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

W. Simon, J. Kassner, O. Litschke, H. Fischer, S. Holzwarth, P. Uhlig
IMST GmbH, Germany
E-Mail: simon@imst.de
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**

**Digital BeamForming (DBF)**

- Antenna elements
- Transmit / receive circuitry
- Phase setting on baseband level

© IMST GmbH - All rights reserved
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

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 $\lambda$ forces high integration density
- different RF circuits must be integrated in a multilayer design to stay within size limits

Use of LTCC technology

Flexibility in building up arrays of different sizes
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?
## Comparison of the Methods

<table>
<thead>
<tr>
<th>Diskretization Method</th>
<th>MoM</th>
<th>FEM</th>
<th>FDTD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wires, Surfaces</td>
<td>Polyeder</td>
<td>Voxel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Tetraeder)</td>
<td>(Cubes)</td>
</tr>
<tr>
<td>Discretization Effort</td>
<td>Only Objects</td>
<td>Entire computational domain</td>
<td>Entire computational domain</td>
</tr>
<tr>
<td>Boundary Conditions</td>
<td>„built-in“</td>
<td>ABC</td>
<td>ABC</td>
</tr>
<tr>
<td>Method</td>
<td>Frequency Domain</td>
<td>Frequency Domain</td>
<td>Time Domain</td>
</tr>
<tr>
<td></td>
<td>Linear Equations (Full Matrix)</td>
<td>Linear Equations (Band Structure)</td>
<td>Iterative Calculation in Space and Time</td>
</tr>
<tr>
<td>Numerical Effort</td>
<td>~ n³</td>
<td>~ n²</td>
<td>~ n</td>
</tr>
</tbody>
</table>
# Comparison of the Methods

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

- **DUT**
- **Port**
- **Simulation Box**
- **Graded Mesh**
- **Boundary Condition**
FDTD Basics: Spatial Discretisation

Maxwell’s Equations

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

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

Spatial discretization

\[
\mu \frac{\partial \vec{H}}{\partial t} = - \frac{1}{\Delta x} \sum \vec{E}
\]

\[
\varepsilon \frac{\partial \vec{E}}{\partial t} = \frac{1}{\Delta x} \sum \vec{H} \cdot \vec{J}
\]

6 Field components per cell
Ex, Ey, Ez, Hx, Hy, Hz

 يون
Mem = 24 Byte / cell

© IMST GmbH - All rights reserved
Time discretisation for FDTD

- Initial values:
  \[ E^0, H^0 \]

- Steady state:
  \[ E^{n-1}, E^n, E^{n+1}, H^{n-1}, H^n, H^{n+1} \]

- Update equation for \( E_x \)

\[
E_x^n = E_x^{n-1} + c_k d_k \left( \Delta H_z^{n-\frac{1}{2}} + \Delta H_y^{n-\frac{1}{2}} \right)
\]

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

Time step \( \Delta t \sim \delta_{\text{min}} \)
FDTD Time step

Time Step limited by spatial resolution

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

- Mesh resolution \( \Delta \leq \lambda / 10 \)
- Classical FDTD stability criterion
- Small details: long simulation time
Time Domain Simulation: Digital Pulse

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.

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](http://www.empire.de)
KA-Band TX frontend

- IF-cable and connector calibration
- DC-connector
- IF-cable 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
- $\lambda/2$ 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

- LTCC (Ferro A6)
- cavity
- patch
- feed probes
- calibration probes
- hybrid ring
- calibration network
- RF interface (including impedance match)
- 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 element placed in cavity to reduce coupling between elements
Hybrid ring coupler

- phase shift for circular polarisation
- absorbs the coupled cross polar signal
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 RF circuitry
- integrated liquid cooling
LTCC frontend: RF circuitry architecture

- top view, partly deconstructed for insight in inner layers
- \( \frac{3}{4} \) of antenna parts removed
- \( \frac{1}{2} \) of LO network removed

![Diagram of LTCC frontend]

- Liquid cooling pipework
- Antenna elements
- LO distribution network

© IMST GmbH - All rights reserved
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 (temperature dependent resistance)
- Resistor paste to create heat
- Data interface for temperature readout
- Connection to cool system
LTCC frontend: Cool system measurement

Temperature distribution at 30,8 W heat power; 1/2 tile

- 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: E-Feld @ 30.5 GHz

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 ⇒ [Link](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
- Separate DC networks for gate and drain supply for PA
**LTCC frontend: RF chipset**

- Mixer combines 870 MHz IF and 30.6 GHz LO
- PA Output power: ~ 10 dBm

Bond wires included in simulation.
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

© IMST GmbH - All rights reserved
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

© IMST GmbH - All rights reserved
LTCC frontend: Calculated far field patterns

Co-Pol

Gain [dBi]

angle [deg]

© IMST GmbH - All rights reserved
LTCC frontend: Calculated far field patterns

X-Pol

Gain [dBi]

angle [deg]
Scanning has very low impact on reflection 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

- Squeegee
- Via Fill Paste
- Stencil
- LTCC
- Porous Stone
- Vacuum

© IMST GmbH - All rights reserved
Conductor Printing: Screen Printing

print paste on screen

squeegee action

screen

paste is forced through the screen

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

© IMST GmbH - All rights reserved
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

- LO connector (2x)
- DC connector (4x)
- IF connector
- Liquid cooling outlet
- Liquid cooling inlet
- Mixer, filter, PA (64x)
Manufacturing: RF assembly

- **PA:**
  - Avago AMMC-6232
  - ~15 dbm – 20 dbm

- **Mixer:**
  - Hittite HMC329

- **IR Filter:**
  - Specific design

Diagram:
- Mixer
- PA
- Capacitor
- Bond wire
- IR Filter
Manufacturing: quality inspection (antenna side)

Cut through LTCC

cavity

patch

antenna feed

antenna feed

short via
Manufacturing: quality inspection (circuit side)

Cut through LTCC

cooling channel

thermal via

via

metal

resistive paste
Measurements: LTCC Tile 4

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

![Graph showing Sij dB vs freq[GHz]]
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!

© IMST GmbH - All rights reserved
Measurements: far field (previous design)

Scanning in -45°, RHCP

Co-Pol

EIRP [dBm]

angle [deg]
Measurements: far field (previous design)

Scanning in -45°, LHCP

X-Pol

X-Pol

EIRP[dBm]

angle[deg]
Conclusion

• Successful 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
The authors wish to acknowledge the funding of this work within the framework of the SANTANA 3 project by the German Aerospace Center (DLR) on behalf of the German Federal Ministry of Economics and Technology (BMWi) under research contract 50YB0710.
IMST: Sophisticated technology plus broad experience

IMST GmbH is a competence centre and professional development house for high-frequency circuits, wireless modules, and communications systems. We provide individualized support to any customer during every phase of product development, from initial consulting to series production. IMST has the added resources of critical partnerships in the commercial marketplace and in the publicly sponsored research sector.

The company was founded in 1992 and currently has 145 employees in the areas:

IMST.Research: Applied research for radio communications, radar systems, microsystems and nanoelectronics.

IMST.Development: Contract-based industrial design and development, from microelectronics to product realizations in software and hardware.

IMST.Products: EDA-Electronic Design Automation Software: Empire - A full 3D electromagnetic simulation tool; wireless solutions and radio modules - customized and tailored to our clients needs.

IMST.Testing: Accredited test center for type approval, mobile terminals, antennas and RF circuits.

One of our core competencies is antenna design and development. We can elegantly integrate electronically controllable antennae for mobile satellite communication into the outer shell of vehicles, ships, and aircraft, while allowing electronically controlled repositioning of the antenna beam.

IMST is leading innovator of digital communications technology. We offer prototypes of localization and positioning systems based on ultra-wide band technology. We create solutions by designing and producing both hybrid and fully integrated circuits for our customers. IMST GmbH is certified according to ISO 9001:2008. The laboratories of the IMST test centre are accredited according to DIN EN ISO/IEC 17025.

For more information visit www.imst.com.