulation & design of single parts (antenna, chipset, LO network,..)
- simulation of complete module from all PA's to antenna:
    - 17 metallization layers
    - 16 LTCC tapes
    - 56000 objects
    - simultaneous excitation of all 64 PA ports
    - calculation of farfield, coupling to calibration network, …..
- redesign / tuning of critical parts

- 1652x1649x225 FDTD cells= 613 Million cells
- grid: 10 µm < Δ < 215 µm
- Simulation time < 9 h on a dual quad core PC
- Memory usage ~20 GB
- Simulation time on a multi PC cluster with 7 standard PC's (CPU I7 920): 4 h

LTCC Frontend: calculation of complete array

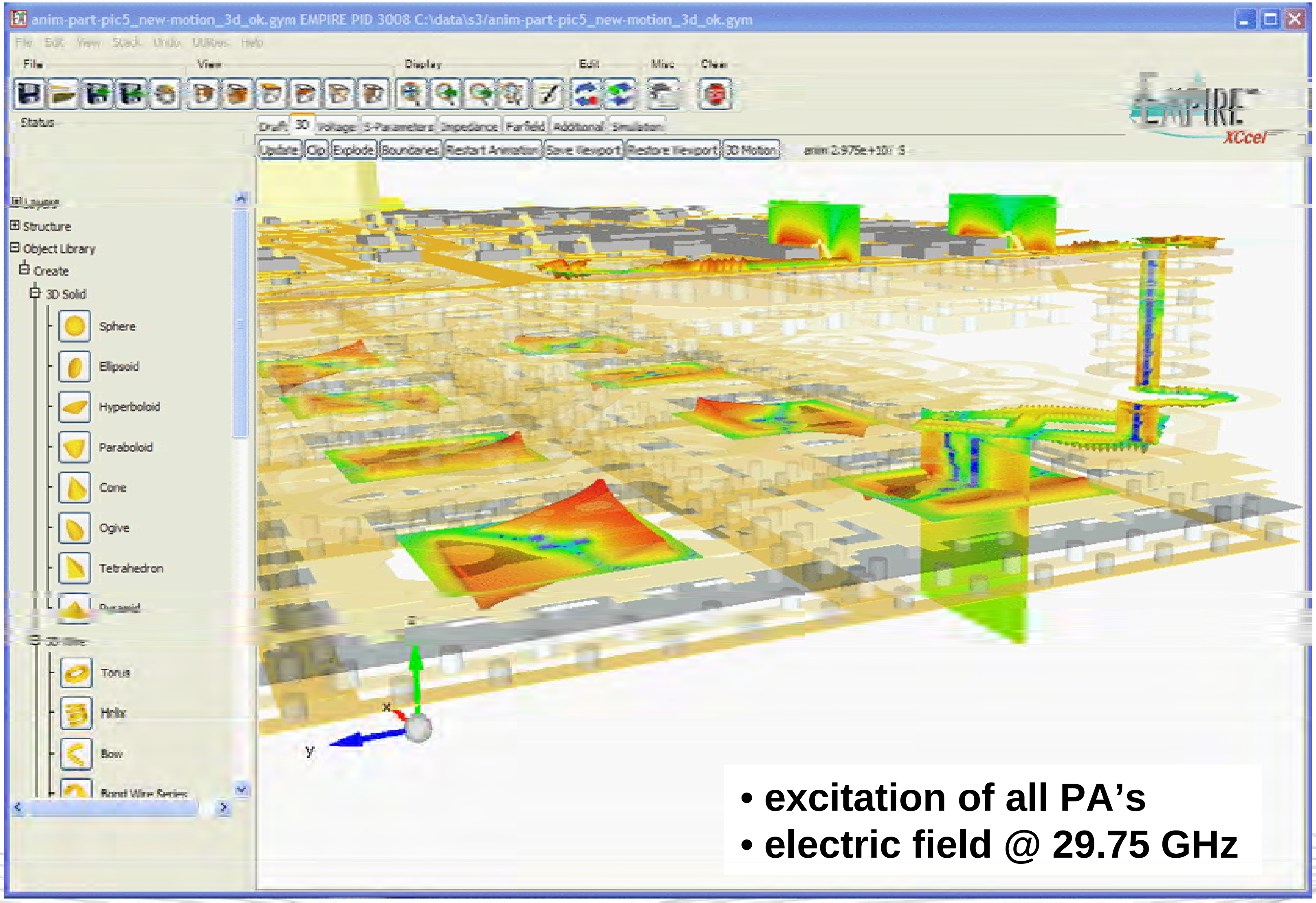


calculation of
return loss for
different
scan angles

calculation of
field patterns for
different
scan angles

detailed view
antenna corner

LTCC frontend: Detailed view of one RF path

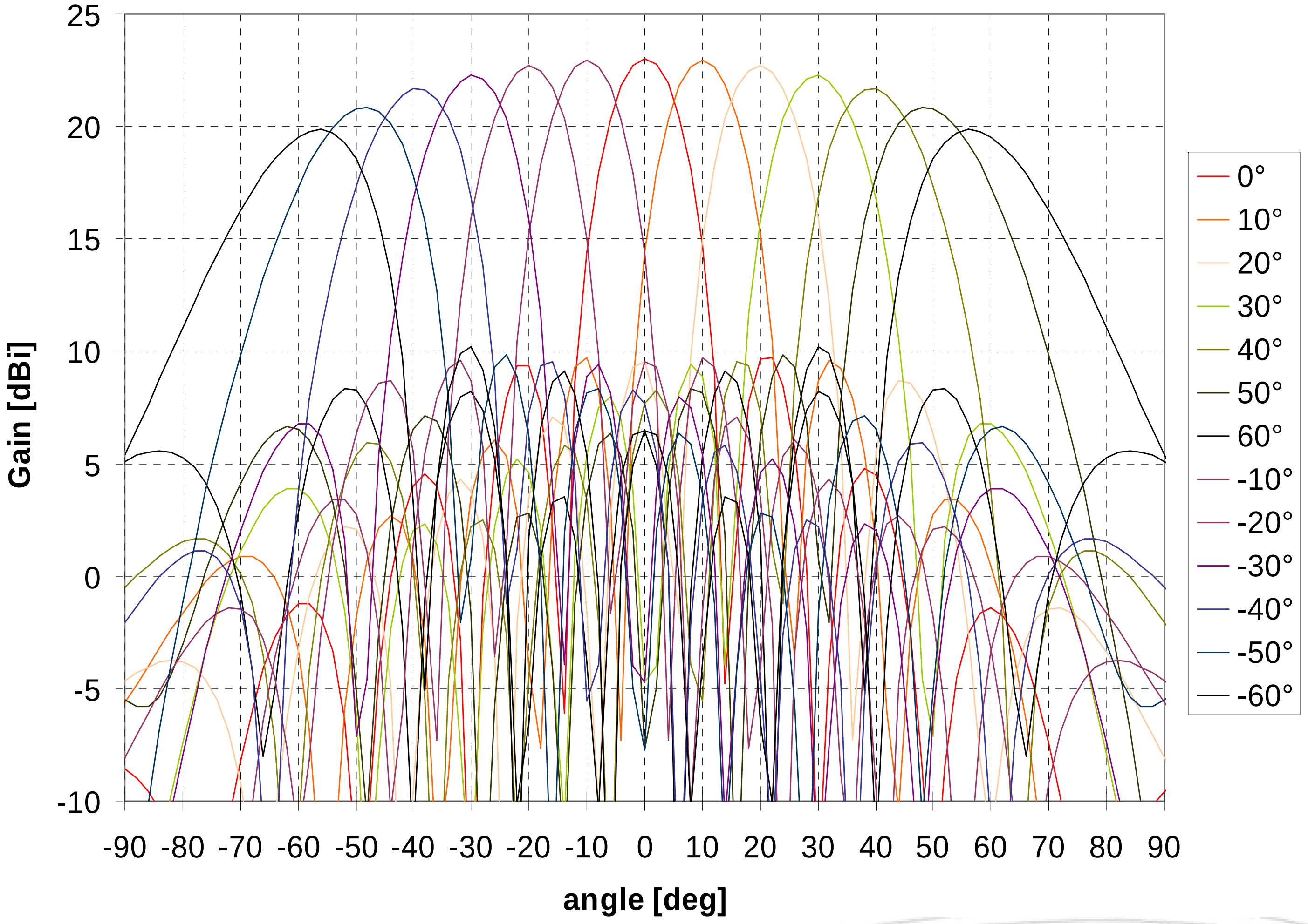


- **excitation of all PA's**
- **electric field @ 29.75 GHz**

Animation ⇒ http://www.empire.de/media/img/ganim/PA_to_antenna.gif

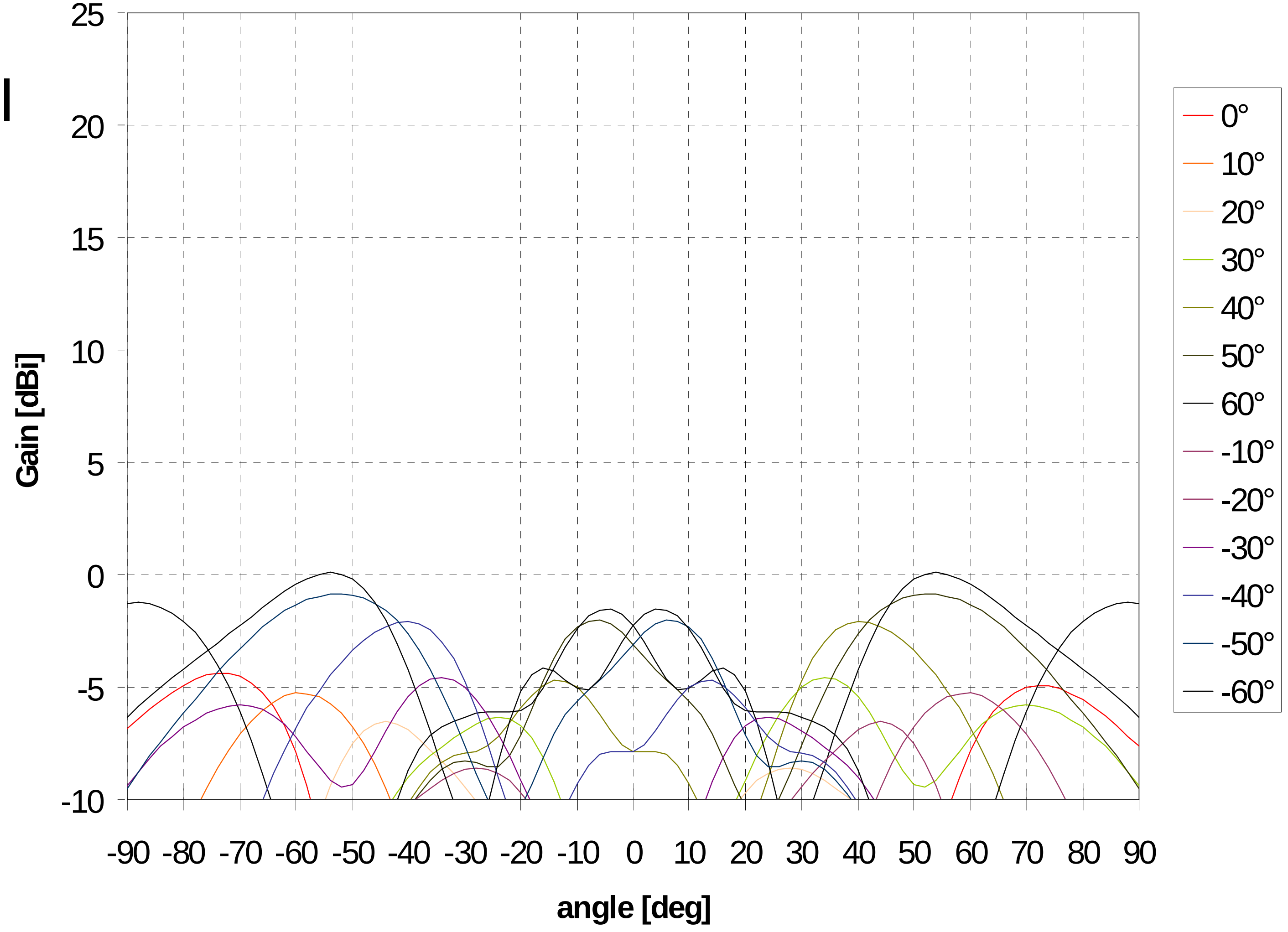
LTCC frontend: Calculated far field patterns

Co-Pol

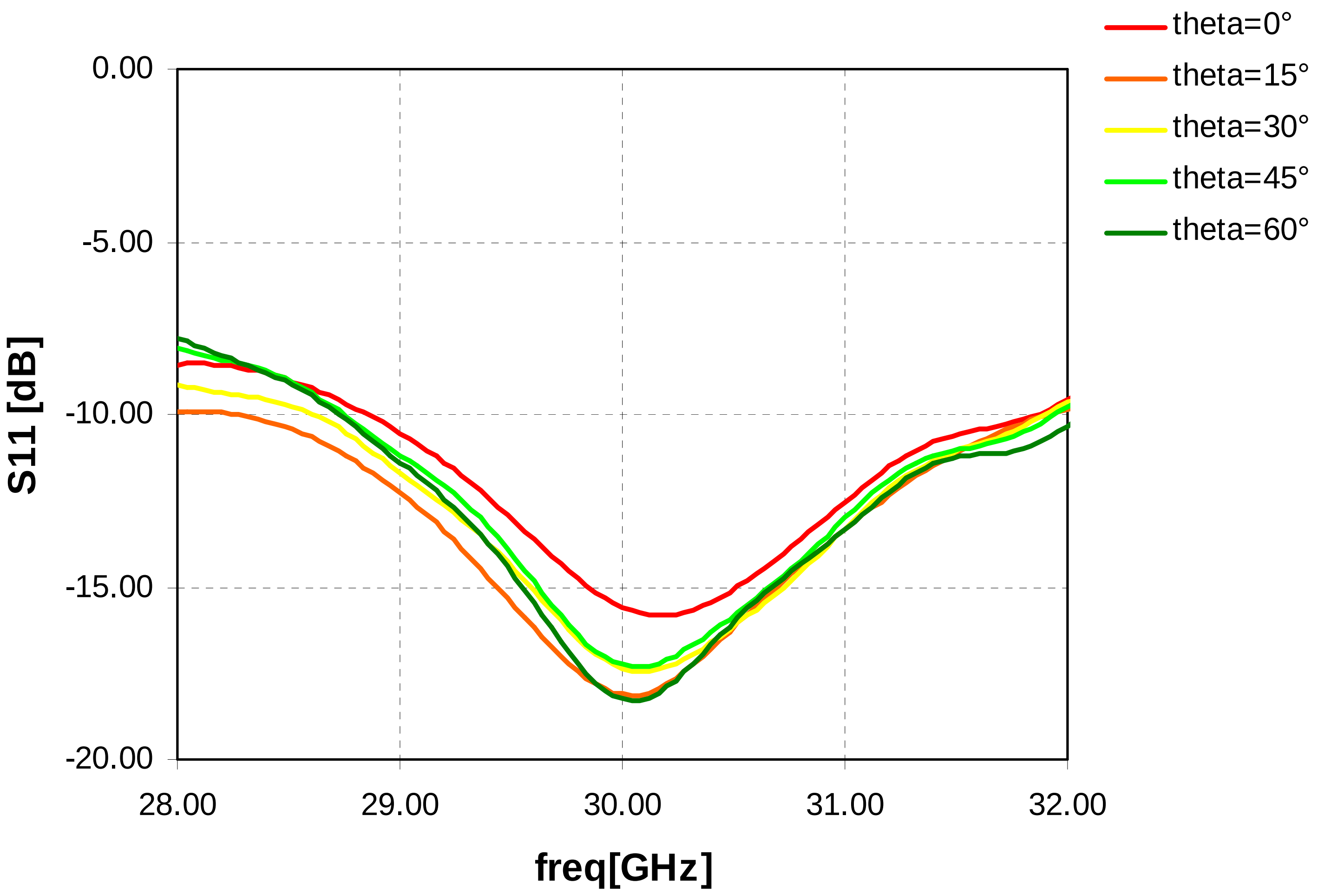


LTCC frontend: Calculated far field patterns

X-Pol



LTCC frontend: Calculated Scan Reflexion. Coeff.



Scanning has very low impact on reflexion coefficient

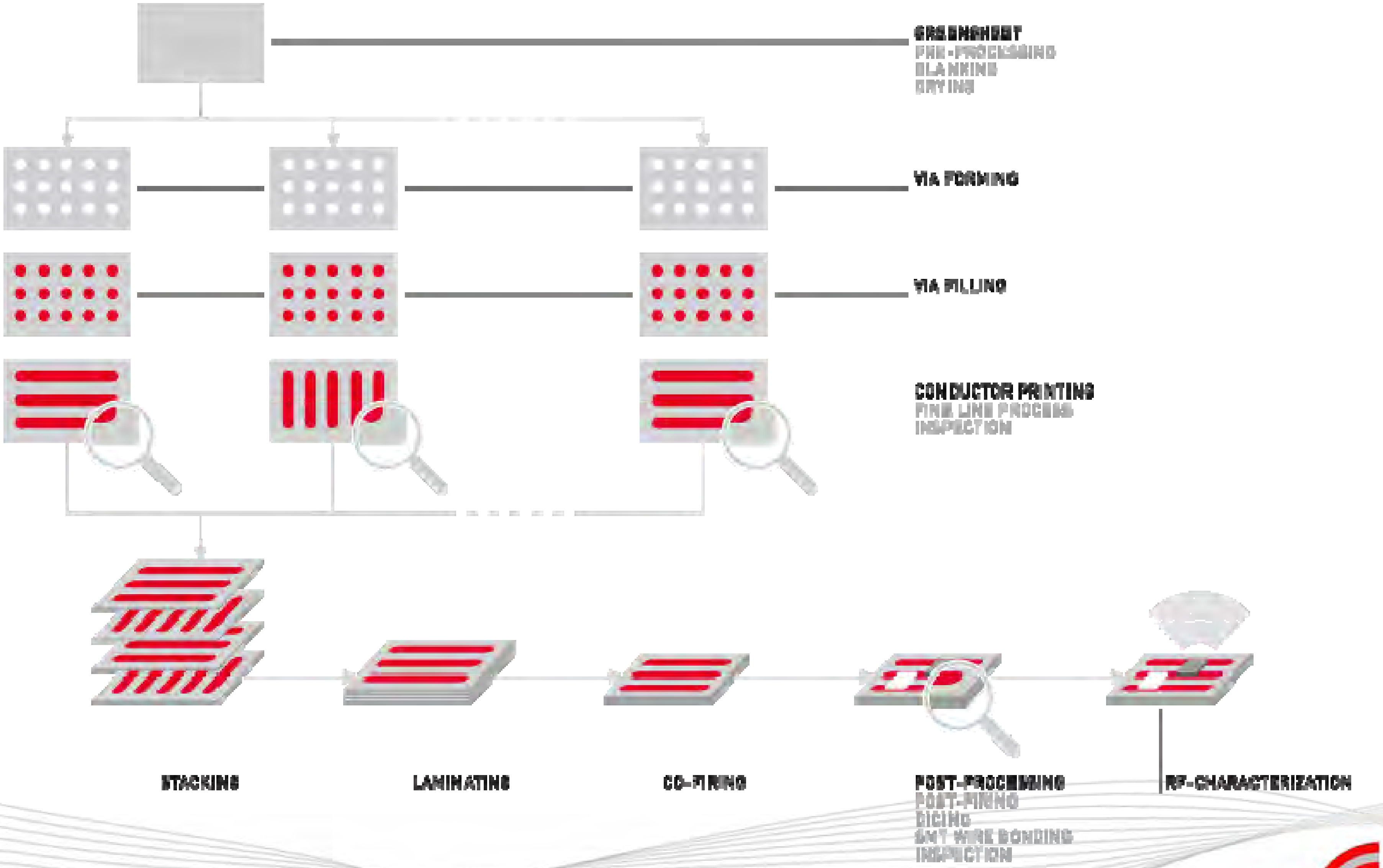
No scan blindness, low coupling of antenna elements

Advantages of LTCC

Low Temperature Co-Fired Ceramic

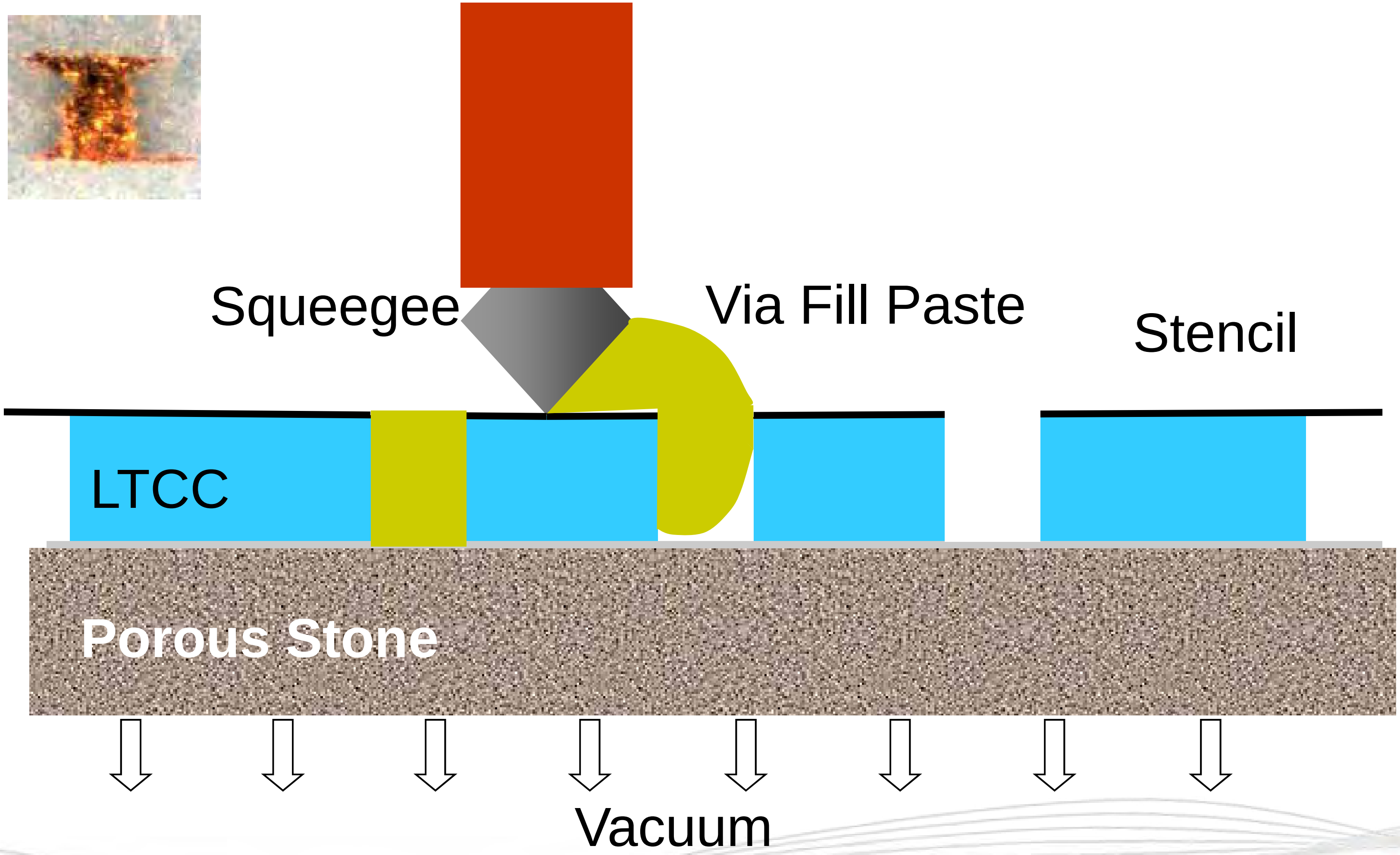
- → (Nearly) arbitrary Number of Layers (Multilayer)
- → Co-Firing of Conductors, Resistors and Dielectrics
- → High Conductivity Metals: Gold and Silver
- → Parallel Processing of Layers, Screen Printed Structures
  - ► Low Production Costs / High Yield
- → 3-Dimensional Integration of RF- and Microwave-Functions Including Antennas
- → Integrated Resistors, Capacitors and Inductors
- → Robust and Hermetic Substrate Provides Housing Functions

LTCC Process

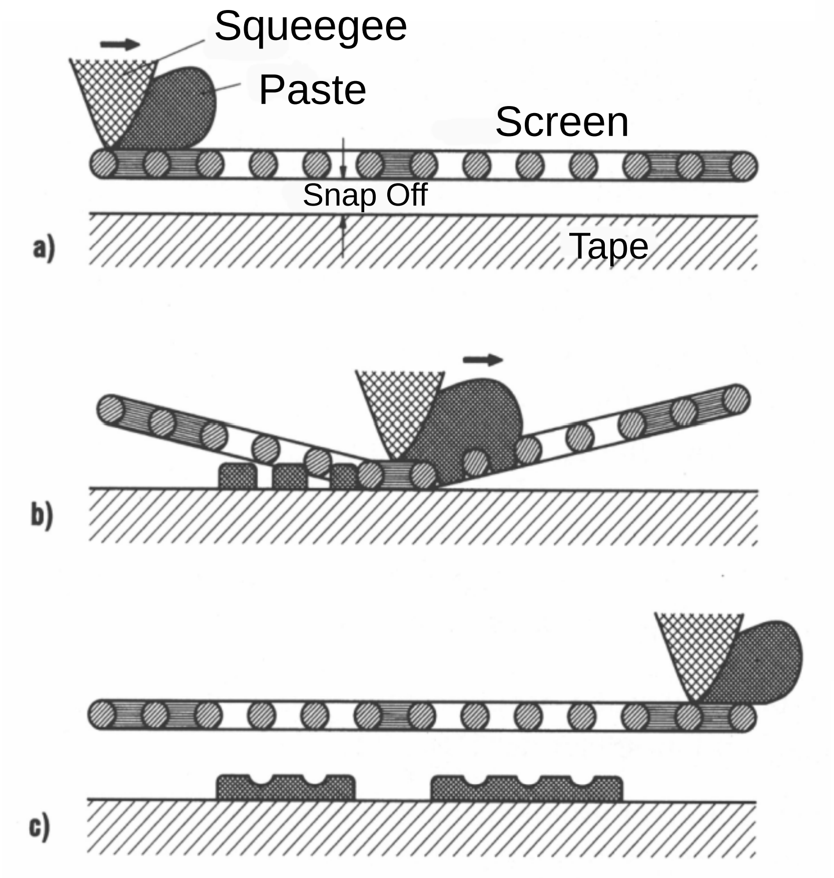


Via and Cavity Formation: CNC Punch

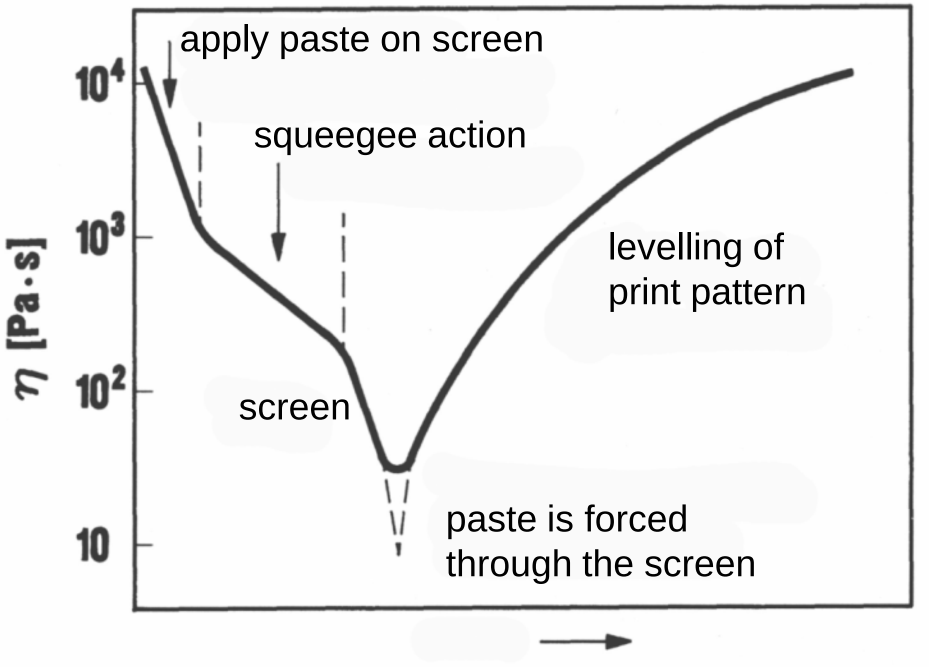
Via Filling:Stencil Printing



Conductor Printing: Screen Printing



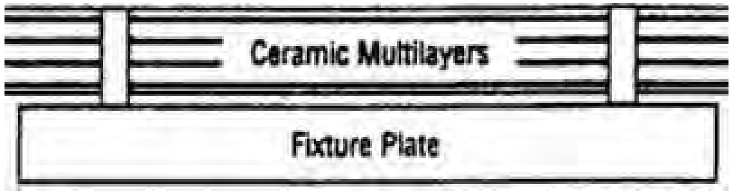
printing process

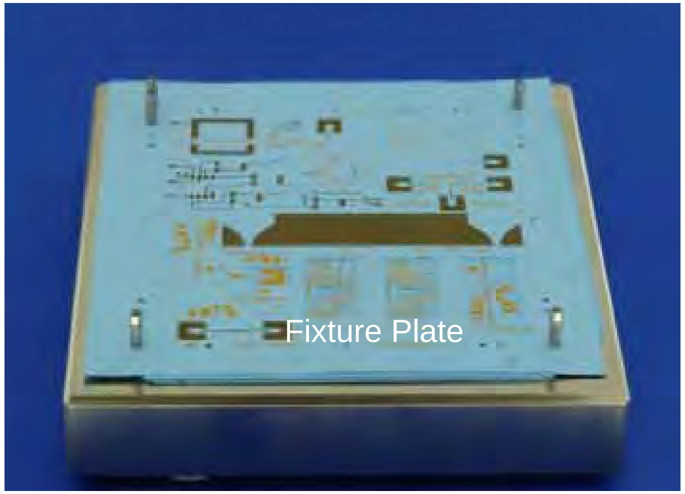


thixotropic behaviour of paste during the printing process

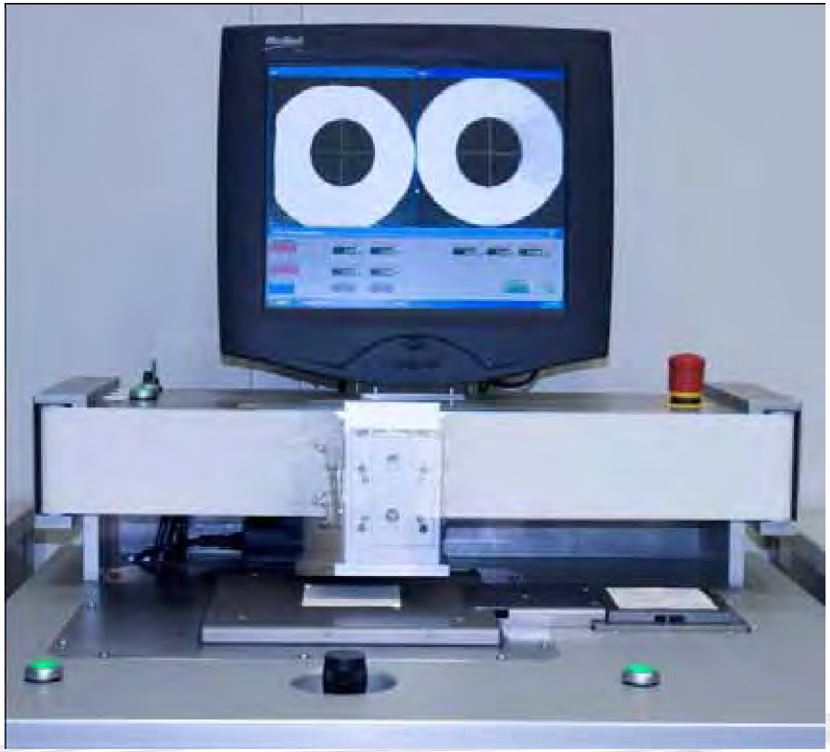
Source: Menz, Mohr: „Mikrosystemtechnik für Ingenieure“

Stacking





- place tape on alignment table
- alignment in x-y-theta
- transfer to stacking table with vacuum pick-up
- stack and collate



Isostatic Lamination Press

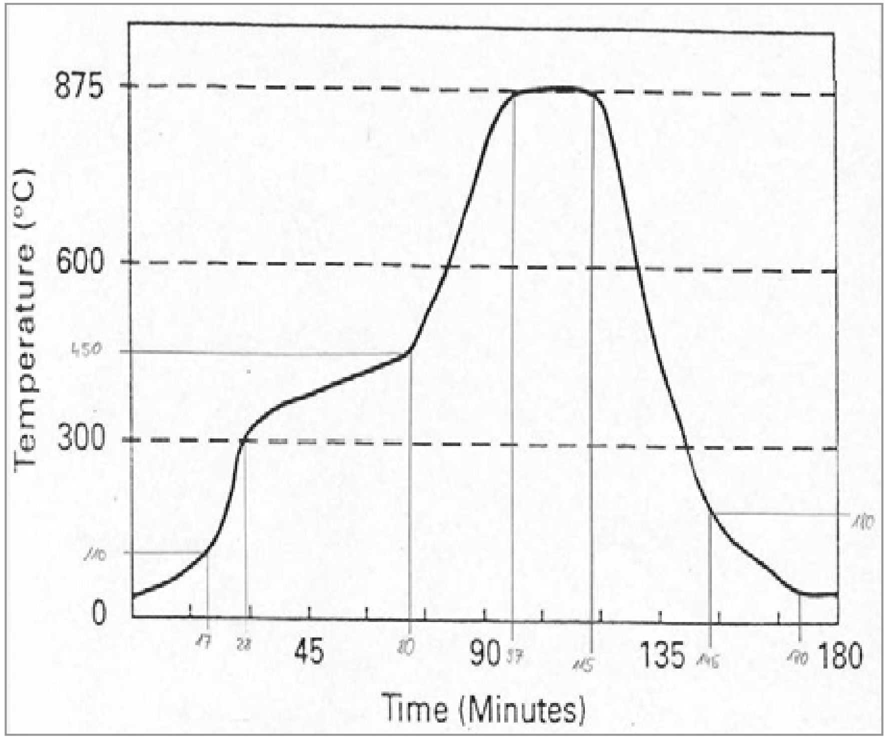
- ✓ Pressure chamber filled with water
- ✓ Homogenous distribution of pressure and temperature
- ✓ Advantages for the ML process: Controlled shrinkage, cavities and complex conductor patterns

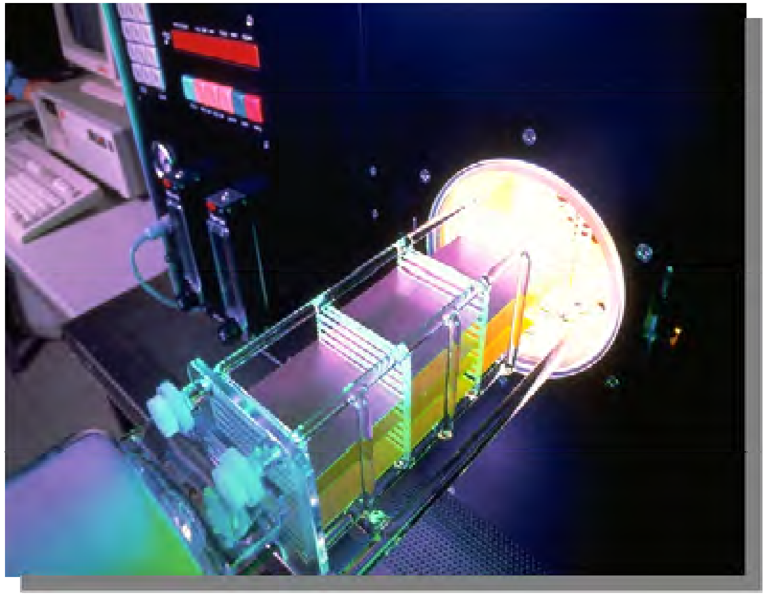
Pressure Chamber:	4“ x 5“ x 1.5“
Max. Temperature:	80°C
Max. Pressure:	5000 psi (34,5 MPa)
Typ. Lamination time:	3 – 5 min

Burnout and Sintering

T < 900°C: Co-firing of Tape, Conductors, Resistors and Dielectrics

Temperature Profile





Typical LTCC design rules

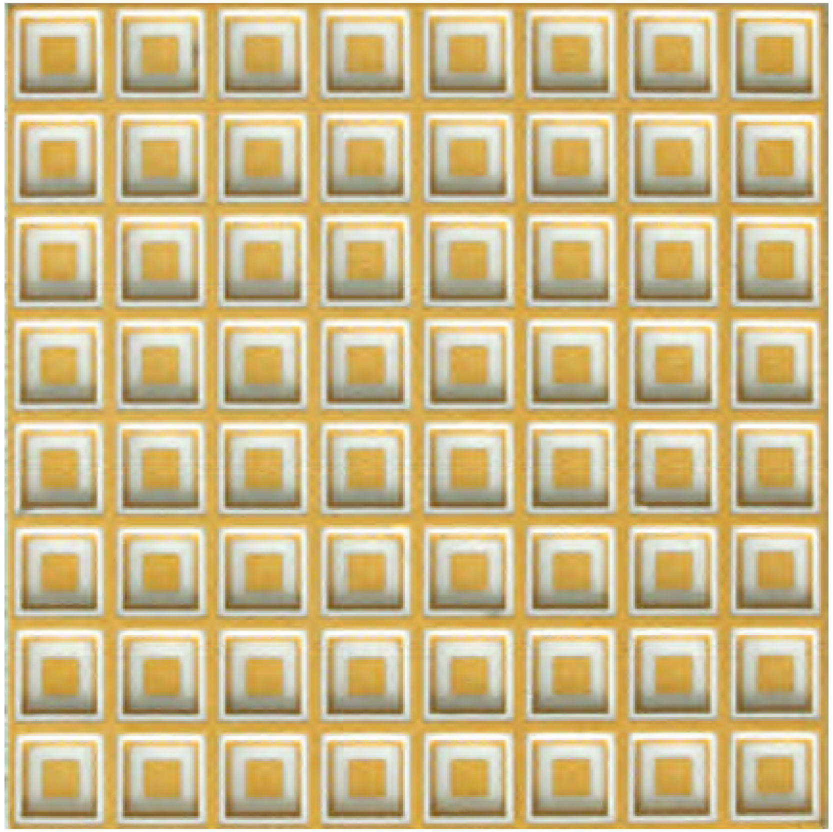
- Minimal Conductor width: 100 µm
- Minimal spacing between conductors 100 µm
- Viahole diameter:
  e.g. 150 µm, 175 µm, 250 µm , 2500 µm
  general rule: d > 70% of layer thickness
- Spacing between viaholes:

  2-3 x via diameter
- Tape thickness

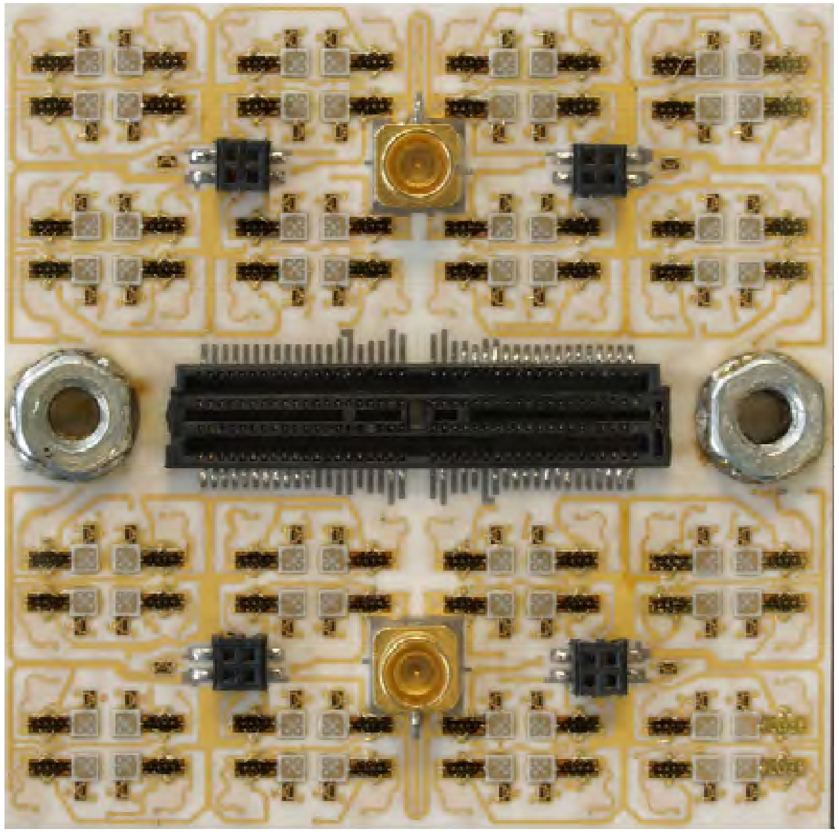
  e.g. Dupont 951: 2 mils, 4.5 mils, 6.5 mils, 10 mils
- Total metal coverage per tape < 50 %

- Shrinkage in x,y direction ~ 15 % ➢ over scale RF layout before processing

Manufacturing: RF assembly

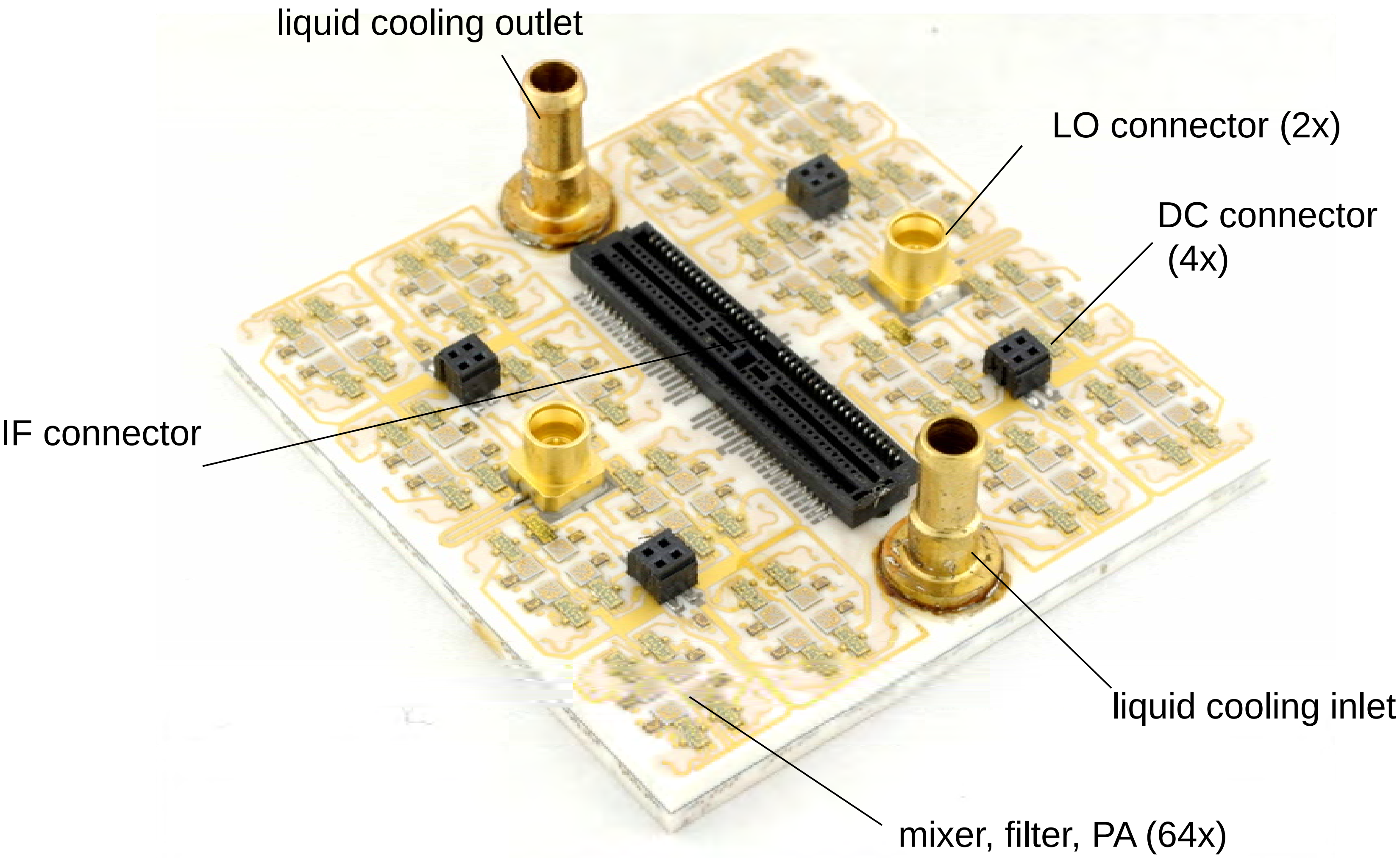


Top side: antenna

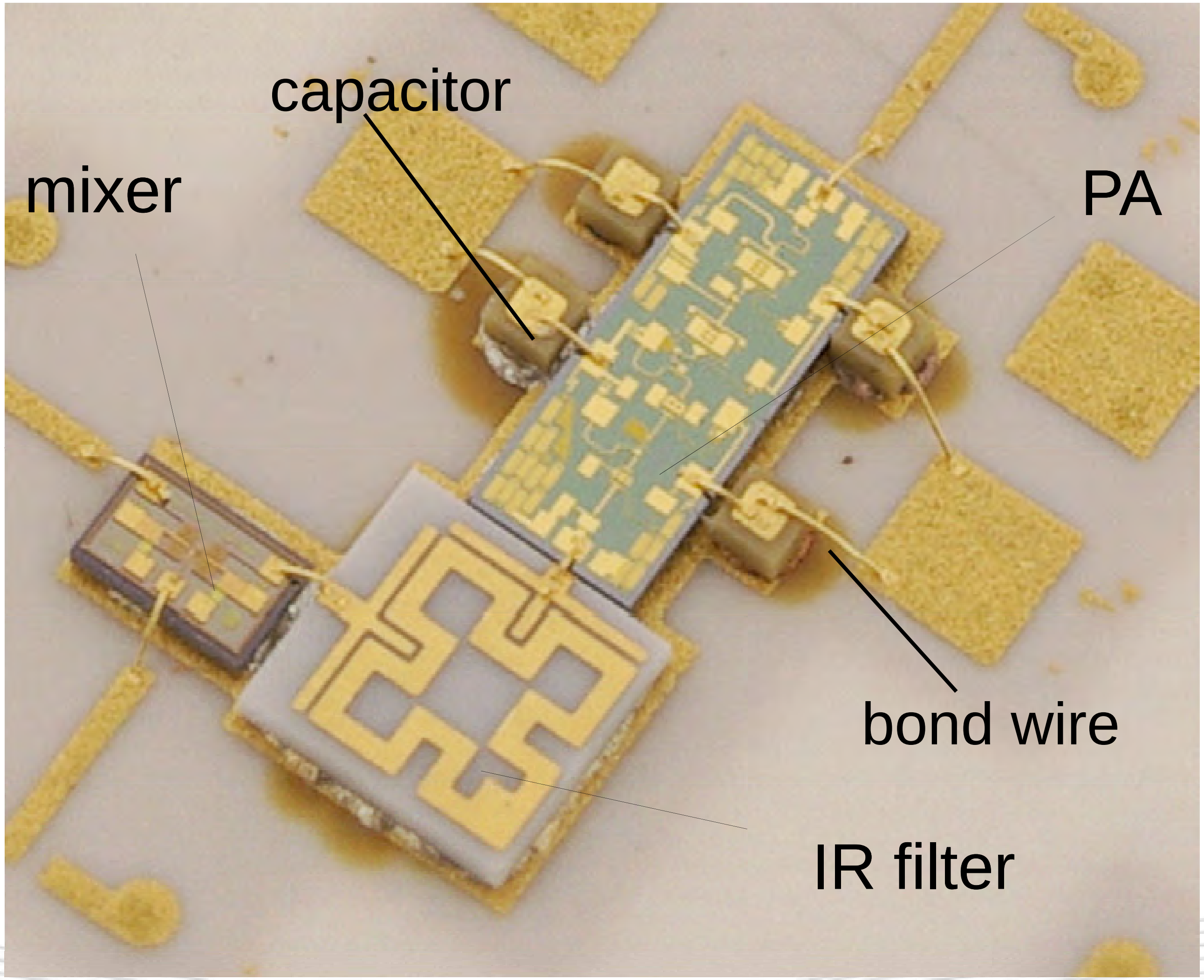


Bottom side: RF

Manufacturing: RF assembly



Manufacturing: RF assembly

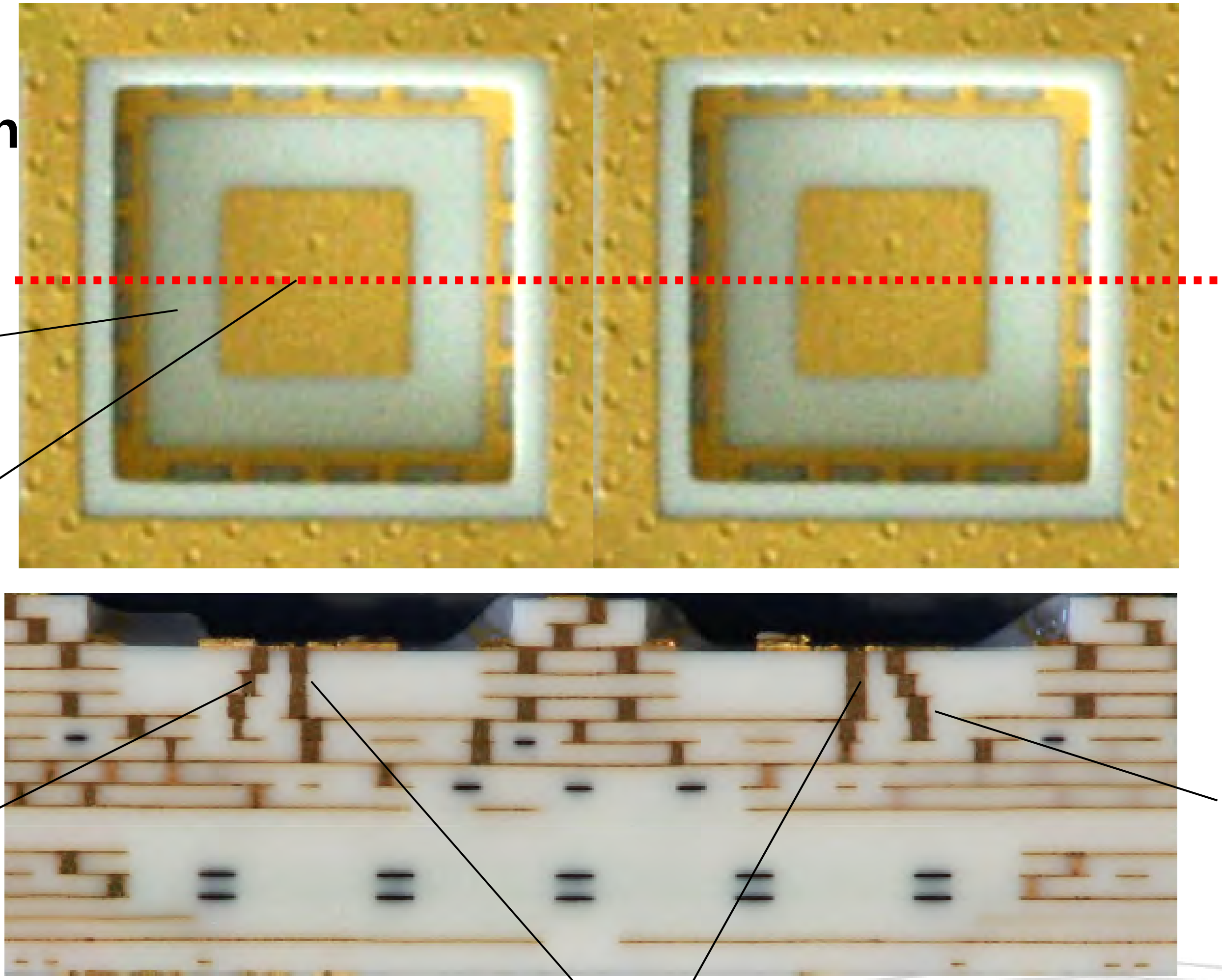


PA:
Avago AMMC-6232
~ 15 dbm – 20dbm

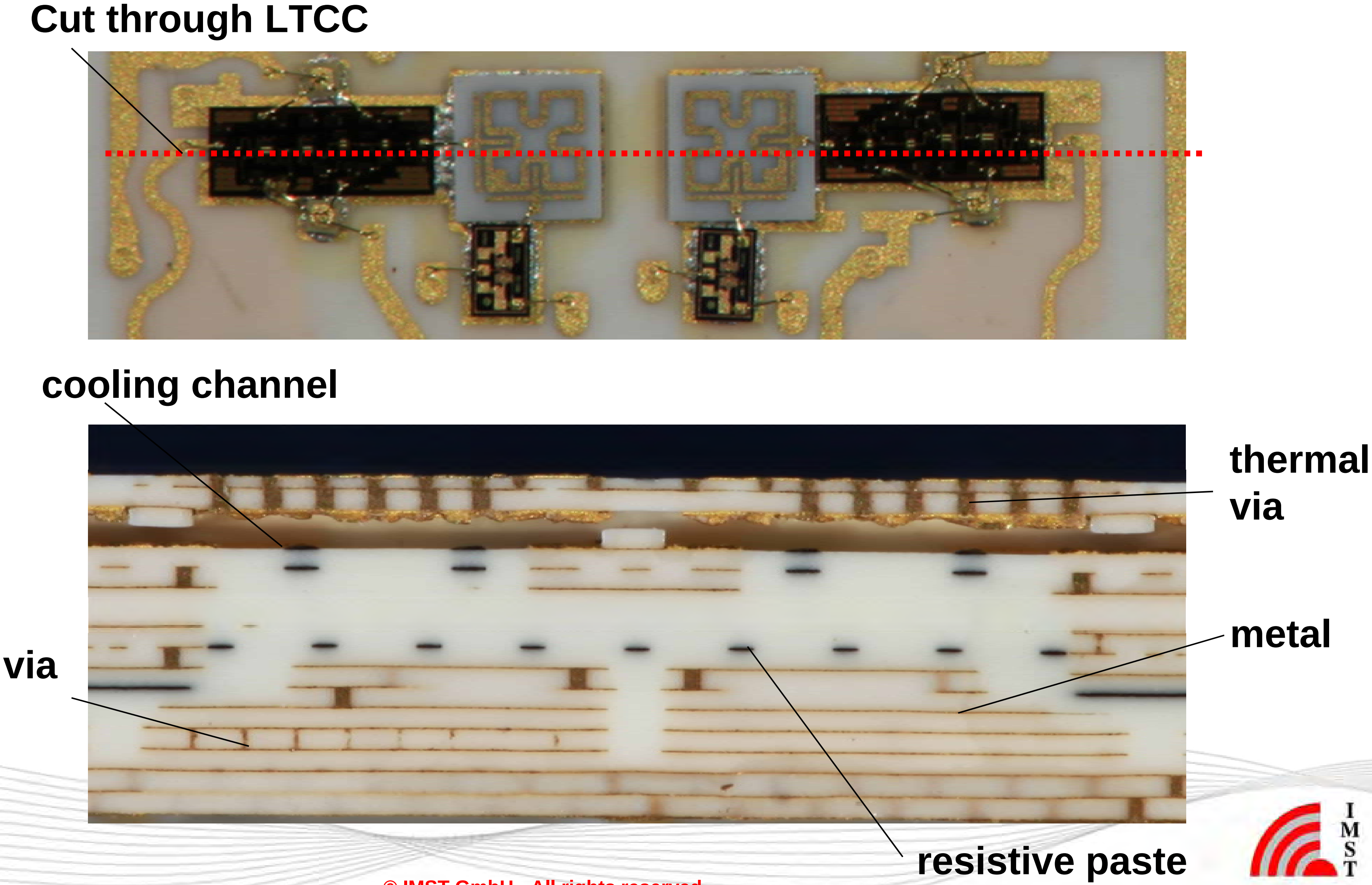
Mixer:
Hittite HMC329

IR Filter:
Specific design

Manufacturing: quality inspection (antenna side)

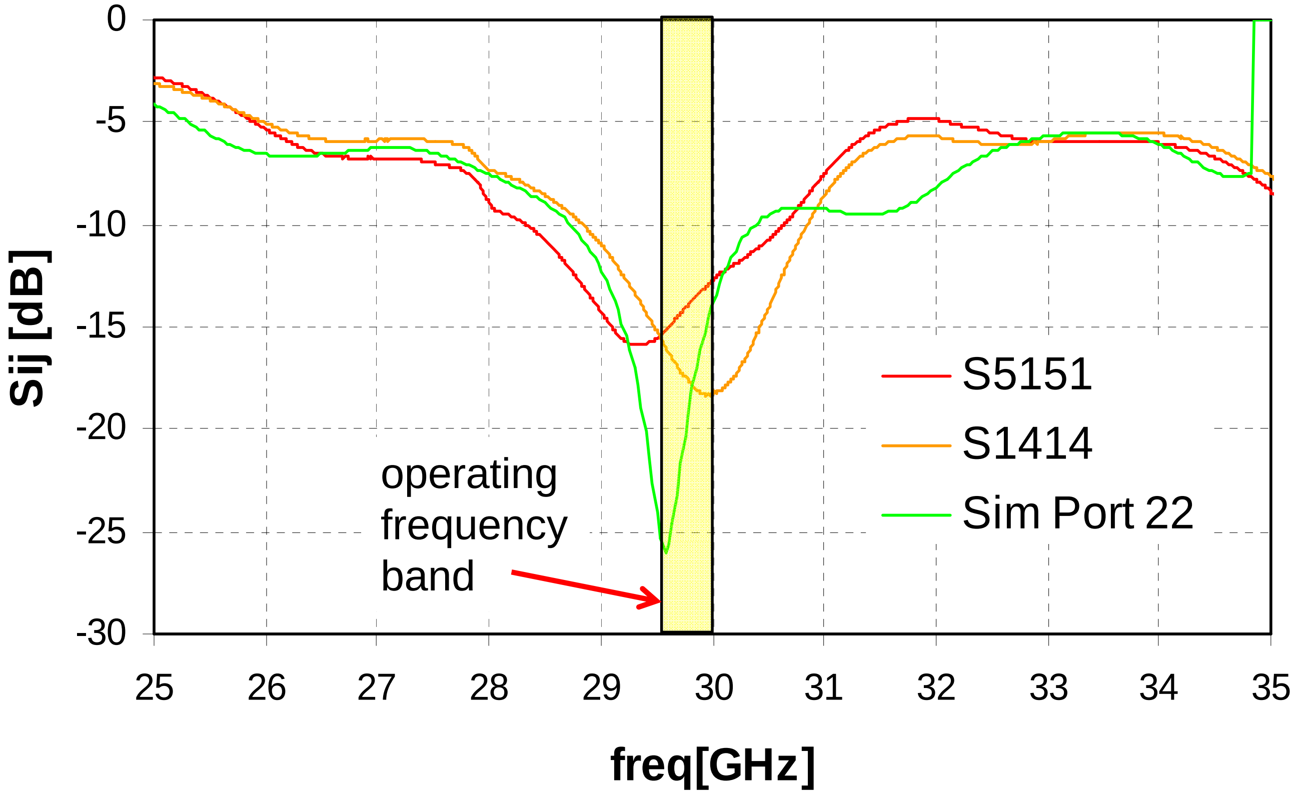


Manufacturing: quality inspection (circuit side)



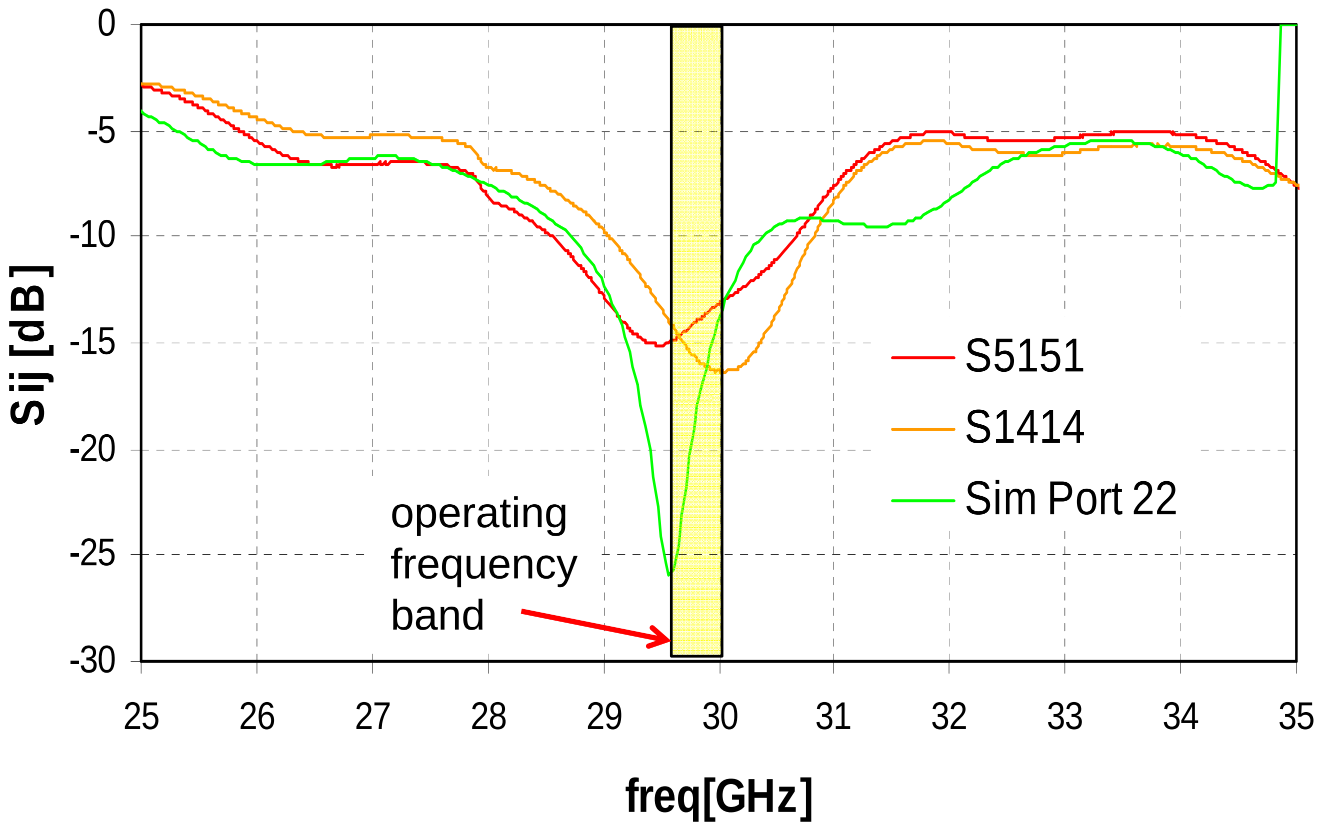
Measurements: LTCC Tile 4

- On wafer measurements of antenna ports (passive)
- Measurement of all antenna elements
- Exemplary results of 2 identical elements



Measurements: LTCC Tile 5

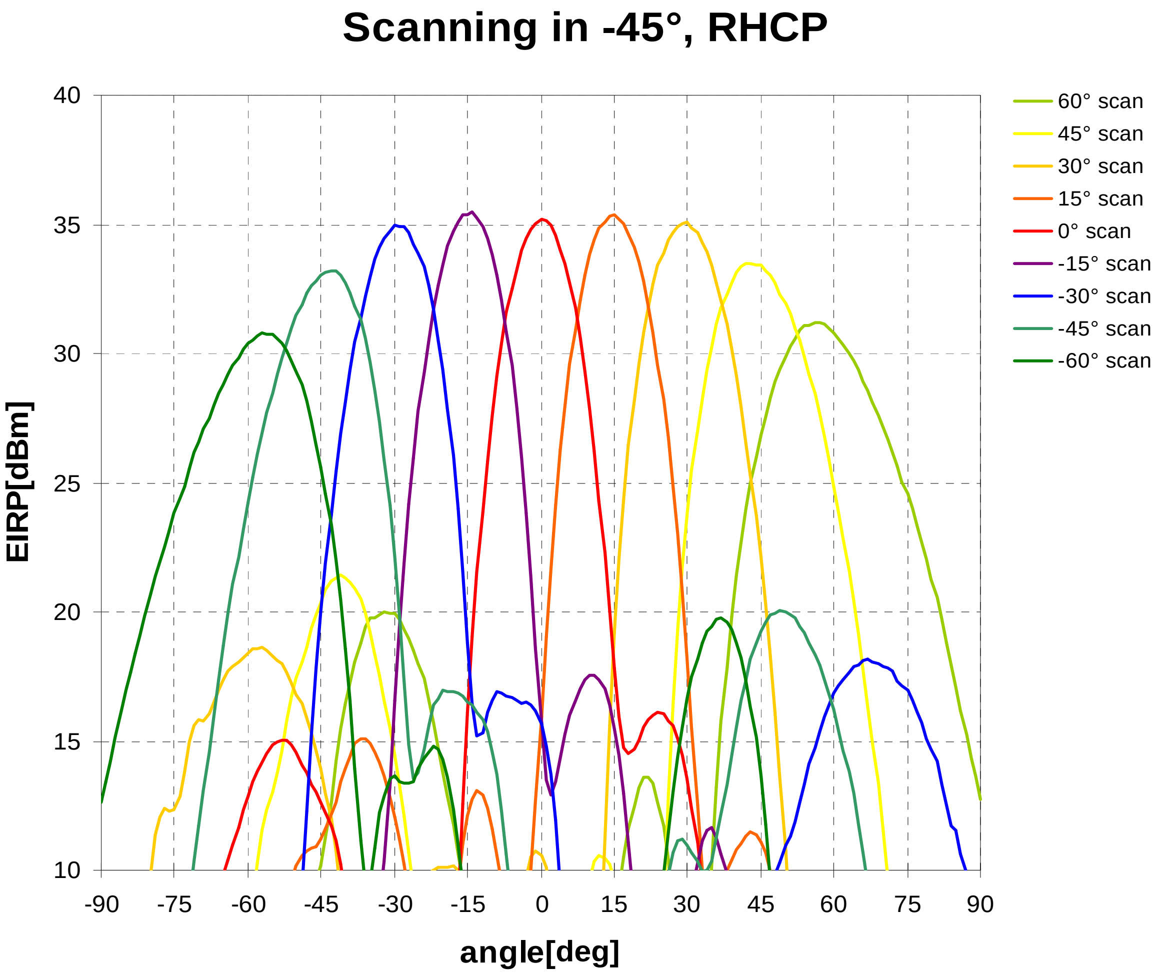
- On wafer measurements of antenna ports (passive)
- Measurement of all antenna elements
- Exemplary results of 2 identical elements



Very high reproducibility of LTCC manufacturing!

Measurements: far field (previous design)

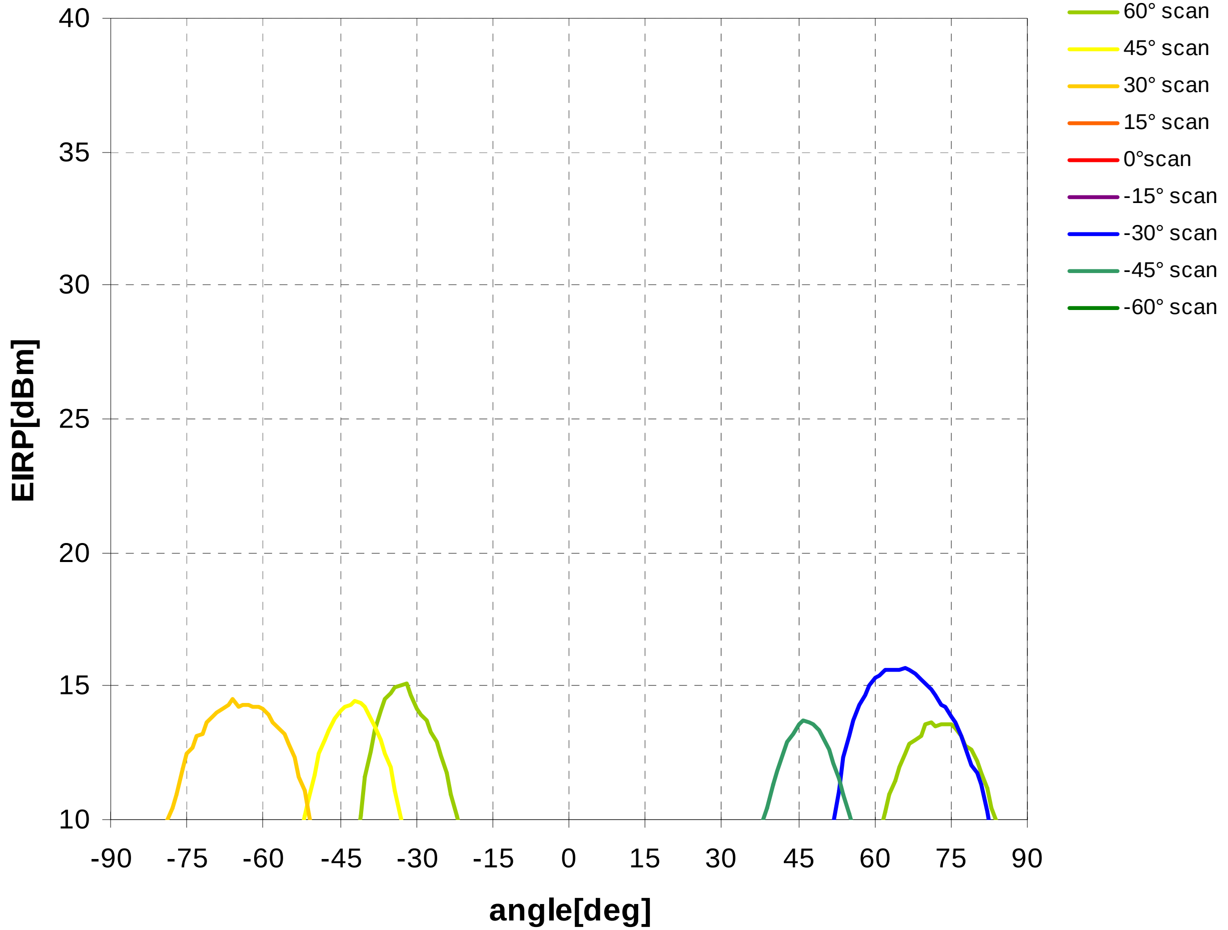
Co-Pol



Measurements: far field (previous design)

Scanning in -45°, LHCP

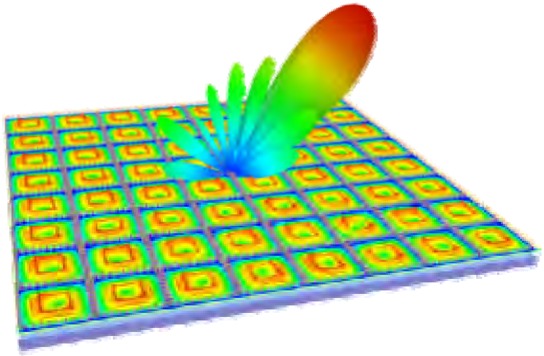
X-Pol



Conclusion

- Sucessful design of a DBF frontend module with 8x8 antenna elements
- Very high integration level of system functionalities achieved
- High integration density of RF, IF and DC circuitries requires full wave 3D EM simulation
- Successful manufacturing of multilayer LTCC tiles including cooling channels
- measurements show good RF performance as well as good agreement with simulations and very high reproducibility in LTCC manufacturing process

Acknowledgement



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