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46TH EUROPEAN MICROWAVE CONFERENCE 2016
The 46th European Microwave Conference

New Developments for Satellite Communications on the Move

WM07

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Slide 1

Active Multiple Feed per Beam SatCom Antennas with GaN SSPA at K-Band

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Outline

- **Introduction**
- **MFB Architectures**
- **GaN Power Amplifiers**
- **Power Amplifier Integration**
- **Conclusion**

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- GaN Power Amplifiers
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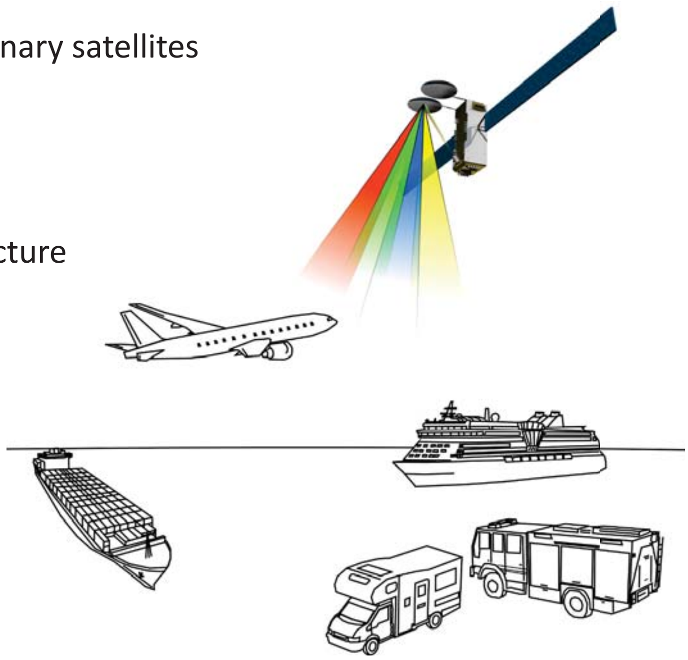
Motivation

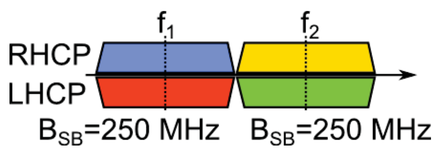
- Technology for active feeds for geostationary satellites
- K/Ka-band

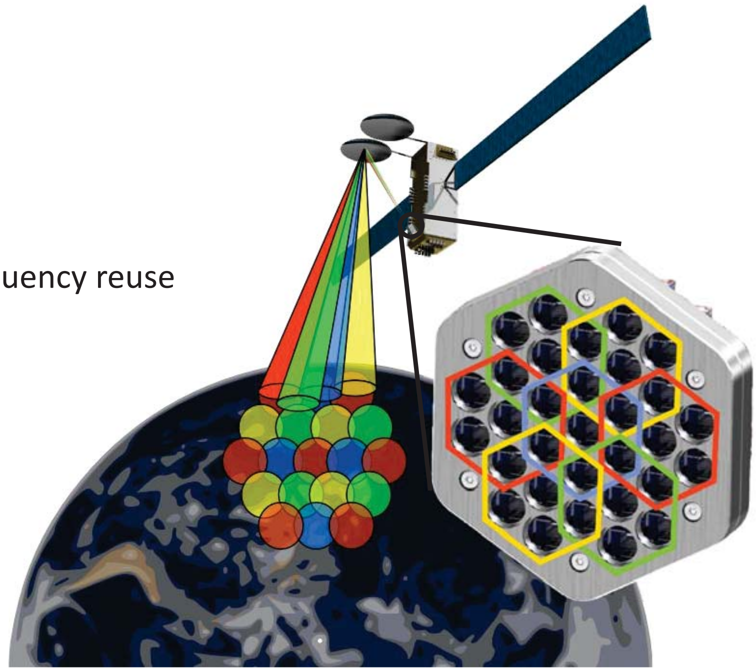
- Users
  - Independent of terrestrial infrastructure
  - Airplanes
  - Ships (cruise liners or cargo vessels)
  - Camper, mobile homes
  - Disaster management
  - Rural / lower developed regions



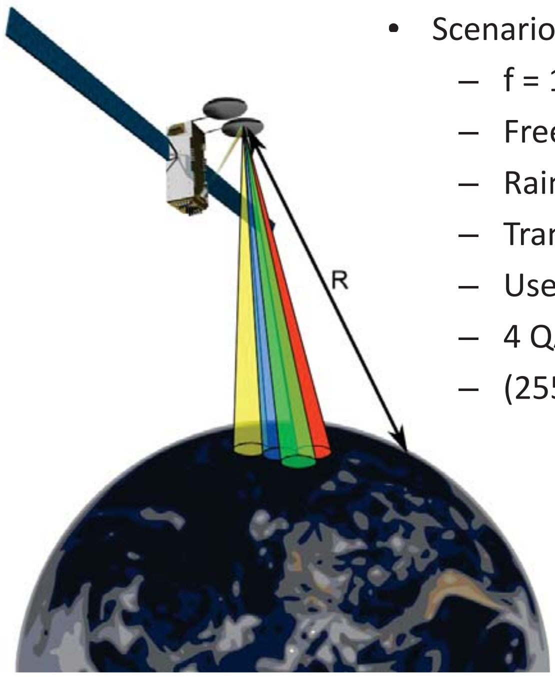
Multiple-Feed-per-Beam

- High-throughput satellite
  - Multispot-beam
  - Four color scheme
  - High gain antenna
  - ➔ Higher capacity through frequency reuse
- Multiple feed per beam
  - Overlapping beams
  - Shared feed antennas





Link Analysis

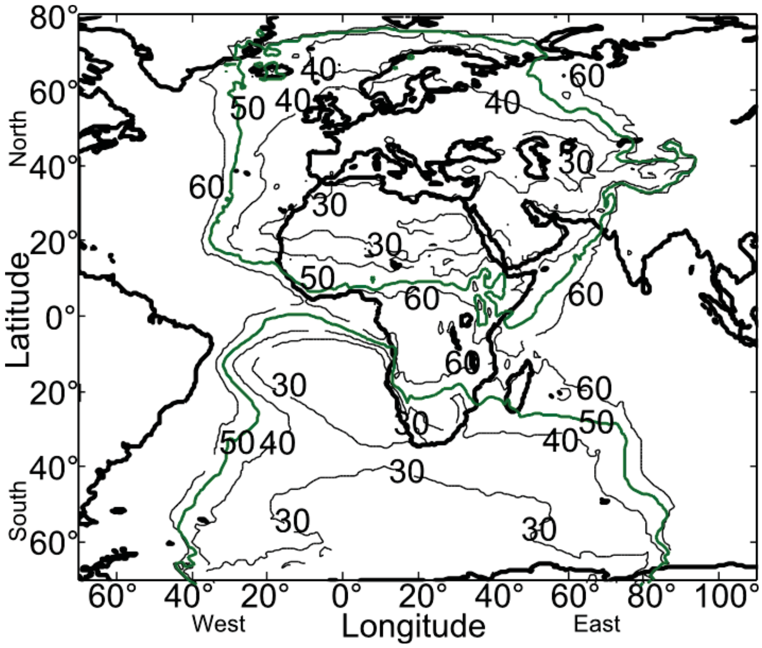


- Scenario
  - f = 19GHz, B = 250 MHz
  - Free space loss: distance 35,700 km < *R* < 41,700 km
  - Rain attenuation (ITU-R P.618-10)
  - Transmit antenna gain: G_{TX} > 42 dBi
  - User terminal: G/T ≈ 20 dB/K
  - 4 QAM modulation
  - (255,233)-RS coding

Required Power

- 99.5% availability (2 days p.a.)
- Here:
  - EOC-gain
  - Full bandwidth used

- 50 W per beam
- Adaptive coding & modulation can increase availability



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Beam Performance

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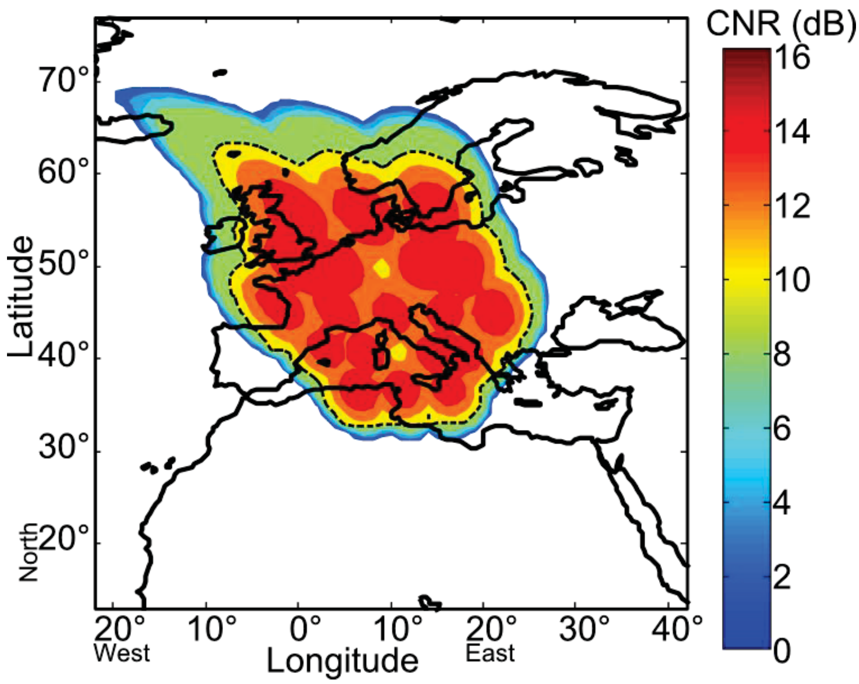
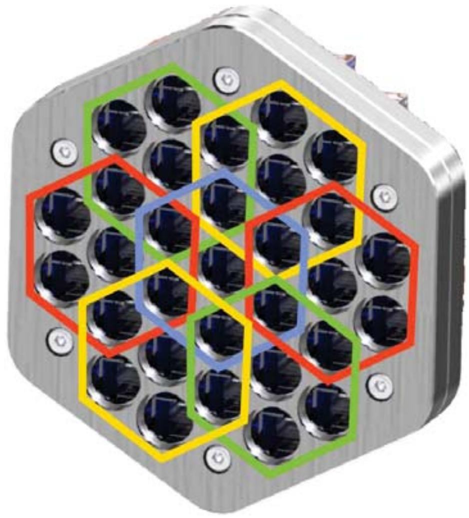
- Example: 19 beams
- P_{beam} = 50 W
- CNR = 10.5 dB required



Results

- Approx. 50 W per beam required
- 7 feeds per beam
- 7.1 W per feed
- Shared PAs for shared feeds

➔ SSPAs in GaN technology



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Architecture Considerations

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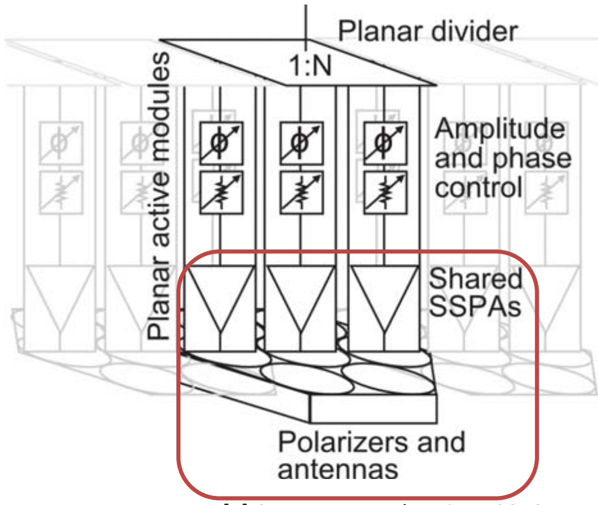
- SSPAs directly at antenna ports
- High power region (antennas, polarizers): waveguide technology
  - Low loss
  - High power handling capability



[1] C. Rave, A. Jacob: MiKon 2016

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Architecture Considerations

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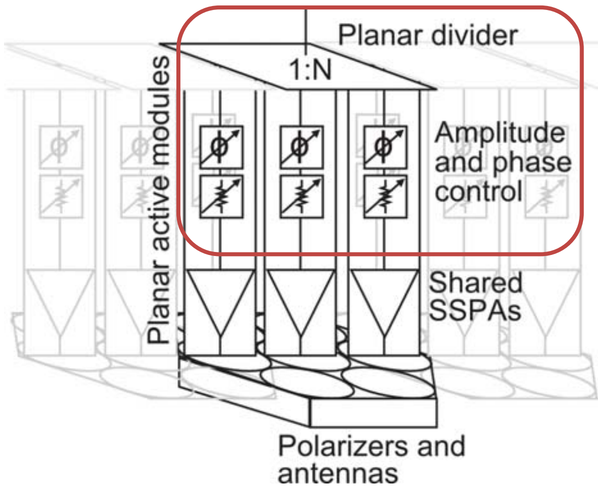
- Low power region (beam forming network): planar technology
  - Low impact on total efficiency
  - Low heat, relaxed thermal management
  - PCB technology: small form factor, light weight
- Phase and amplitude control
  - Reconfigurable feed
  - Reflector steerable



[1] C. Rave, A. Jacob: MiKon 2016

Radial Divider

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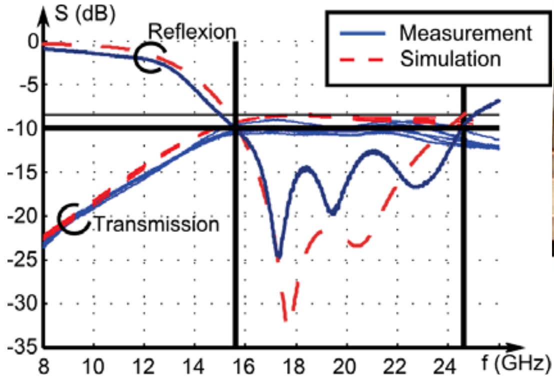
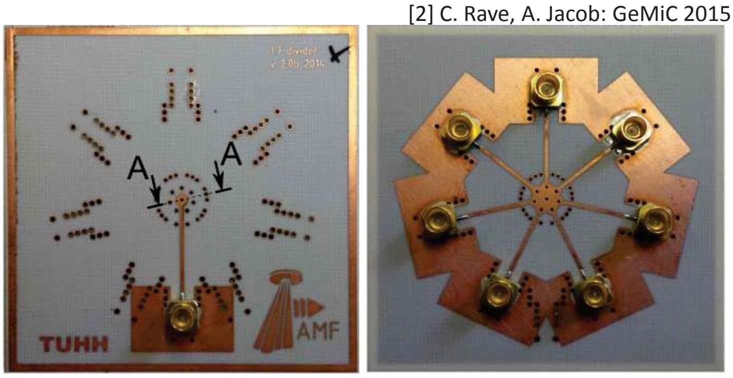
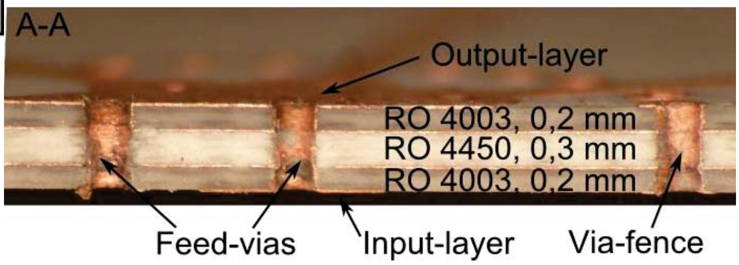
- 1:7 power divider
- Planar technology
  - ø=7mm
  - h=0.5mm
- 9 GHz bandwidth
- < 3.4 dB loss



[2] C. Rave, A. Jacob: GeMiC 2015





Multifeed Setup

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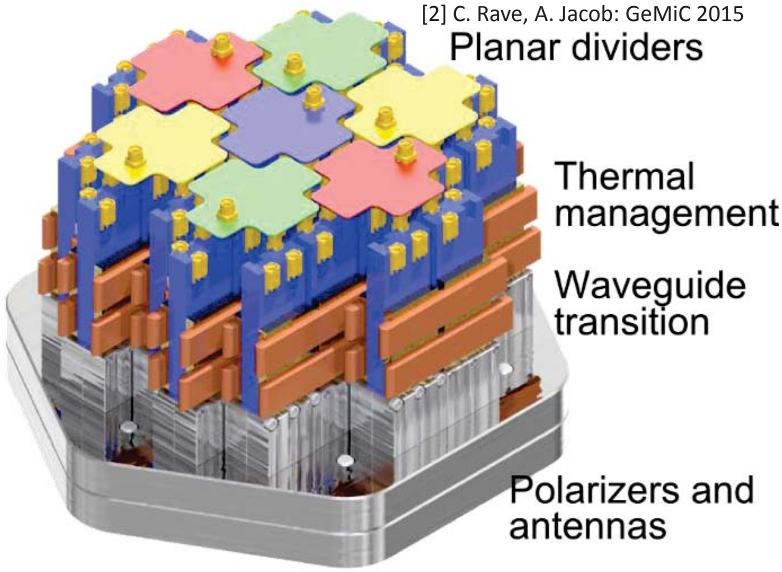
[2] C. Rave, A. Jacob: GeMiC 2015



[3] C. Rave et al.: ESA Workshop on Advanced Flexible Telecom Payloads, 2016

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GaN SSPA

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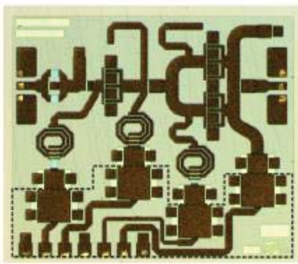
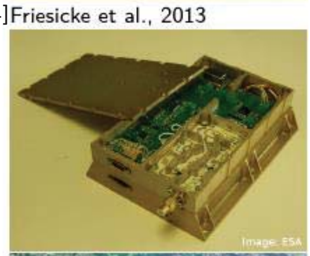
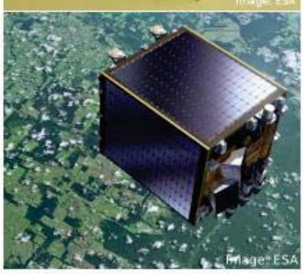
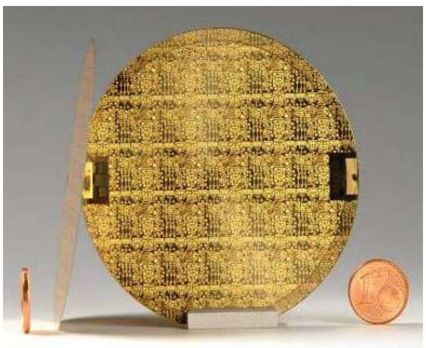
- Watt-level output powers at K-band demonstrated with GaN
- Reliability evaluated and improved (ESA GREAT^2)
- X-band transmitter on Proba-V
- European GaN process for space needed



[4]Friesicke et al., 2013







GaN SSPA Design for SatCom

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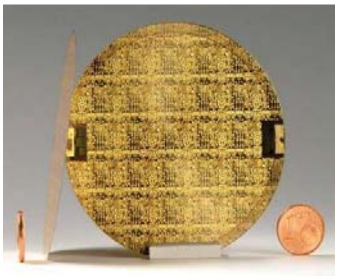
- SSPA output power requirement depends on the active antenna architecture
- Demonstrator designs:
  - 1-5 W for high element count arrays
  - 5-10 W for lower element count, MPMs
- TTC applications with large ground segment antennas require lower radiated powers → GaN MPMs

- Technology: Fraunhofer IAF 250 nm AlGaN/GaN on SiC
  - Breakdown voltage > 120 V
  - f_t > 28 GHz
  - f_{max} > 60 GHz
  - P_{out} = 5 W/mm @ 10 GHz



GaN SSPA – 4 W

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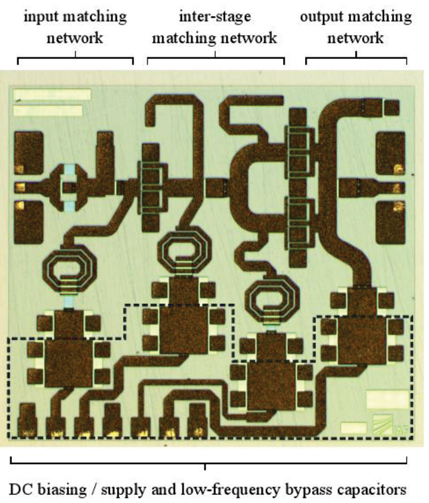
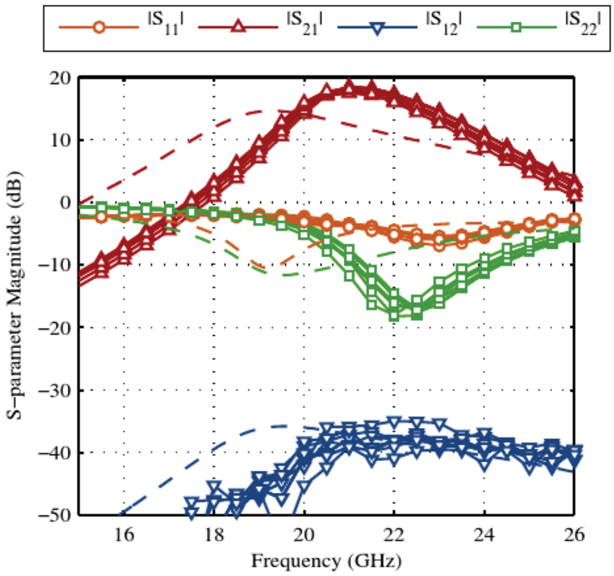
- 4 W demonstrator design
- Ongoing: integration

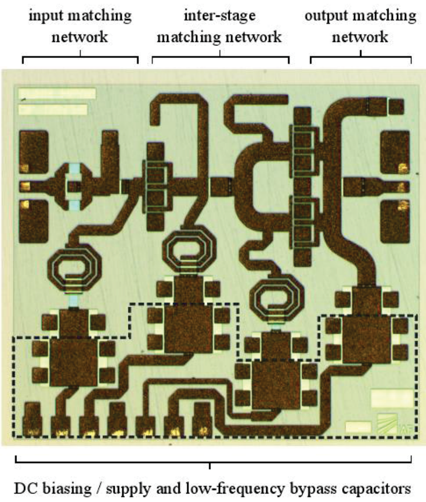


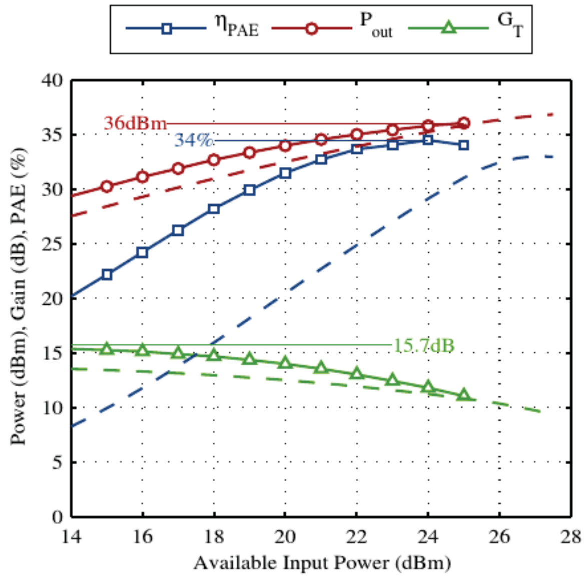


[4] C. Friesicke et al.: *A Linear 4W Power Amplifier at K-Band Using 250nm AlGaN/GaN HEMTs*, 8th European Microwave Integrated Circuits Conference, 2013

GaN SSPA – 4 W

- 4 W demonstrator design
- Ongoing: integration

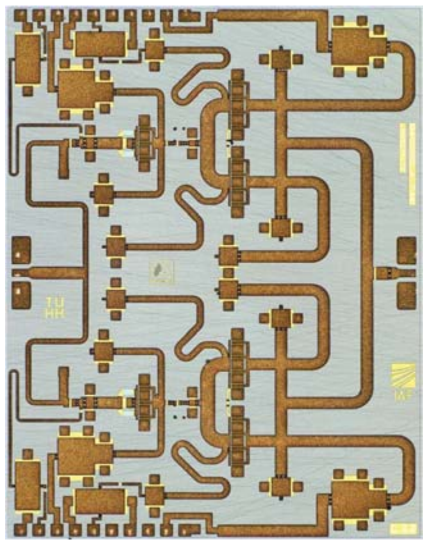




[4] C. Friesicke et al.: *A Linear 4W Power Amplifier at K-Band Using 250nm AlGaN/GaN HEMTs*, 8th European Microwave Integrated Circuits Conference, 2013

GaN SSPA – 10 W

- Demonstrator developed in LEVERAGE/LEVERAGE-2 projects
- Two-stage design with aggressive staging ratio
- Design targets for matching: high PAE
- 2nd harmonic termination for final stage
- Ongoing: demonstrator integration

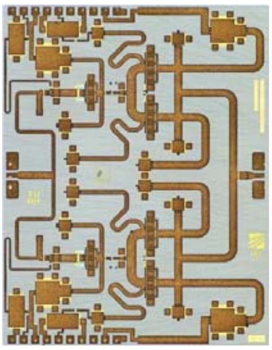


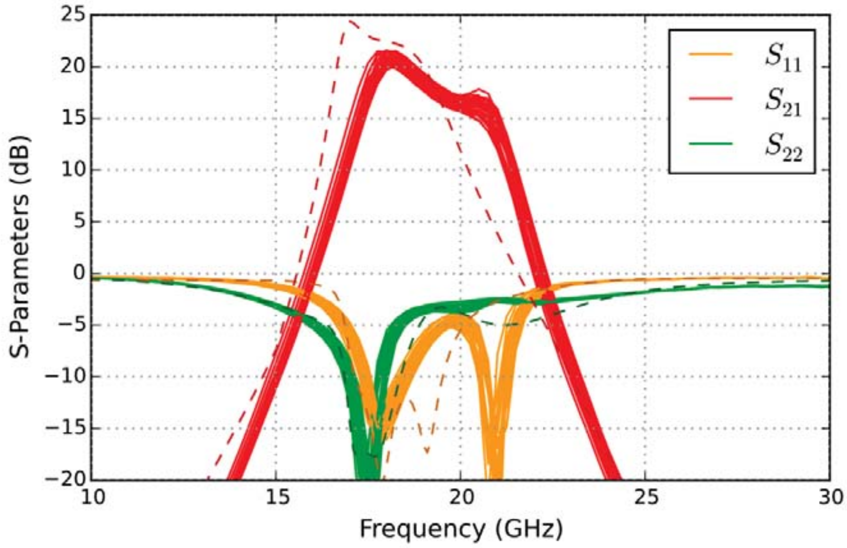
[5] C. Friesicke et al.: *A 40 dBm AlGaN/GaN HEMT Power Amplifier MMIC for SatCom Applications at K-Band*, International Microwave Symposium 2016

GaN SSPA – 10 W

Measurements – Small Signal

- More than 20 dB gain @ 18.2 GHz
- 30/37 cells of 4" wafer
  - Very good yield and homogenity





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GaN SSPA – 10 W

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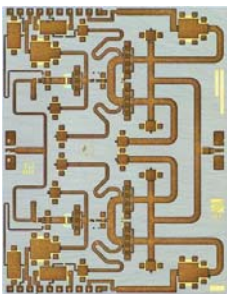
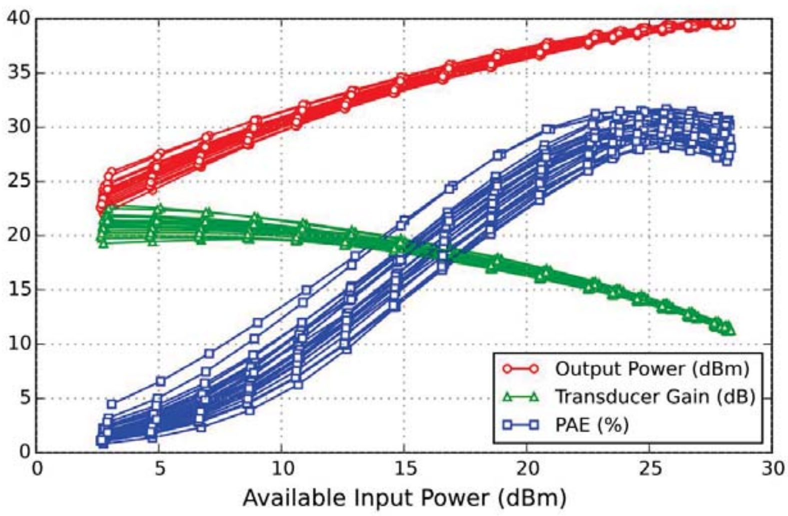
Measurements – Large Signal

- P_{sat} between 39.6 and 40 dBm
- (between 9 and 10 W)
- Power density > 3 W/mm
- Peak PAE between 28 and 32 % (@7.5 dB compression)
- Large signal gain 13.5 dB





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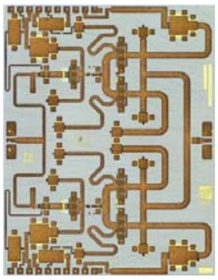
State of the Art

Frequency	Power	PAE	Lin. Gain	Technology	Ref. / Year
21 – 23 GHz	37 dBm	48%	16.7 dB	.15 µm GaN	[6] (2012)
20 GHz	33 dBm	40%	11 dB	.25 µm GaN	[7] (2012)
22 GHz	36 dBm	34%	16 dB	.25 µm GaN	[4] (2013)
18 – 20 GHz	31 dBm	22%	20 dB	.25 µm GaN	[8] (2014)
2 – 18 GHz	37 dBm	20%	22 dB	.15 µm GaN	[9] (2014)
6 – 18 GHz	40 dBm	15%	20 dB	.15 µm GaN	[10] (2015)
18 – 19 GHz	40 dBm	30%	20 dB	.25 µm GaN	[5] (2016)

Not many published GaN HPAs at lower K-band

- [6] 5 Watt Doherty by TriQuint/Qorvo → already mid K-band
- [9], [10] are TWAs by TriQuint/Qorvo → optimized for bandwidth, not PAE
- [4], [7], [8] are previous results from TUHH / Fraunhofer IAF



[5] C. Friesicke et al.: *A 40 dBm AlGaN/GaN HEMT Power Amplifier MMIC for SatCom Applications at K-Band*, International Microwave Symposium 2016

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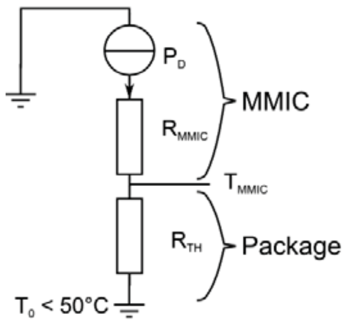
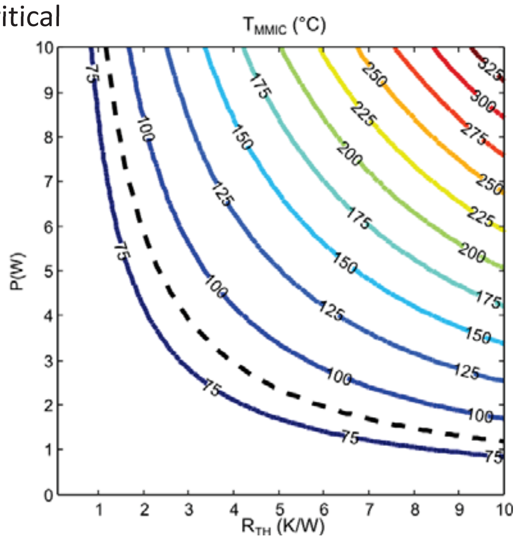
PA Integration

- GaN power amplifier
  - Moderate efficiency (η_{PAE}=0.2 .. 0.4)
  - Thermal management, thermal expansion critical





➔Multiple MMICs, power combining

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Thermal Management

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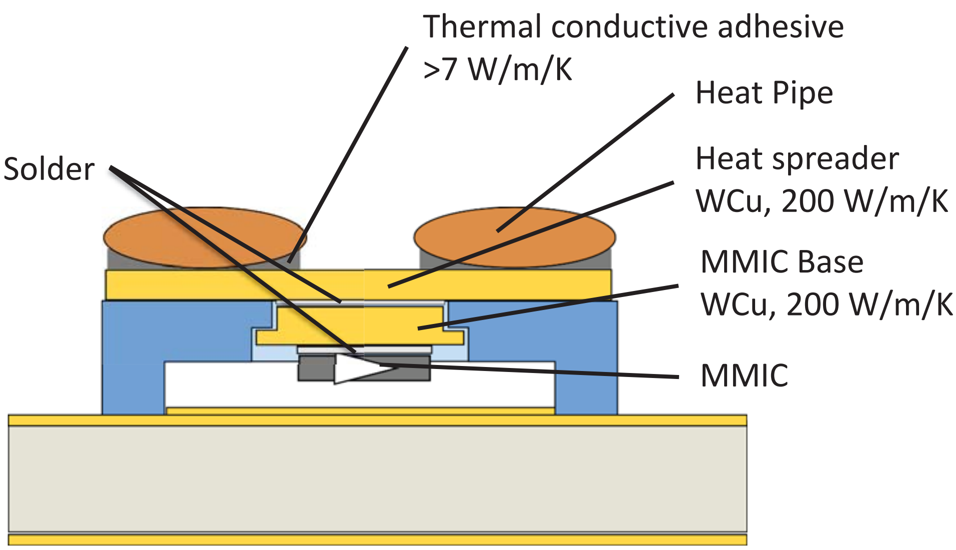
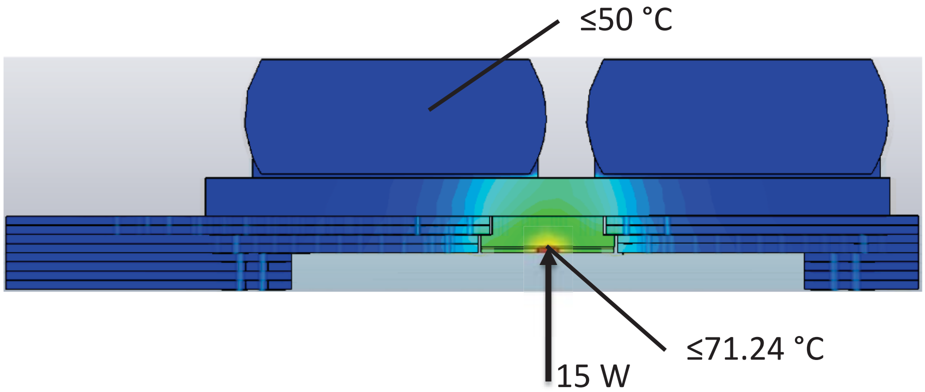
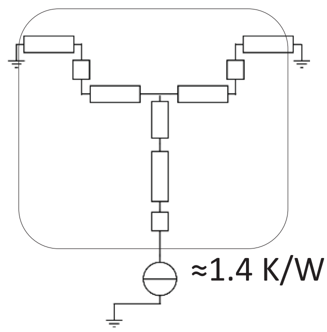


Thermal Analysis





Measured ≈ 1.45 K/W

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Conclusion

- High throughput satellite
  - Multi spotbeam, frequency reuse
  - Multiple feed per beam antenna
  - Low power per feed allows for use of SSPA technology
- GaN SSPA technology
  - 4 W and 10 W demonstrated
  - Peak PAE > 30 %
- SSPA integration
  - Thermal management concept

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DLR

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- [9] *TGA2214: 2 to 18 GHz 5 Watt GaN Power Amplifier*, Triquint, 2014, Preliminary Datasheet.
- [10] *TGA2574: 6 to 18 GHz 10 Watt GaN Power Amplifier*, Triquint, 2015, Datasheet.

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mmW solutions. Enabling a new world

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Highly Integrated 20GHz/30GHz QFN Packaged ICs for Low-Cost SATCOM AESAs

October 2016

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1

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Purpose of Presentation

- SATCOM applications can benefit from AESA (Active Electronically Steered Antenna) technology
- Overview of AESA fundamentals and challenges
- Show how planar solutions at 20/30 GHz require increased functional integration
- Illustrate how the capability of silicon technologies can provide a platform for this integration, and in doing so, enable other enhanced performance possibilities
- Show examples of SATCOM ICs that demonstrate the requisite functions for successful deployment of mmW AESAs

2

mmW solutions. Enabling a new world

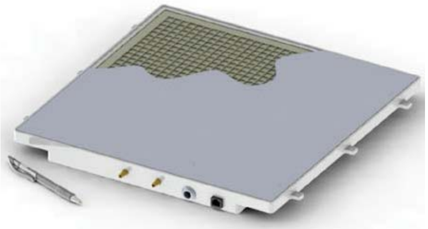
Multiple SATCOM Applications Can Benefit from AESA Technology

- Fixed UTs that auto-point at GEO satellites
- Fixed UTs that track MEO/LEO satellites
- Mobile UTs that track GEO/MEO/LEO satellites
- Feed arrays that illuminate reflector antennas

3

mmW solutions. Enabling a new world

Why mmW AESAs for SATCOM?



- AESA advantages
  - No moving parts, high reliability
  - Soft failure mechanism
  - Low profile, small size and lightweight
  - Flexibility to meet regulatory compliance (sidelobes, etc.)
- mmW AESAs
  - Short wavelengths mean many antenna elements can be located in compact, highly directive apertures

4

mmW solutions. Enabling a new world

AESAs for Emerging SATCOM Applications

- AESAs traditionally use brick type TRMs installed orthogonally to the array
  - MMIC/discrete-hybrid assemblies in machined metal enclosures, with
  - Expensive and bulky (size, weight)
  - Limit the range of platforms and compromise performance for antenna size/gain/rotation
- Planar solutions have ICs mounted in the same plane parallel to the array using all SMT assembly
  - Lower profile antenna - reduced wind drag and detectability
  - Lower size and weight for tower mounting and smaller platforms (UAV)
- Lower cost – enabling new applications
  - Next generation SATCOM
  - Commercial radar
  - 5G terminals

5

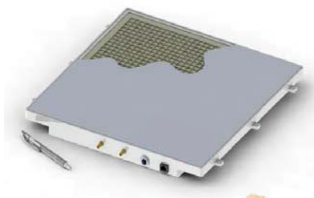
mmW solutions. Enabling a new world

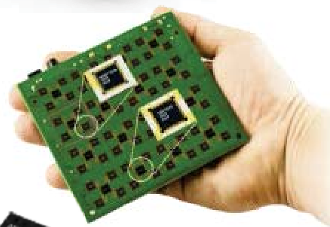
Silicon Enables Low Size, Weight, & Cost AESAs

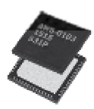
Traditional Hermetic Tx/Rx Modules
with GaAs/GaN chip and wire assembly

95% Cost Reduction

90% Weight Reduction







SATCOM planar solutions

6

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SATCOM AESA Considerations

7

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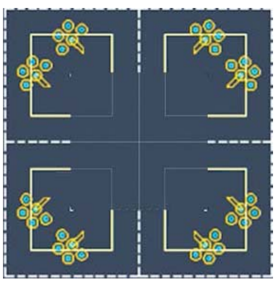
AESA Lattices at 20/30 GHz

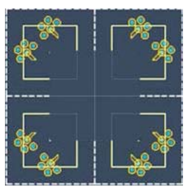
- λ/2 lattices at SATCOM 20/30 GHz are quite small
- The only way to have planar AESAs at these frequencies is to fit the electronics within the lattice using <u>highly integrated silicon ASICs</u>

K-Band (20 GHz)



7.5 mm

Ka-Band (30 GHz)



5.0 mm

8

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mmW solutions. Enabling a new world

G/T for Receive AESAs

- G/T is a figure of merit for a receiver
- More difficult to achieve good G/T for a receive array than EIRP for a transmit array
  - G/T follows 10*log(N) while EIRP follows 20*log(N)
- G/T equation
  - $4\pi Ae/\{\lambda o^2 * [Tsky + To(F^* \, L_{OHMIC} - 1]\}$
  - Good G/T requires low system NF and place receiver as close to the elements as possible

- Where
  - N = number elements
  - Ae = effective radiating area
  - λo = free space wavelength
  - F = receiver noise factor
  - L_{OHMIC} = feed loss
  - Tsky = sky temperature
  - To = 290 degK

AESA ICs mounted at the radiating elements provide lowest feed loss and maximum G/T

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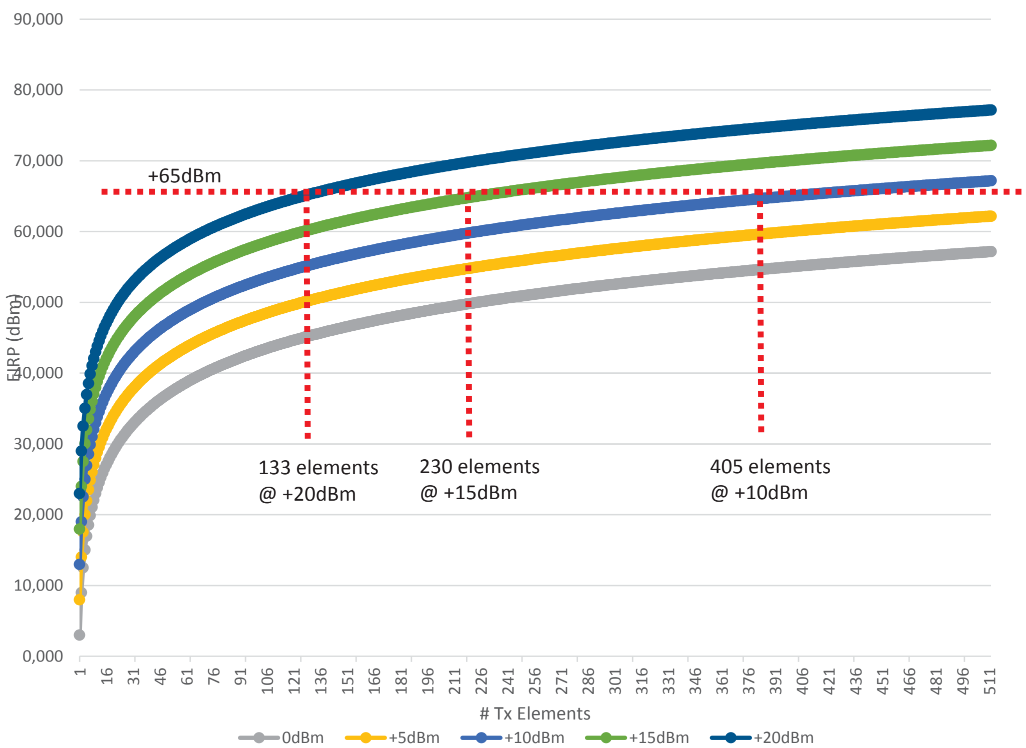
mmW solutions. Enabling a new world

EIRP vs. Conducted Power/Element



10

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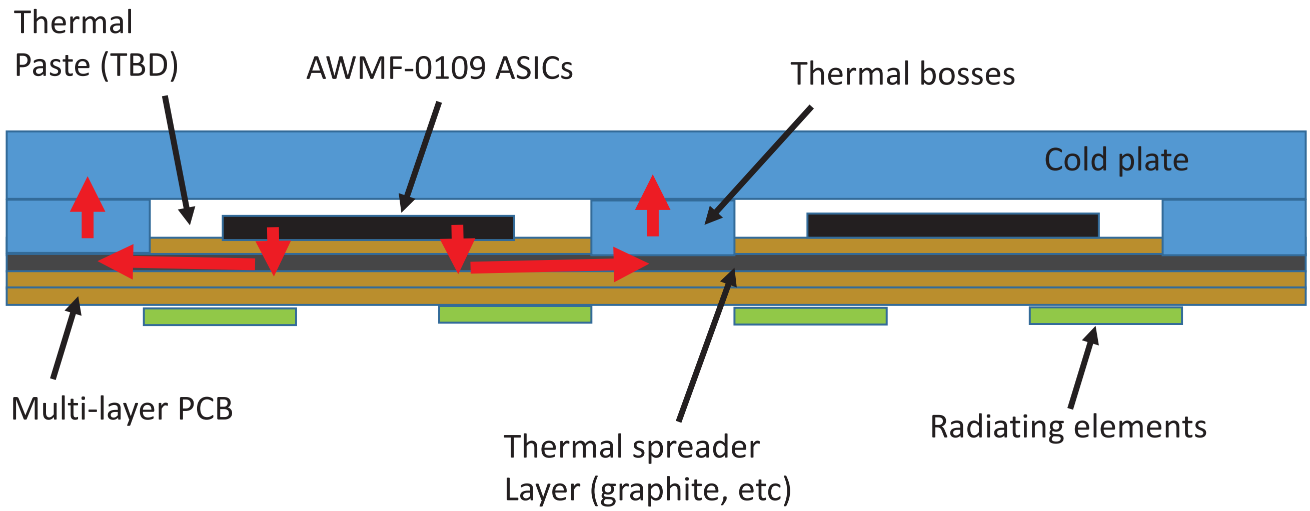
AESA Mechanical Construction



- Heat flows into PCB
- Lateral heat spreader in PCB
- Thermal bosses remove heat from PCB thermal spreader

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So How Can Highly Integrated Silicon ASICs Help SATCOM AESAs?

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Silicon Integration Benefits

- High-density integration combines mmW, analog, and digital control functions on a single IC:
  - ICs fit within the lattice for lowest feed loss
    - Highest G/T and EIRP
  - Simple serial control interface (SPI) reduces signal routing
  - High quality telemetry can be sampled, digitized on-chip, and reported to the host system via the serial interface

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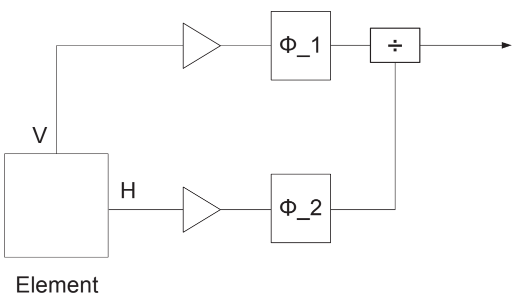
Flexible Polarization in SATCOM Silicon AESA ASICs

Circular polarization:
Element provides spatial orthogonality
Silicon provides electrical orthogonality



ϕ_1	ϕ_2	Pol
Θ	Θ + 90°	RHCP
Θ	Θ - 90°	LHCP
Θ	Θ	Slant Linear-H
Θ	Θ ± 180°	Slant Linear-V

Polarization can be fully programmable in silicon AESA ASICs

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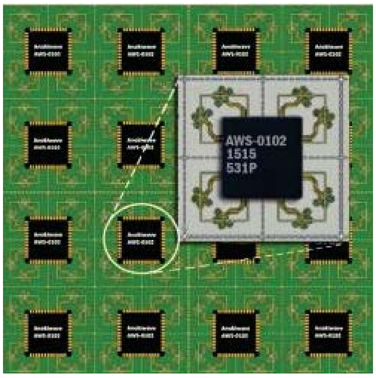
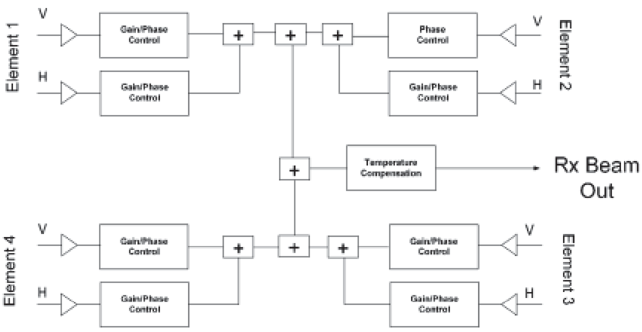
K-Band SATCOM Rx Quad Core IC

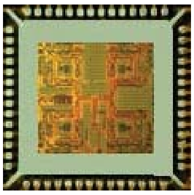


64 Element K-Band Array Using Anokiwave Quad Core Rx SATCOM IC



<u>AWS-0102</u>
<u>AWMF-0112</u>
Quad Core IC
7x7mm QFN

5a991.f



- 17.7 - 20.2 GHz operation
- Polarization flexible (selectable RHCP, LHCP, linear)
- 22 dB gain/channel
- 3.4 dB NF
- Quad or Octal Configuration
- 5 bit gain/phase control

Enables Low Cost All Silicon SATCOM Planar Arrays

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K-Band SATCOM Rx Quad Core IC

- 17.7-20.2 GHz Rx only
- Supports 4 antenna elements
- Polarization flexible (RHCP, LHCP, linear)
- 22 dB gain, 3.4 dB NF
- 5 bit phase control (LSB=11.25 deg)
- 5 bit gain control (0-15.5 dB, LSB=0.5 dB)
- Temperature sense and report to host system
- Temperature compensated gain
- DC power: 0.3W

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mmW solutions. Enabling a new world

Multiple Data Slides

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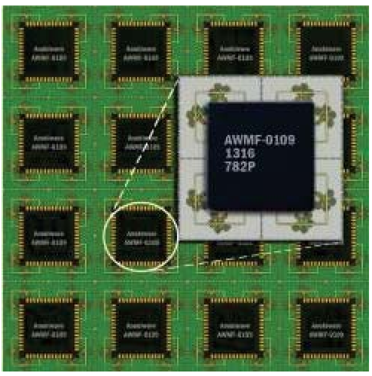
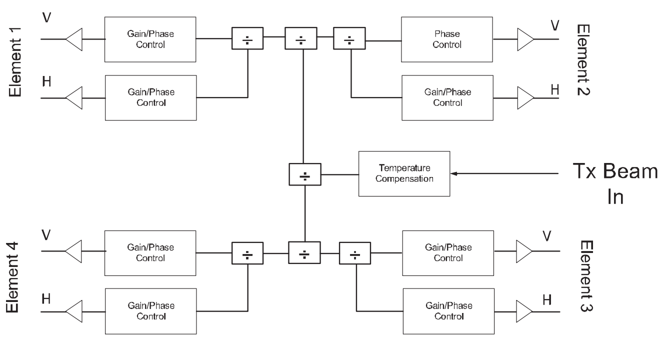
Ka-Band SATCOM Tx Quad Core IC





AWMF-0109
AWMF-0113
Quad Core IC
6x6 mm QFN

5a991.f

64 Element Ka-Band Array Using Anokiwave Quad Core Tx SATCOM IC

- 27.5 – 30.0 GHz operation
- Polarization flexible (selectable, RHCP, LHCP, Linear)
- 22 dB gain/channel
- +12 dBm output power per output port
- Quad or Octal Configuration
- 5 bit gain/phase control

Enables Low Cost All Silicon SATCOM Planar Arrays

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mmW solutions. Enabling a new world

Ka-Band SATCOM Tx Quad Core IC

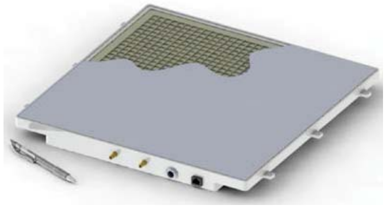
- 27.5-30.0 GHz Tx only
- Supports 4 antenna elements
- Polarization flexible (RHCP, LHCP, linear)
- 22 dB gain, +12 dBm OP1dB
- Output power detect and telemetry
- 5 bit phase control (LSB=11.25 deg)
- 5 bit gain control (0-15.5 dB, LSB=0.5 dB)
- Temperature sense and telemetry
- Temperature compensated gain
- DC power: 0.9W (q) 1.35W (P1)

mmW solutions. Enabling a new world

Multiple Data Slides

mmW solutions. Enabling a new world

Conclusion



- AESAs highly useful for variety of SATCOM applications
- 20/30 GHz AESAs pose challenges (G/T, lattice, etc.)
- Silicon technology is the key to enabling planar AESA solutions at 20/30 GHz
  - Low profile planar solutions for lower size, weight, cost
- Quad core IC data was presented that demonstrates the requisite functions for successful deployment of mmW AESAs

mmW solutions. Enabling a new world

Thank You !

Wide-angle scanning phased array antennas at Ka band

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EuMW 2016
Microwaves Everywhere

Outline

- Motivation
- Requirements for Satcom on the move (SOTM) at Ka-band
- Phased array fundamentals
- Dual-polarized cavity antenna
- Dual-polarized stacked patch antenna
- System architectures for phased array antennas
- Active reflectarray demonstrator
- References

Motivation

- Increasing demand for broadband mobile SATCOM links at Ka band

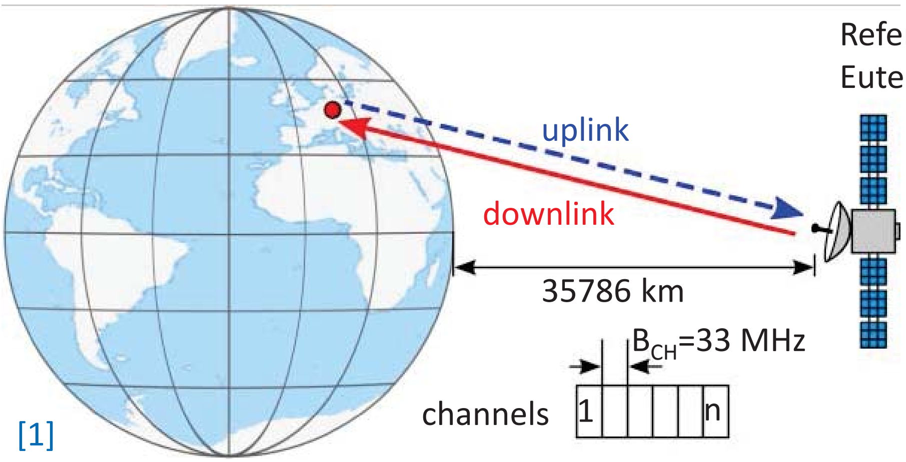
enables

  - High speed internet services
  - Voice communication
  - Real-time air-traffic management
  - Safety & security services

Objectives:

- Array architecture for up- and downlink at 30 / 20 GHz
- Low profile & lightweight architecture
- Flexible and scalable system design
- 2D electrical beam steering up to 60°

Satcom requirements – scenario



Reference scenario based on Eutelsat Hot Bird 6 (13° E)

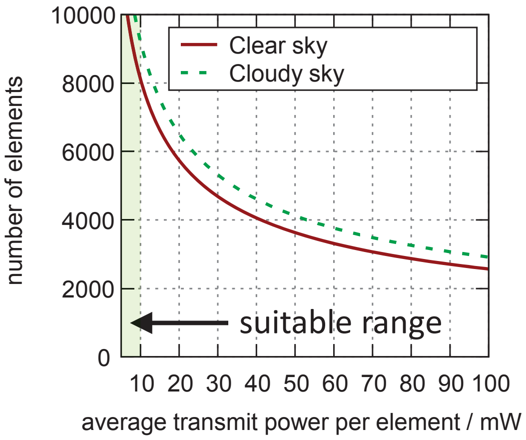
EIRP=57 dBW
G/T=14 dB/K
SNR=10 dB

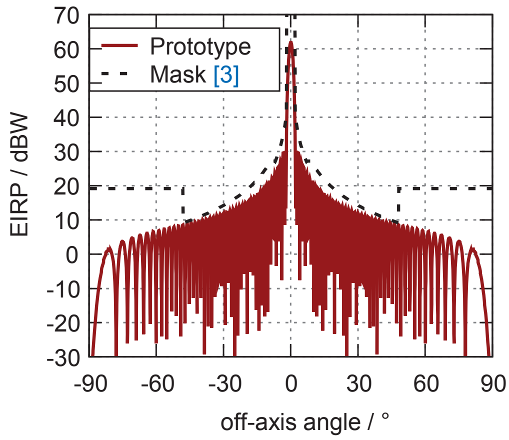
Satcom using geostationary orbit (GEO)

Further reading: [2]

- Continuous coverage of specific region by only 1 satellite
- Path losses are significantly higher as for lower orbits
- Terminal requires precisely adjustable radiation characteristic (2° orbit spacing)

Satcom requirements – TX

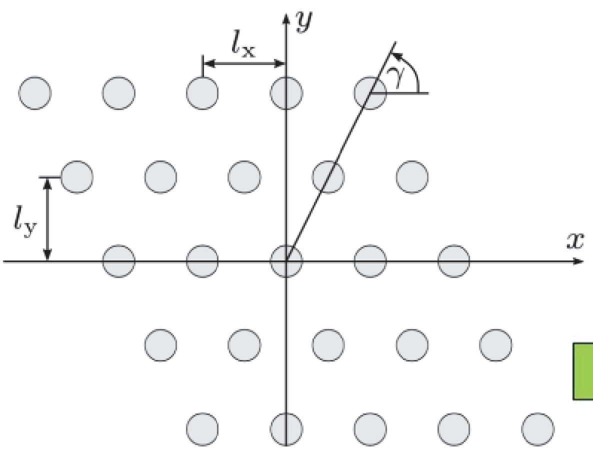




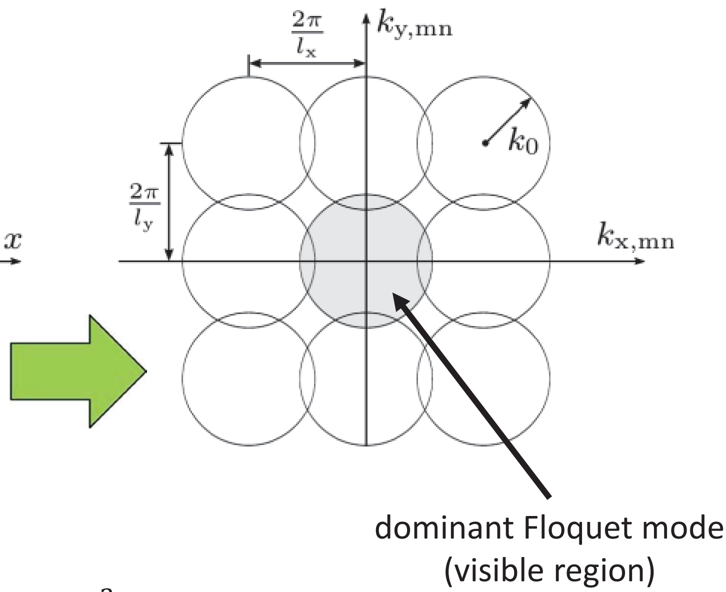
- Optimum EIRP is about 62 dBW (equivalent to 32.84 $^{dBW}/_{40kHz}$)
- Maximum permissible levels of off-axis EIRP are very stringent [3]
  - → Large number of elements in favor of less output power per element
  - → Prototype employs 90×90 elements with Gaussian amplitude taper ($\alpha = 2$)

Planar array fundamentals

unit cell lattice



grating lobe diagram ($\gamma = 90°$)

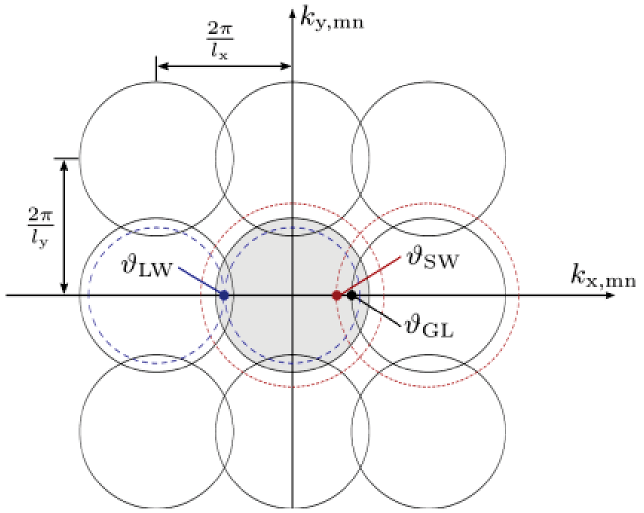


<u>family of Floquet mode circles:</u>

$$\left(k_{x,mn} - \frac{2\pi m}{l_x} - \frac{n l_y}{\tan(\gamma)}\right)^2 + \left(k_{y,mm} - \frac{2\pi n}{l_y}\right)^2 = k_0^2 \sin(\vartheta_0)^2$$

Planar array fundamentals

- Higher order Floquet modes
  → grating lobes at ϑ_{GL}



- Gain degradation or even scan blindness occurs closer to boresight mainly caused by
  → Parallel-plate mode resonances
  → Surface wave resonances:

$$\beta_{SW} = \sqrt{k_0^2 - k_z^2} = \sqrt{(k_0^2 + \alpha_{SW}^2)} \geq k_0$$

$$\sin(\vartheta_{SW}) = \left| \frac{\beta_{SW}}{k_0} - \frac{\lambda_0}{l_{x,y}} \right|$$

  → Leaky wave resonances:

$$k_{LW} = -j\alpha_{LW} + \beta_{LW} \text{ with } \beta_{LW} \leq k_0$$

$$\sin(\vartheta_{LW}) = \left| \frac{\beta_{sw}}{k_0} - n\frac{\lambda_0}{l_{x,y}} \right| \quad \forall\, n \in \mathbb{Z}$$

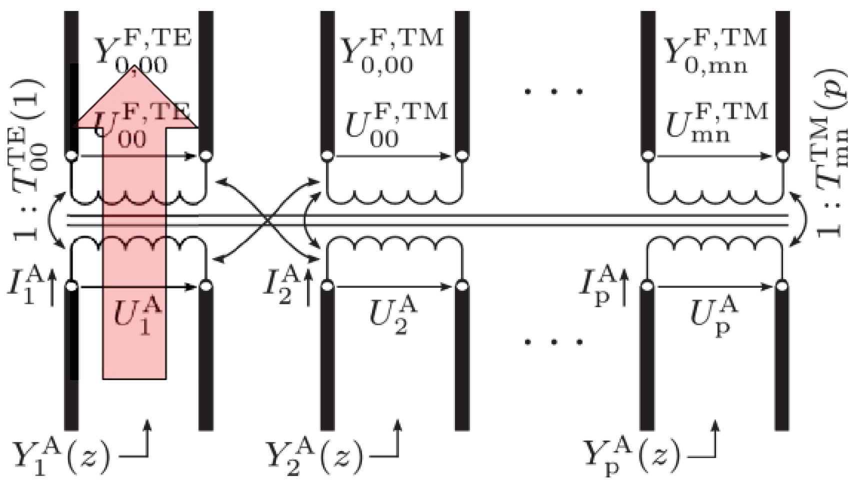
Planar array fundamentals

Design Goal: Maximize power transfer to the dominant Floquet-Mode (TE or TM)

Free space Floquet modes

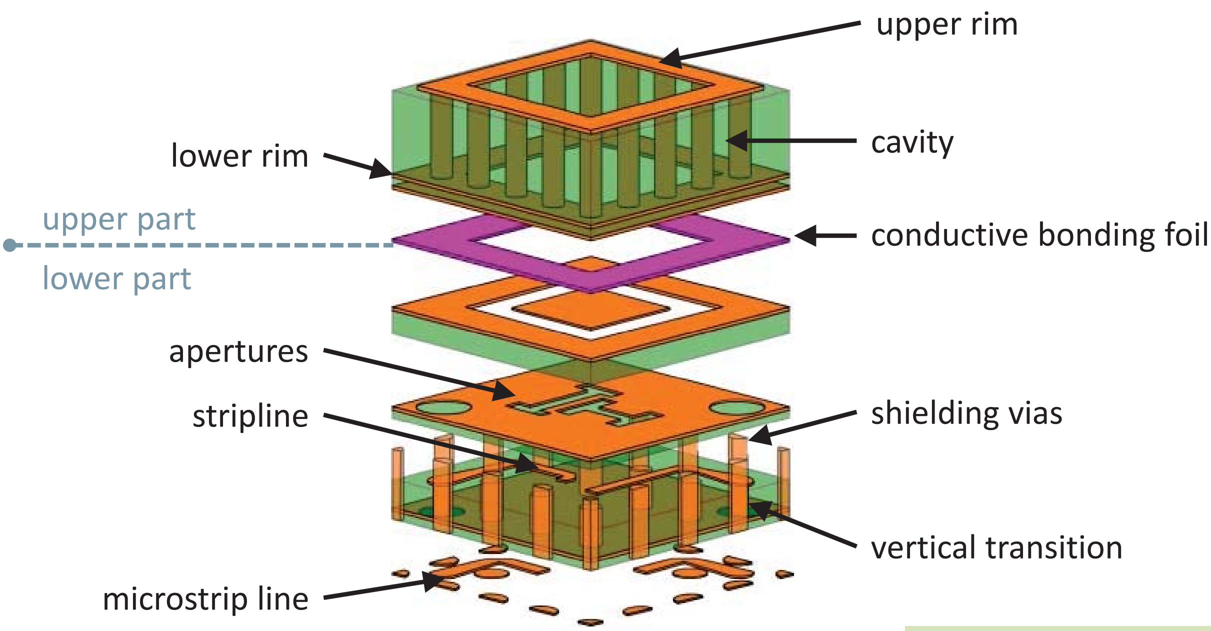
Floquet modes of the aperture

Further reading: [4,5,6]



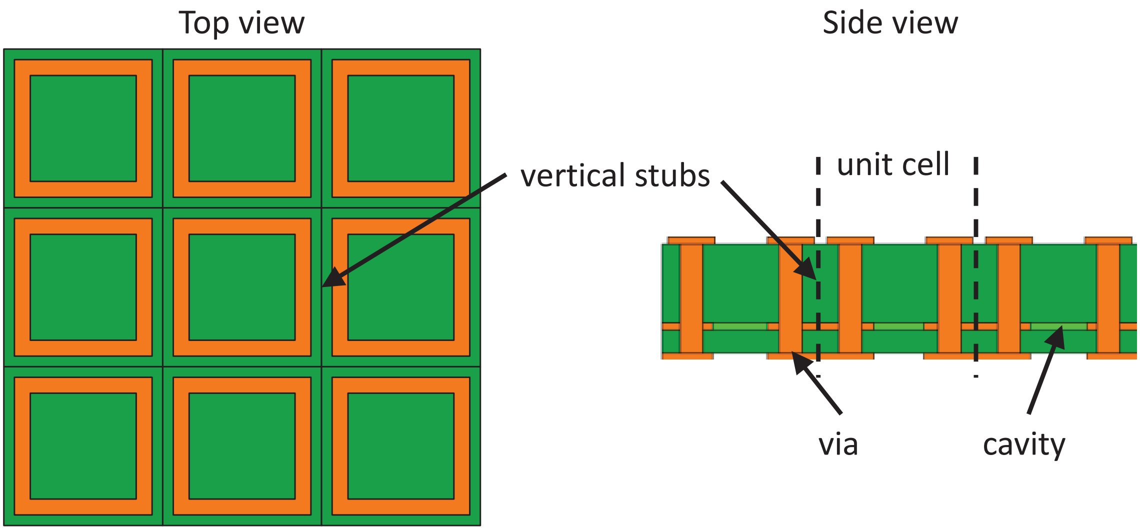
- I = modal currents
- U = modal voltages
- Y_0 = modal characteristic admittances
- T = transmission (coupling) factors

Dual-polarized cavity antenna



Further reading: [7]

Dual-polarized cavity antenna

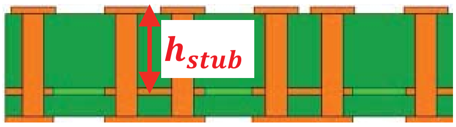


- Cavity is formed within the top laminate by a series of surrounding vias
- Coupling between the radiating and evanescent modes in the aperture plane can be controlled by the stub width and depth

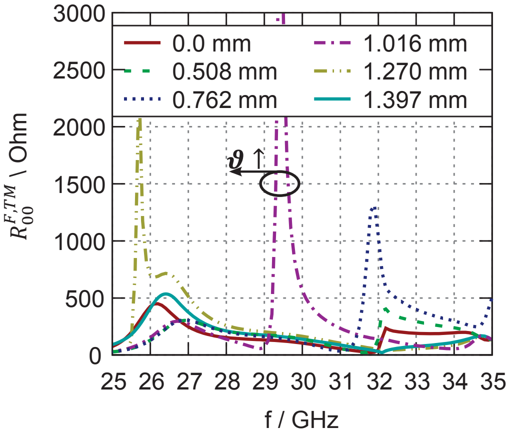
Dual-polarized cavity antenna

Simulated resistance of the TE/TM Floquet mode as a function of the stub depth

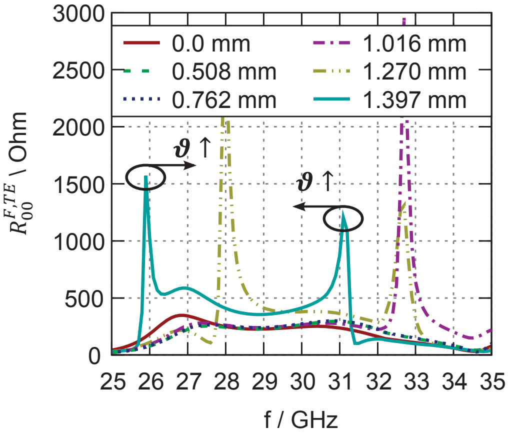
- Total height of the cavity kept constant
- Minima → surface wave resonances
- Maxima → leaky wave resonances



E-plane scan @ 60°



H-plane scan @ 60°

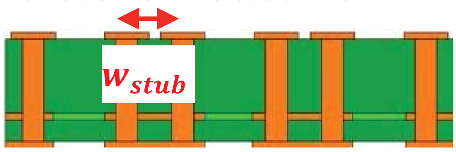


Slide 11

Dual-polarized cavity antenna

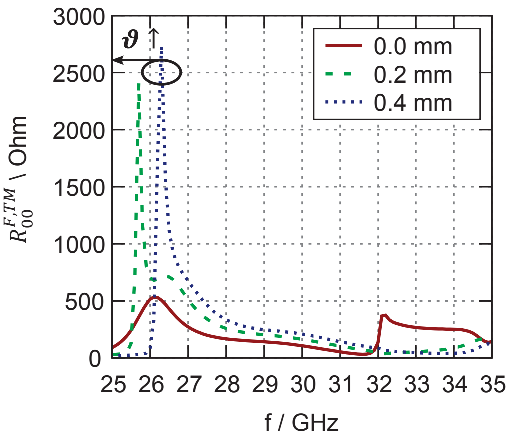
Simulated resistance of the TE/TM Floquet mode as a function of the stub width

- Minima → surface wave resonances
- Maxima → leaky wave resonances

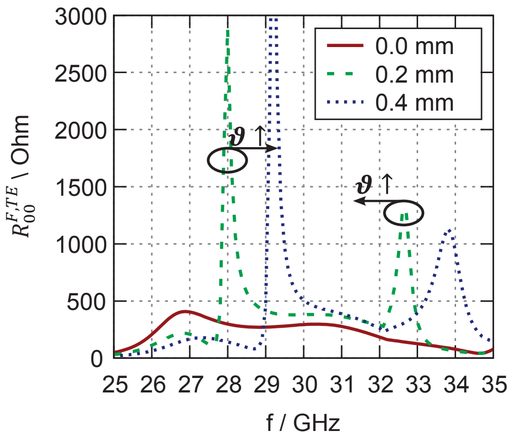


→ Similar scan performance in the E-/H-plane can be adjusted

E-plane scan @ 60°

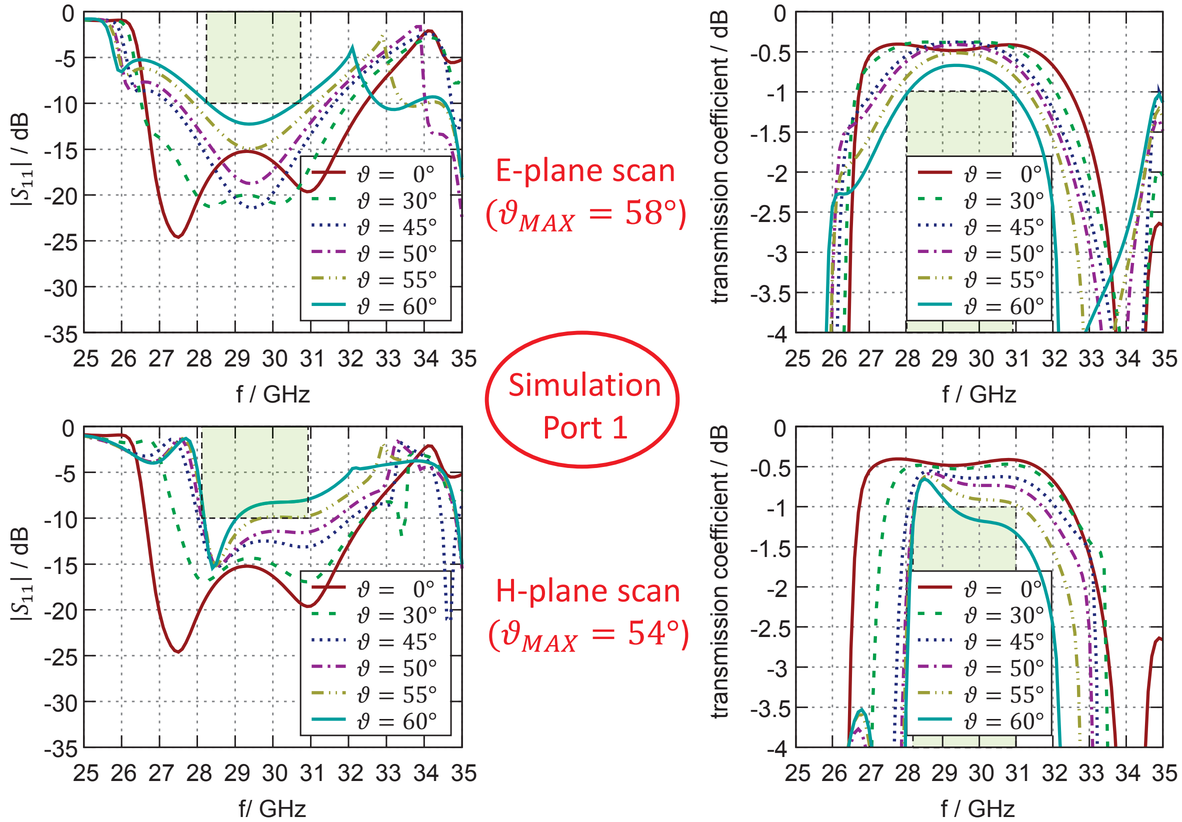


H-plane scan @ 60°



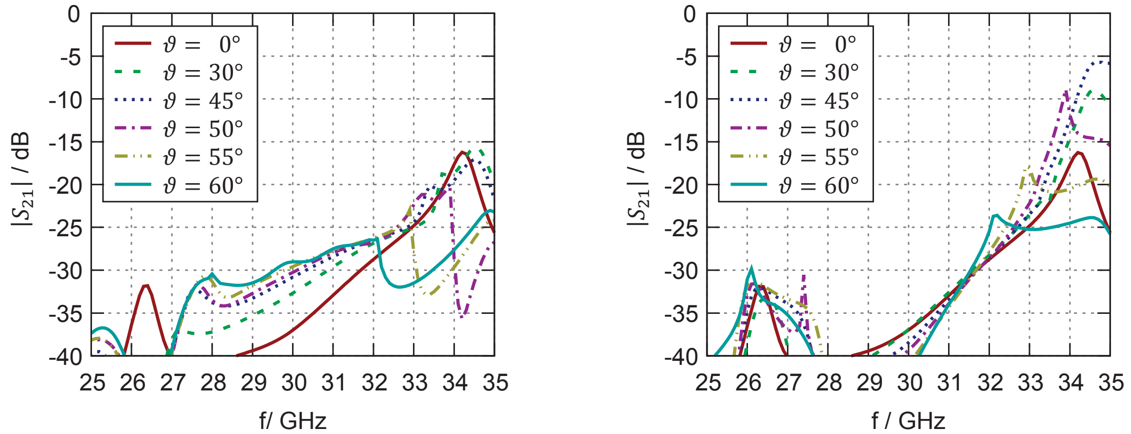
Slide 12

Dual-polarized cavity antenna



Slide 13

Dual-polarized cavity antenna



Please Note:

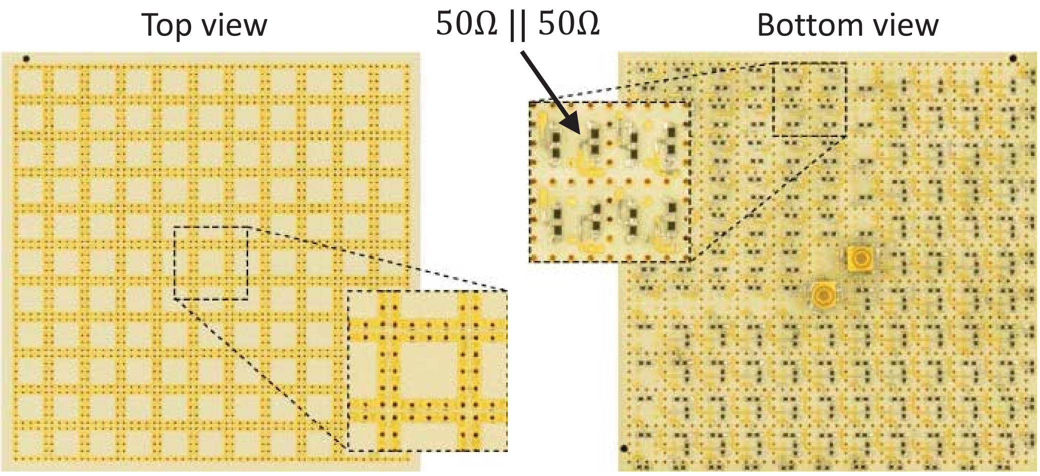
- Mutual coupling to adjacent unit cell elements is independent of scan angle [4]
- Holds certainly not for coupling coefficient $|S_{21}|$ of the dual-polarized unit cell

Alternative antenna design: [8]

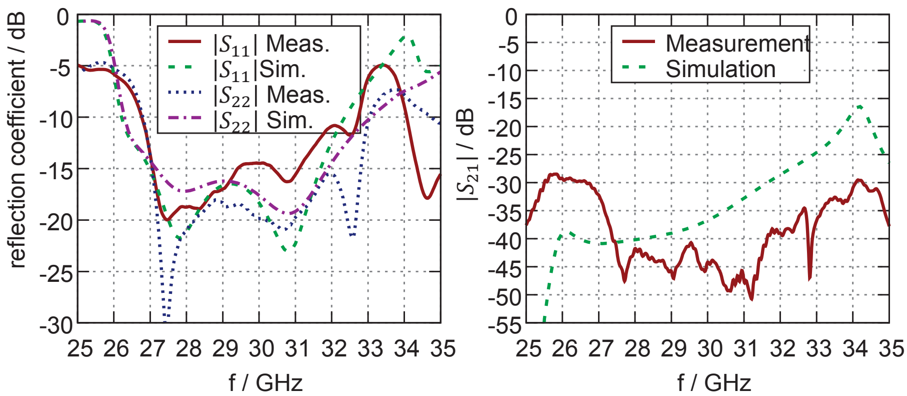
Slide 14

Dual-polarized cavity antenna

- Verification of the scan performance by means of the embedded element pattern
  - →11x11 passive array prototype
  - → Dual-polarized element in the center is fed only
  - → All other ports are terminated

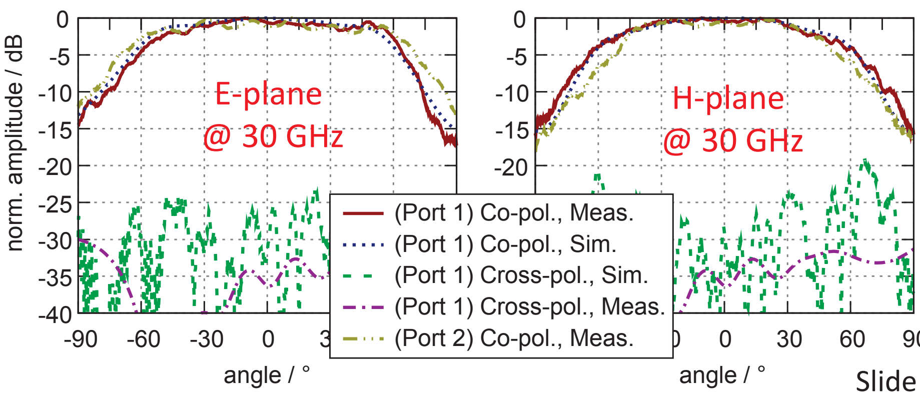


Dual-polarized cavity antenna

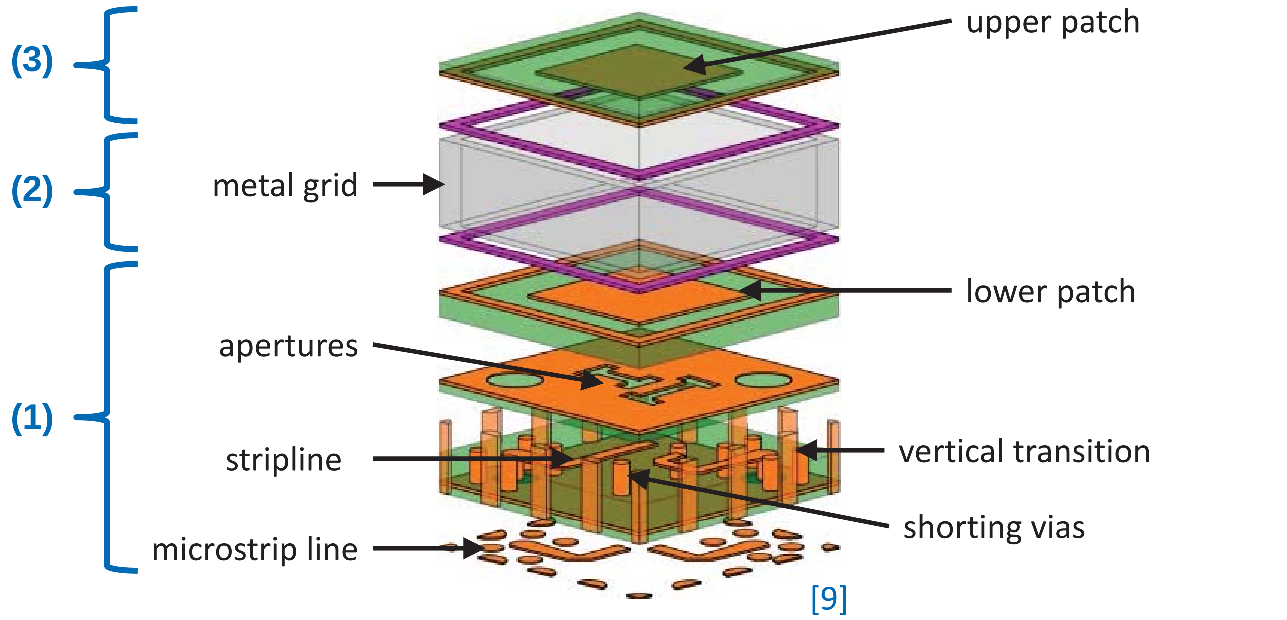


- Large impedance bandwidth
- High port-to-port isolation

- Wide element pattern
- Low cross-polarization
- Gain approx. 5-6 dBi



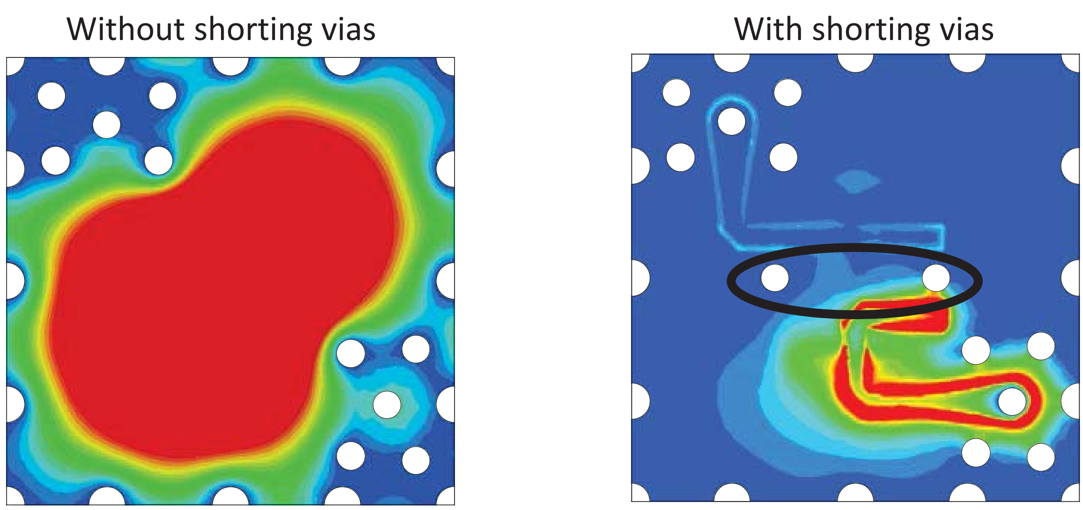
Dual-polarized patch antenna



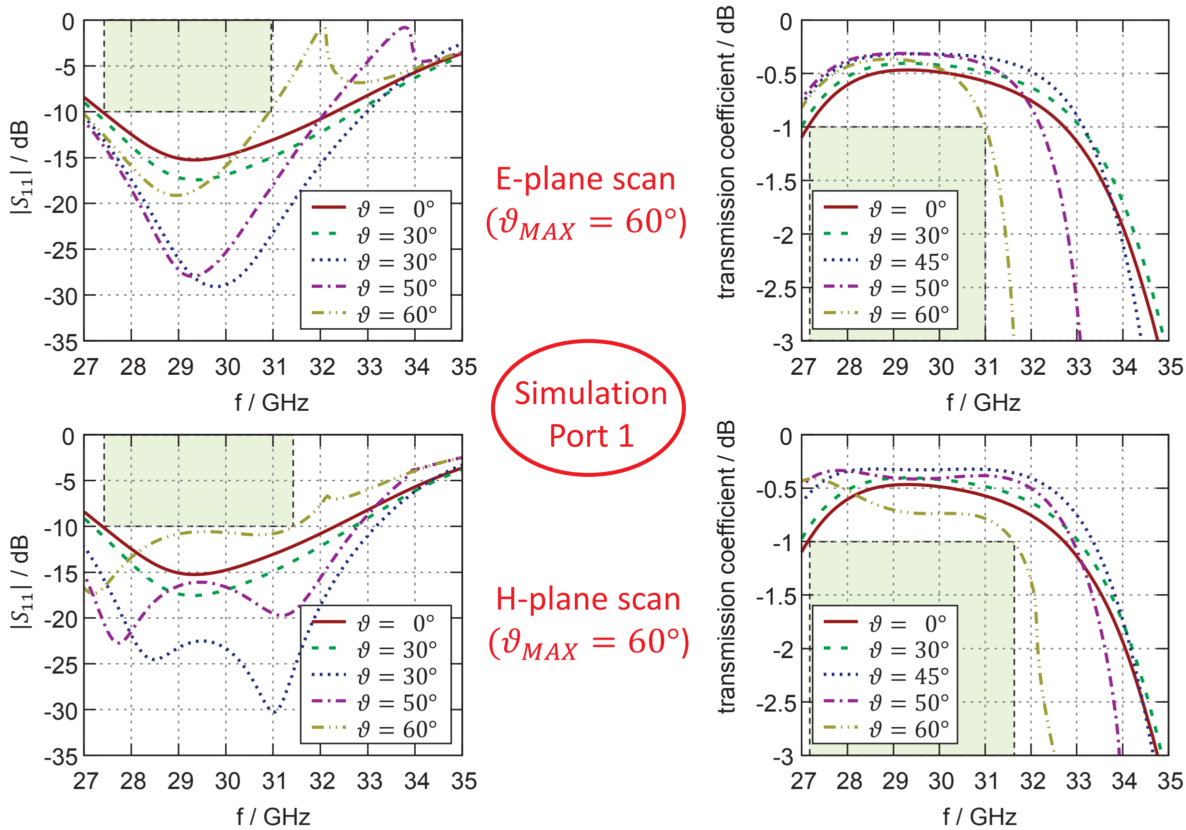
- Thin dielectric sheet on the very top → surface wave resonances are shifted to larger ϑ

Dual-polarized patch antenna

- Electric field distribution within the cavity of the stacked patch antenna element
  → Strong parasitic coupling to parallel-plate mode @ 29.4 GHz
  → Excited by the slot apertures
  → Shorting vias between both ground planes were introduced

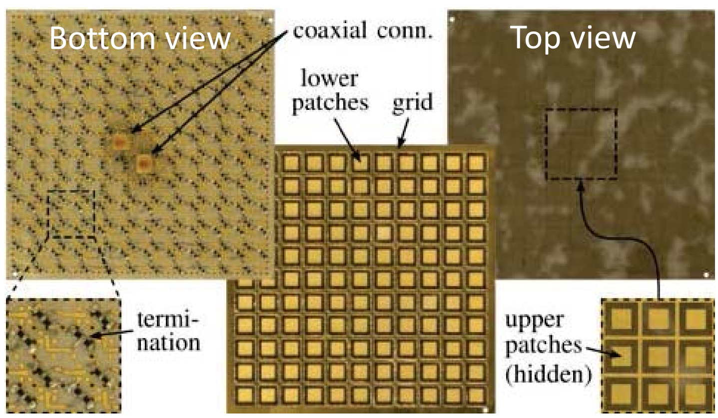


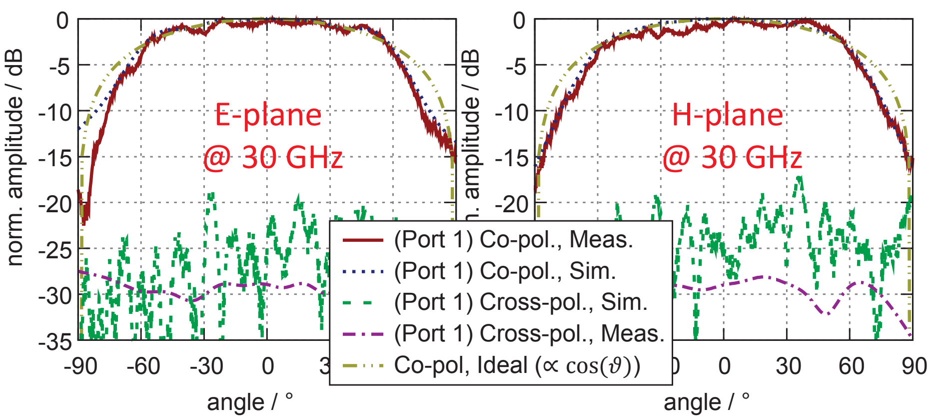
Dual-polarized patch antenna



Slide 19

Dual-polarized patch antenna

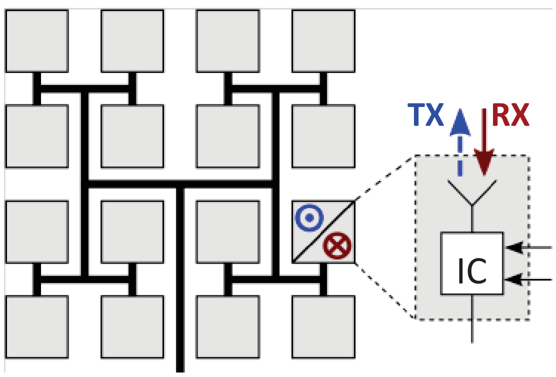


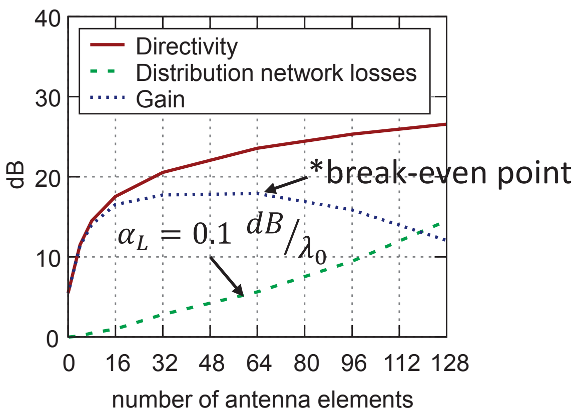


Slide 20

Phased array architectures

- Array architecture with printed RF/LO distribution network





- Planar transmission lines exhibit high losses at mm-wave
- As the number of radiating elements increases

  → Beam width gets narrower, **but** gain degrades noticeable after BEP*
- Additional amplifiers for loss compensation required

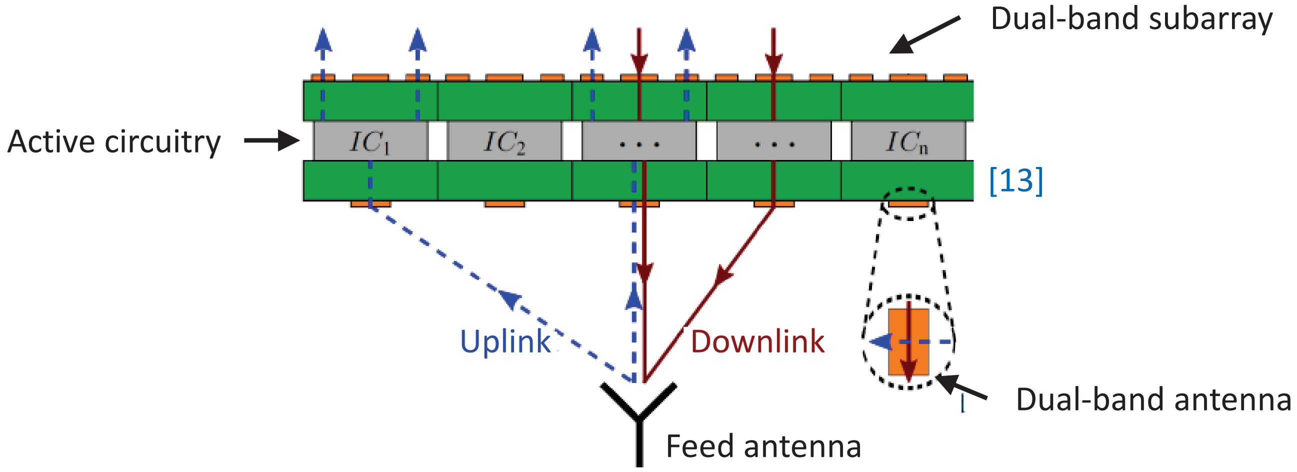
  → Packaging and heat removal becomes more complex

<u>Further reading:</u> [10,11,12]

Slide 21

Phased array architectures

- <u>Transmitarray architecture:</u>



- space-fed arrangement

  → no RF distribution network required

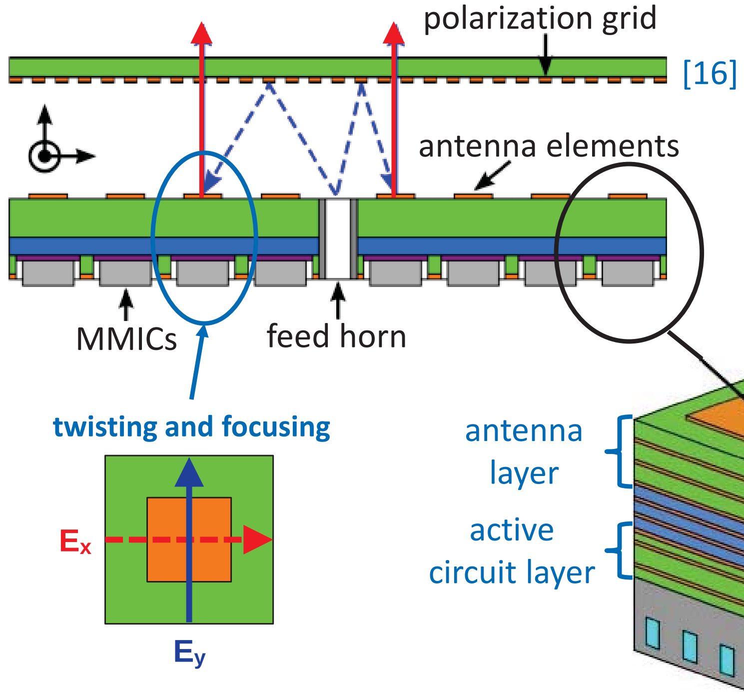
  → scalable and flexible architecture

<u>Further reading:</u> [14,15]

Slide 22

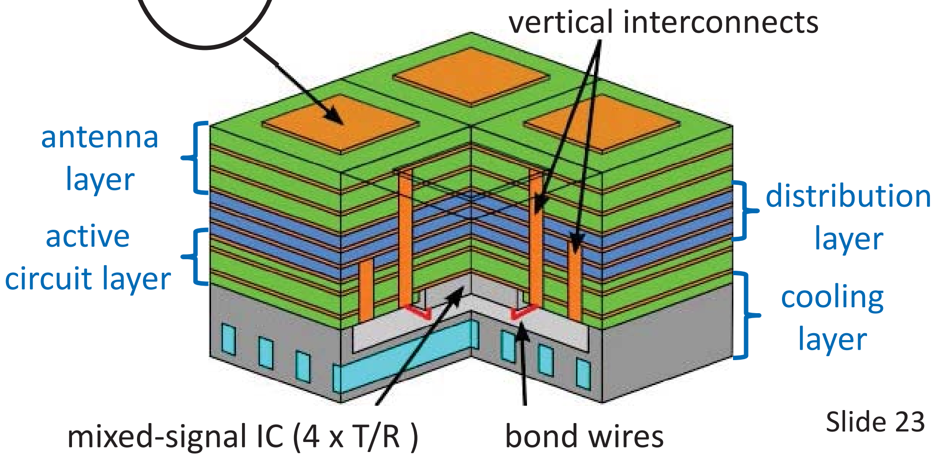
Phased array architectures

- (Folded) Reflectarray architecture:



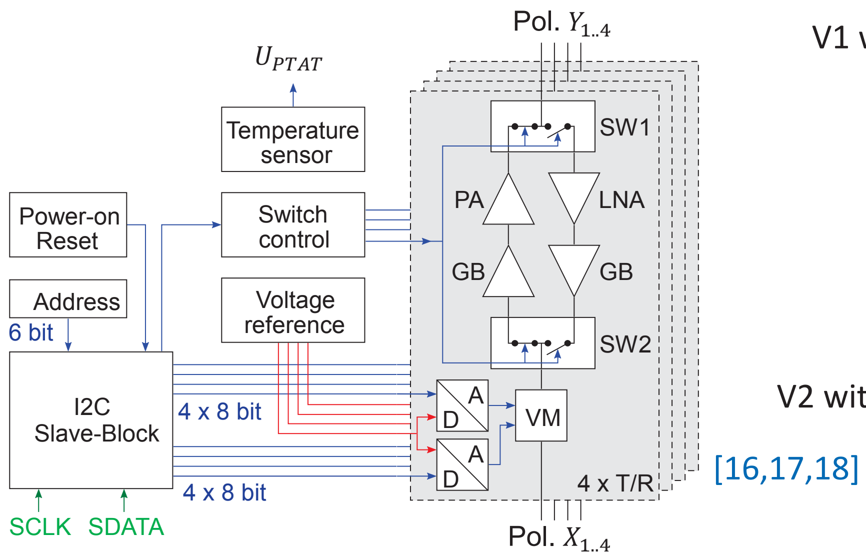
Further reading: [15,17]

- Planar module concept:



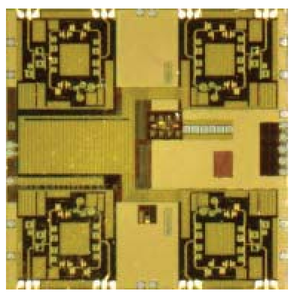
Slide 23

SiGe BiCMOS transceiver ICs

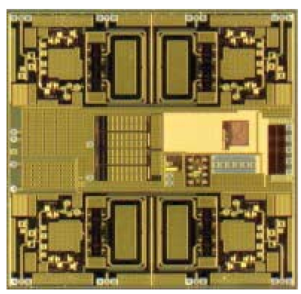


[16,17,18]

V1 with nMOS SPDTs (3.6x3.6 mm²)



V2 with RF-MEMS SPDTs (4.0x3.85 mm²)

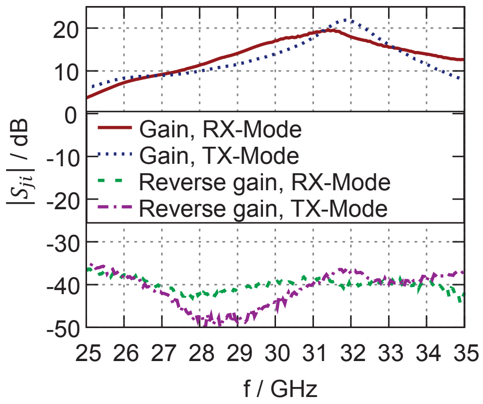


- 4 T/R-modules (RX @ 30 GHz for testing purpose only)
- Communication via serial I2C bus (SCLK/SDATA)
- Joint digital and mixed-signal circuit blocks

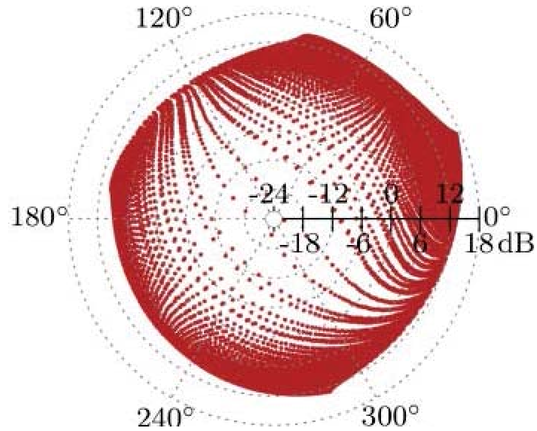
Slide 24

SiGe BiCMOS transceiver ICs

- T/R module characterization (nMOS version)

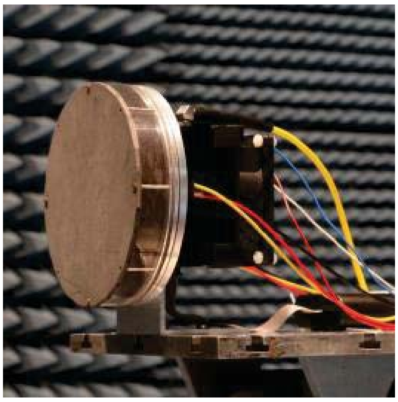


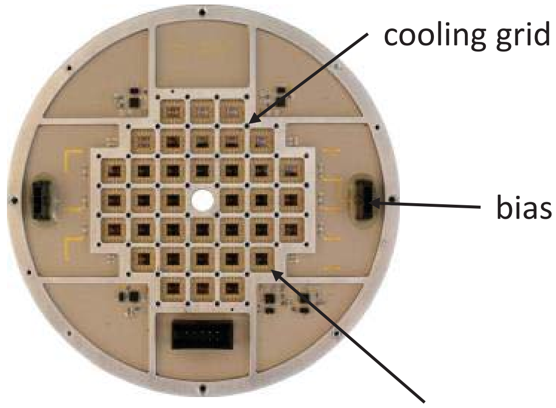
Transmission coefficient @ 30 GHz



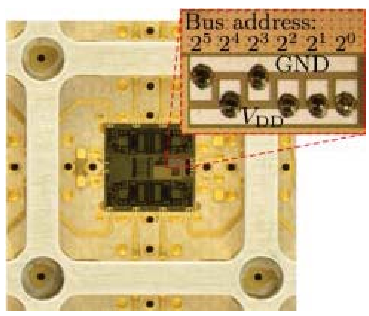
- 65536 amplitude/ phase states
- Transmission tunable from -25.5 dB to 17.1 dB

Active reflectarray demonstrator





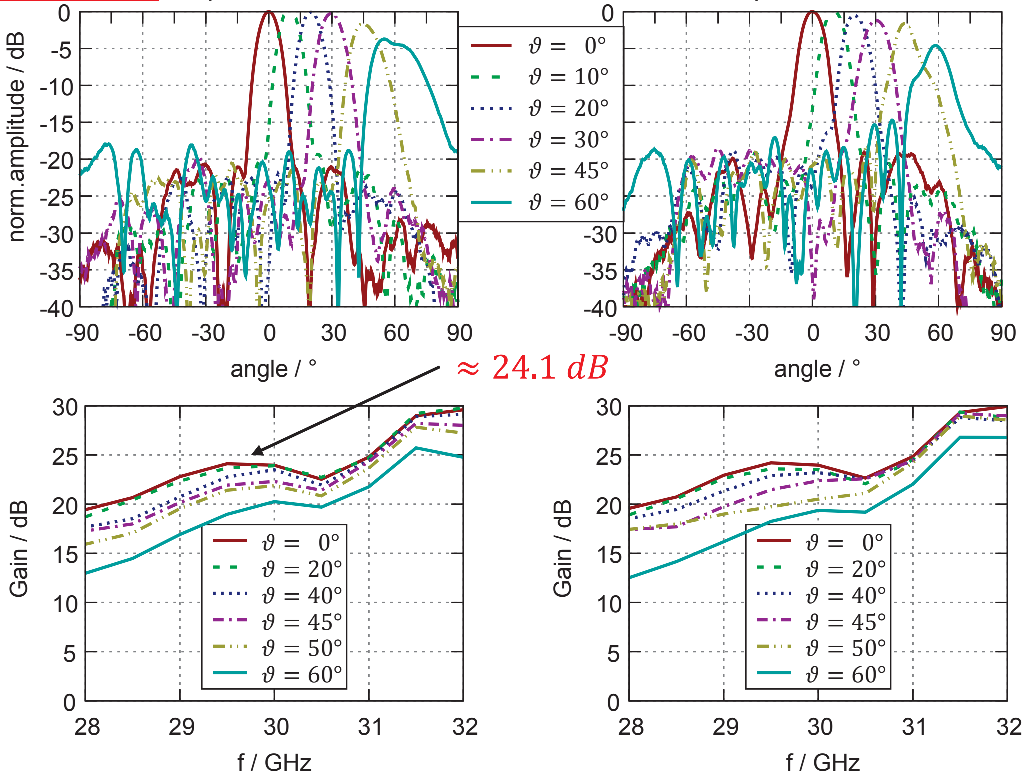
Submodule (2x2 antennas)



- 144 dual-polarized stacked patch antennas
- 36 multifunctional MMIC
  → V1: with nMOS SPDT switches [16]
  → V2: with RF-MEMS SPDT switches
- heat sink/ fan combination
- Can be easily replaced by liquid cooling system

Active reflectarray demonstrator

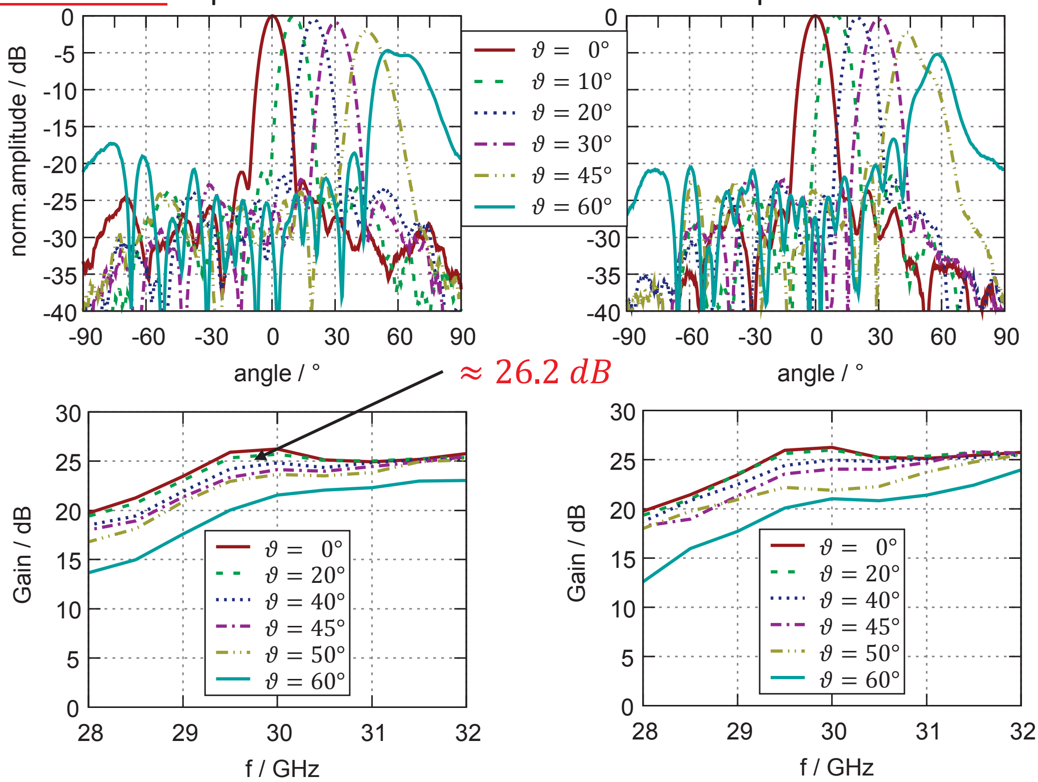
- nMOS-Version: E-plane scan H-plane scan



Slide 27

Active reflectarray demonstrator

- MEMS-Version: E-plane scan H-plane scan



Slide 28

Summary and Conclusion

- Requirements for Satcom on the move (SOTM) at K-/ Ka-band are very stringent
  → Innovative array architectures
- Dual-polarized antenna element are presented
  → Reasonable bandwidth
  → Efficient wide-angle scanning
  → High port-to-port isolation
- Active reflectarray demonstrator using SiGe BiCMOS MMICs
  → Scalable and flexible architecture
  → Highly-integrated module concept based on PCB technology
  → Enhanced by multifunctional MMICs with very fine amplitude/phase stepping
  → MMIC-version with integrated RF-MEMS demonstrated successfully

Slide 29

Acknowledgment

The author gratefully acknowledge the valuable contributions by …

- The European Commission
- The FLEXWIN Consortium (http://www.flexwin.eu)

Slide 30

Thank you
for your attention!

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89081 Ulm – Germany
E-Mail: tobias.chaloun@uni-ulm.de

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[1] Map source in figure © OpenStreetMap contributors (https://www.openstreetmap.org/copyright/en)

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The 46th European Microwave Conference

Modular Panel Array for SatCom-on-the-Move Applications

Patrick Schuh

B. Schweizer, Th. Müller, A. Müller and M. Böck

Airbus DS Electronics and Border Security

Slide 1 of 37

Outline

- Motivation / Principle Concepts / Architecture
- Panel design
  - Antenna
  - Mechanics / Cooling
- Multifunction Corechips
  - Block diagram / Design targets
  - Packaging
  - Test of packaged MMICs
- Antenna Demonstrator

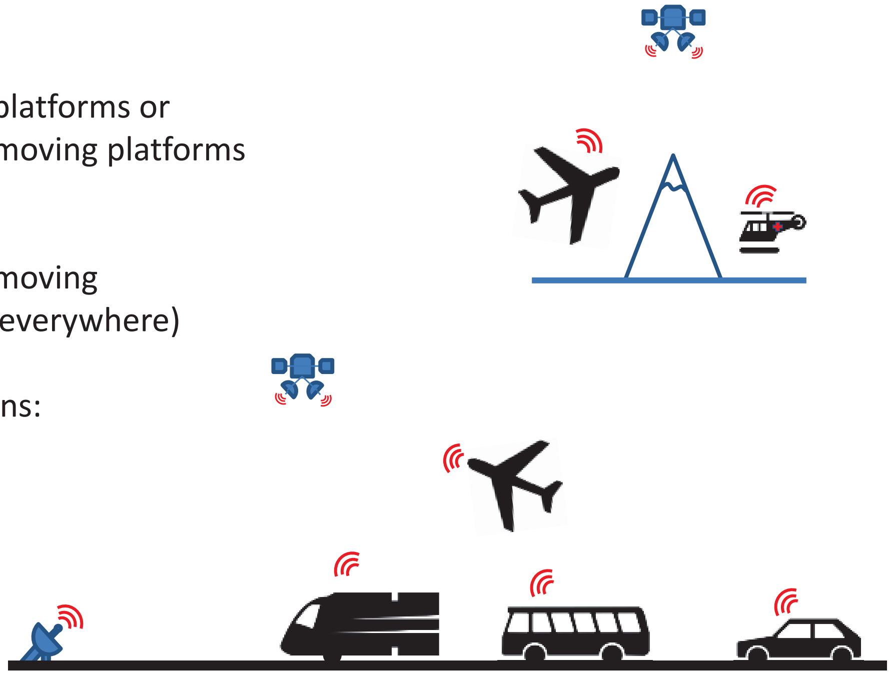
Future Applications

In future many different scenarios :

PtP Communications:
between 2 moving platforms or
between fixed and moving platforms

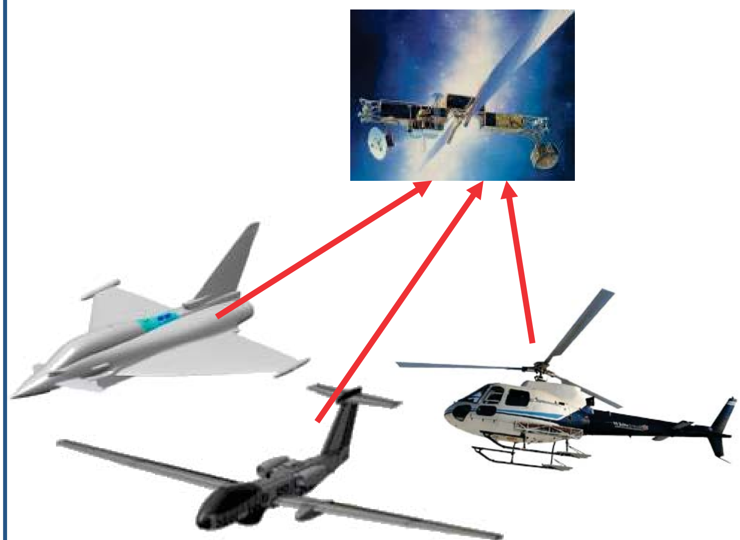
PtMP Communications:
between fixed and moving
platforms (Internet everywhere)

Different Satellite constellations:
LEO, MEO or GEO



Product Opportunities I

SatCom Datalink for Helicopter, Fighter Aircraft, UAV

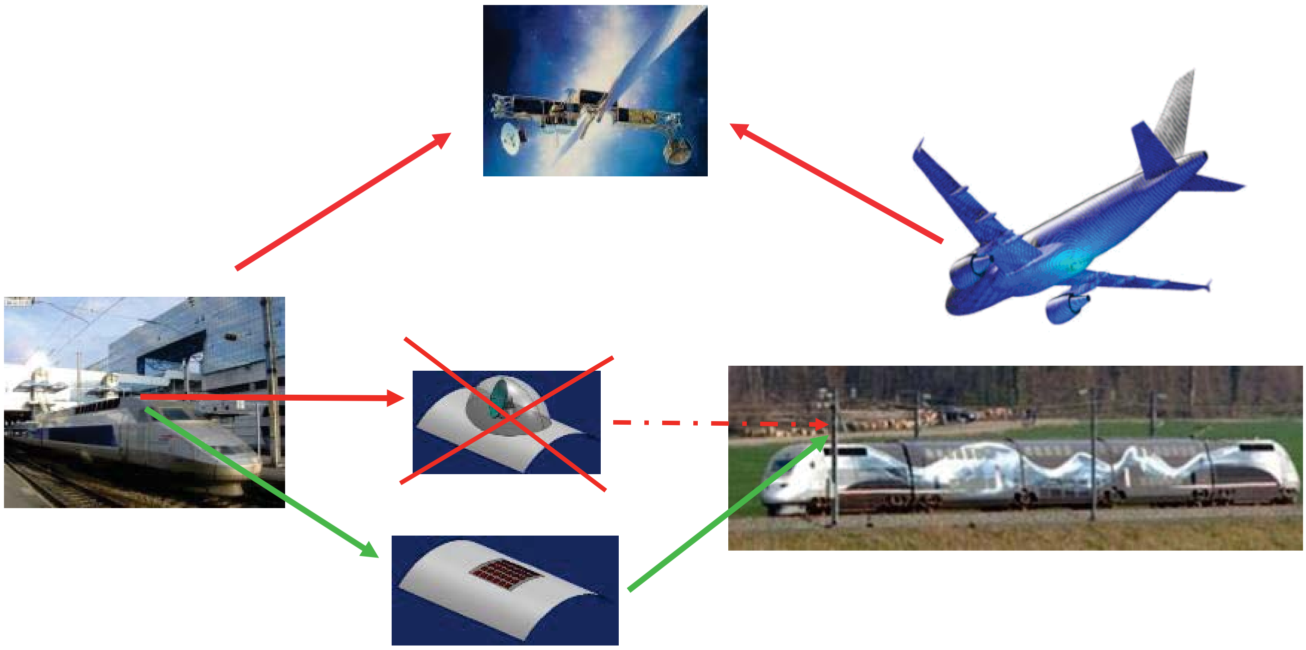


Line of sight Datalink for UAV

2010 Real Flight Demonstration

Product Opportunities II

SatCom Datalink for commercial airliners and high speed trains

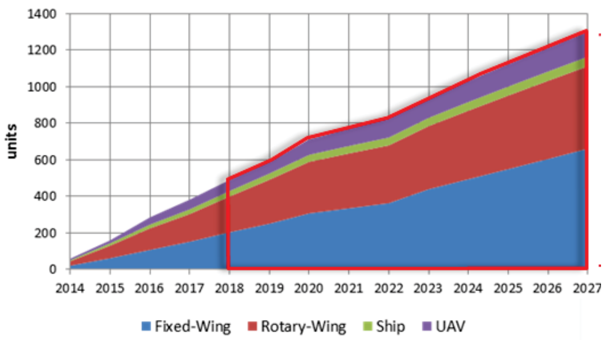


WM07 New Developments for Satellite Communications on the Move

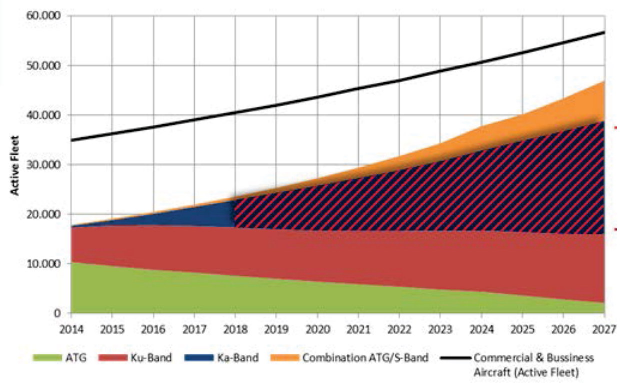
Slide 5 of 37

Potential Market Volumes (Airborne terminals)

Defence and Govermental Market



Commercial Market



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– Civil passenger aircrafts: Market forecasts Airbus, Boeing, Bombardier
– High-Speed trains: Frost & Sullivan, Internet

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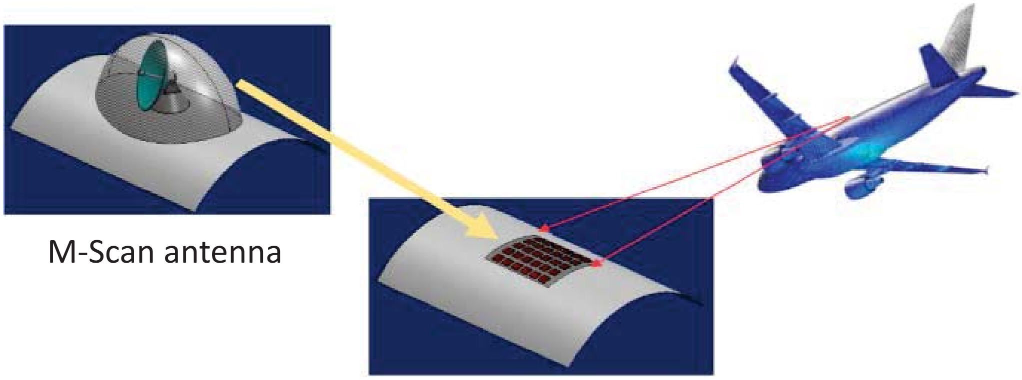
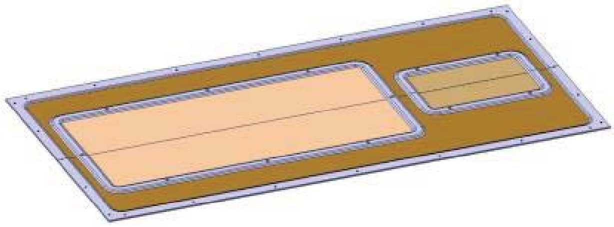
Structure Integrated Antenna (SIA)



E-Scan antenna

SIA Aperture with Tx/Rx Windows



Direct embedding of the electromagnetic window in the aircraft structure.
Glass fiber composite ←→ Carbon composite

Advantages of SIA concept

Today	Tomorrow	Today	Tomorrow

Main benefits of Structure Integrated Antenna frontends

- Remarkable reduced volume & weight of apertures and complete Frontends
- Significantly reduced drag for data link antennas for airliners, high speed trains and other platforms
- Load-bearing installation and reduced RADAR signature for military platforms
- increased reliability due to e-scan technology (Graceful degradation)

SWaP-C

Size

- Compact size, especially mounting depth is a key asset
- Lower drag, important for almost all moving platforms

Weight

- Reduction in weight important for all airborne platforms (Fuel saving)

Power

- Low power consumption is important
- Lower dissipation power allows air cooling (no liquid cooling in commercial aircrafts)

Cost

- For the commercial market key asset, in the military domain gaining importance

Outline

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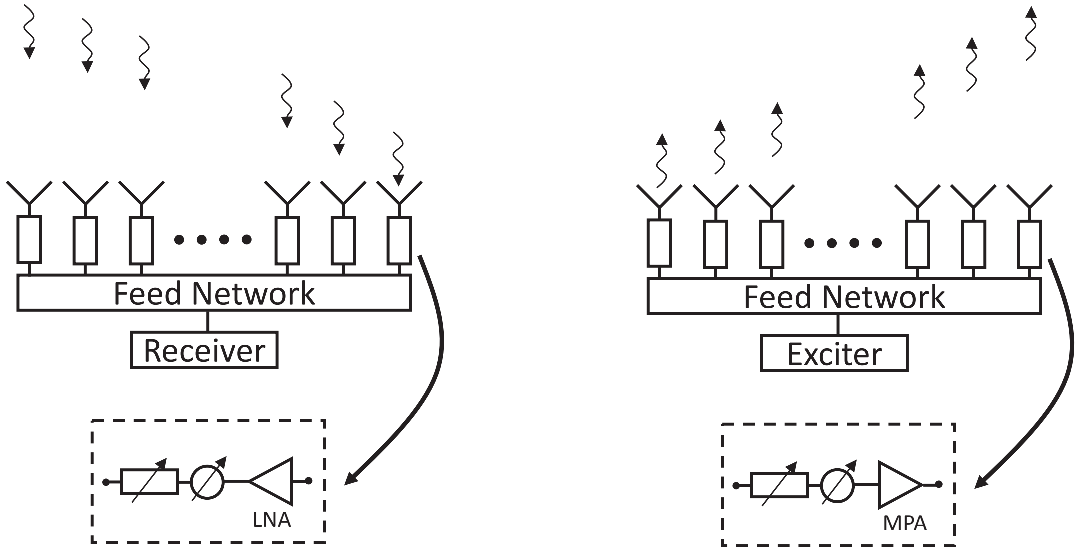
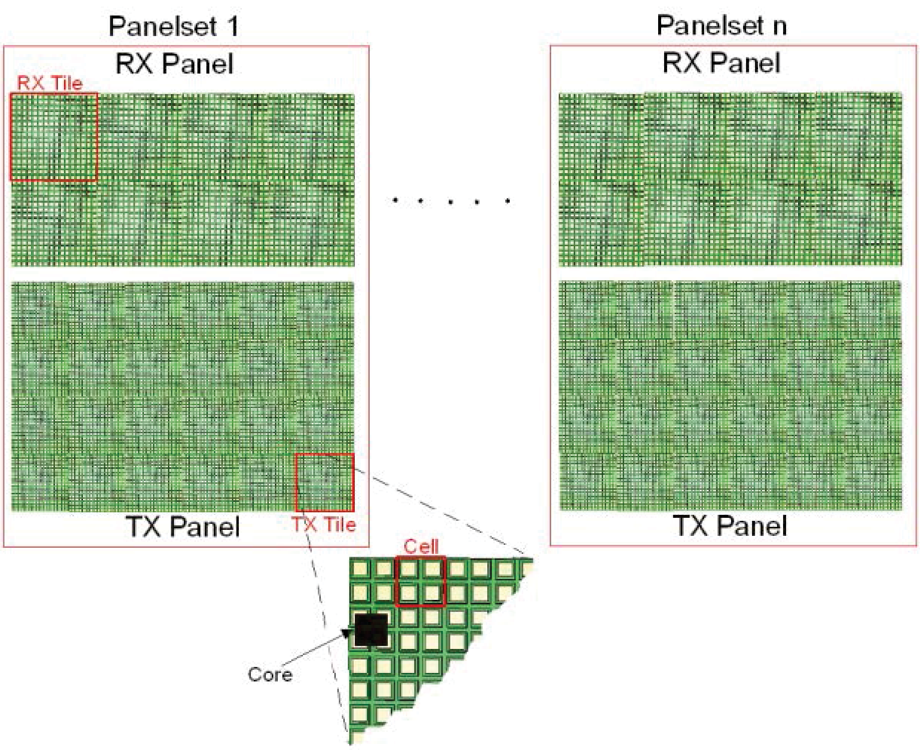
Analog beamforming AESA



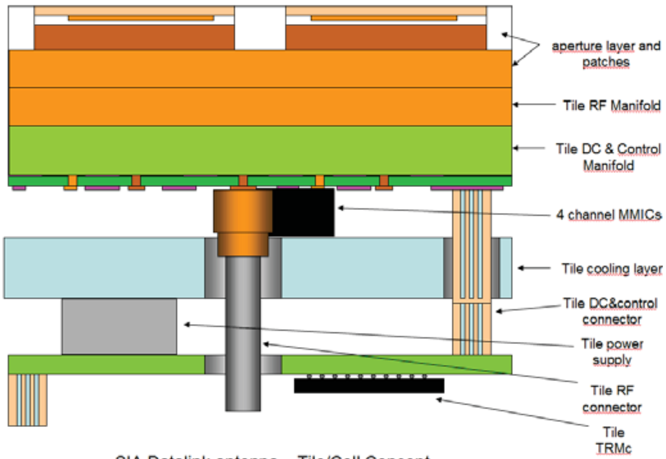
The Tx and Rx modules are key-components of the phased-array

They provide low-noise amplification (Rx) or output power (Tx) while providing phase and amplitude settings (beamforming)

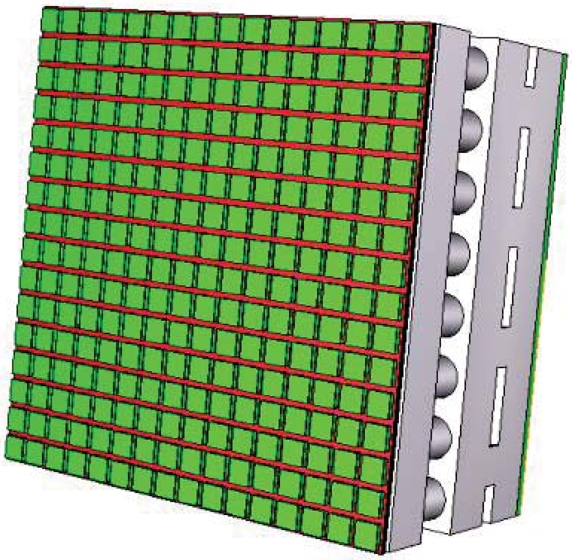
Scalable Panel Concept



Antenna Concept



SIA Datalink antenna – Tile/Cell Concept

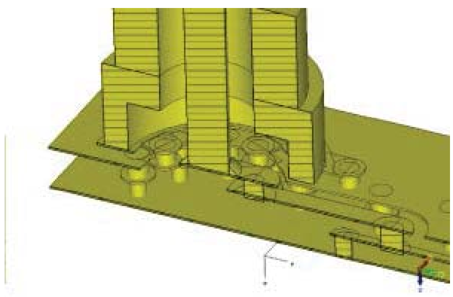


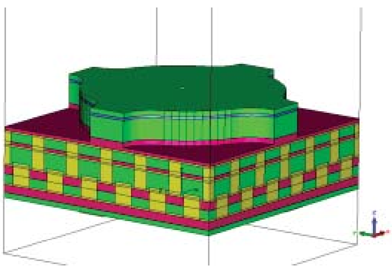
- Multilayer RF PCB
- High integrated Corechips
- Cooling structure

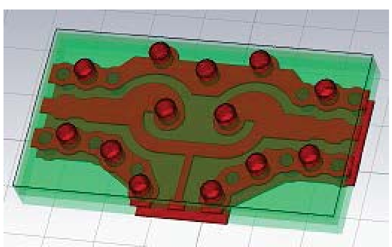
High density RF PCB

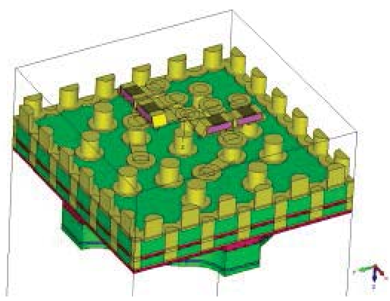
High density RF PCB incorporates:

- Antenna elements (dual polarization)
- RF Manifold
- DC and Control Manifold
- Vertical RF interconnects
- RF transitions (Manifold side)



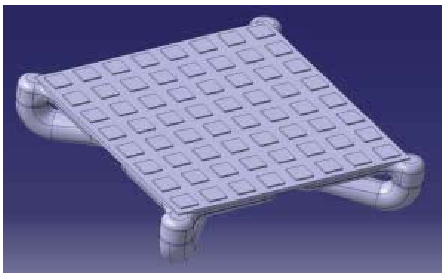


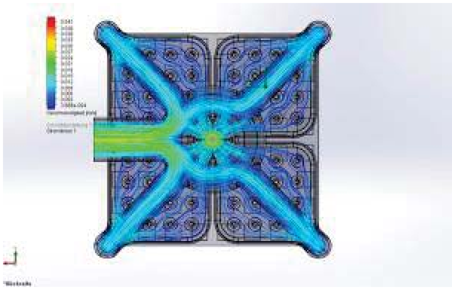




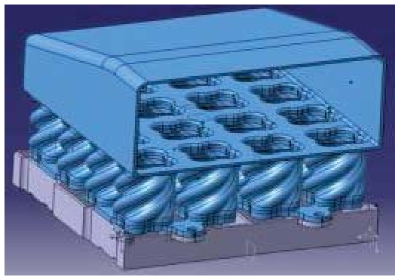
Cooling / Mechanic

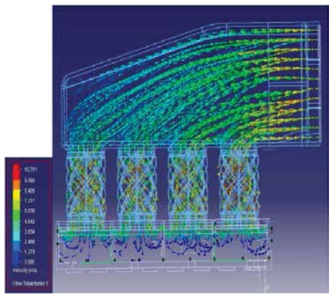
Liquid Cooling





Air Cooling





Test of cooling solution

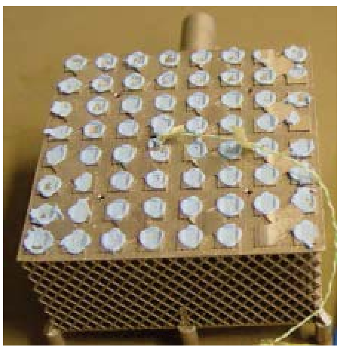
Device under test:

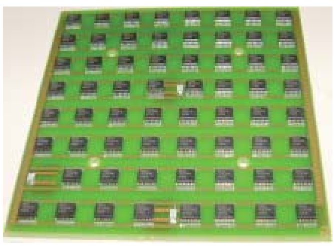
Test PCB with dummy heat sources
Cooling structure fabricated with additive layer manufacturing (ALM)

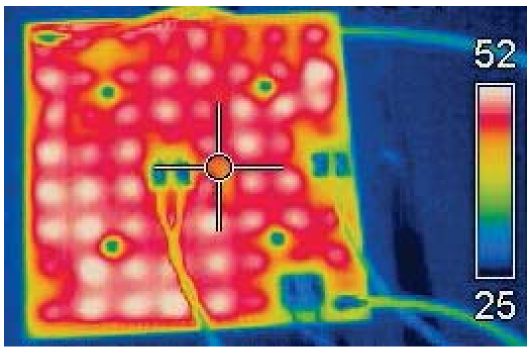
Results:

at nominal operation the „Cores“ reach a maximum temperature of 67°C...68,8°C

(simulated: 66,5°C...68°C)







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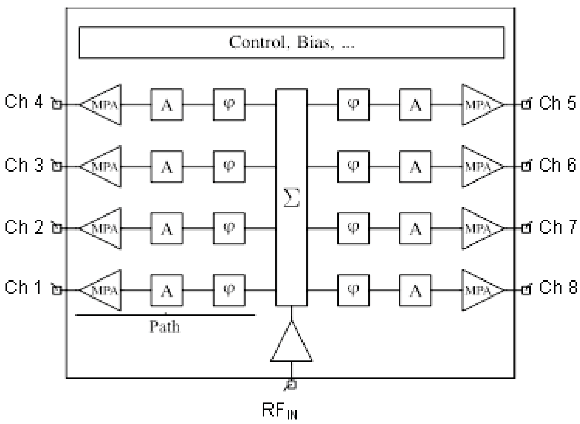
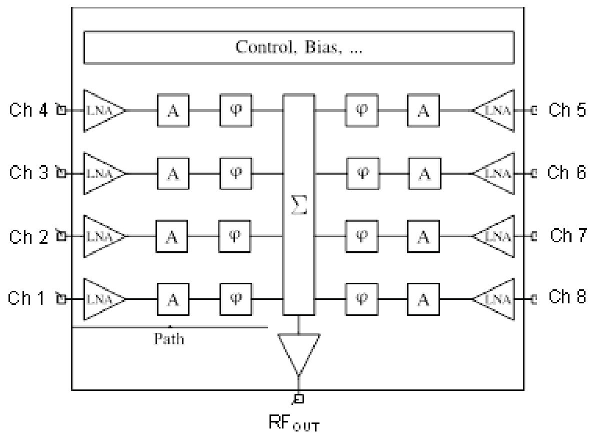
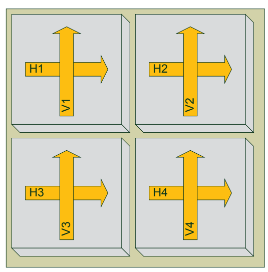
Multifunction Core Chips (Tx / Rx)





8 Channels for 4 Radiating Elements in vertical / horizontal polarisation

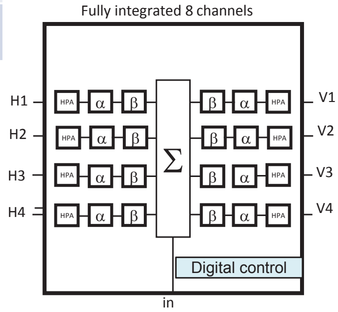


8 channel Ka-band TX chip

Parameter	Design target
Frequency	Ka-Band (27.5GHz – 31GHz)
Number of channels	8
RF output power per channel	> 12dBm
Amplitude dynamic range	> 11dB
Amplitude resolution	> 5 bit
Phase control / resolution	360° / 6 bit
DC power consumption	~ 1300mW

TX chip

Fully integrated 8 channels



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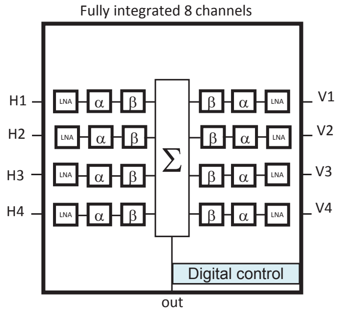
8 channel K-band RX chip

Parameter	Design target
Frequency	K-Band (17.7GHz – 22GHz)
Number of channels	8
Gain per channel	20 dB
Noise figure	3 dB
Input IP3	-30 dBm
Amplitude dynamic range	> 15.5dB
Amplitude resolution	> 5 bit
Phase control / resolution	360° / 6 bit
DC power consumption	~ 600mW

RX chip

Fully integrated 8 channels

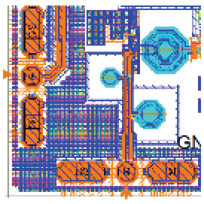


WM07 New Developments for Satellite Communications on the Move

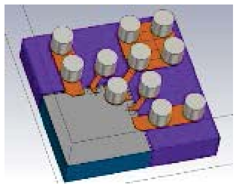
Chip Package Co-design

A co-design between chip and package and even package and PCB is necessary due to
- High frequency range of operation
- High integration density
- Multichannel approach

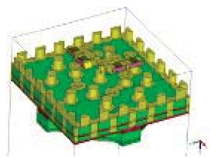
MMIC



Package

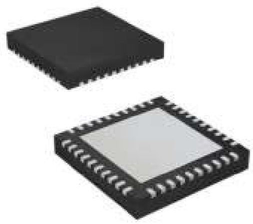


PCB

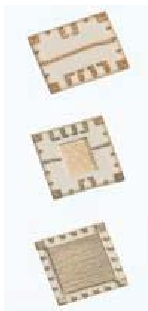


Different Package Solutions

Quad-flat-no-leads (QFN)
- Widely used package
- Molded or air package
- Reasonable loss at Ka-Band for the air-package
- Non-hermetic
- Low-cost

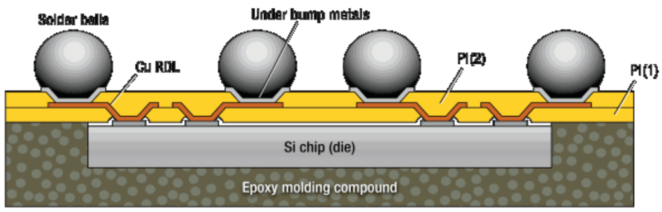


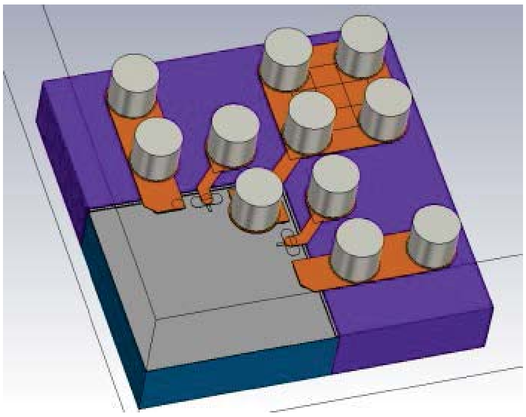
Liquid Crystal Polymer (LCP)
- Quasi hermetic package
- Low-loss at Ka-Band for the air-package
- Cavity can be designed to reduce interconnects costs
- Medium-cost



Ball Grid Array (BGA)
- Very high integration level if high pin counts needed
- Reasonable losses at Ka-Band possible
- Medium to high cost

eWLB Package Solution





embedded wafer level ball grid (eWLB)

- Very compact packaging => low impact to RF
- Cooling opposite to PCB (chip backside)
- Very high volume technology

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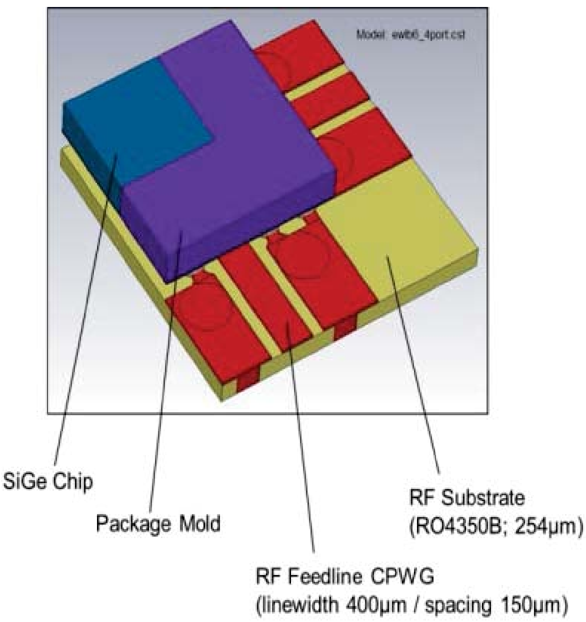
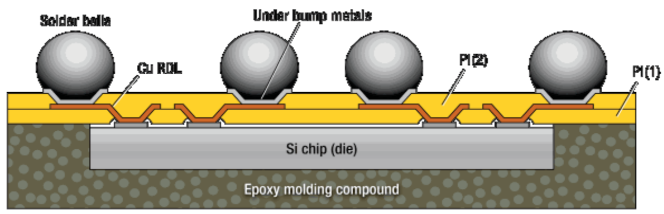
Package Transition





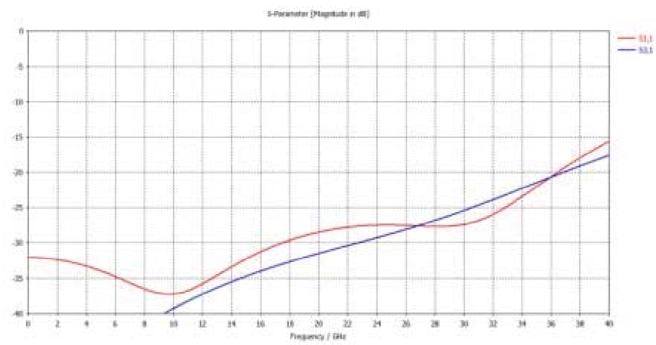
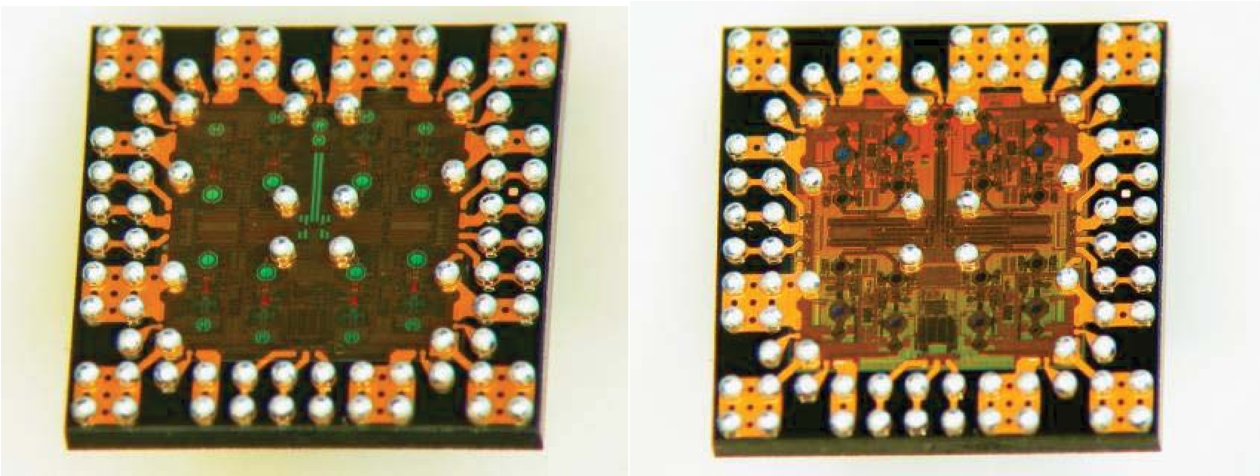


Photo of packaged Corechip

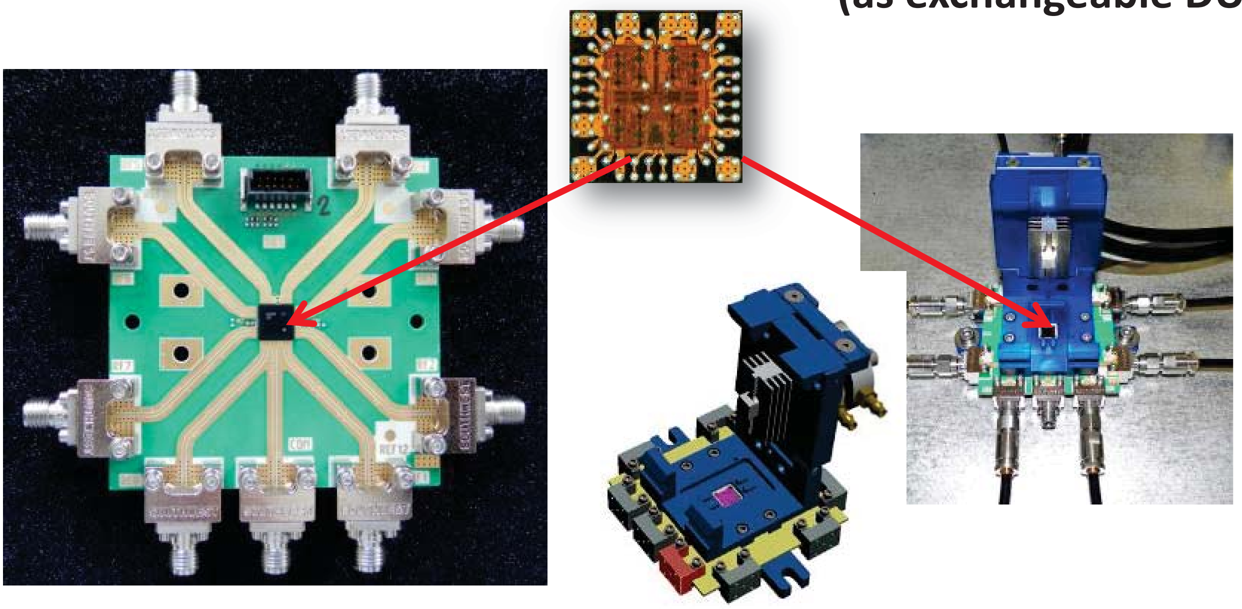


Package size:	6 x 6 mm²
Chip size:	4 x 4 mm²

Measurement Environments

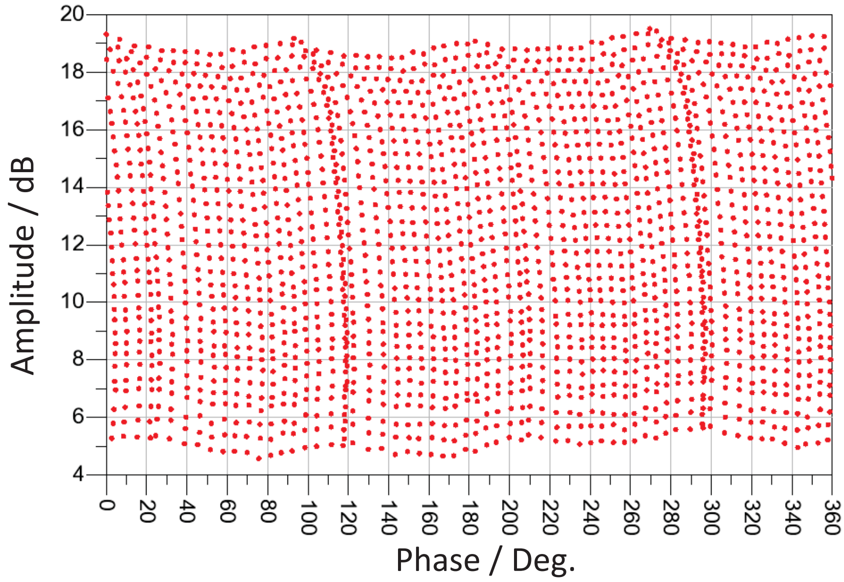
Soldered on Test Board

In Test socket (as exchangeable DUT)

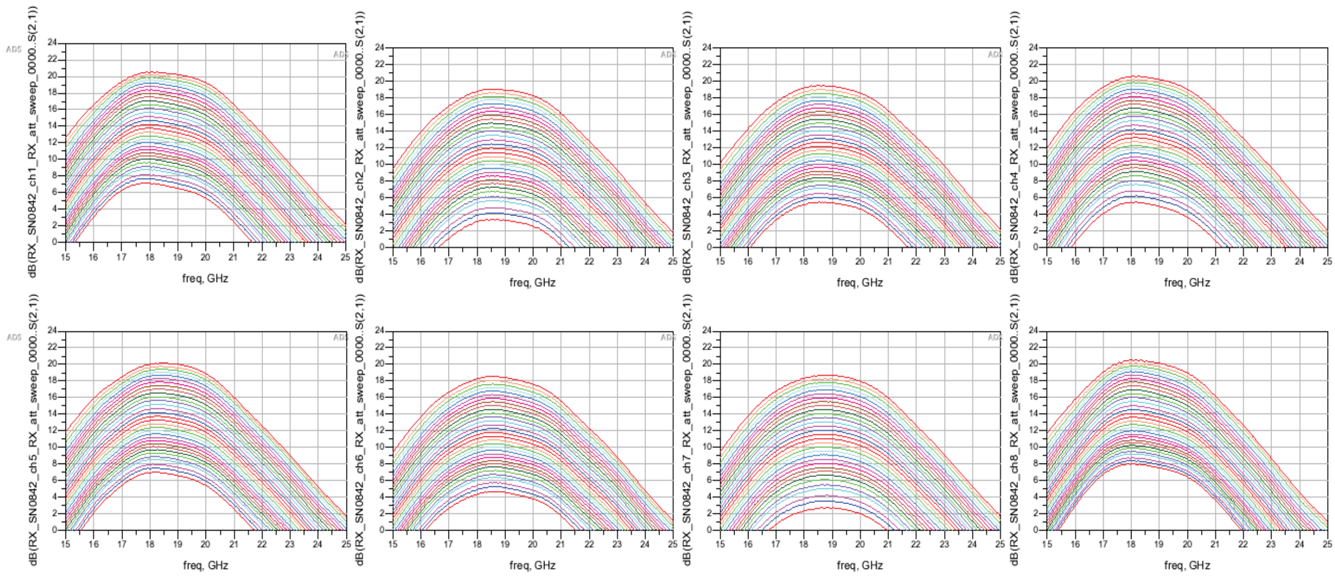


Measurement in Testsocket

Test of packaged Rx-Corechip
Gain Phase Map



Test of all 8 channels RX MMIC



Very good uniformity between channels
Good attenuator dynamic range

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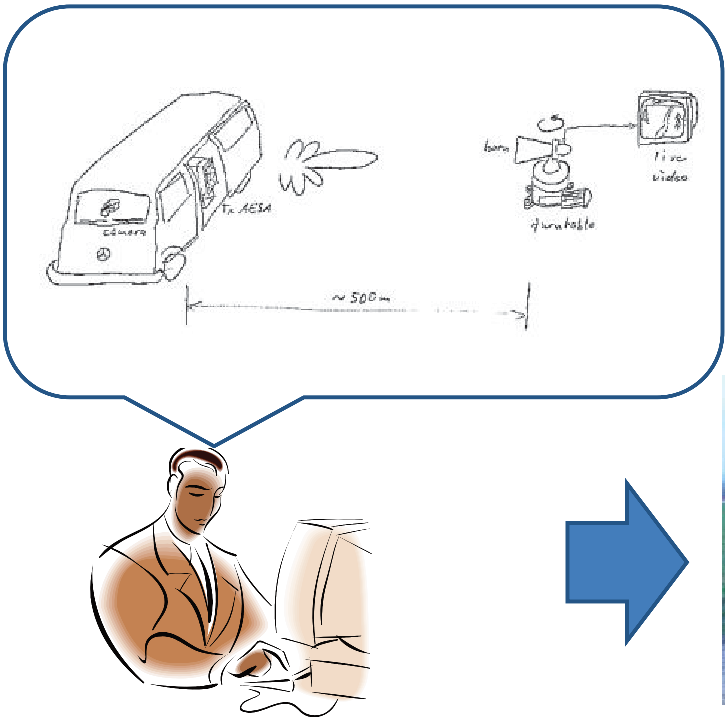
  - Block diagram / Design targets
  - Packaging
  - Test of packaged MMICs
- Antenna Demonstrator

EuMW 2016
Microwaves Everywhere

AIRBUS
DEFENCE & SPACE

From Idea to Reality



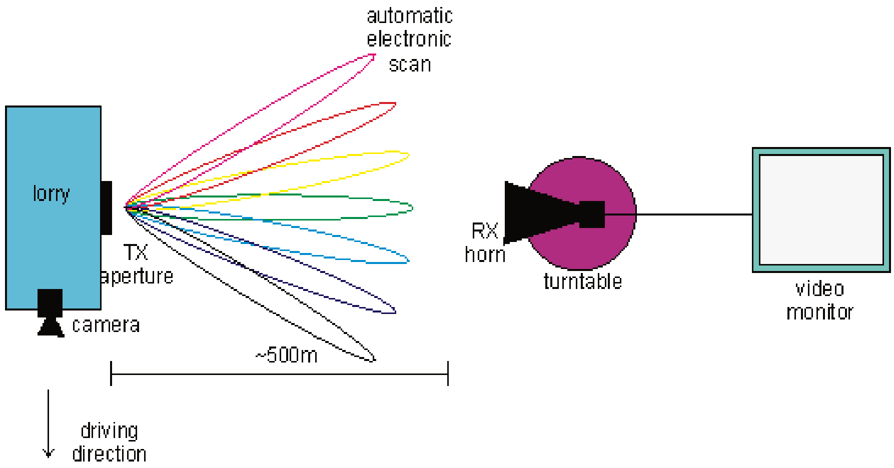
Demonstrator setup

TX System

- Video Camera
- Video Signal preprocessing
- AESA Controlling
- TX Frontend
- UAV Structure Radom

RX System

- Horn antenna
- Turntable
- Turntable Controlling
- Video Signal preprocessing
- Video monitor



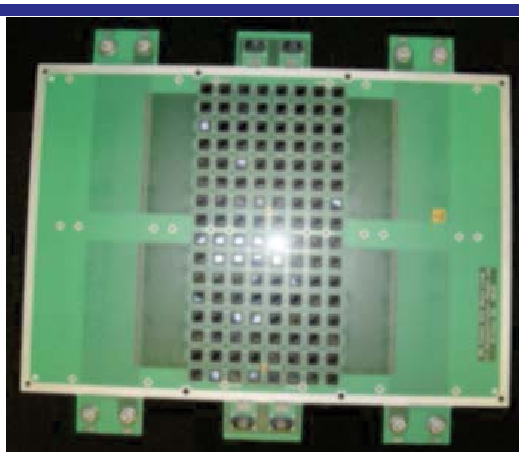
Link Demonstration

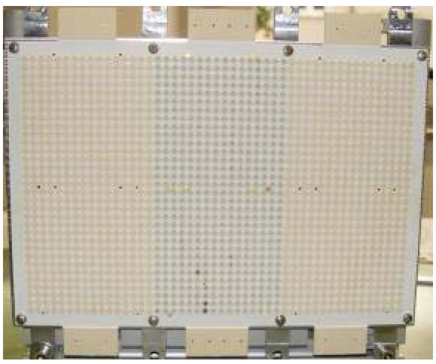
- TX System mounted in lorry
- RX System on ground
- Lorry driving along RX System while transmitting live high data rate video signal (HD)

Antenna TX Demonstrator

Mechanical Integration

128 housed TX Cores soldered to TX Panel (including Manifolds and Radiating Elements) => 512 patches

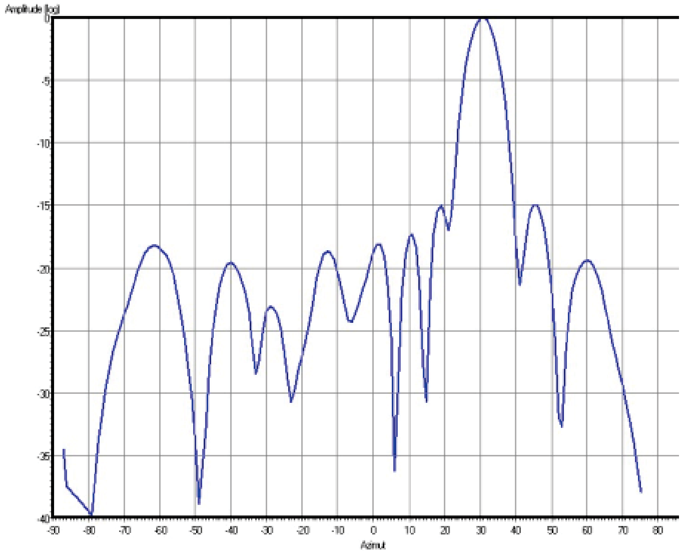




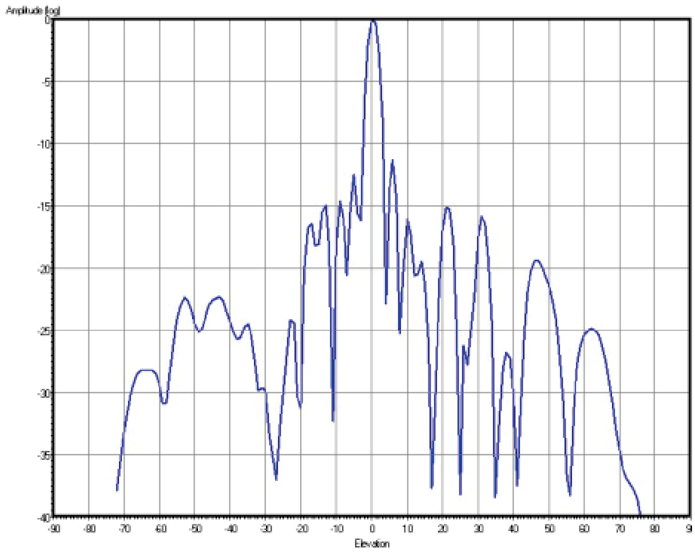
Antenna Diagramm

Beam [Azimut 30°; Elevation 0°]

Far Field Azimut-Cut



Far Field Elevation-Cut



Outdoor Demonstration I

- TX AESA in moving vehicle
- GPS and compass sensor in vehicle measuring position and attitude of Antenna
- TX AESA aiming to fix RX station while the platform is moving
- Transmission of live video stream to RX station

Outdoor Demonstration II

TX Panel transmitting
Live HD video stream

Conclusions

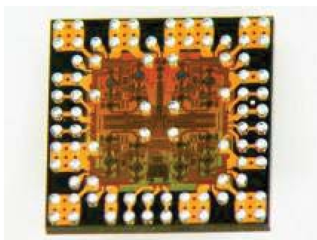
- New module Panel for SatCom-on-the-move applications:
  - Multichannel Corechips available
    - K-Band RX Corechip
    - Ka-Band TX Corechip

  - New packaging technology (eWLB) successfully demonstrated for frequencies up to Ka-Band

  - Different cooling structures tested for
    - Liquid Cooling
    - Air Cooling

    enabled by ALM technology

- Transmit Panel tested in outdoor environment



The Vision


Antennas are needed everywhere!
SAT NAV
Multimedia
Mission Com
Tactical Data Link
Intra Flight
Intra Flight
Fleet Mgmt
Multimedia
SAT NAV
ATC & Battlefield Comms
Terrain NAV & Landing

Techniques and Technologies for SatCom Antenna Systems

F.E. van Vliet, M. van Wanum
S. Monni, R. Bolt

Introduction

Topic: Techniques and Technologies for SatCom Antenna Systems

Two major but separate developments will be discussed:

1. Enabling Microwave ICs
   - Performed together with Airbus Defence & Space

2. A Single transmit+receive aperture
   - Performed together with ESA-Estec

Microwave Front-End

Chip requirements

Transmit

- Approx. 30 GHz, wavelength 10 mm
- For planar dense phased array, this leaves 5x5 mm^2 per element
- Area is limited
  - Power consumption is severely constrained
  - Two polarizations need be controlled, this doubles hardware

  - Due to space reasons 4 antenna elements served by 1 chip
  - After routing and packaging: Chip size max 4x4 mm^2

Receive

- Approx. 20 GHz, wavelength 15 mm, more space available
- same approach as TX used
- Input compression point relatively mild

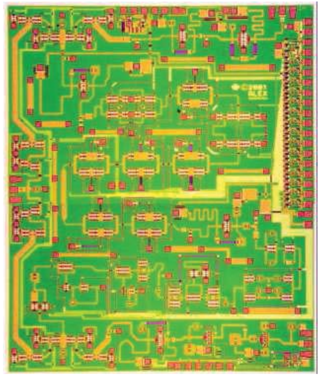
What’s inside that chip….

Bias circuits
- Bandgap
- PTAT
- Regulator

Undervoltage detection
Power-on-Reset
Temperature sensor
8-bit ADC (for digital reading of temp.)
DACs
- 8x 8 bit for VGA
- 16x 6 bit for VM

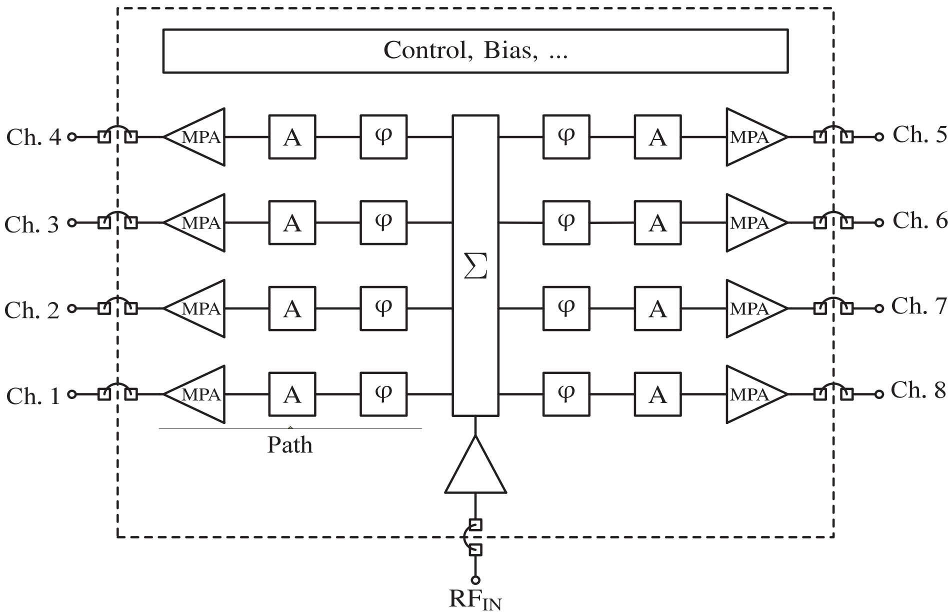
Serial digital IO
Decoder for VM (“corrected” cos+sin)
8x LNA/PA, VGA, VM
7x Wilkinson
Common amplifier

Smaller than a single-channel GaAs core chip

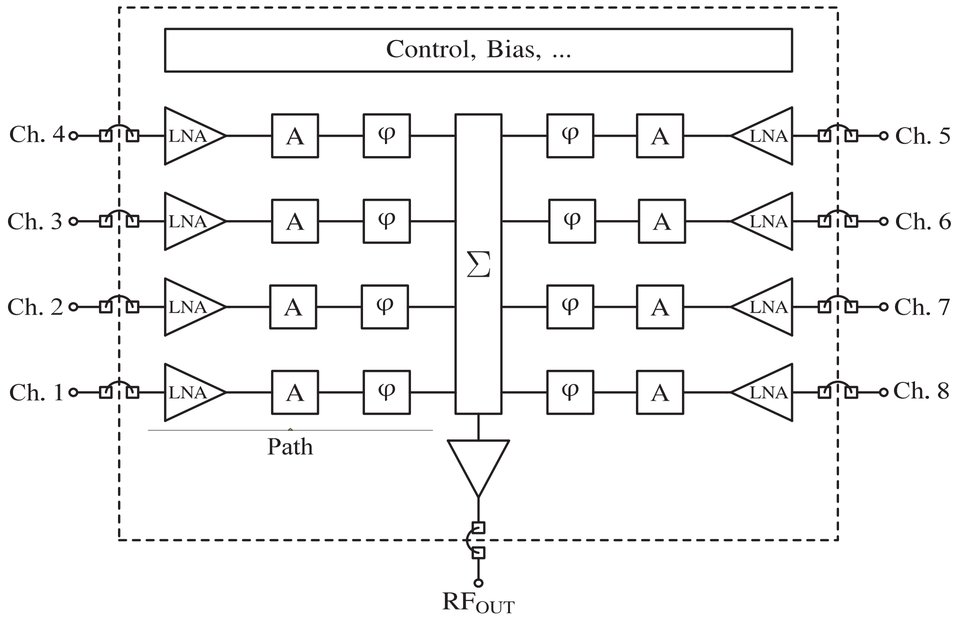


4.5x5.5 mm^2

Block diagram TX chip



Block diagram RX chip

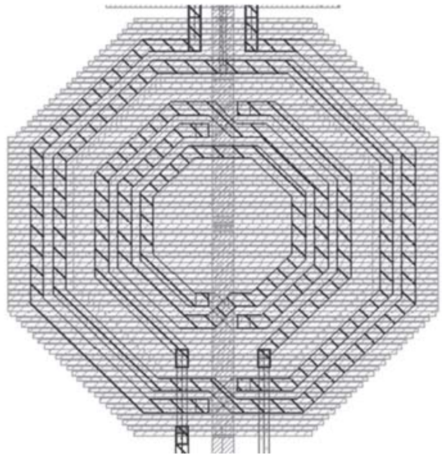


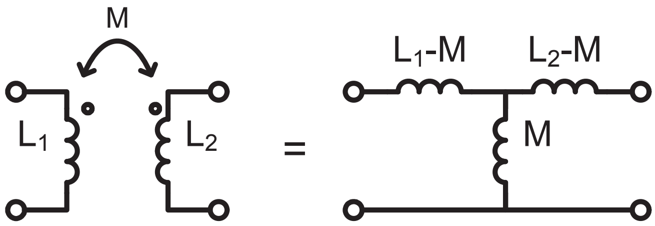
Design methodology

- Classical III-V
  - Model in 50 Ω microstrip environment + EM simulation
- Classical IV (Si)
  - Extraction RC → RLC(K)
  - Large layout freedom
  - RLC(K) extraction is not very accurate at mmWave
- Combined approach
  - For local interconnect RLC extraction
  - For larger areas EM simulations
  - Large error on small contributions leads to small overall error
  - Requires blackboxing, risk of missing parasitics
  - Very demanding chip / packaging interaction
    - Due to frequency and number of I/Os

Use Transformers!

- Transformer with low coupling factor gives 3 inductors in the area of 1
- Solution is RF layout friendly
- But not all component value combinations can be realized
- The loss of a transformer with a low coupling factor is the same as for lumped L-C-L matching network

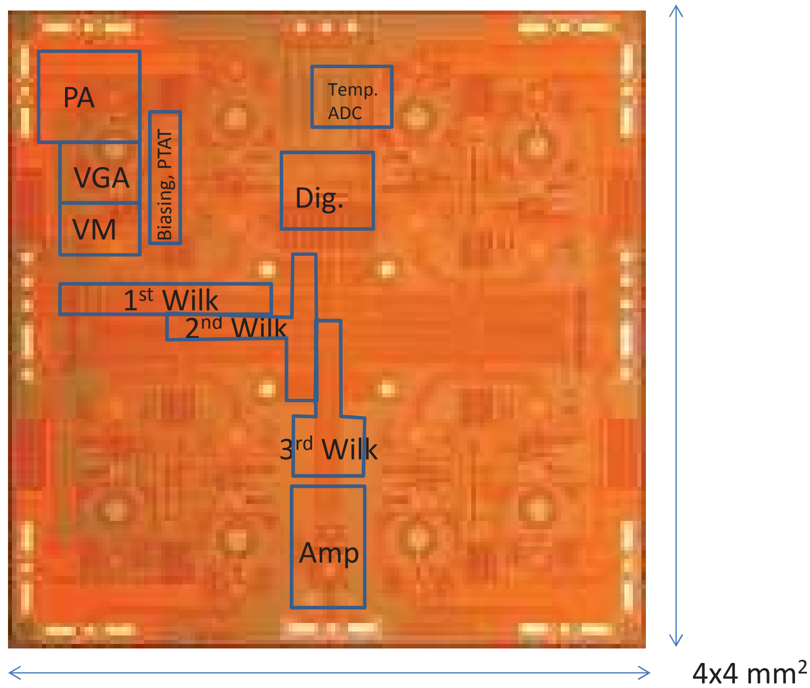




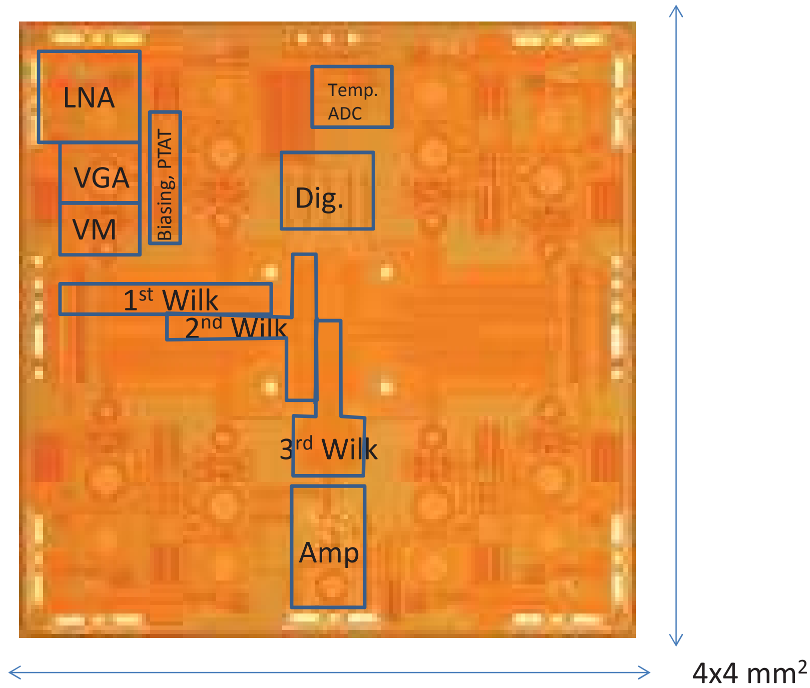
Power consumption

- Power constrained due to thermal reasons
- Selection of optimal supply voltage
  - Lower voltage
    - Higher maximum current
    - More functions in parallel
  - Higher voltage
    - easier to make power
    - transistor stack (VGA, VM, next slide)
    - Higher internal impedances (2 mAp/2Vp = 1 kΩ powerload)
- For receive, 2.5 Volt supply allows for stacking of transistors
- For transmit, 3.0 Volt supply allows for more efficient power generation
- These choices are technology dependent
  - NXP 0.25um BiCMOS, generation 8

Chip Layout - TX



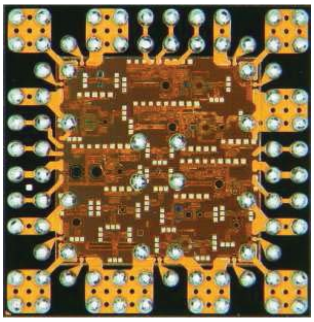
Chip Layout - RX



Packaging

- Flip-chip package used to mount chip on PCB
  - ☺ Good RF performance: low loss, good matching
  - ☹ Bad thermal performance: heat can only flow through balls

- Exposed chip back side used for thermal path
  - ☺ Separation of RF and thermal performance!

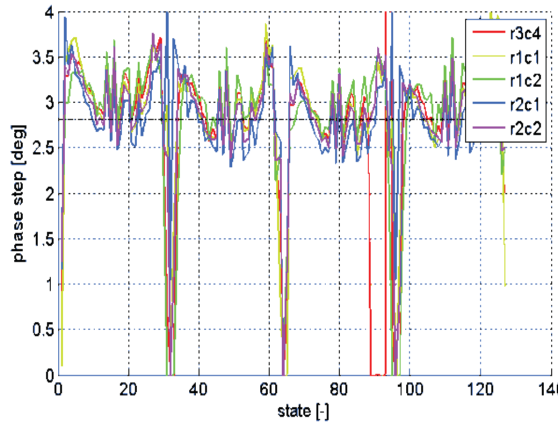


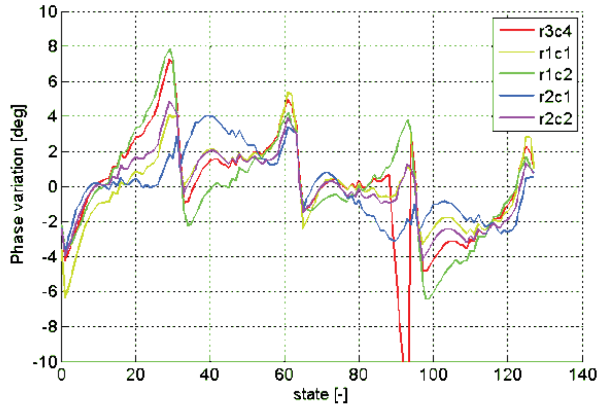
Characterisation

Issue: lengthy measurements (several hours), leading to oxidised probes and varying contacts

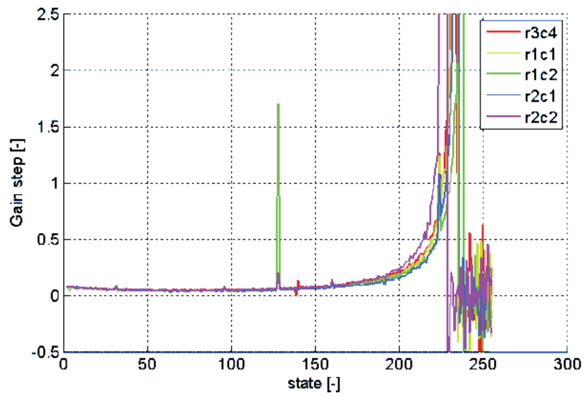
Solution: Cascade InfinityQuad probes,
with sharp tungsten (W) tips
with custom mixed DC+RF probes
on a fixed grid

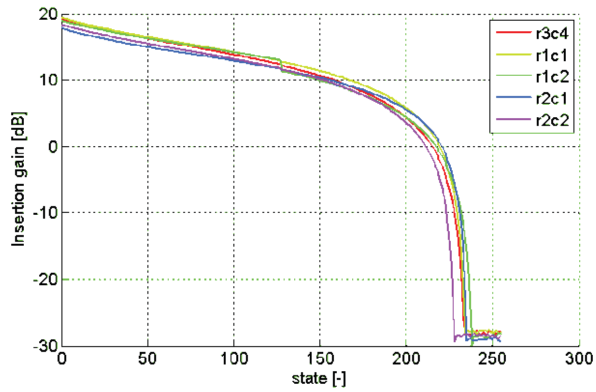
RX: VM performance





RX: VGA performance





Summary of measurements

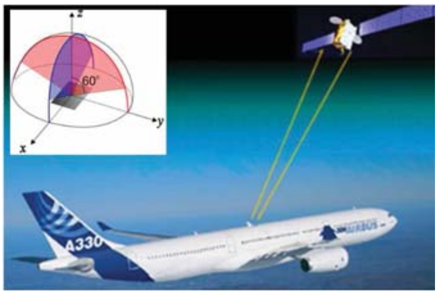
Transmit		
	Frequency	27-31.5 [GHz]
	Gain	25 [dB]
	Pout	10 - 13 [dBm]
	Pdc	1450 [mW]
Receive		
	Frequency	17.7-22 [GHz]
	Gain	20 [dB]
	NF	3.1 [dB]
	IIP3	-30 [dBm]
	Pdc	600 [mW]

Antenna Technology

Requirements: ACTiFE

Advanced Antenna ConcepTs for aircraft in-Flight Entertainment

- Frequency, in Ku-band:
  - Receive: 10.70 – 12.75 GHz
  - Transmit: 14.0 – 14.5 GHz
  - Integral bandwidth of 30%
- Polarization:
  - Receive: circular (LH or RH)
  - Transmit: variable linear
  - Cross polarization: ≥ 15 dB (all beam/pol setting)
- Scan range:
  - 360 degrees in azimuth
  - 60 degrees in elevation
    - Mainly electronically
    - Limited mechanically, to cover F.o.V.
- Structural constraints:
  - Low drag
  - Low impact on A/C-structural integrity
  - Integration of Tx and Rx in single panel(s)

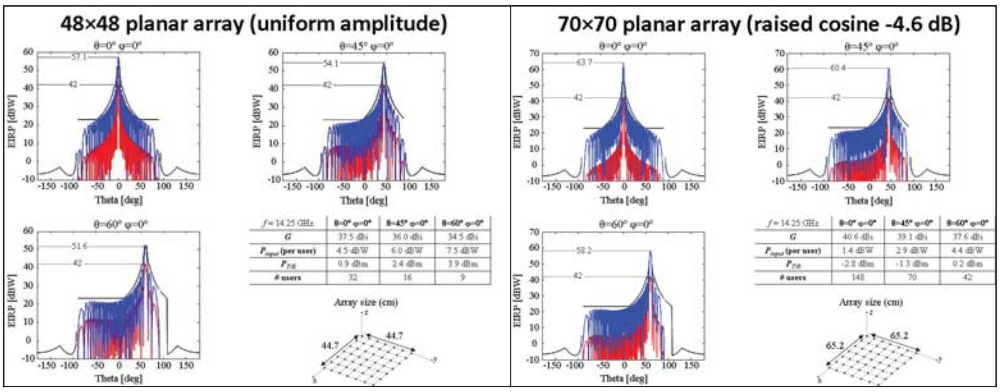


Array architecture

- Uplink and down link are at separate frequency bands
- Two possible array approaches:
  - Single antenna array for RX and TX
    - wideband antenna technology
    - larger module to contain both TX and RX functions
    - challenging if wide scanning, dual polarization is required
  - Separate array antennas for RX and TX

Array size – TX radiation patterns

- Considerations
  - ETSI mask definition (and ITU-R)
  - Tapering (raised cosine) for optimum fit within mask
  - Defined Tx data uplink
  - Limitations on array size (trade-off physical size, cost, number of elements, etc.)
  - Number of identical users (airplanes) for one satellite
- 48x48 and 70x70 Tx elements considered



48×48 planar array (uniform amplitude):

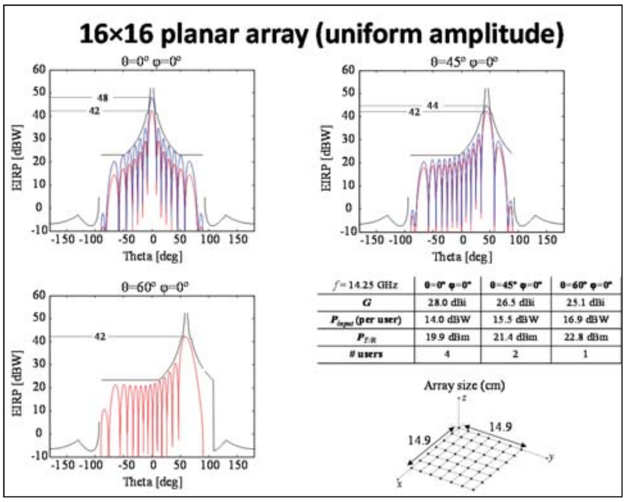
f = 14.25 GHz	θ=0° φ=0°	θ=45° φ=0°	θ=60° φ=0°
G	37.5 dBi	36.0 dBi	34.5 dBi
P_{input} (per user)	4.5 dBW	6.0 dBW	7.5 dBW
$P_{T/R}$	0.9 dBm	2.4 dBm	3.9 dBm
# users	32	16	9

70×70 planar array (raised cosine -4.6 dB):

f = 14.25 GHz	θ=0° φ=0°	θ=45° φ=0°	θ=60° φ=0°
G	40.6 dBi	39.1 dBi	37.6 dBi
P_{input} (per user)	1.4 dBW	2.9 dBW	4.4 dBW
$P_{T/R}$	-2.8 dBm	-1.3 dBm	0.2 dBm
# users	148	70	42

Demonstrator Antenna definition

- Considerations
  - Enough array elements to perform large scanning
  - Restrict no. of elements to limit material/component cost and test-time
  - Dual polarization for testing cross-polarization
  - Focus on Tx beam pattern setting
- Demonstrator antenna array
  - Gain at 10.7 GHz: 22.6 dB
  - Uniform illumination
  - 60° scan angle
  - 16x16 dual polarized



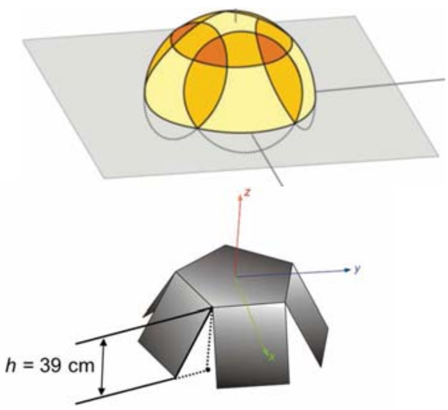
f = 14.25 GHz	θ=0° φ=0°	θ=45° φ=0°	θ=60° φ=0°
G	28.0 dBi	26.5 dBi	25.1 dBi
P_{input} (per user)	14.0 dBW	15.5 dBW	16.9 dBW
$P_{T/R}$	19.9 dBm	21.4 dBm	22.8 dBm
# users	4	2	1

System: Conclusions

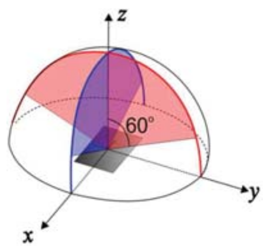
- 70x70 elements array as basic ‘flat’ antenna panel
- Electronically scanning up to at least 60°
- Fits Tx mask: enabling multiple users and/or high data rate per user
- Relatively low Tx power level per array-element
- Adequate Rx sensitivity with feasible receive NF per array-element

Structural evolution of antenna system

- Demand for structures with limited height, footprint:
  - Drag
  - Structural impact on A/C
- Reduced system complexity



	Fully electronic	Minor mechanical
# panels	6	1
# elements	2x13824	2x4900
System height	~40cm	~30cm
Scan range/panel	θ=45° φ=360°	θ=60° φ=360°

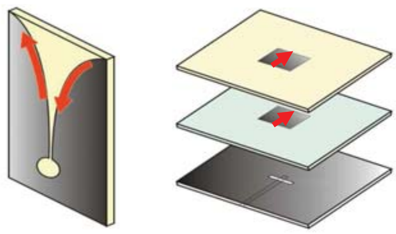


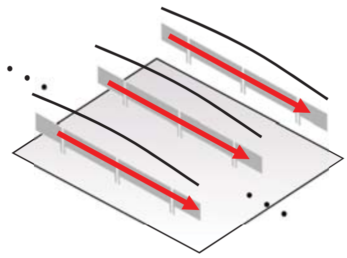
Antenna concept

- Combined requirement on bandwidth, far-out scan and cross polarization:
  - State of the art does not fulfil all of these

	Vivaldi	Stacked patches
BW	1:2.5 ☺	25 % ☹
X-pol	–10 dB ☹	–15 dB ☺

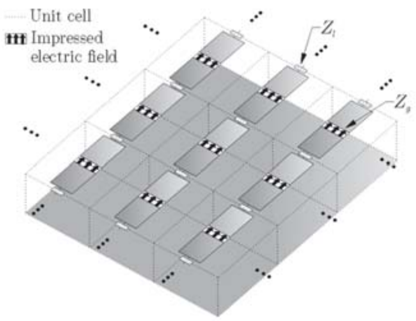
	Connected Dipoles
BW	40 % ☺
X-pol	–15 dB ☺

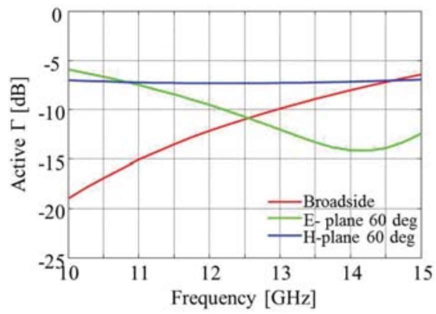




Dimensioning of the dipoles

- Optimization through a genetic algorithm:
  - Minimize the fitness function: $max_f(\Gamma_B, \Gamma_{E\theta_{max}}, \Gamma_{H\theta_{max}})$
  - Which is an analytical function of, amongst others, geometrical parameters: $Z_l = (j\omega C)^{-1}, \delta, w, h, Z_g$
- Unit cell size, d_x and d_y, are chosen fixed (eventually 0.435x0.435= 9x9 mm^2)





Optimization:

- C = 2.80 pF
- w = 4.5 mm
- δ = 5 mm
- h = 7.3 mm
- Z_g = 327.4 Ohm

↓

Γ_{max} = –7.05 dB

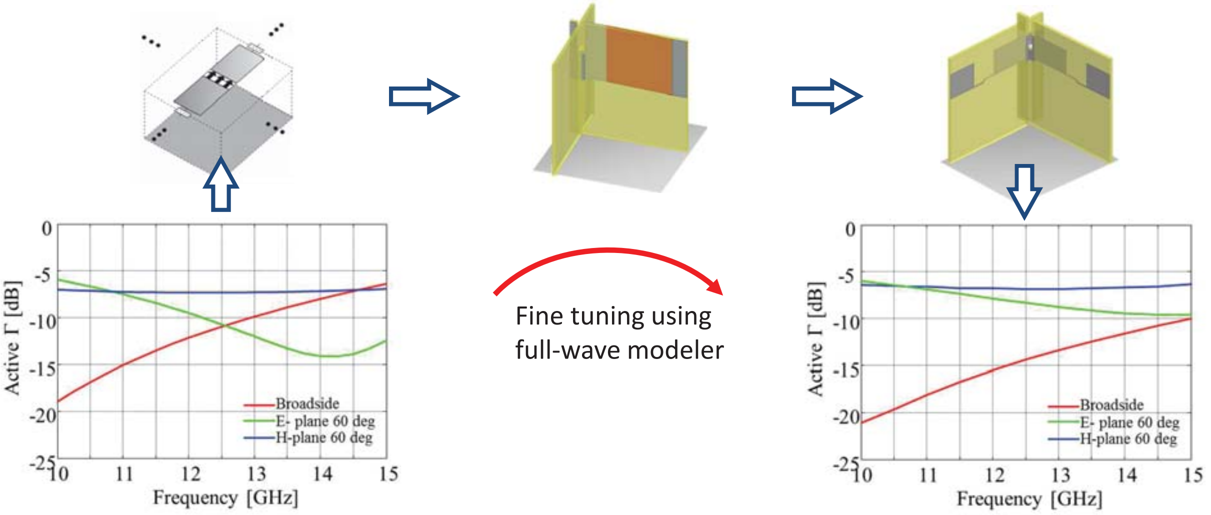
80% matching efficiency

From idealized to realistic dipoles

- Idealized feed
- Idealized capacitance
- Horizontal dipoles

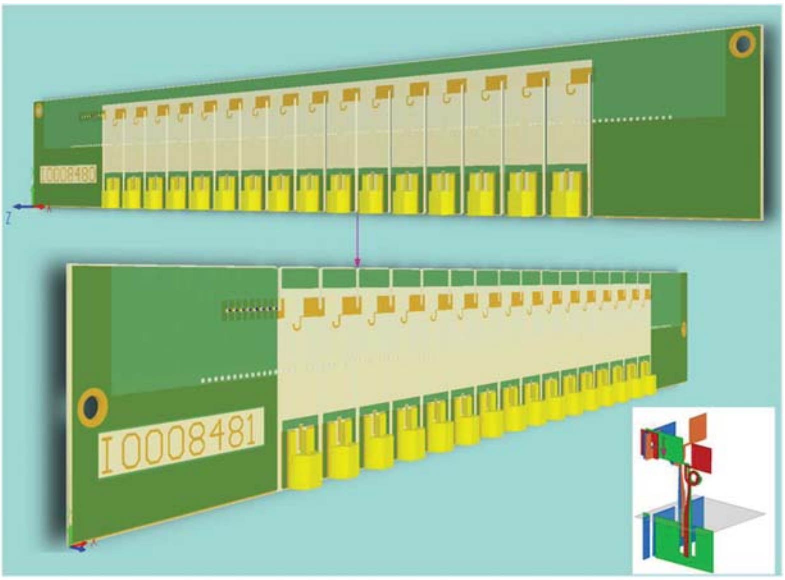
- Idealized feed
- Real capacitance (overlap)
- Vertical dipoles

- Real feed
- Real capacitance (overlap)
- Vertical dipoles



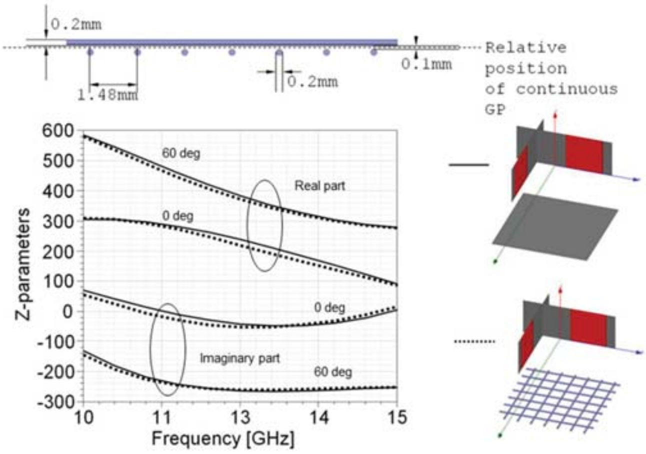
Practical implementation of the design (I)

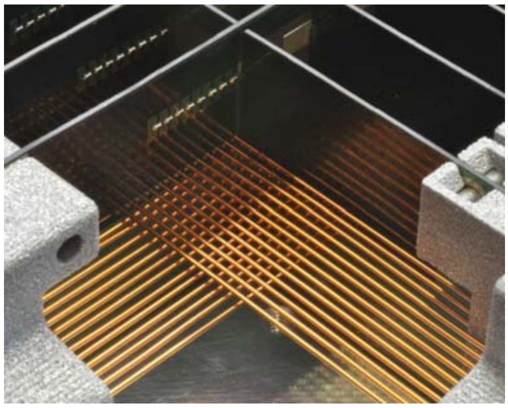
- Multi-layer PCBs and interleaving orthogonal linear array panels.



Practical implementation of the design (II)

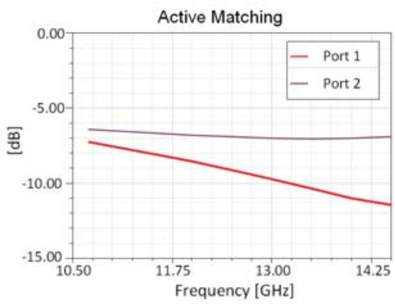
➢ Implementation of the ground plane through a wire grid.

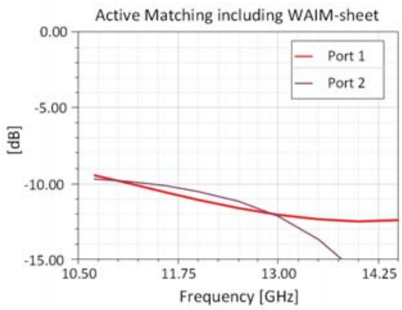


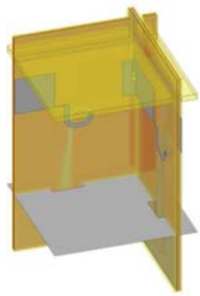


Practical implementation of the design (III)

➢ Introduction of a wide angle impedance matching (WAIM) structure;

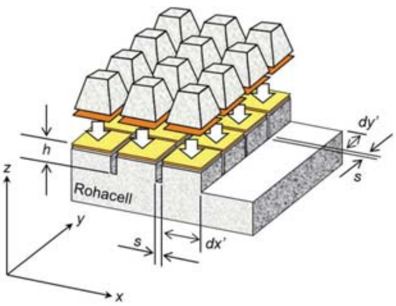


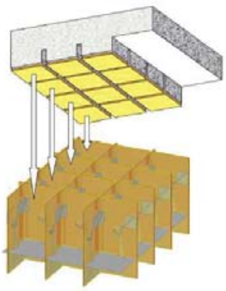




➢ WAIM implementation;

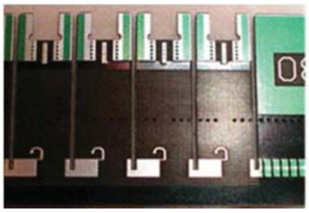
Rohacell
CuClad 6250, 38 μm
RO6010, 254 μm
CuClad 6250, 38 μm
Rohacell

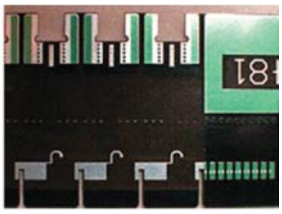




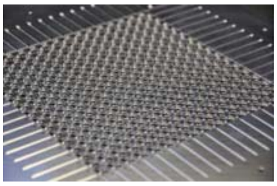
Practical implementation of the design (IV)

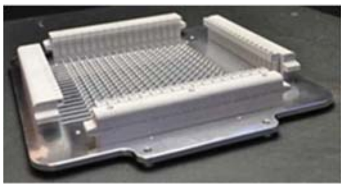
- Antenna panels:

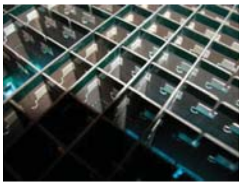


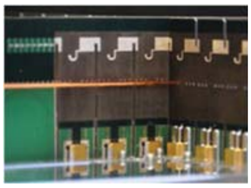


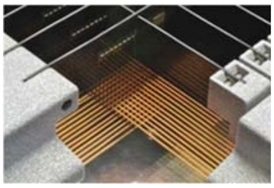
- Assembly:

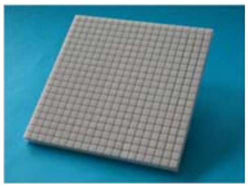


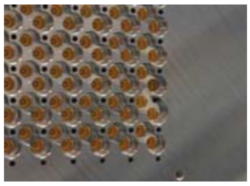






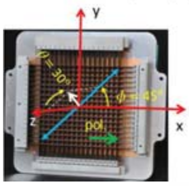


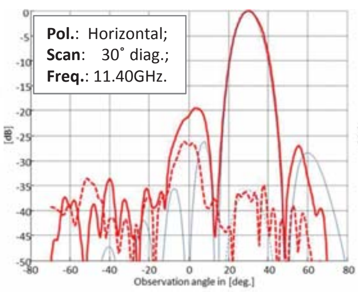


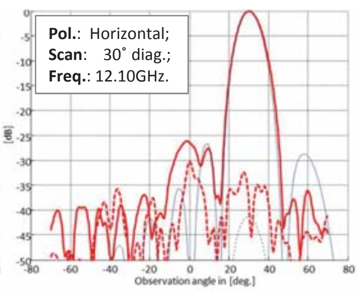


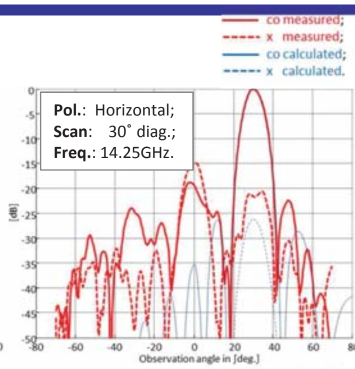
Experiment at radiation pattern level: D-plane

- Patterns scanning to 30˚ in the diagonal plane:

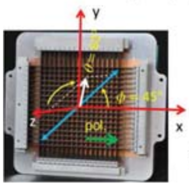


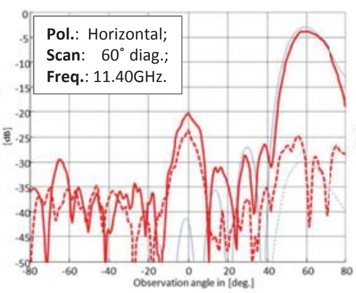


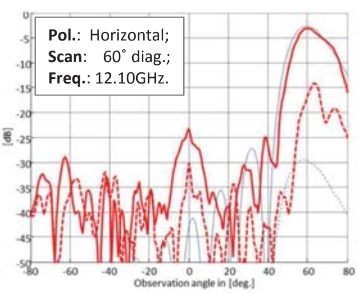


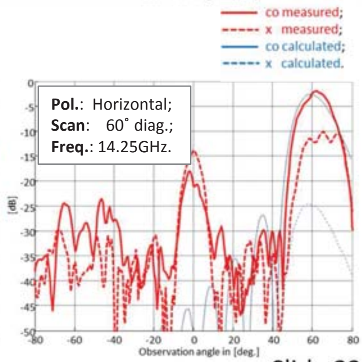


- Patterns scanning to 60˚ in the diagonal plane:

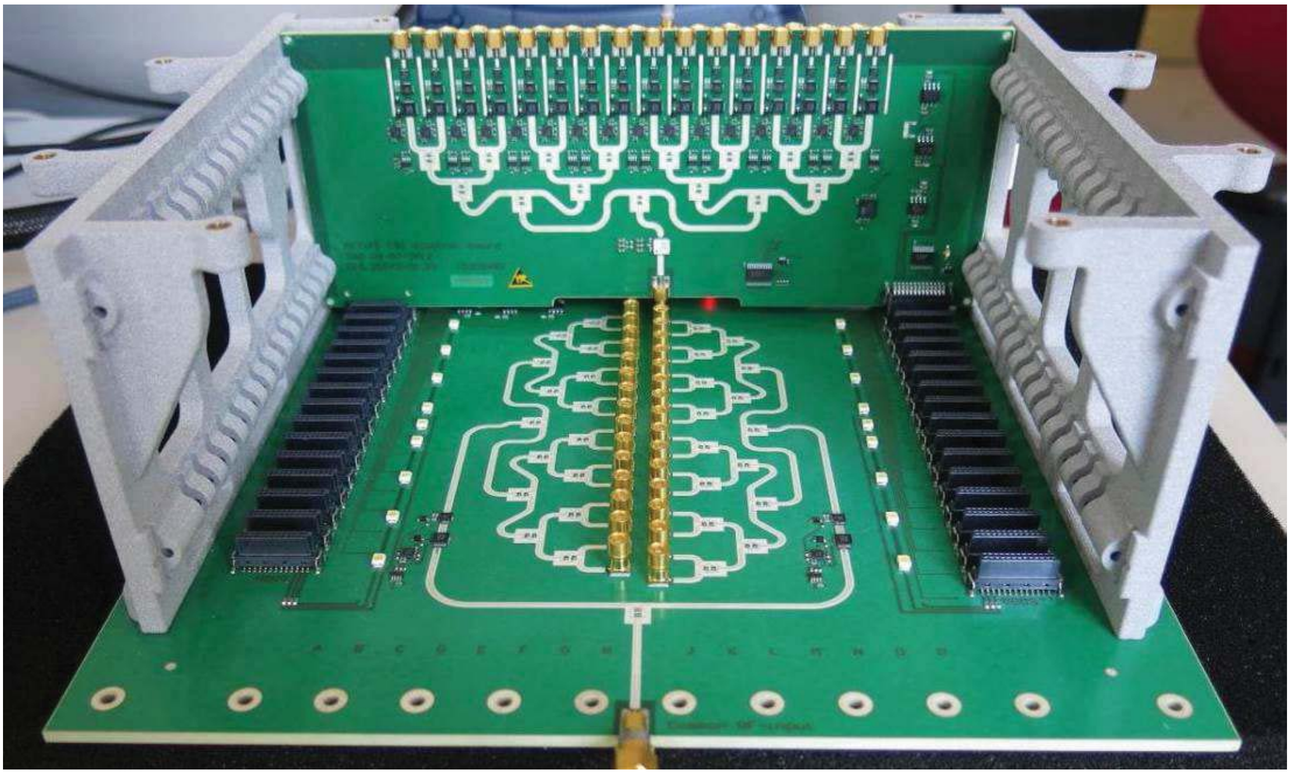






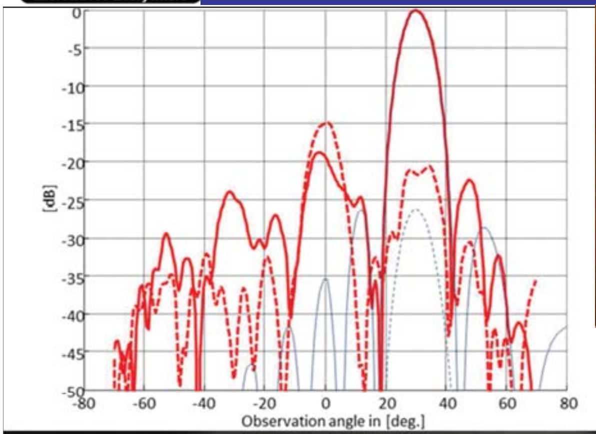


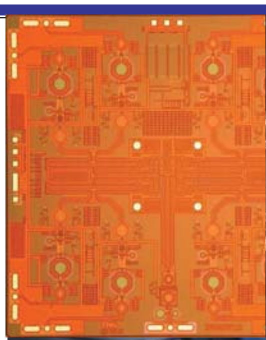
An inside view

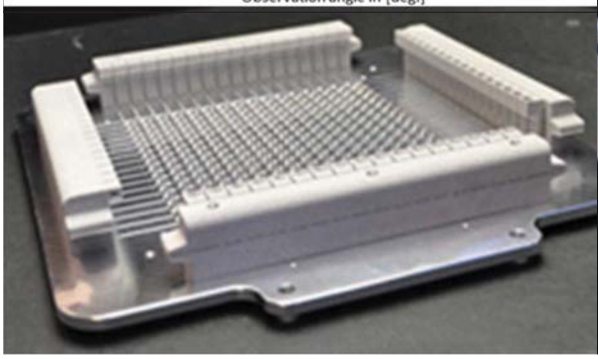


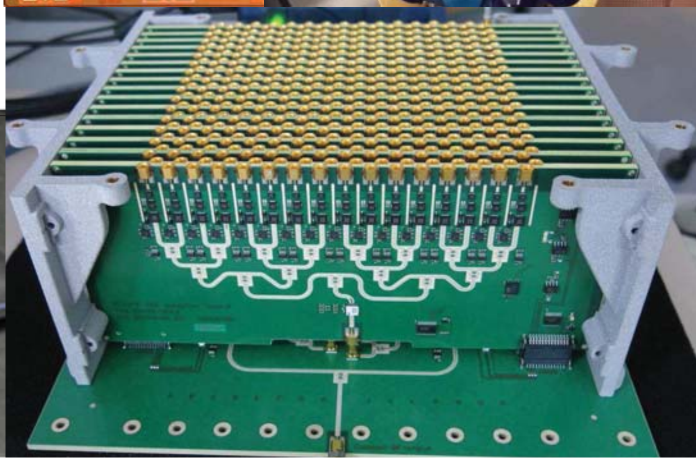
In conclusion

In conclusion …









Acknowledgement

➢ We kindly acknowledge the support of Airbus Defence and Space for the microwave developments and contributions to these slides

➢ We kindly acknowledge the support of ESA-ESTEC for the antenna developments and contributions to these slides

[1] "Characterization of a dual-polarized connected-dipole array for Ku-band mobile terminals", D. Cavallo et.al., IEEE Trans. Ant.& Prop., Feb. 2016.

[2] "Fully-Integrated Core Chip for X-Band Phased-Array T/R modules", F.E. van Vliet et.al., IMS 2004.

Electronically Liquid Crystal-based Beamsteering Antennas for SatCom-Applications

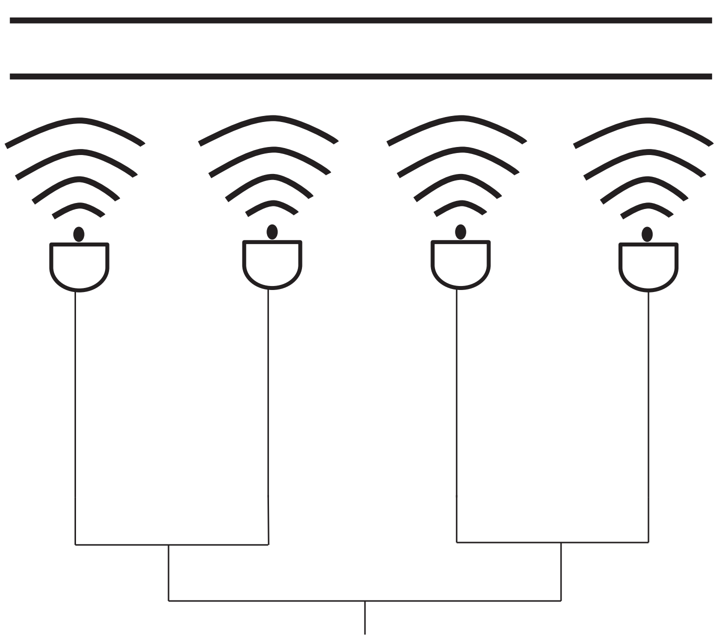
Matthias Jost

Technische Universität Darmstadt

jost@imp.tu-darmstadt.de

Motivation

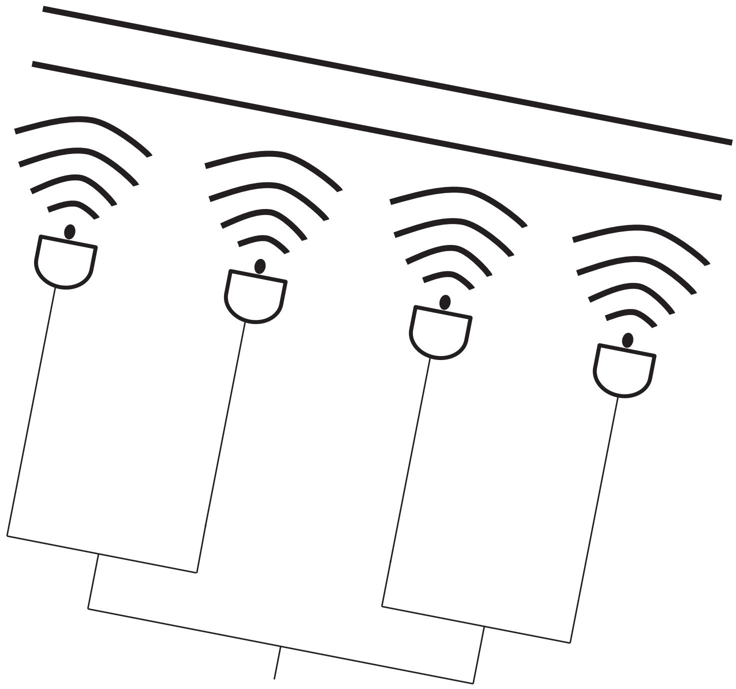
Why phase shifters?



- fixed lines
  - ➢ broadside radiation

Motivation

Why phase shifters?



- fixed lines
  - broadside radiation
  - tilted radiation by mechanical rotation

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Motivation

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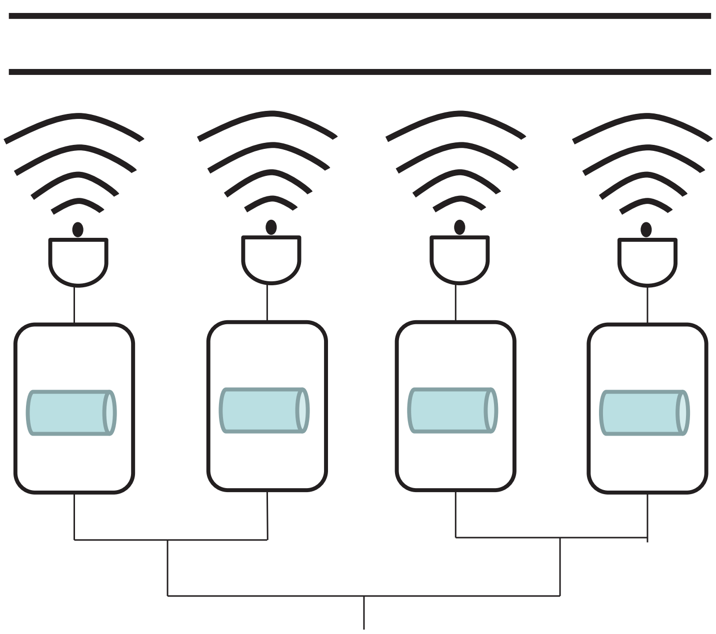
DARMSTADT

Why phase shifters?



- fixed lines
  - broadside radiation
  - tilted radiation by mechanical rotation

- phase shifters (equal orientation)
  - broadside radiation

WM07 New Developments for Satellite Communications on the Move

Motivation

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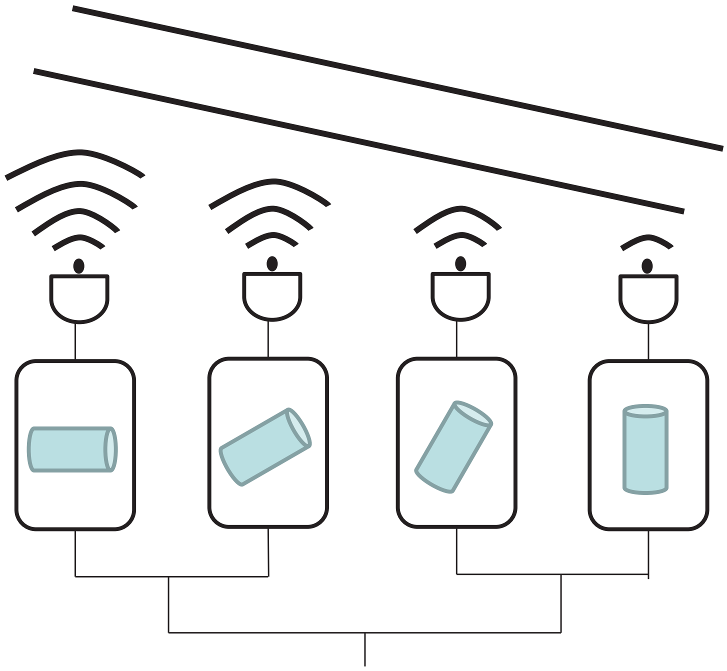
Why phase shifters?



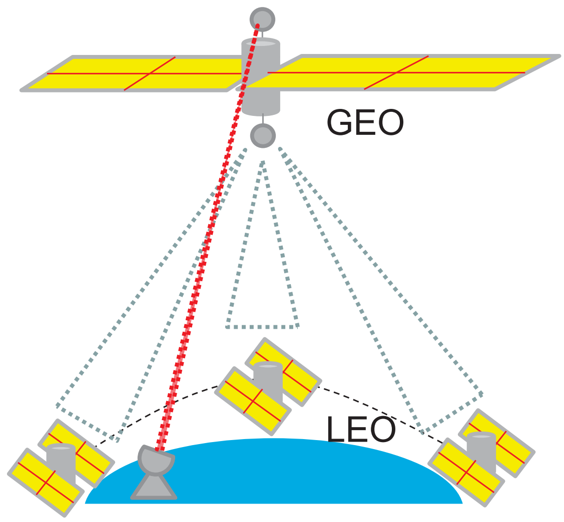
- fixed lines
  - broadside radiation
  - tilted radiation by mechanical rotation
- phase shifters (equal orientation)
  - broadside radiation
- phase shifters (continuous orientation)
  - tilted radiation

Motivation

TECHNISCHE UNIVERSITÄT DARMSTADT

Onboard internet, satellite TV reception in automobiles, ships, boats, airplanes

Transceiver antennas for inter-satellite links (GEO → LEO), High-Q-tunable filters for satellite transponders



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Motivation

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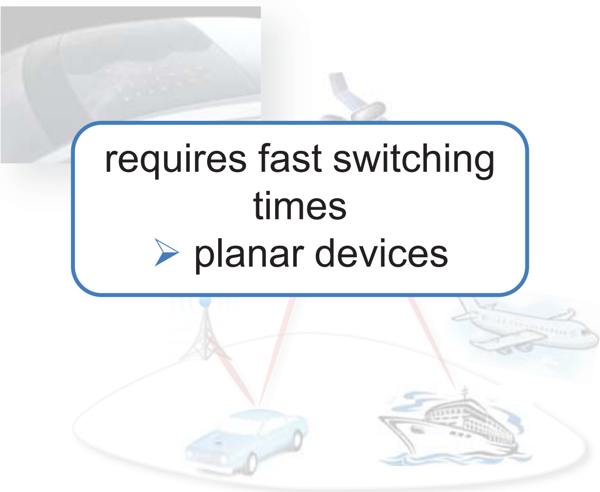
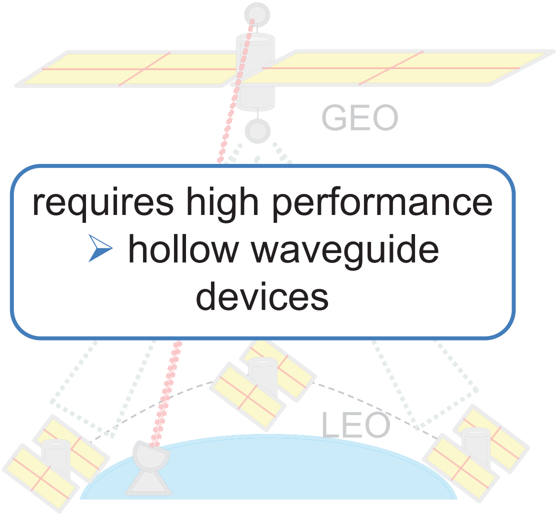
Onboard internet, satellite TV reception in automobiles, ships, boats, airplanes



requires fast switching times
➢ planar devices

Transceiver antennas for inter-satellite links (GEO → LEO), High-Q-tunable filters for satellite transponders



requires high performance
➢ hollow waveguide devices

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Content

TECHNISCHE UNIVERSITÄT DARMSTADT

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- Fundamentals of Liquid Crystal
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- Planar phased array antennas
- Conclusion

Fundamentals of Liquid Crystal

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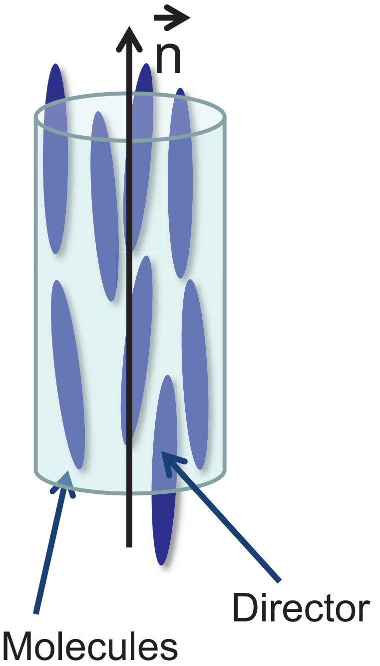

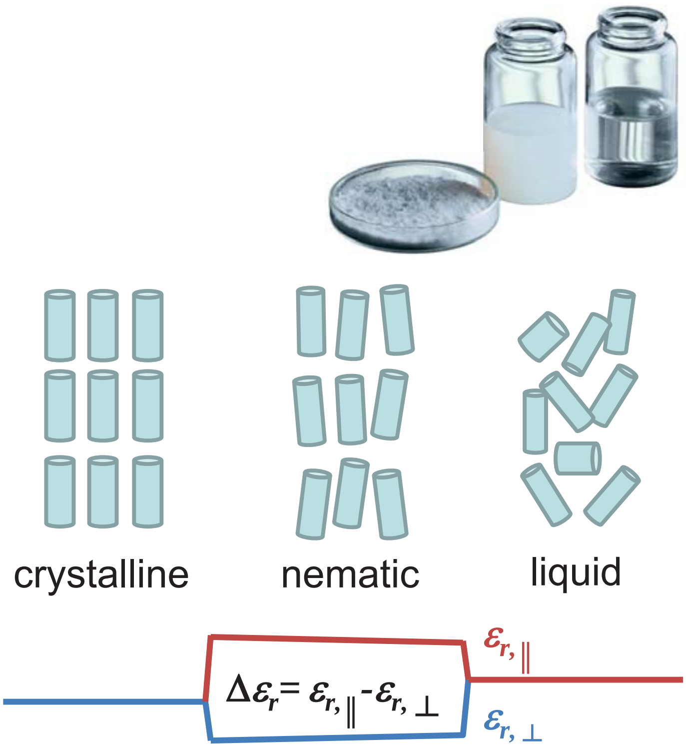

Fundamentals of Liquid Crystal

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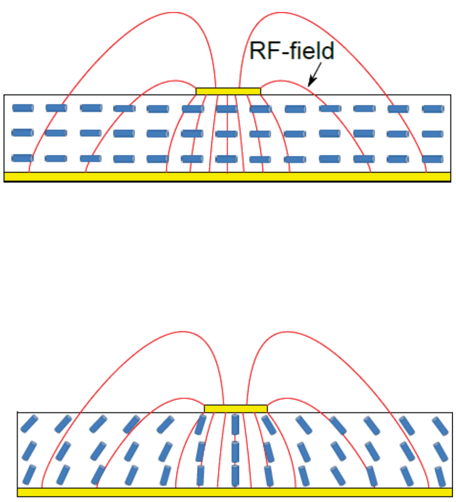

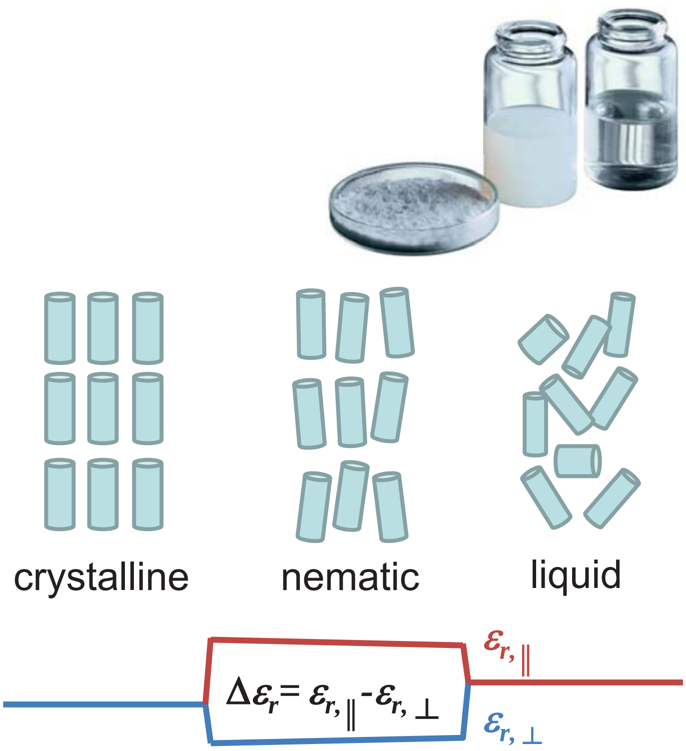

Fundamentals of Liquid Crystal

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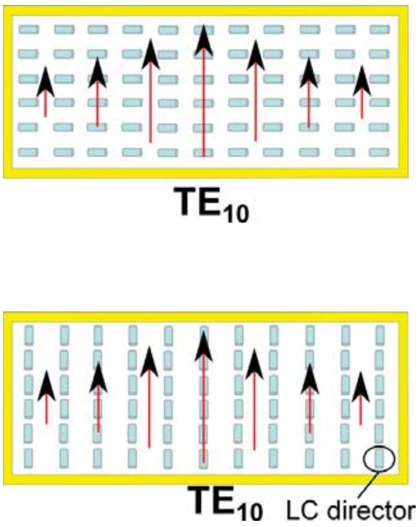

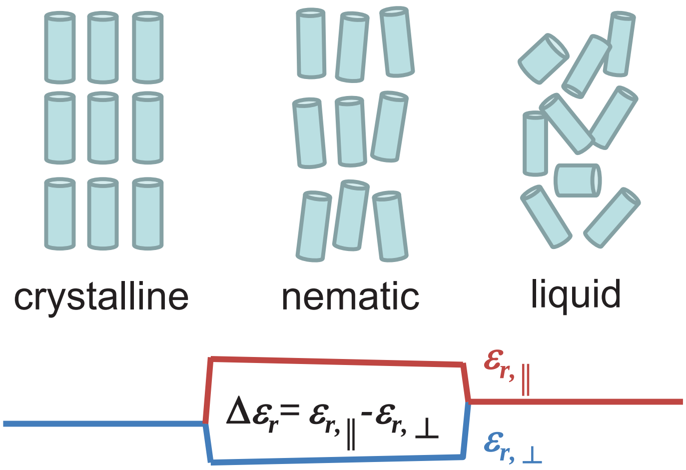

Fundamentals of Liquid Crystal

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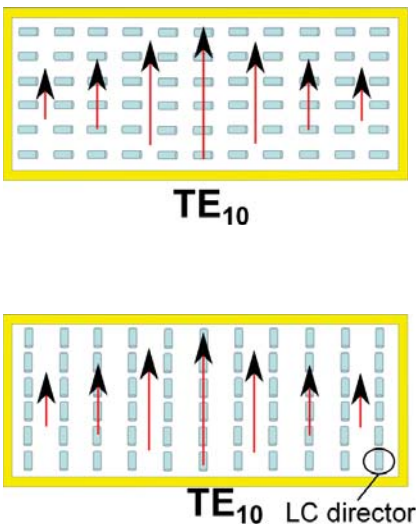

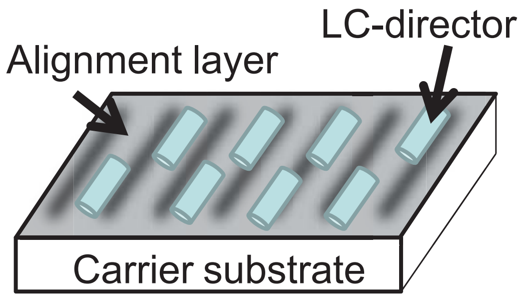

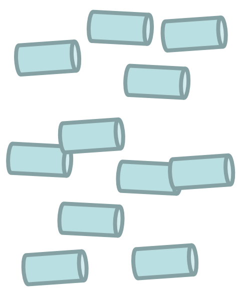

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Fundamentals of Liquid Crystal

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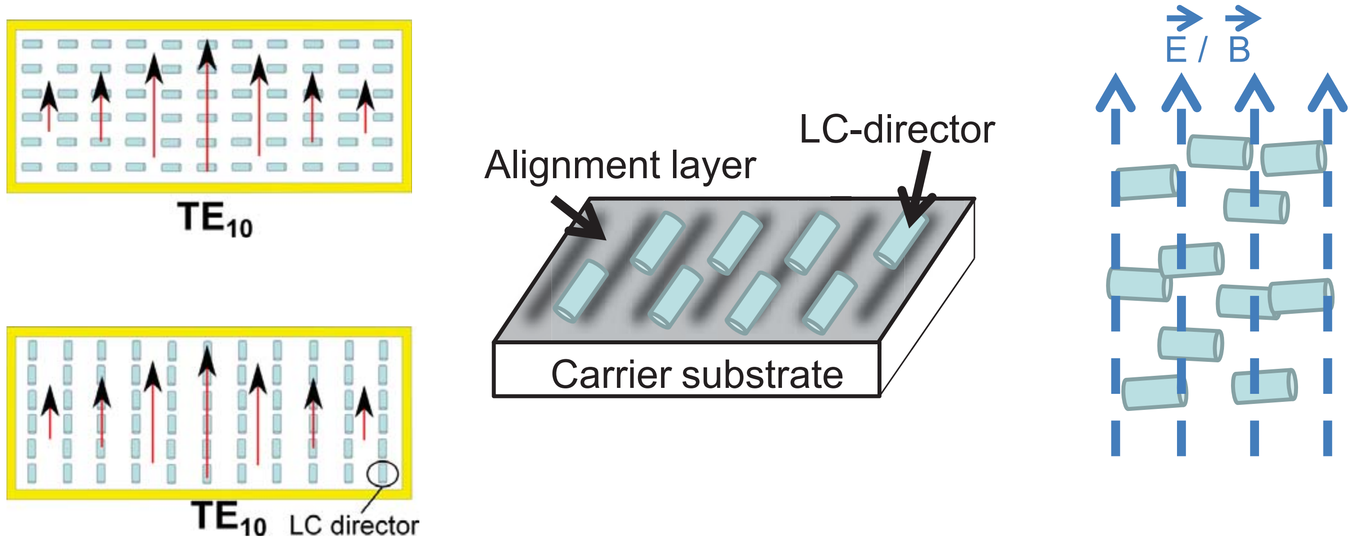

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Fundamentals of Liquid Crystal

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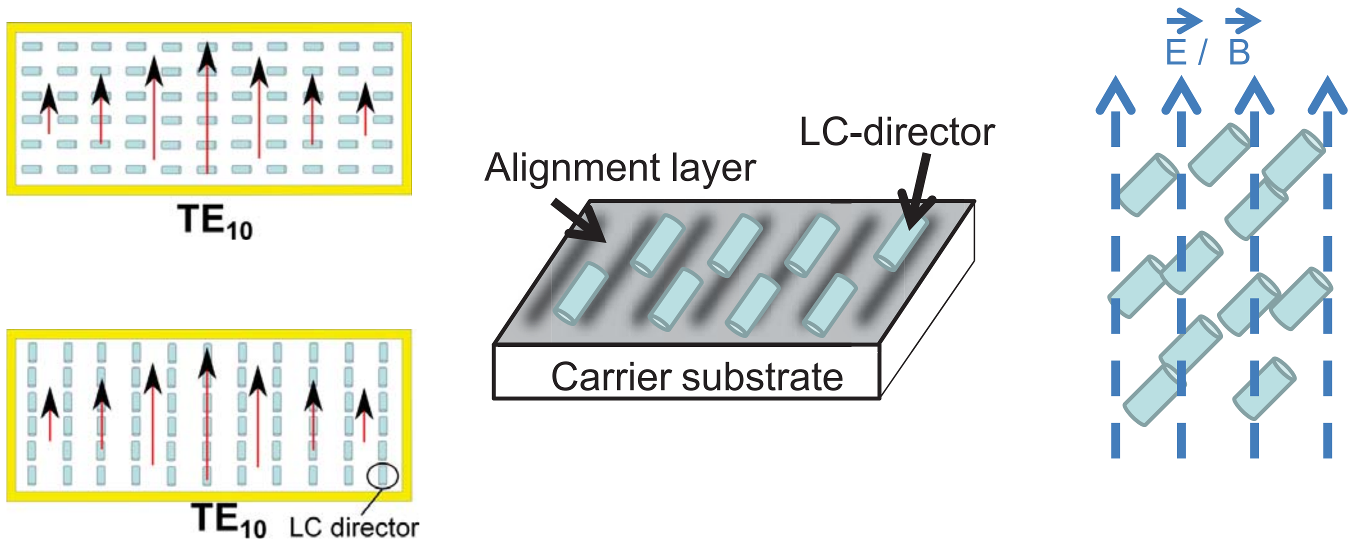
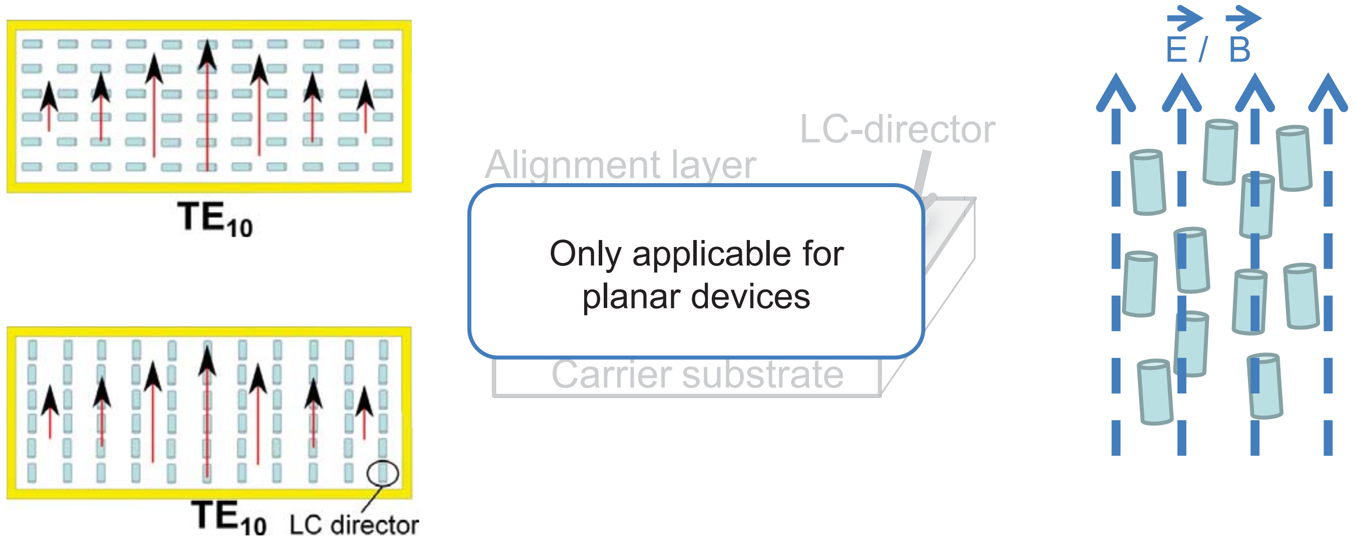


Fundamentals of Liquid Crystal



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Fundamentals of Liquid Crystal

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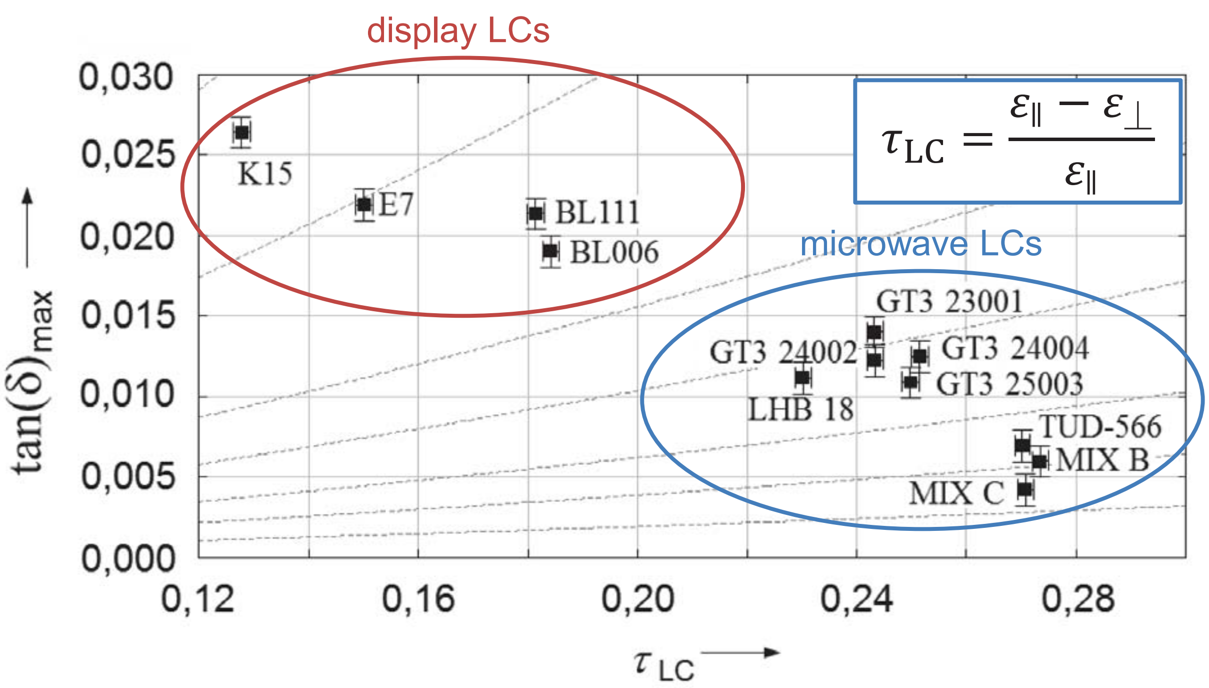

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Fundamentals of Liquid Crystal

MERCK

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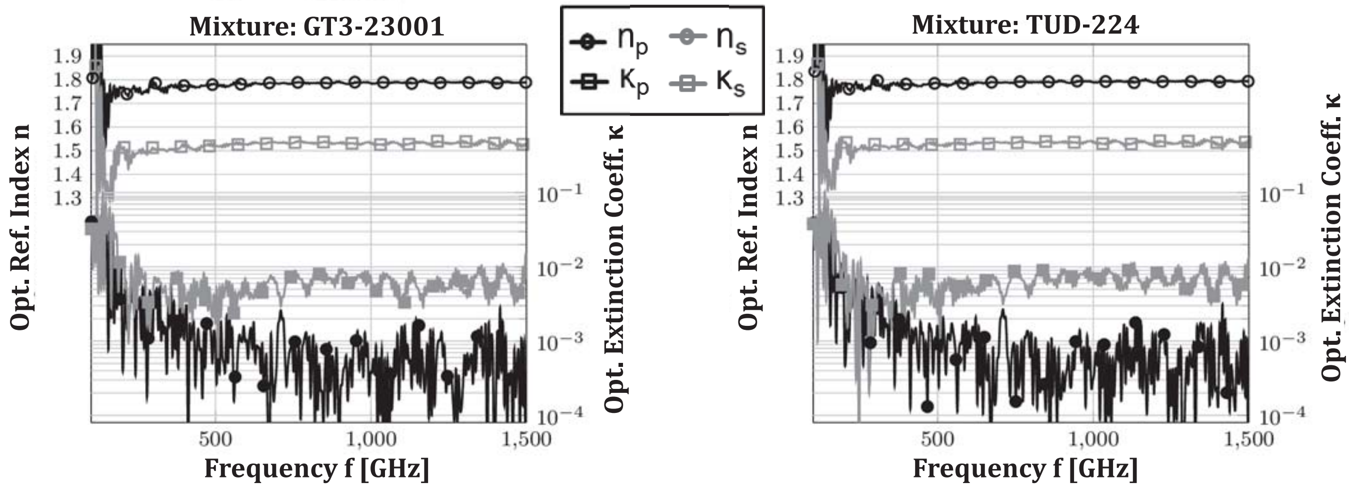

Mischung	ε_p	$\tan\delta_p$	ε_s	$\tan\delta_s$
GT3-23001	3.1909	0.0175	2.3435	0.0286
TUD-224	3.2059	0.0148	2.3502	0.0341
TUD-424	3.2903	0.0147	2.3763	0.0329
TUD-325	3.4067	0.0164	2.3629	0.0317
TPX (Lit. 1.45-1.46)	2.0776	0.0201	--	--

Average value at 0.5-1.5 THz,
tanδ is determined by the dynamic range of the system

Mischung	ε_p	$\tan\delta_p$	ε_s	$\tan\delta_s$
GT3-23001	3.19	0.0035	2.41	0.0143
TUD-224	3.18	0.003	2.41	0.0125
TUD-424	3.27	0.0033	2.45	0.0126
TUD-325	3.22	0.0025	2.42	0.0111

Reference values for 19 GHz and R.T. (Source: Merck)

[Wei+13b]

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Content

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation
- Fundamentals of Liquid Crystal
- High performance phase shifter
- Planar phased array antennas
- Conclusion

High performance phase shifter

LISA-ES

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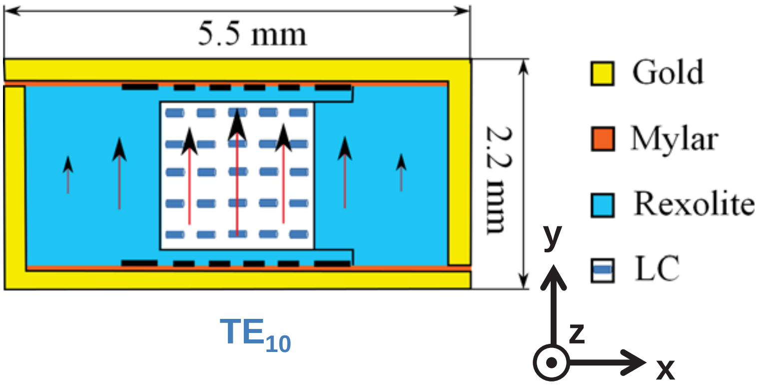
- Partially filled with LC
  - reduced dielectric loss
- Two-piece container with two filling holes
- Biasing system processed on Mylar films
- Split-block is electroplated with Au
  - avoid passivation



Material	ε_r	tanδ
Rexolite	2.53	$6.6 \cdot 10^{-4}$
$LC_{\parallel}$	3.27	$2.2 \cdot 10^{-3}$
$LC_{\perp}$	2.39	$7 \cdot 10^{-3}$

High performance phase shifter

LISA-ES

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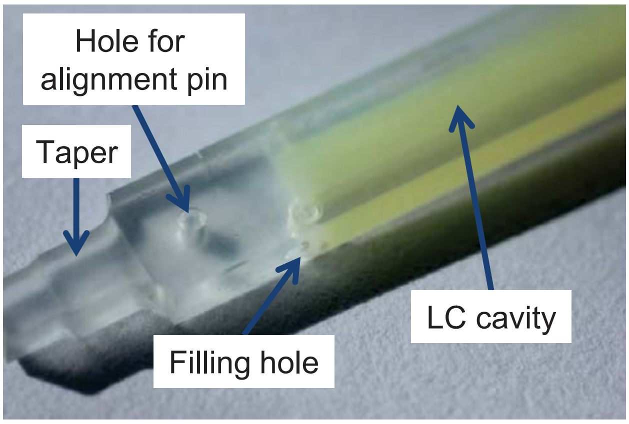
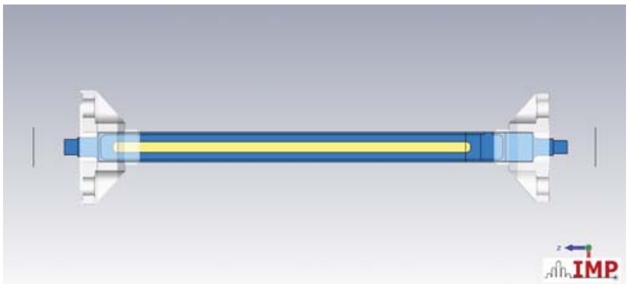
- Dielectric tapering
  - two steps
  - mix of discrete and continuous
- Alignment
  - transversal misalignment < 0.1 mm
  - angular misalignment < 0.2°
- Filling
  - under normal conditions
  - sealing with orthogonally aligned pins
- Metallic tapering
  - two steps
  - discrete





High performance phase shifter
LISA-ES

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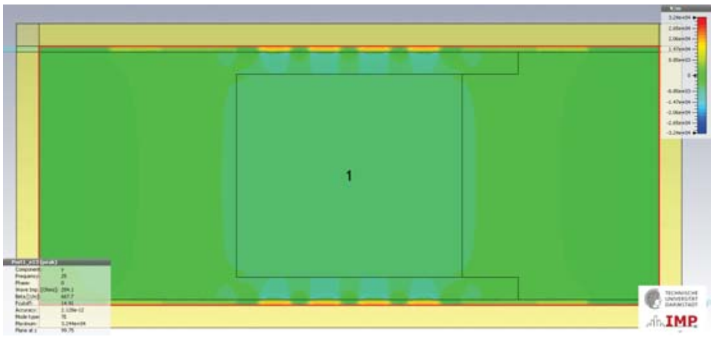
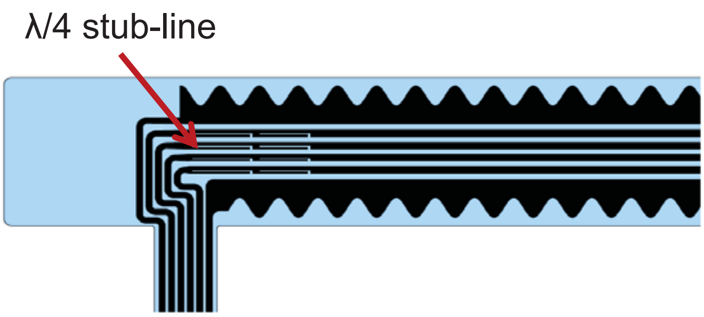
- Stripline modes occur between biasing lines and waveguide walls
  - RF is focused in non-tuneable material
- Implementation of λ/4-stub lines and stepped impedances
  - suppression of stripline modes
  - RF field is concentrated in the LC
- λ/4-stub lines are already sufficient





High performance phase shifter
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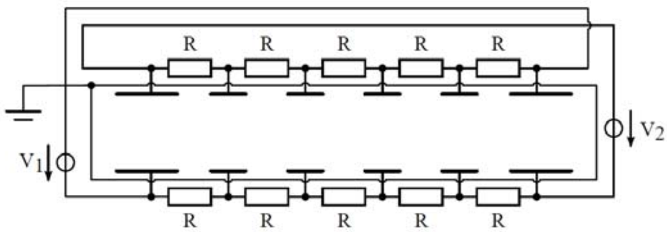
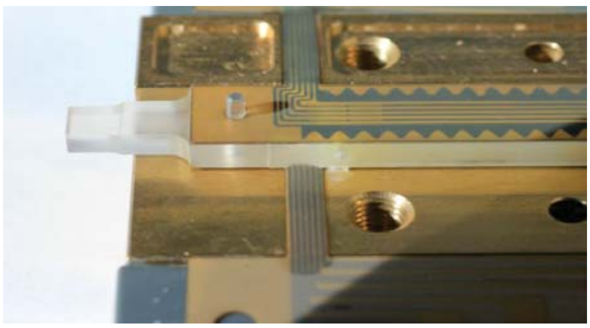
- Electrodes are connected to voltage dividing network
  - only two voltage sources are needed
- Biasing electrodes are processed on 50 µm thick Hostaphan films
  - breakdown voltage: 220 kV/mm
  - narrowest structure: 60 µm
- LC cavity has a total length of 120 mm
  - $\Delta\varphi_{sim} \approx 600°$
- Measurement are carried out in two steps
  - WR42 & WR28



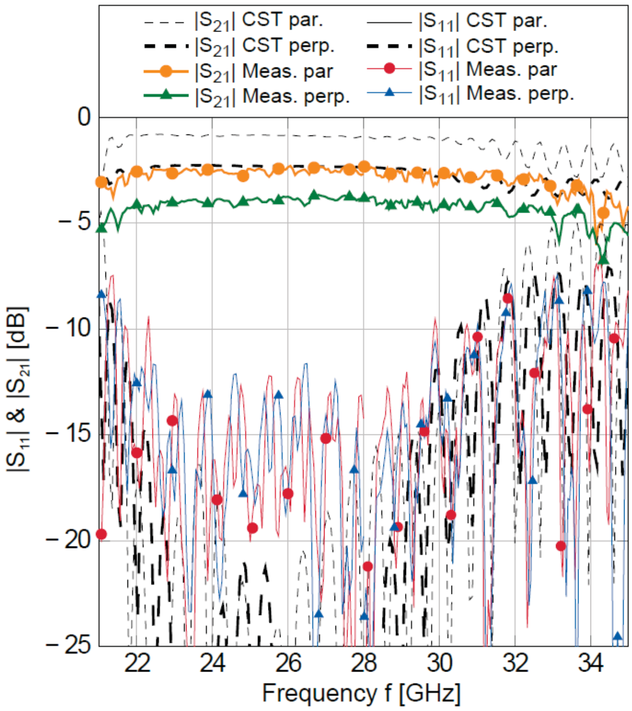


WM07 New Developments for Satellite Communications on the Move

High performance phase shifter

LISA-ES

- Results
  - Return loss better than 12 dB
  - Insertion loss around 3 dB (4 dB) for parallel (perpendicular) orientation
- No perfect match to simulations



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Microwaves Everywhere

High performance phase shifter

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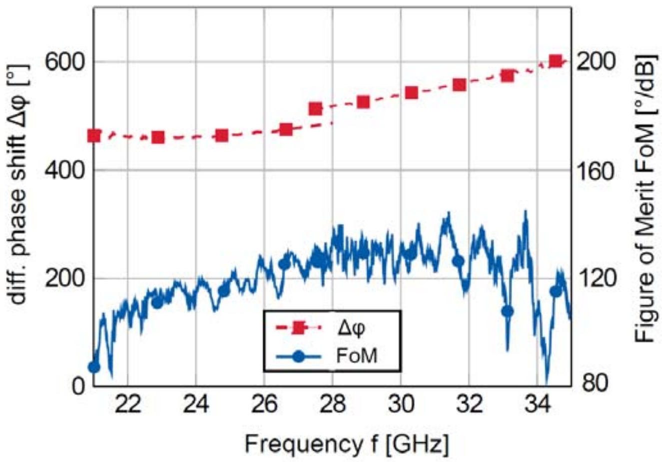
TECHNISCHE UNIVERSITÄT DARMSTADT

- Results
  - Return loss better than 12 dB
  - Insertion loss around 3 dB (4 dB) for parallel (perpendicular) orientation
- No perfect match to simulations

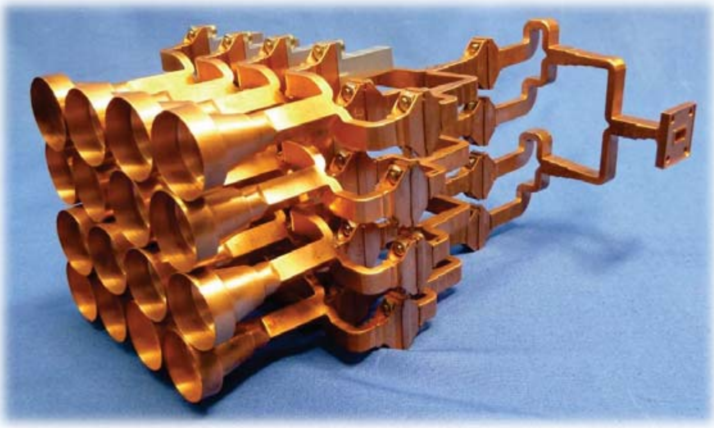
$$FoM = \frac{\Delta\varphi}{IL}, \quad [FoM] = °/dB$$

- differential phase shift better than 460°
- FoM around 130°/dB



High performance phase shifter

LISA-ES



High performance phase shifter

LISA-ES

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Technology	Topology	f [GHz]	Δφ [°]	IL [dB]	FoM [°/dB]	Ref.
Varactors	loaded transmission line	6	410	6	68	[Ell+03]
InGaAs	PIN switch diodes	28	349	7.8	45	[Yang+11]
MEMS	distributet MEMS CPW	40	84	1.8	47	[Bar+98]
	loaded transmission line (4 bit)	60	250	3	83	[Kim+02]
	Hybrid distributed RTPS	15	337.5	2.2	153	[Pil+12]
MEMS & CMOS	RTPS (CMOS 0.18 μm)	65	144	3.2	42	[Cha+13]
BST	loaded CPW	9	405	7.6	53	[Saz+11]
	loaded CPW	40	600	27	22	[Velu+07]
LC	inverted microstrip line	24	330	3	110	[Mue+04]
	finline	40	303	4.8	62	[Mue+05]
	ridged waveguide	94	500	7.2	69	[Mue+06]
	loaded CPW	20	90	1.5	60	[Goe+09]
	hollow waveguide (magn. biasing)	35	110	0.55	200	[Gae+09]
	hollow waveguide	29	550	4.2	130	[Wei+13a]
	hollow waveguide (magn. biasing)	100	309	2.3	135	[Jost+13]
LC & LTCC	SIW waveguide	28	400	9.7	41	[Str+14]
LC & MEMS	loaded line	93	190	4.5	42	[Fri+11]
LC & CMOS	CPW (CMOS 0.35 μm)	45	275	5.35	52	[Fra+13]

WM07 New Developments for Satellite Communications on the Move

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Planar phased array antennas

SatCom On-the-Move Applications

Onboard internet, satellite TV reception in automobiles, ships, boats, airplanes

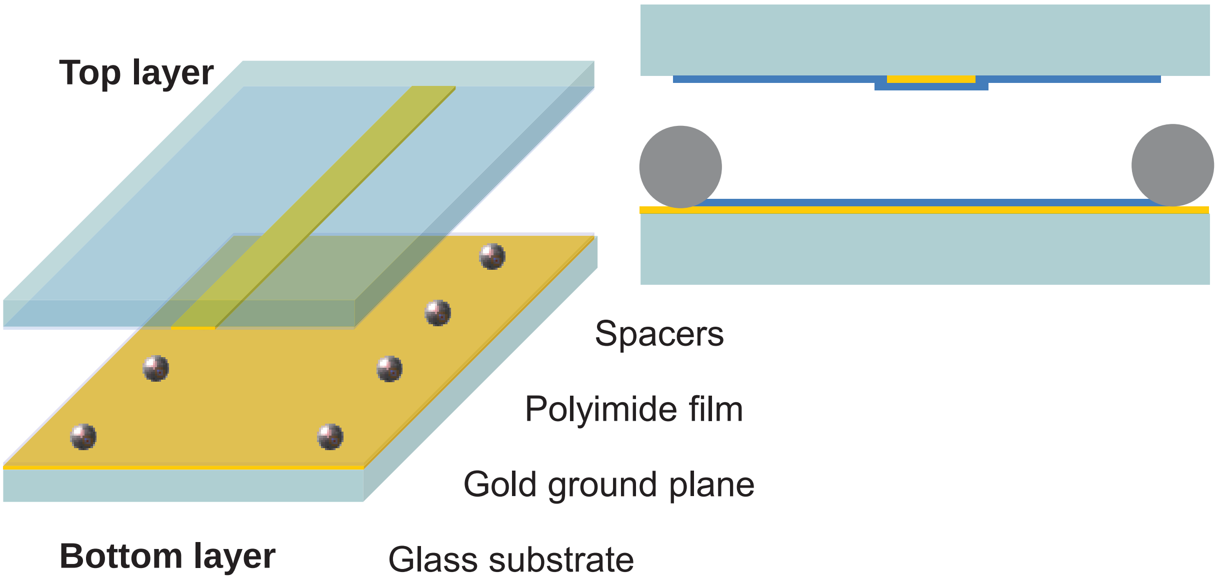
Large Market Potential
- Future GEO-/MEO-/LEO-Satellites for Broadcasting & Communications Services in **C-/Ku-/Ka-/K**-Bands

Demand
- Electronically Reconfigurable Antennas
- Affordable: Low Cost Technology
- Aesthetic: Compact and Low-Profile

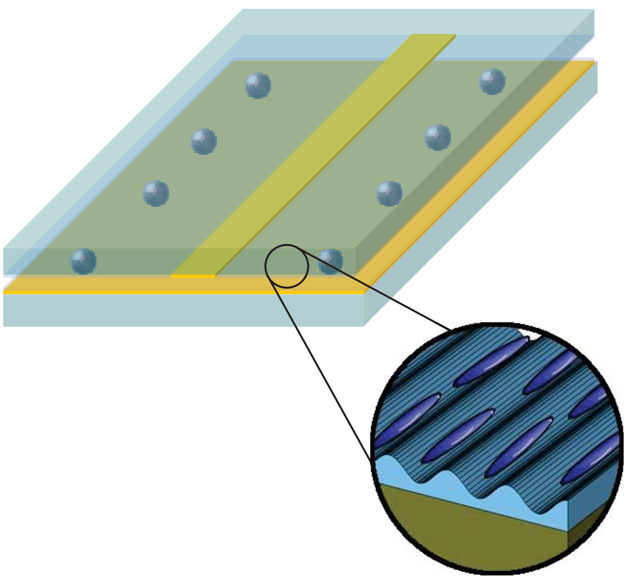
Some Requirements

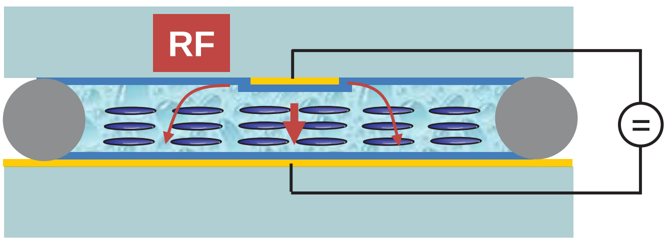
Phased-Array	Phase Shifter
Large Scanning Range	360° Phase Shift
High Antenna Gain	Low-Insertion Loss
2D beam steering	Compact $A < (\lambda_0/2)^2$
Low cost	Full integration

Planar phased array antennas



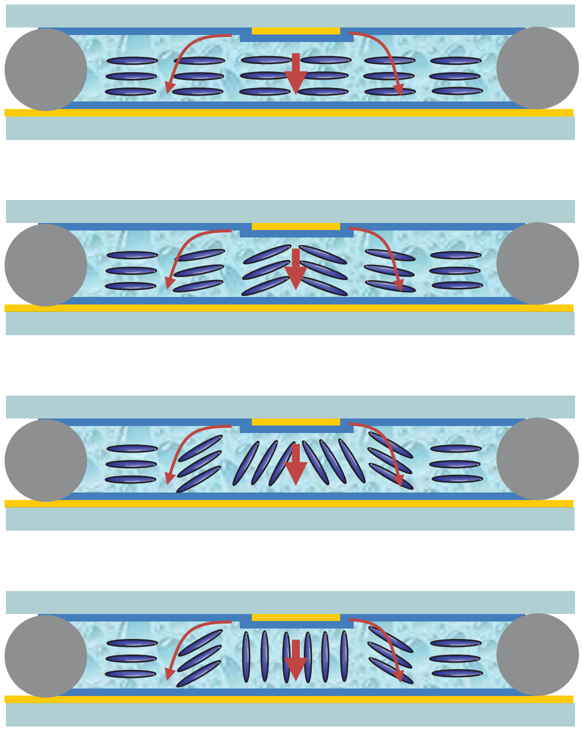
Planar phased array antennas

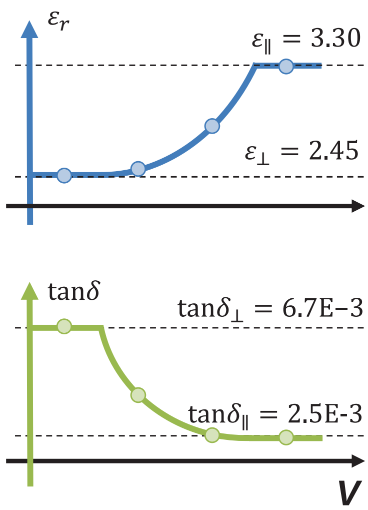




- Sealing
- LC fill
- Pre-alignment effect (Polyimide film)
- RF field propagating along structure
- Applying DC voltage to tune the LC

Planar phased array antennas



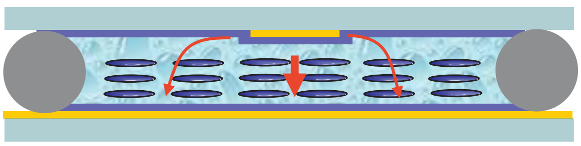


Material Quality

$$\eta = \frac{\tau_{\mathrm{LC}}}{\tan\delta_{\max}} = \frac{\varepsilon_{\parallel} - \varepsilon_{\perp}}{\varepsilon_{\parallel} \cdot \tan\delta_{\perp}}$$

Planar phased array antennas

Response Times (Planar topology)



$$\tau_{\mathrm{off}} \propto \frac{\gamma^*}{K_{ii}} \cdot d^2$$

$\tau_{\mathrm{off}} = 1 \ldots 20\ \mathrm{s}$

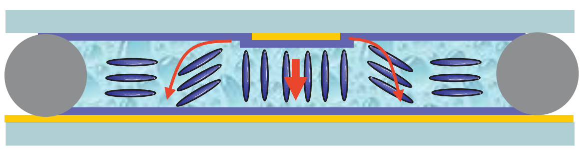
Applying Bias

Compared to
2…15 ms in LCD

Releasing Bias

$$\tau_{\mathrm{on}} \propto \frac{\gamma}{K_{ii}} \cdot \frac{d^2}{\left({}^{V}/_{V_{th}}\right)^2 - 1}$$

$\tau_{\mathrm{on}} = 10\ \mathrm{ms} \ldots 1.3\ \mathrm{s}$



EuMW 2016
Microwaves Everywhere

Planar phased array antennas

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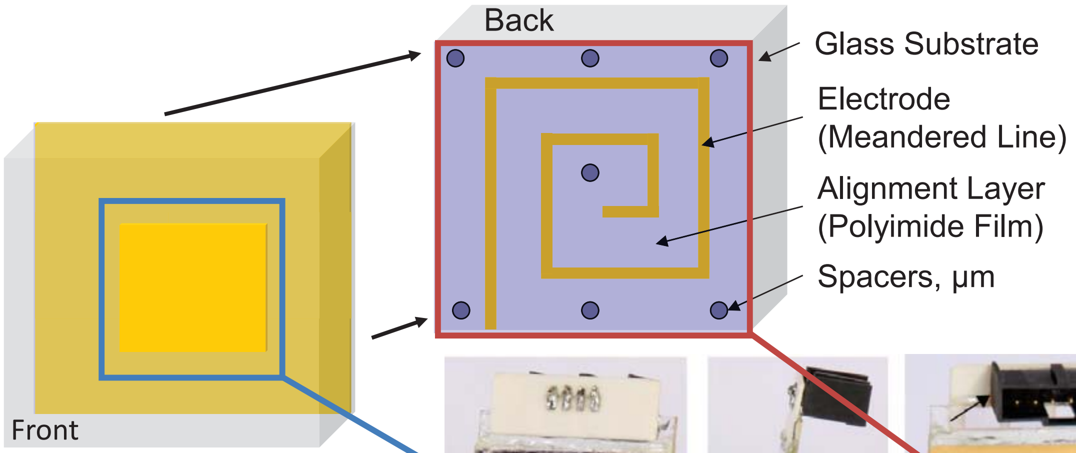
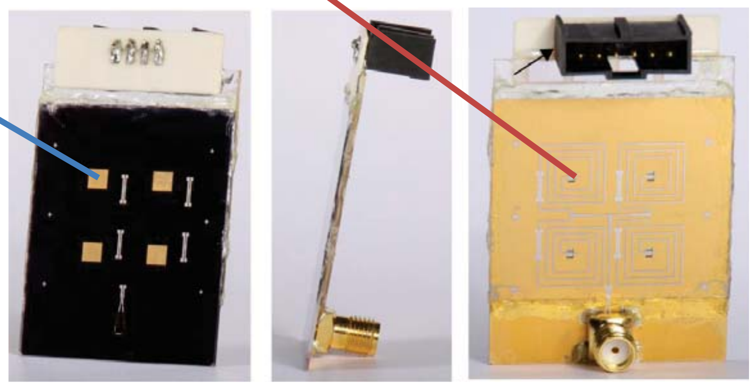


- FoM = 90°/dB @ 17.5 GHz
- ℓ = 6.1 λ_0
- 100 µm LC layer
- Response time ≈ 10 s
- G_{max} = 6 dB



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Planar phased array antennas

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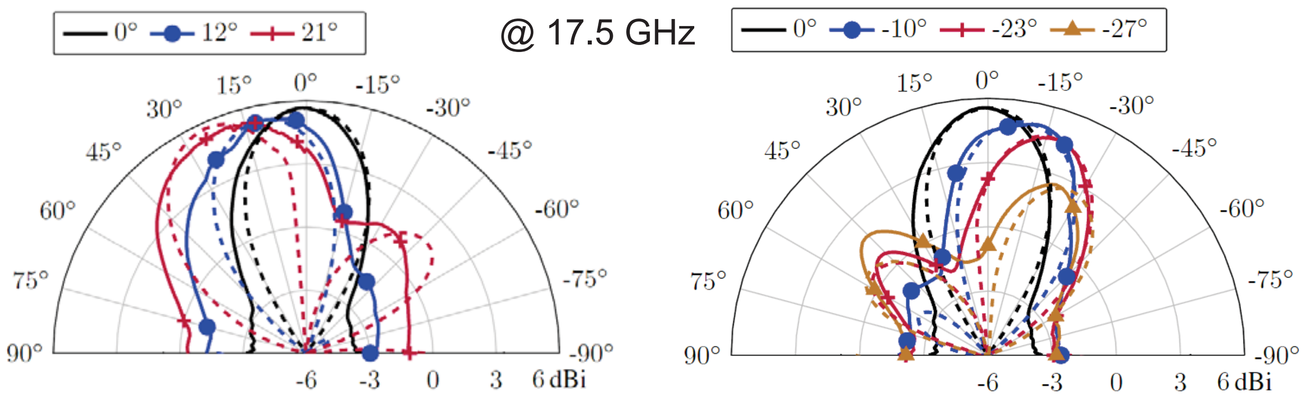

WM07 New Developments for Satellite Communications on the Move

Planar phased array antennas

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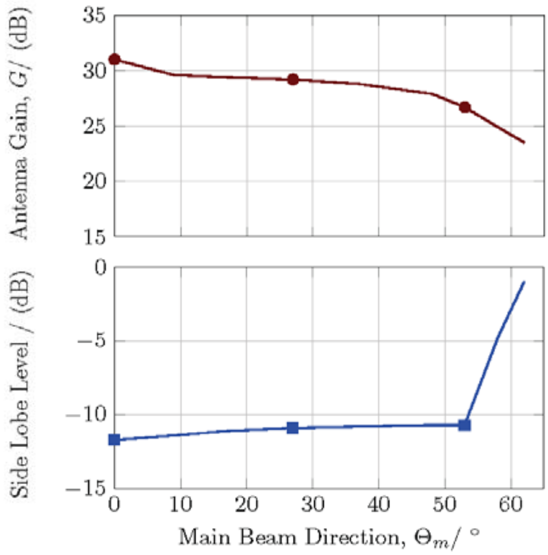
High Gain ➡ Larger Aperture

- Technology and proposed layout are scalable
- 8 x 8 Elements (Lab Demonstrator)
- 64 x 64 Elements (Commercial)

G_{max} > 30 dB → 30 cm x 30 cm, including **32 x 32 rad. elements** + biasing patches

☑ Grating lobe free region $\Theta_m < \pm 55°$



Planar phased array antennas

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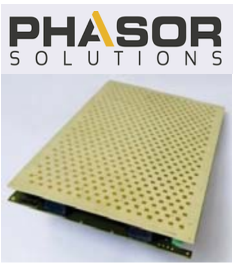
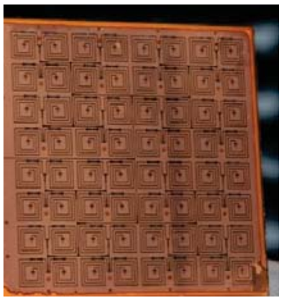


- London, **UK**
- **SiGe** technology
- Quasi phase shifter technology
- Price around 10 k€
- Primarily **military**, then **trains, aviation**



systems alcan Communication is the key

Gefördert durch:

Bundesministerium für Wirtschaft und Energie

eXIST Existenzgründungen aus der Wissenschaft

aufgrund eines Beschlusses des Deutschen Bundestages

http://www.alcansystems.com/

- Darmstadt, **DE**
- **LC based** phased array approach
- High scanning range, no need to any pre-alignment
- EXIST Research Transfer Programme, BMWi
- Product for **transportable terminals** in Q4/2017
- Will be affordable for end-users, mass production

- Redmond, **USA**
- **LC based** Metamaterial antenna: 6.000 $
- Backing by Bill Gates
- Product for **fixed terminals** in Q1/2015
- Currently delayed!

Content

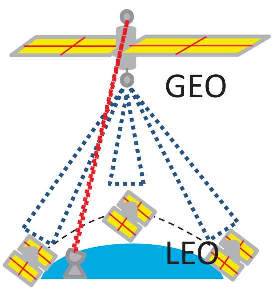
TECHNISCHE UNIVERSITÄT DARMSTADT

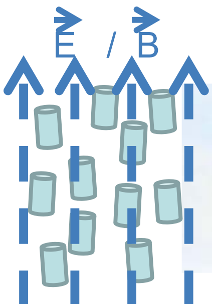
- Motivation
- Fundamentals of Liquid Crystal
- High performance phase shifter
- Planar phased array antennas
- Conclusion

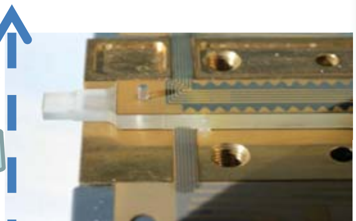
Conclusion

TECHNISCHE UNIVERSITÄT DARMSTADT

- Motivation
- Fundamentals of Liquid Crystal
- High performance phase shifter
- Planar phased array antenna







Acknowledgement

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- Dr.-Ing. Felix Gölden
- Dr.-Ing. Alexander Gäbler
- Dr.-Ing. Onur H. Karabey
- Christian Weickhmann

LISA ES
(50 YB 1113)

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New Developments for Satellite Communications on the Move Part 2 – Aeronautical Terminals

WM07

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Overview of In Flight Connectivity and Airborne Terminals Developments at ViaSat

Ferdinando Tiezzi

ViaSat

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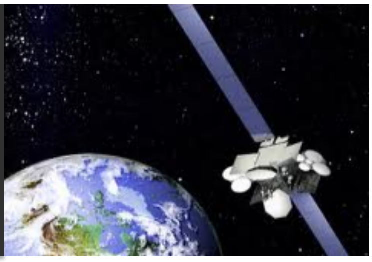
ViaSat Ka-Band Satellite Fleet

ANIK-F2
US Ka Beams
~2 Gbps
~5900 kg

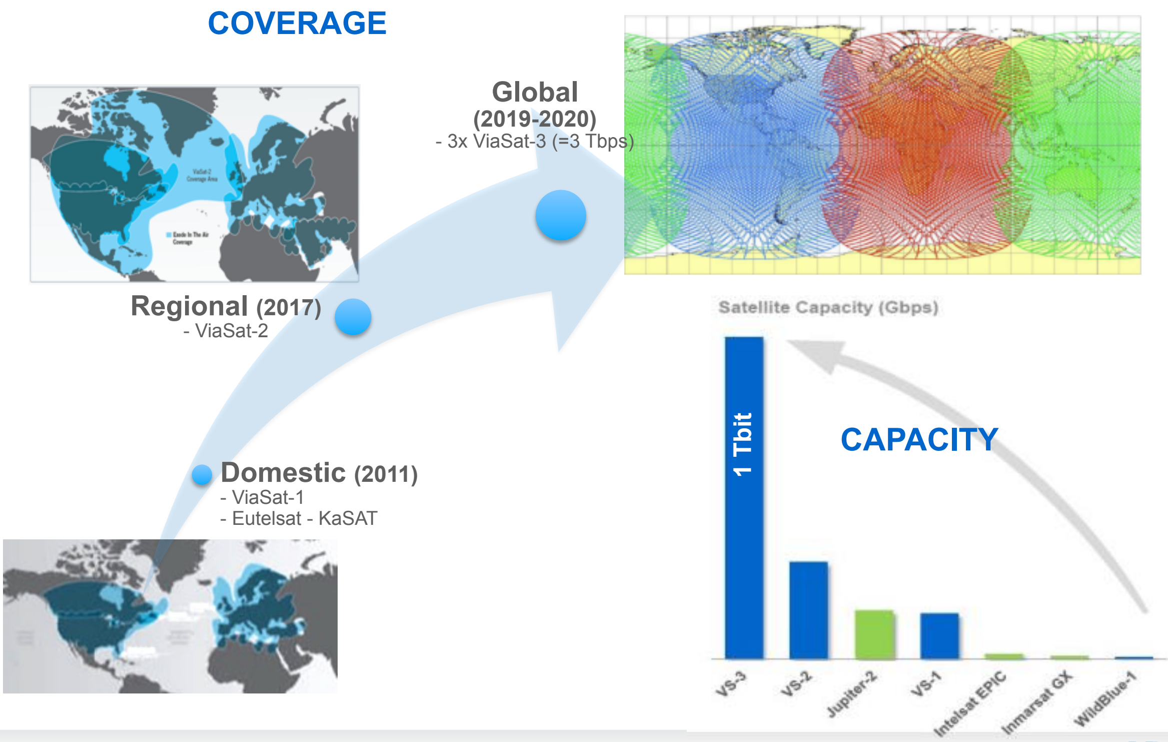


ViaSat-1
~140+ Gbps
~6700 kg

WildBlue-1
~7 Gbps
~4700 kg

ViaSat-2
Launching in 2016
7x the coverage
2x the capacity

ViaSat High Capacity Satellite Roadmap



Residential Broadband Access
EXEDE & Tooway

North America

800,000+ Subscribers

Europe

200,000+ Subscribers

In-Flight Connectivity

- 700+ global aircraft in Ku & Ka bands
- Various Commercial and Government Aircraft
- Millions of operating hours
- High performance ISR missions

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Airlines Value Passengers Engagement
Airlines Value Happy Customers

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Microwaves Everywhere

Yesterday Onboard Wi-Fi Reality

» Not many users
  › **Take Rate 3% to 8%**

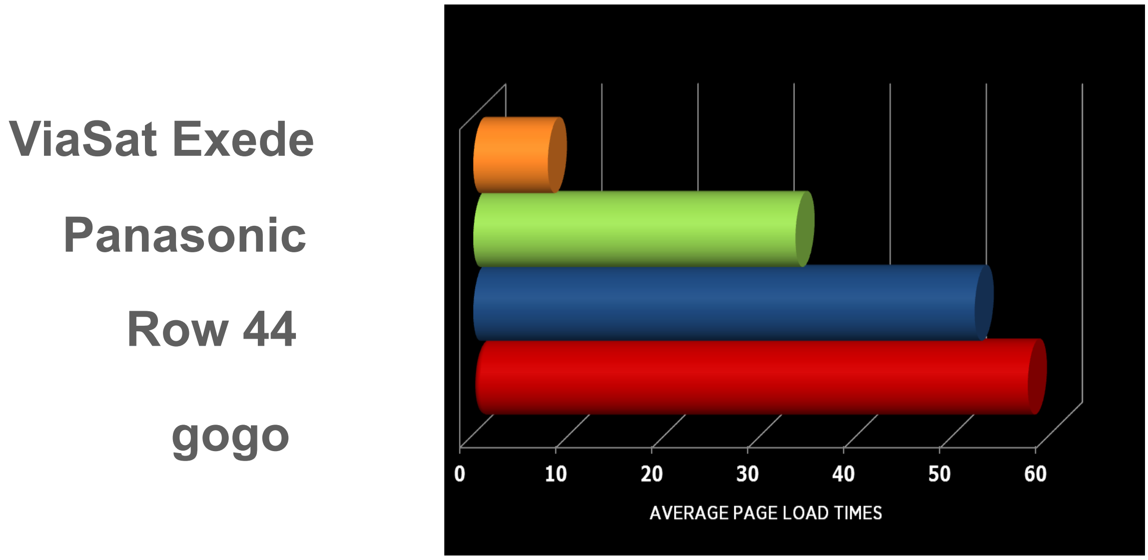
Engagement

» Not very satisfied
  › **Page Load Times**
  › **30 to 60+ sec**

Happy Passengers

Speed = Happy Customers

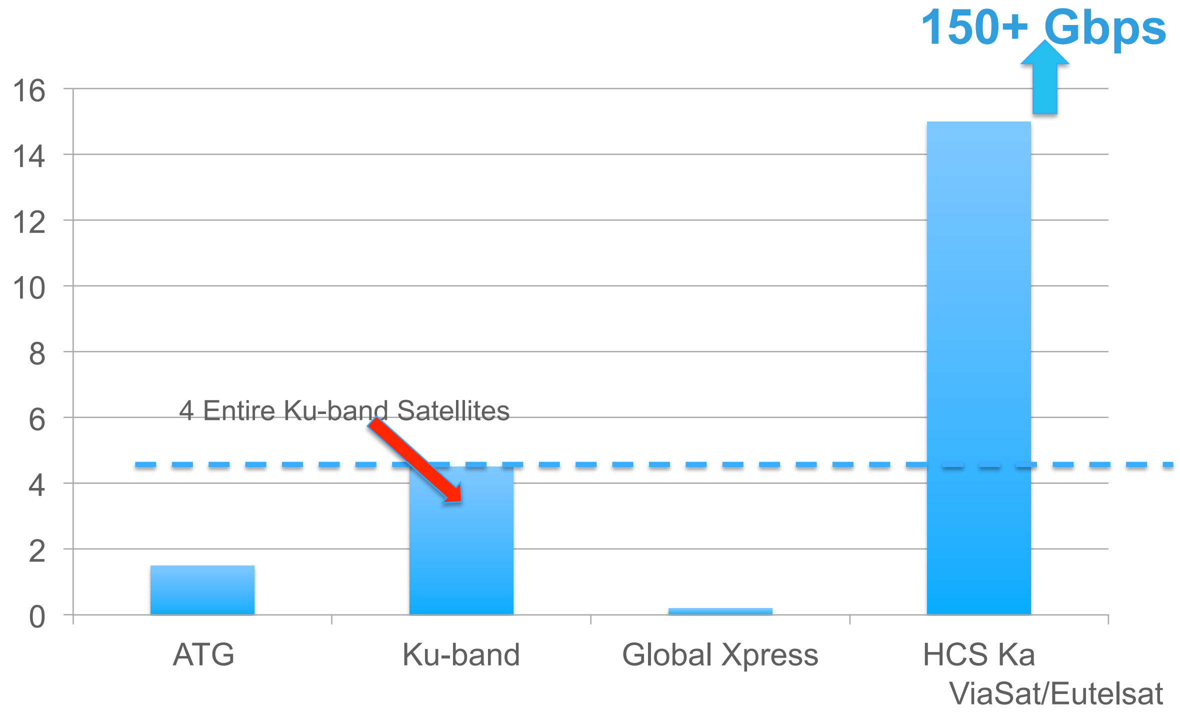
Airline WiFi Web Performance



Bandwidth = Engaged Customers

- Need bandwidth to sustain speed in the face of high penetration
  - Speed = good experience
- Need cheap bandwidth to enable engagement
- How much capacity will it take to achieve engagement & happy passengers?
  - Hypothetical test case:
    - Take rate of 60%
    - 45 MB per session average
    - 2500 aircraft (3 airlines)
    - Two thirds flying
  - **Answer = 4.5 Gbps**

What network can offer this?

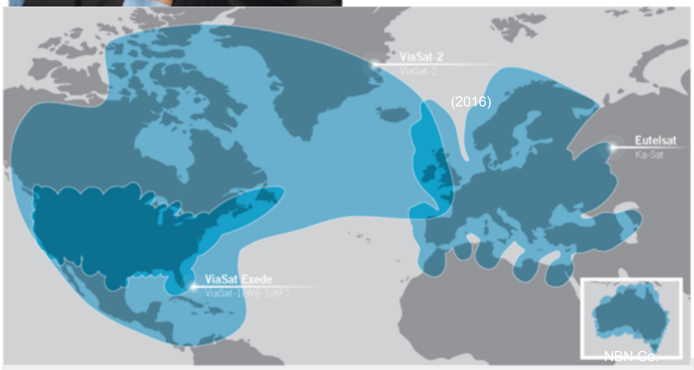


Business Models

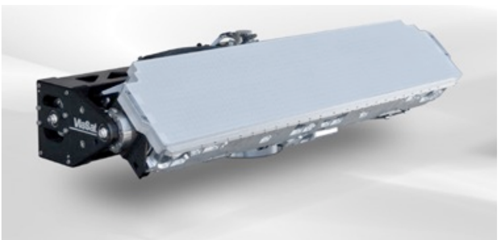
- Bandwidth is the key driver
  - Plentiful & Cheap
  - Enough bandwidth to sustain high speeds in the face of high take rate & usage
- Nobody will sponsor a bad experience
- How much do you give vs. sell?
  - Possible to make everyone happy and make money / enhance value at the same time

Inflight connectivity as at home

- 500+ aircrafts in service
- 1M+ users connected
- 12 Mbps average per passenger
- 50% take up rate



Medium Profile Airborne Antenna



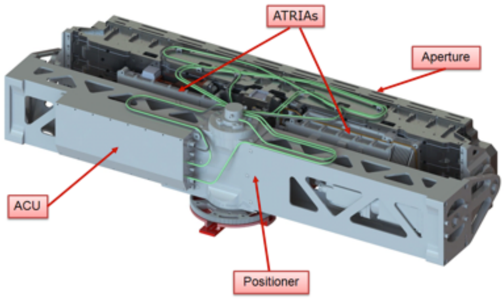
Mantarray-40

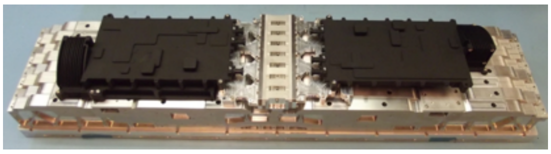
Mantarray-32

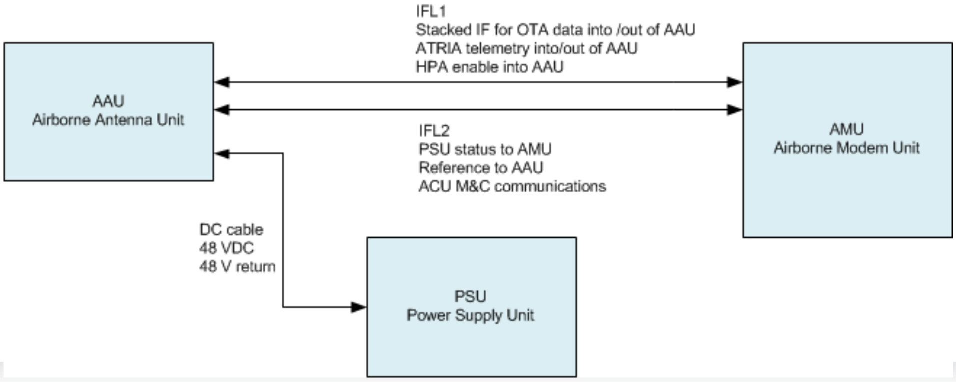
- Medium profile antennas for narrowbody and widebody aircraft
  - Two versions: Mantarray-40 and Mantarray-32
- Radome and mounting kits for various aircraft under development

Item	Description
Antenna Class	Two-way (Tx & Rx) medium profile (height < 10”) airborne antenna
Aperture	Ka-band dual polarized waveguide horn array
Positioner	Elevation (EL)-over-Azimuth (AZ) positioner, DC servo motors
RF Electronics	Built-in airborne transmit/receive integrated assembly (ATRIA) based on SurfBeam 2 consumer technology

Ka Mantarray Architecture







Key Requirements & Capabilities Transmit & Receive Performance

Parameter	Requirement	Capability
Rx RF Frequency	18.3 to 20.2 GHz, 500 MHz Instantaneous Bandwidth	Comply
Rx G/T*	M40: 12.5 dB/K typical, at 19.95 GHz M32: 11.3 dB/K typical, at 19.95 GHz	M40: 12.5 dB/K M32: 11.8 dB/K
Rx/Tx Polarization	Circular, receive orthogonal to transmit polarization	Comply
Tx RF Frequency	28.1 to 30.0 GHz	Comply
Tx EIRP	43.5 dBW minimum, at 29.5 GHz, at 36K feet, level flight, including radome loss of 1.2 dB, excluding pointing loss.	M40: 44.6 dBW M32: 44.4 dBW
Antenna Tx Cross-Pol Discrimination (XPD)	-23 dB max (-25 dB objective), peak of beam	Comply

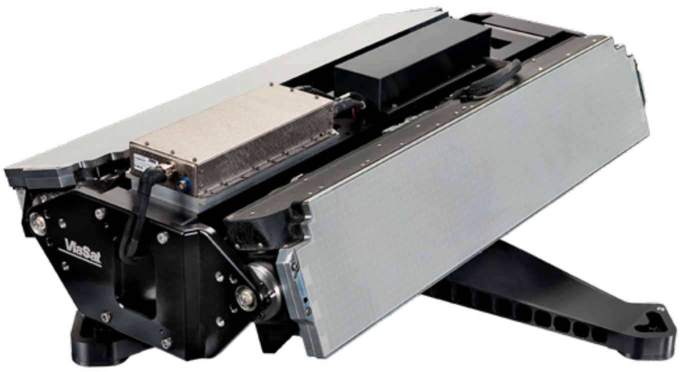
** Altitude = 36,000ft Ambient air temperature = -55°C (218°K) at Altitude*
Sky noise temperature = 10°K at 45° elevation
Aperture and beam former physical temperature is equal to air temperature

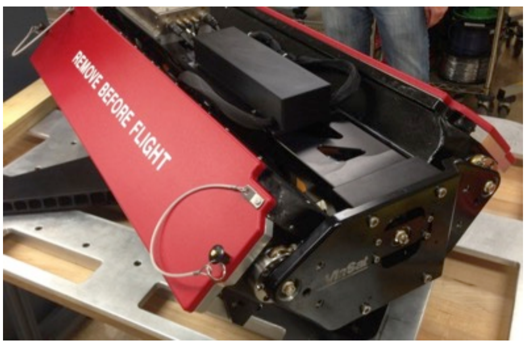
Key Environmental Requirements

Parameter	Requirement	Comply?
Temperature & Altitude	DO-160F Section 4 Cat D2 Mod DO-160F Section 5 Cat A	Comply
Humidity	DO-160F Section 6 Cat C	Comply
Shock & Vibration	DO-160F Section 7 Cat B (Level F2) DO-160F Section 8 Cat S (Curve C)	Comply
Waterproofness	DO-160F Section 10 Cat W	Comply
Fluids Susceptibility	DO-160F Section 11 Cat F (Propylene Glycol Spray Only)	Comply
Sand & Dust	DO-160F Section 12 Cat S	Comply
Fungus	DO-160F Section 13 Cat F	Comply
Salt Fog	DO-160F Section 14 Cat S	Comply
Icing	DO-160F Section 24 Cat A	Comply

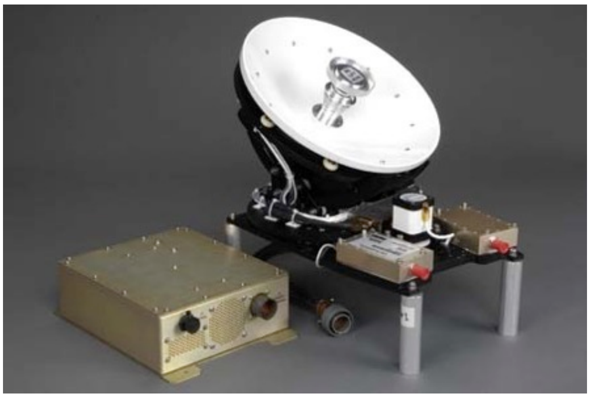
Medium Profile Airborne Ku/Ka

- KuKarray combines Ku-band and Ka-band into a single antenna
- Antenna and radome currently in development – DO-160 certification in late 2014





High Profile Airborne Ku-band

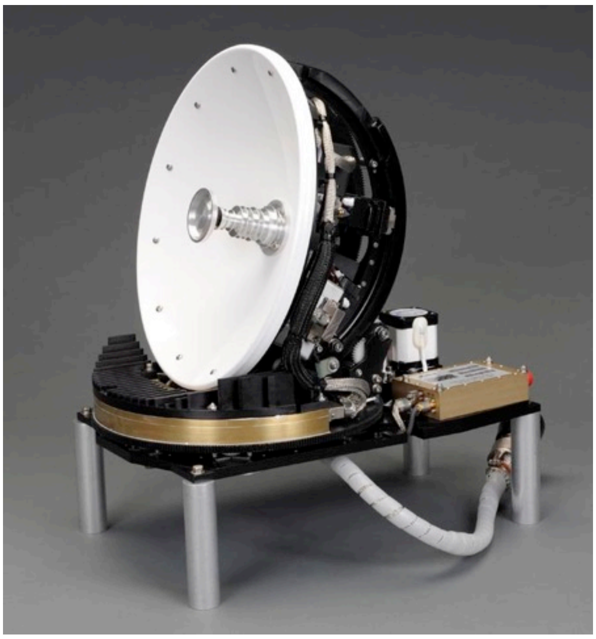


VR-12Ku

VR-18Ku

- Airborne reflector antenna for tail, fuselage or hatch mount
- Operates over ViaSat's Yonder Ku-band network
- Installed on commercial and military platforms
- Over 600 antenna systems delivered
- VR-18Ku in development

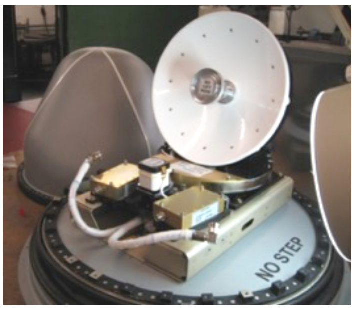
High Profile Airborne Ka-Band



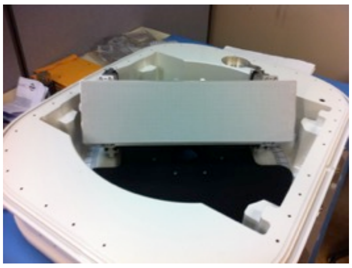
VR-12Ka

- Developed from ViaSat's VR-12 Ku-band antenna product
- Tail, fuselage or hatch mount
- Operates with ArcLight and Surfbeam 2 modems
- Cross-pol or Co-pol versions
- Larger reflector sizes are on the product roadmap – VR-18Ka

Hatchmount Airborne Antennas



» C-130 Hatch mounted VR-12 Ku and Ka



» Developing Ka-band antenna for C-17 hatch

46TH EUROPEAN MICROWAVE CONFERENCE 2016

The 46th European Microwave Conference

Integrating Microwave Components in the Wings of a Remotely Piloted Aircraft

Dr Joseph A. Barnard

Barnard Microsystems Limited

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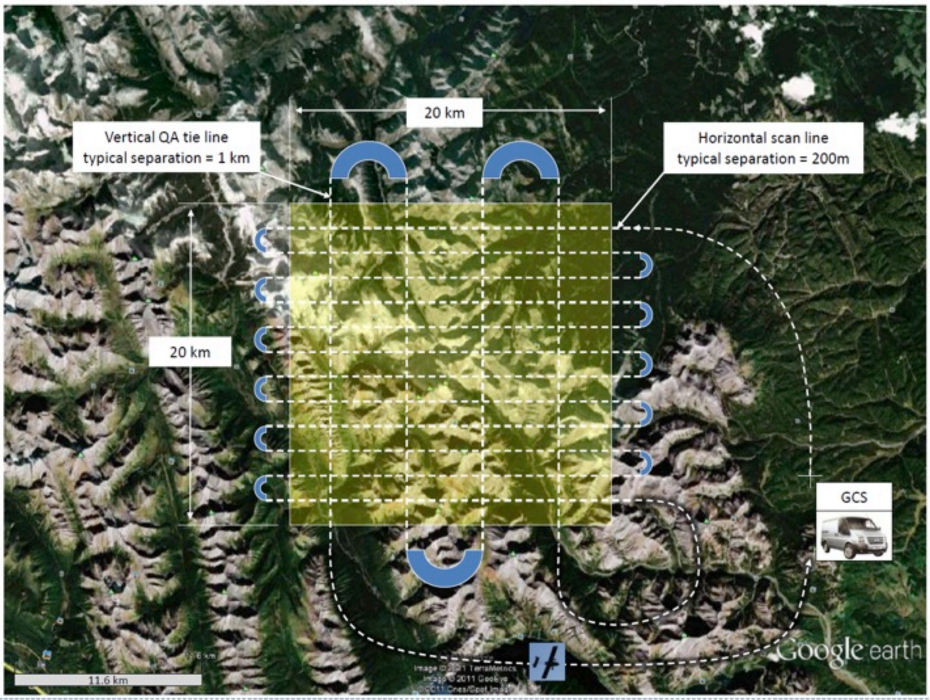
Background

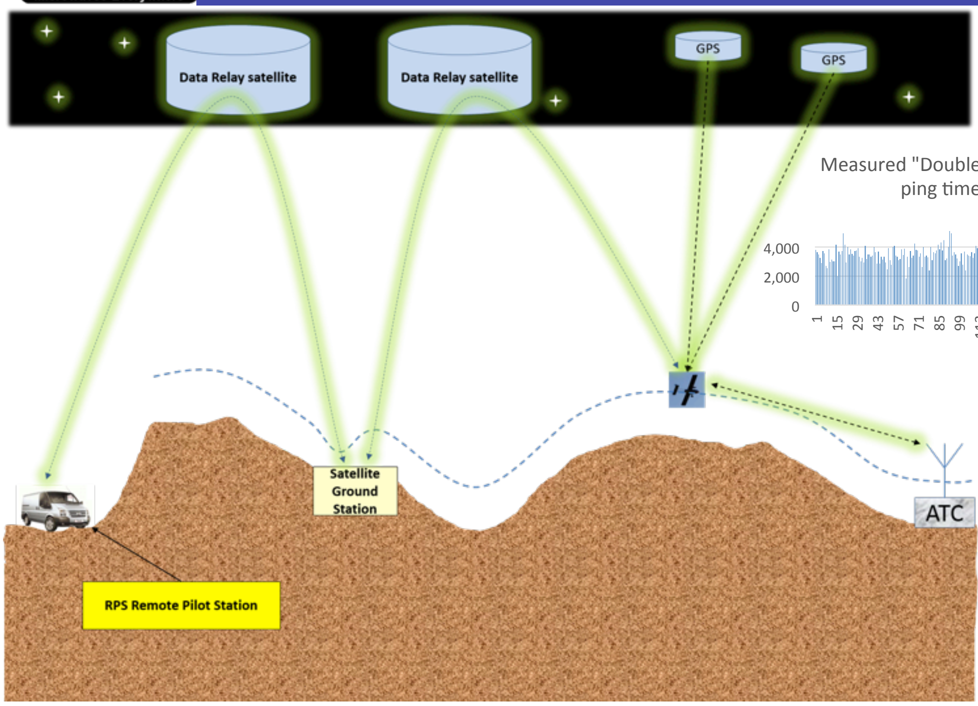


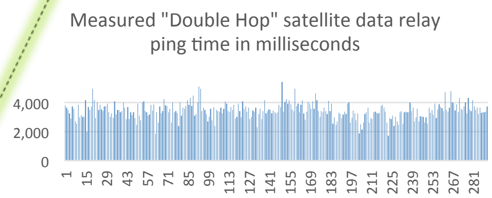
Remotely Piloted Aircraft (RPA) engaged in civilian applications often need to be operated Beyond Line Of Sight (BLOS).

In order to operate BLOS, an RPA requires:

- Reliable airframe and avionics
- **A satellite based communications link with the Remote Pilot Station (RPS)**
- Collision Detect and Avoid system.

Satellite communications in RPA applications





Configuration and data relay path for a "double hop" sitcom terminal to sitcom terminal link. The average data relay latency measured was 3.4 seconds:

- RPA → RPS telem
- RPS → RPA cmds

Example: locating a Ka band satcoms unit on a RPA

Left: the Ka band satcoms terminal mounted in the fuselage of a General Atomics Reaper RPA.

The sheer size, weight and cost of this type of steerable antenna used in this Ka band satcoms terminal makes this solution difficult to implement on a mid-sized RPA engaged in civilian applications.

Typical satcoms data relay bit rates:

- L band: 50 – 150 kbit / sec
- Ka band: 2 – 6 Mbit / sec clear sky

The BML InView RPA, for use in civilian applications

Example of a mid sized RPA engaged in civilian applications: the BML InView, twin engine RPA:

- 6m wingspan
- 800 mm wing chord
- 2x 1,650 Watt electrical generator

The problems with standard satcoms antennas are:

- aerodynamic drag - sometimes
- mechanical reliability
- no graceful degradation

Close up of the Cobham Explorer 325 antenna

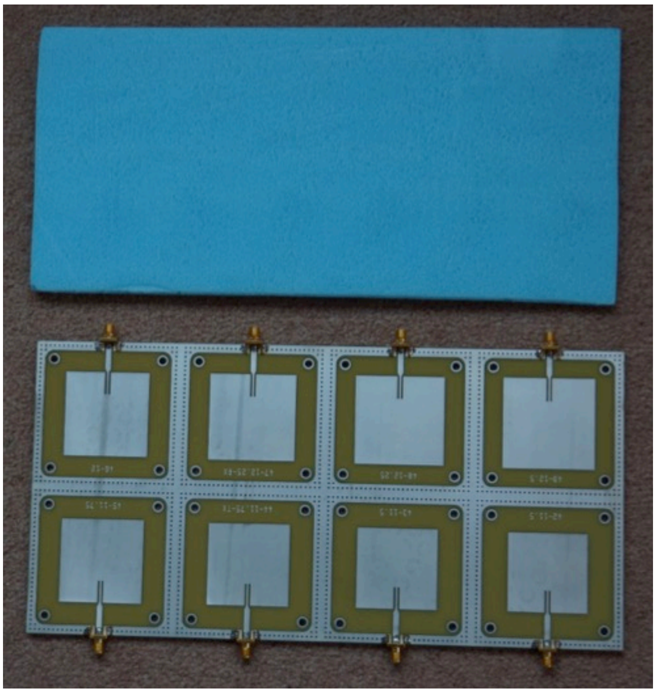
Close up of the mechanically steered L band satcoms unit in the Cobham Explorer 325 terminal, showing the Tx and Rx helical antennas. The good points about this antenna are:

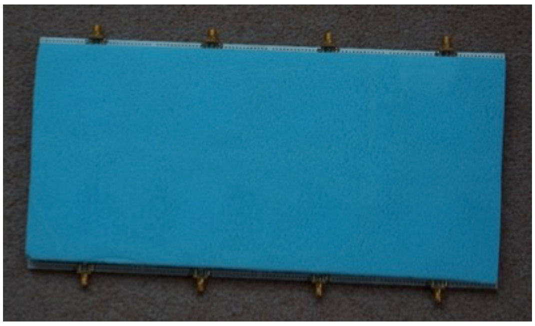
- Horizon to – horizon coverage
- Low cost

The not so good points of this antenna for this application are:

- Aerodynamic drag
- Reliability issue of mechanical beam steering
- Inability to traverse 360° in a continuous rotation

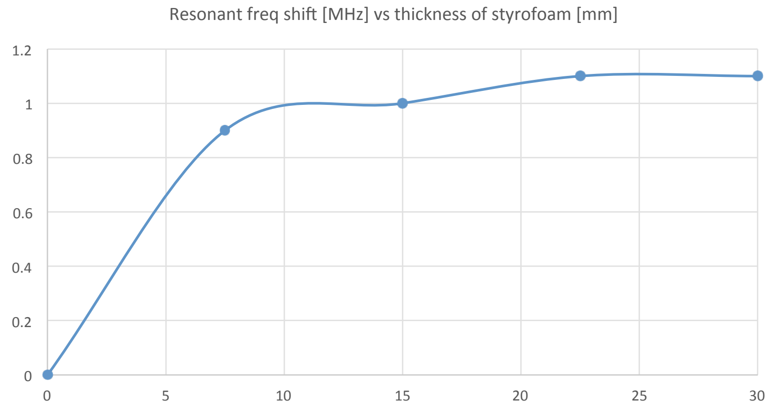
Patch antenna supporting electronic beam steering





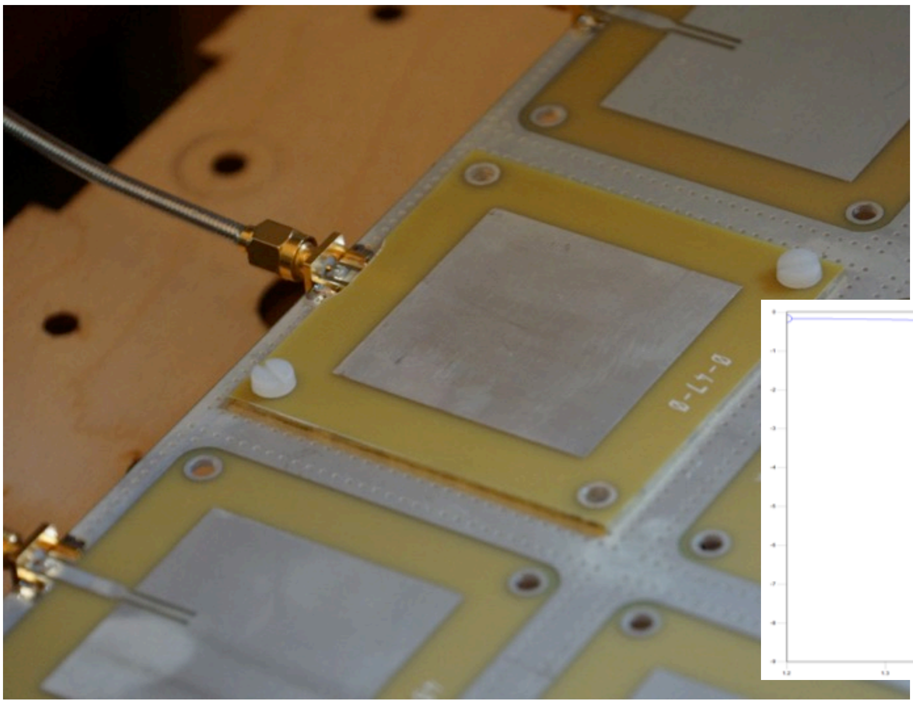
These photographs show the 320 mm x 160 mm prototype L Band patch antenna array, with a Styrofoam ("Blue Foam" cover plate. In this example, we are exciting a linearly polarized signal. Bear in mind the Inmarsat system operates with Right Hand Circularly Polarized (RHCP) signals.

Effect of Styrofoam top cover

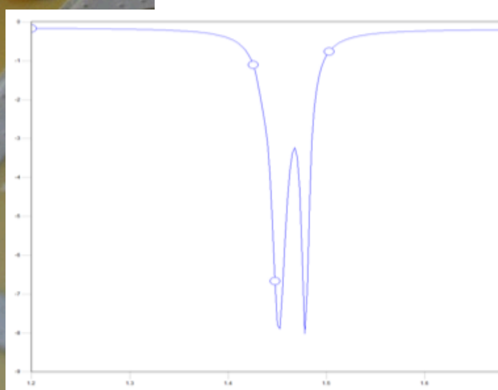


There is a very small frequency change (measured at 100 kHz for a 30 mm thick Styrofoam sandwich) when there is a 7.5 mm air gap between the patches and the Styrofoam sheet.

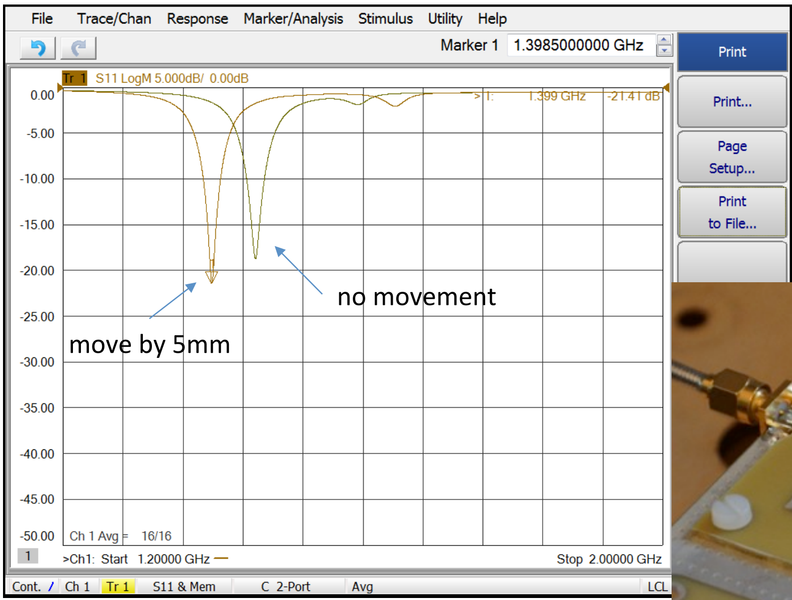
Filter + Patch antenna combination

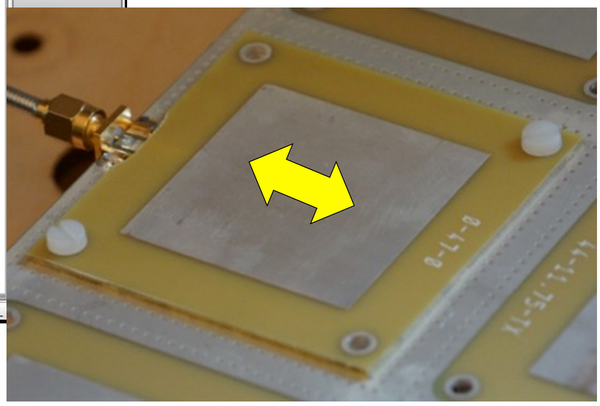


Adding a top resonator patch to form a coupled resonator circuit enables the broad banding of the patch antenna.



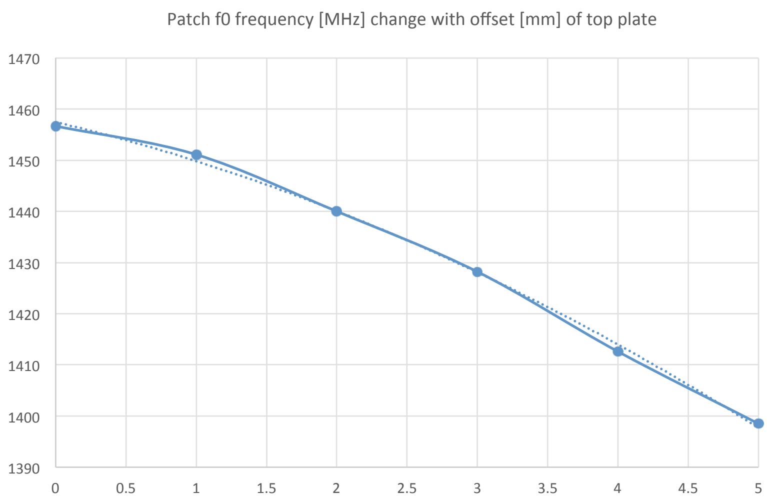
Tuning the patch resonant frequency





Left: moving the top resonator patch with respect to the underlying patch enables the tuning of the resonant frequency of the patch antenna.

Tuning the patch resonant frequency

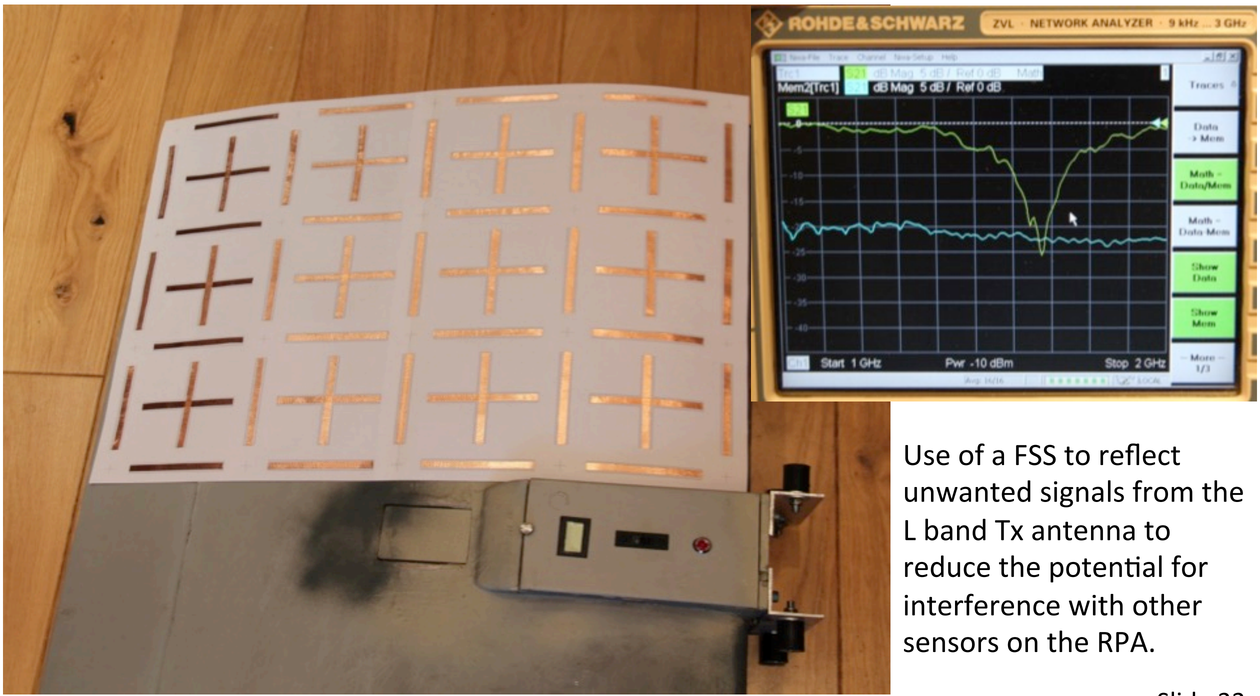


Left: moving the top resonator patch with respect to the underlying patch enables the tuning of the resonant frequency of the patch antenna.

- Solid line = measured
- Dotted line = trendline

The frequency shift is about 55 MHz for a 5mm top patch movement, providing ample opportunity for frequency trimming of the patch resonant frequency to account for dielectric constant differences.

Conformal Frequency Selective Surface



Use of a FSS to reflect unwanted signals from the L band Tx antenna to reduce the potential for interference with other sensors on the RPA.

46TH EUROPEAN MICROWAVE CONFERENCE 2016

The 46th European Microwave Conference

An Integrated Simulation Approach for SATCOM Phased Array Design

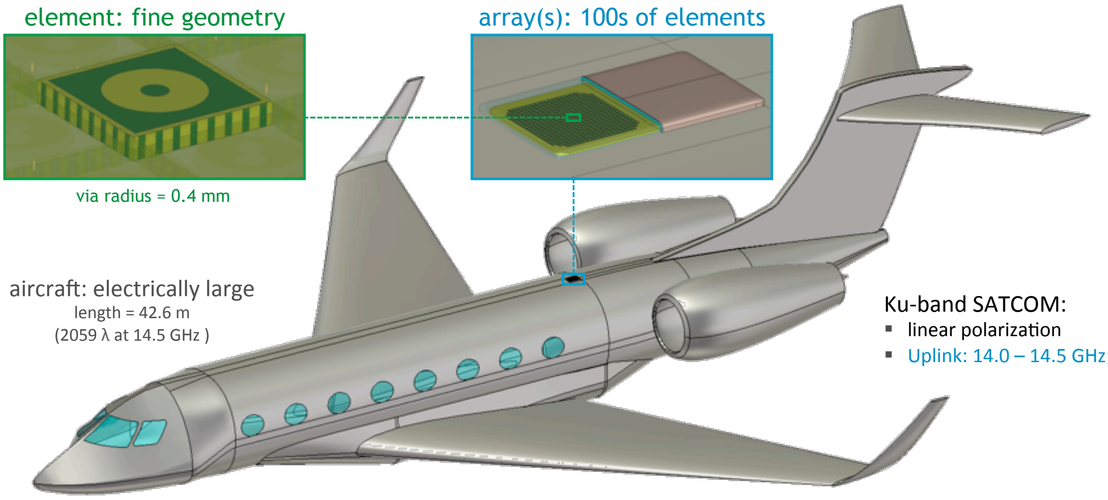
Dr. Marc Rütschlin

CST AG

marc.ruetschlin@cst.com

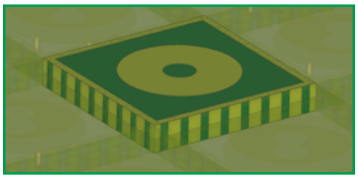
Simulation Challenge

How do we design a SATCOM antenna array with fine geometric detail to function correctly on a large aircraft?



SATCOM Array Design Overview

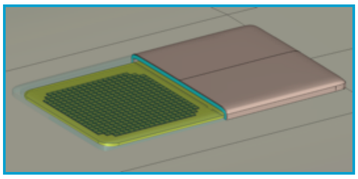
Element design



Of interest:

- Active Element Impedance (AEI) and Active Element Pattern (AEP)
- predict large array performance

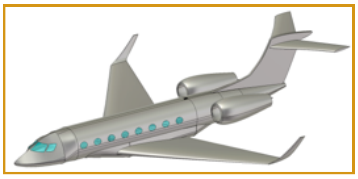
Array design



Of interest:

- real scanning behaviour
- non-periodic structure effects

Place on platform

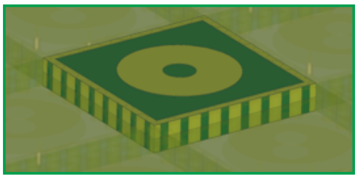


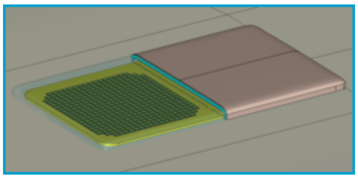
Of interest:

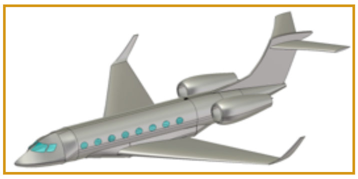
- effect of platform on antenna
- coupling from array to other antennas

Several Simulation Stages

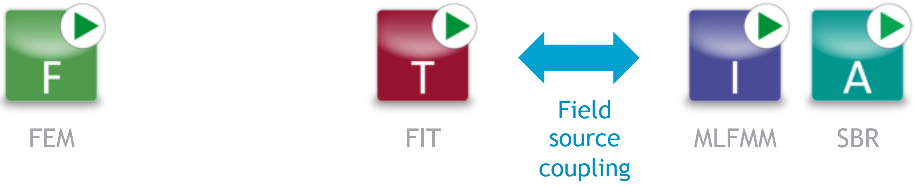
Element design | Array design | Place on platform





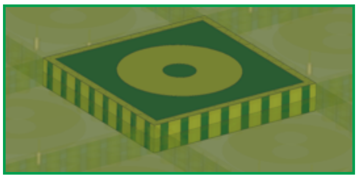


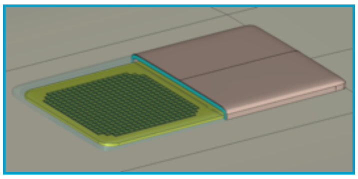
Different solvers required at each stage…

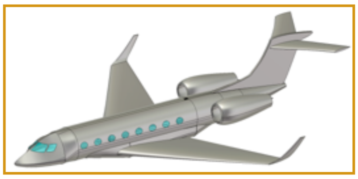


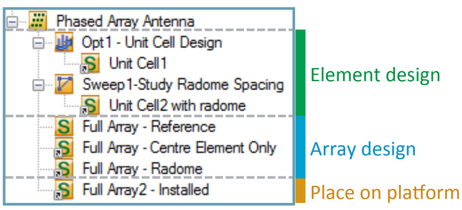
One Simulation Environment

Element design | Array design | Place on platform





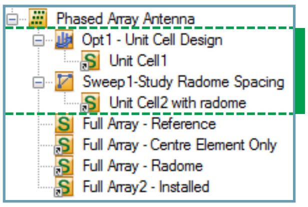


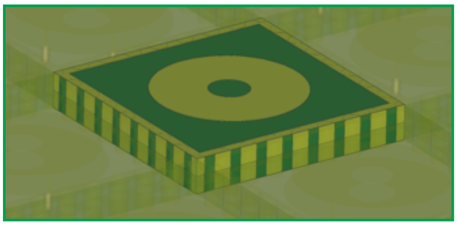


All stages of workflow in one design environment

1. Antenna Element Design

Optimization at unit cell level

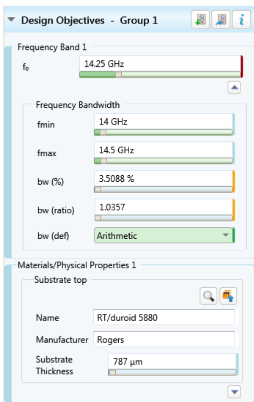




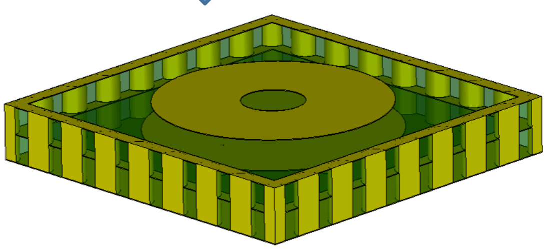
Design with Antenna Magus

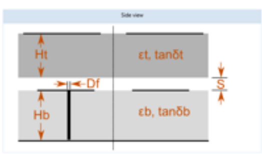
Requirements: low profile, broadband, dual-polarised

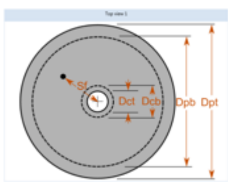
AntennaMagus



Initial design to array element

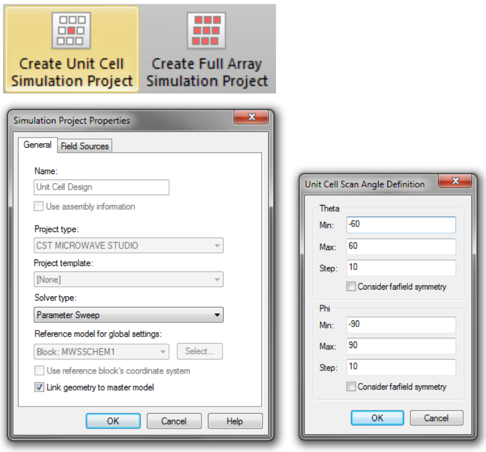


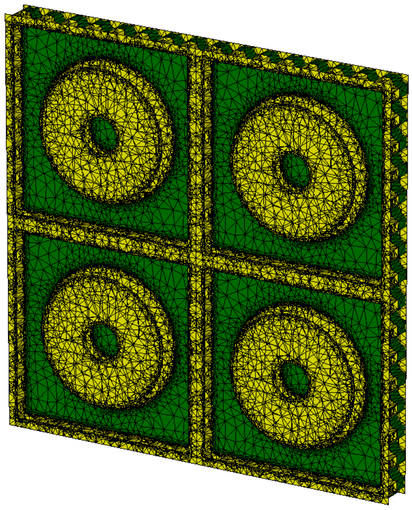




Unit Cell Simulation

Simulate single element at unit cell level with FEM solver





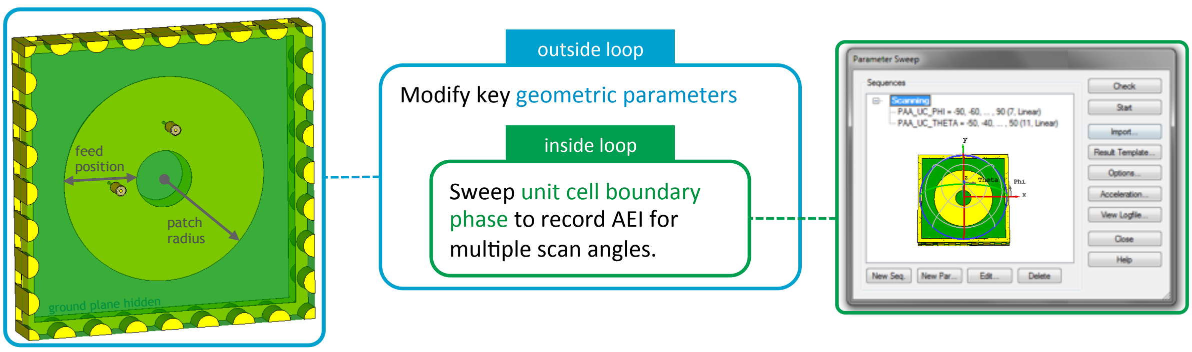
Full Floquet port unit cell boundary conditions

Higher order curved tetrahedral mesh

Element Optimization

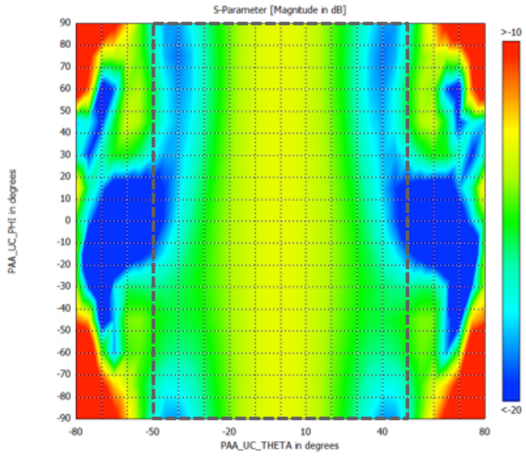
Goal: Active Element Impedance (AEI) < -10 dB

for all scan angles and frequencies of interest!

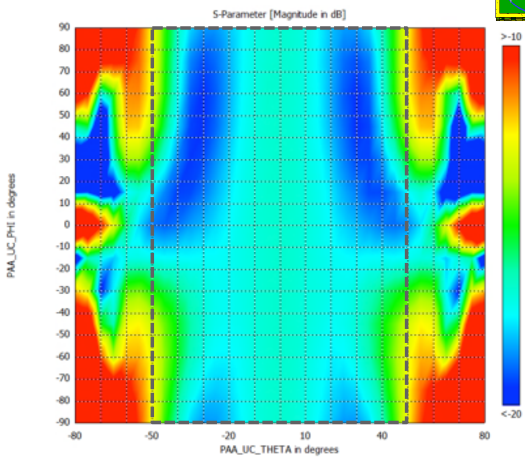


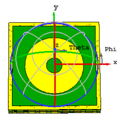
Active Element Impedance

AEI at 14.0 GHz



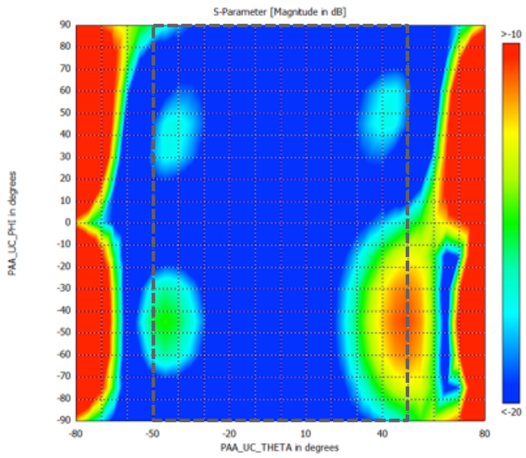
AEI at 14.5 GHz



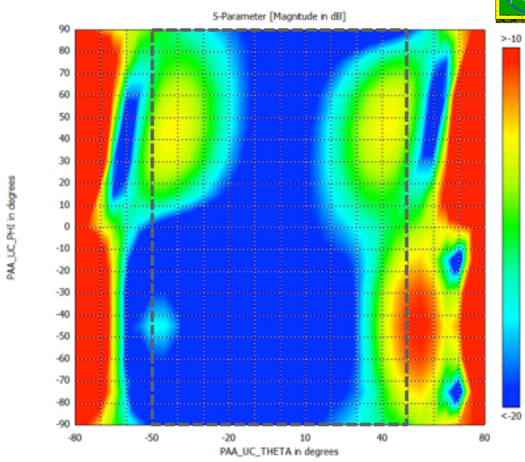


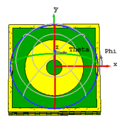
Port Isolation

$|S_{21}|$ at 14.0 GHz



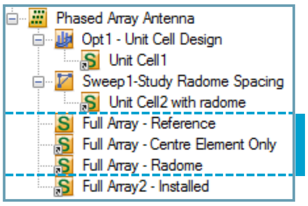
$|S_{21}|$ at 14.5 GHz

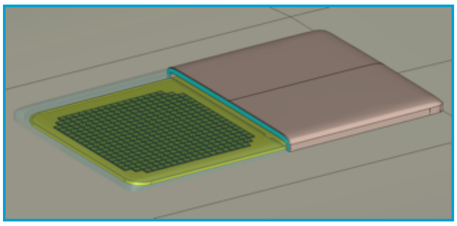




2. Array Design

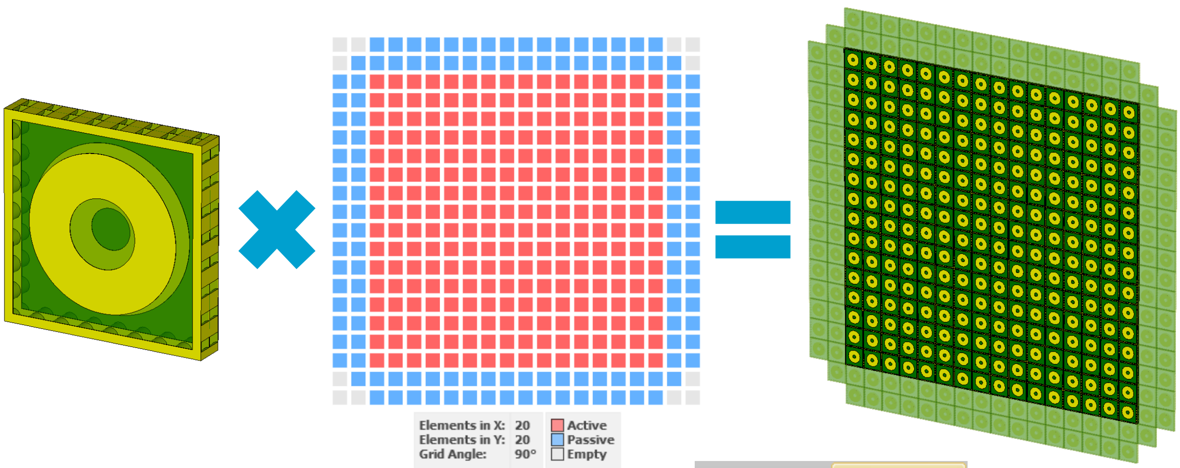
Design at full array level

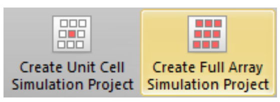




Full Array Construction

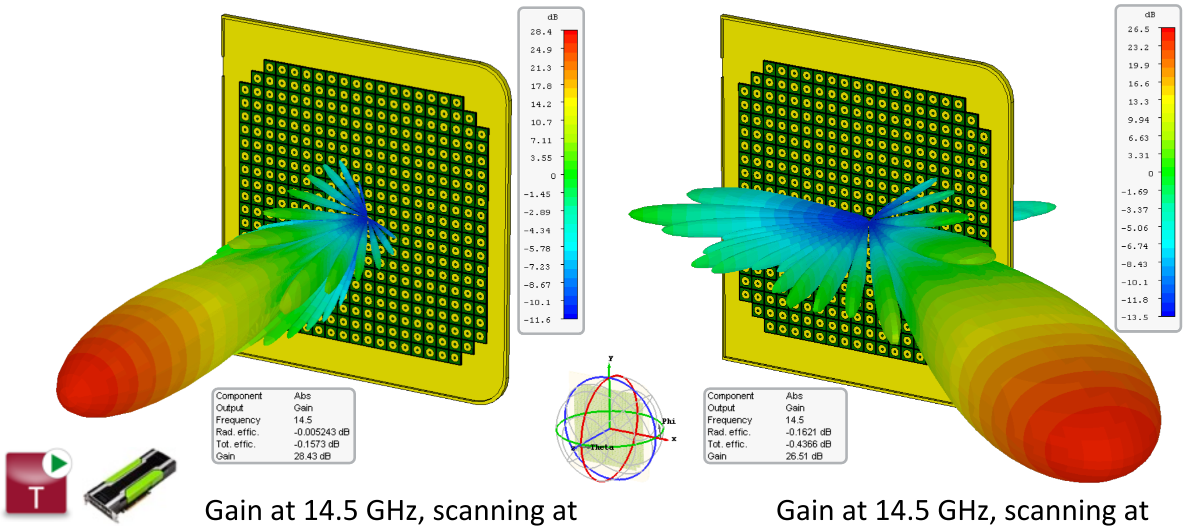
Unit cell with array layout gives full array geometry





Array Simulation – No Radome

Simulate full array without approximation with numerically efficient time domain technique



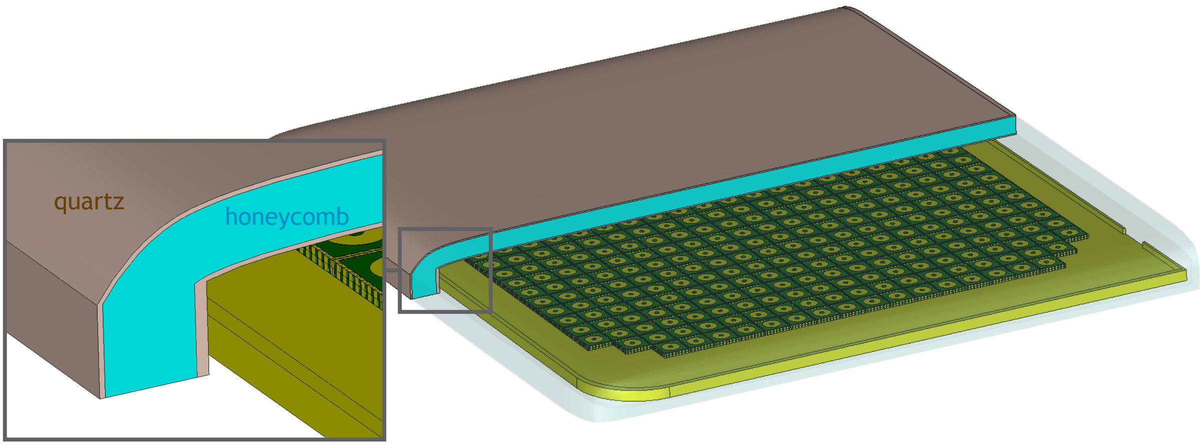
PBA conformal meshing

Gain at 14.5 GHz, scanning at θ = 0º

Gain at 14.5 GHz, scanning at θ = 50º

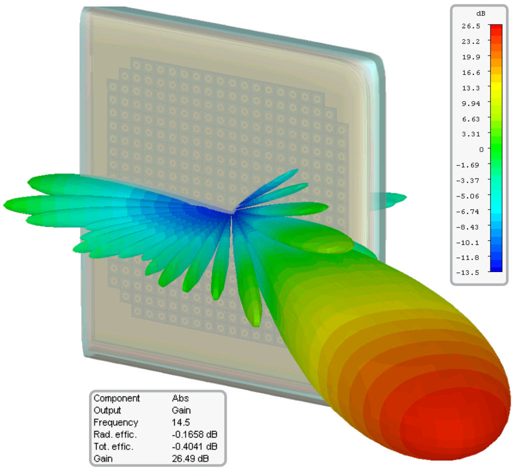
Addition of Radome

Addition of full curved radome to array

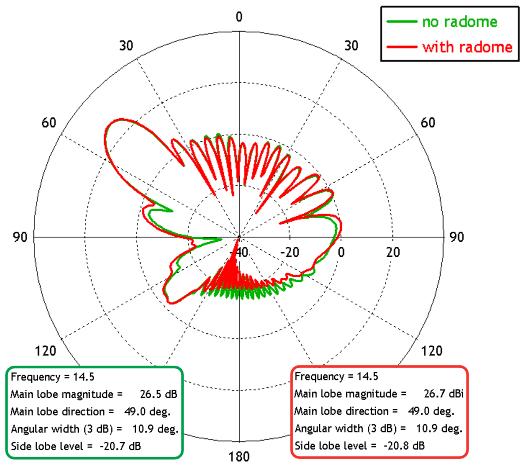


Effect of Radome on Farfield

Farfield with radome

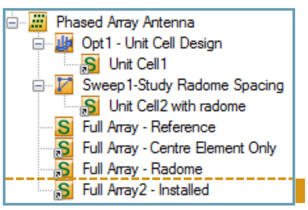


Farfield in vertical plane



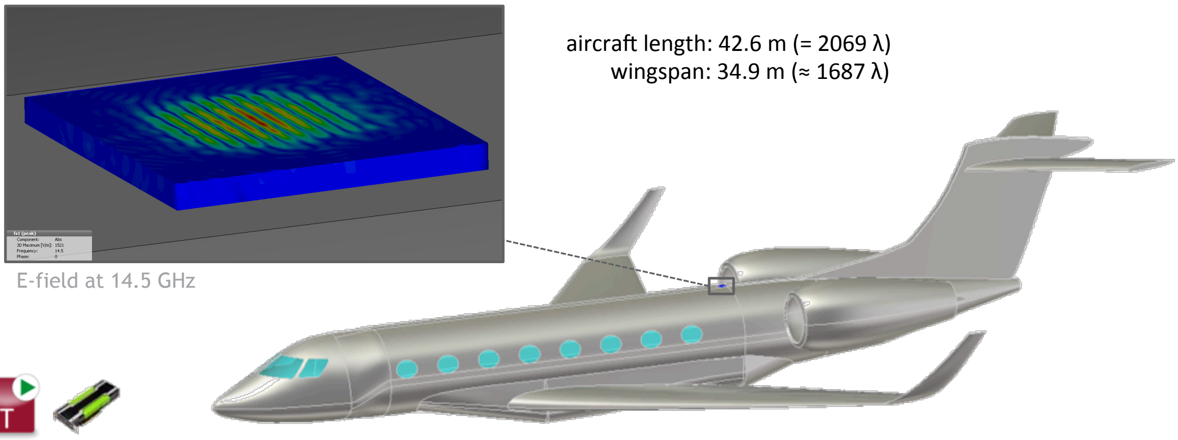
3. Installed Performance

Performance of antenna on aircraft



Simulate Array on Aircraft

Replace antenna detail by equivalent Near Field Source

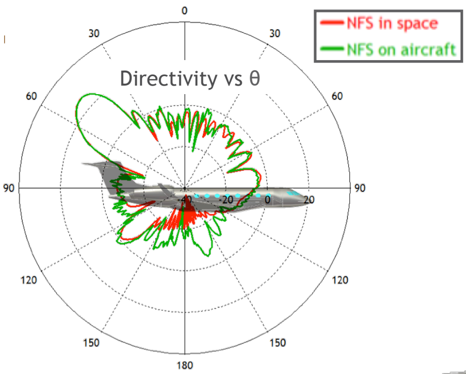


E-field at 14.5 GHz

Simulate antenna with time-domain solver

Installed Performance Effect

Simulate with SBR based Asymptotic solver

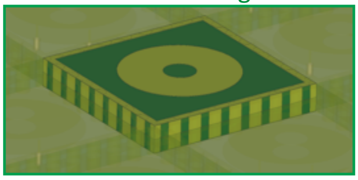


SATCOM Array Design Summary

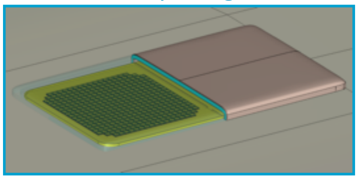
All design stages with suitable solvers in one environment

- Element design: optimisation for all scan angles simultaneously
- Full array: full model with non-periodic effects
- Installed performance: platform effect and coupling

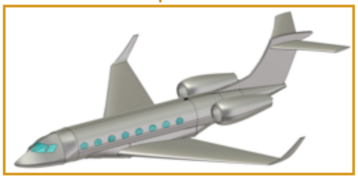
Element design



Array design



Installed performance



46TH EUROPEAN MICROWAVE CONFERENCE 2016

The 46th European Microwave Conference

Why Mechanically Scanned Antennas Have to Cope with the New Generation of Low Profile Aeronautical Terminals ?

Raimondo Lo Forti

Space Engineering S.p.A.

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Introduction

- Satcom On The Move (OTM) is becoming more and more demanding;
- Historically speaking, mechanically scanning antennas represented the answer to the communications OTM via satellite for a long time (the most important example was the Satcom on the ships);
- Recently the migration of Satcom OTM from the ships to the High Speed Trains and, later on, on-board the aircrafts has shown the needs of having low profile antennas for minimizing the installation issues;
- Since then it seemed that mechanical antennas had no more room due, manly, to its dimensions;
- Therefore a more and more attention was paid to the flat antennas;
- Final step was to think about the possibility of introducing Phased Arrays for solving all these issues;
- <u>We will concentrate our analysis on the airborne satellite antennas.</u>

Satcom antenna OTM expected characteristics

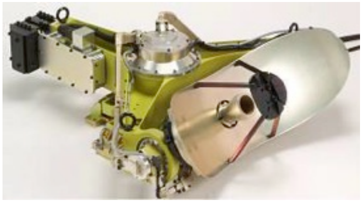
- Low profile antenna is requested in order to disturb as less as possible the aircraft flight;
- Good RF performance between 0 and 90 degrees;
- Good agility in the beam steering, both in azimuth and elevation;
- Good RF power handling (especially for military use);
- Capability of handling more than one frequency band is a plus;
- Capability of handling both Tx and Rx frequency bands, with the same aperture, is a merit;
- Low weight is very much appreciated;
- Third axis scanning capability is welcome;
- Antenna patterns compliance with ETSI masks is mandatory.

Satcom OTM:Technology evolution step by step

- First example (being used as comparison of conventional reflector antenna mechanically steered)

- PROS:
  - ✓ Very simple and well consolidated solution (even with 3 axes beam scanning).
- CONTRAS:
  - ✓ Beamwidth too large;
  - ✓ Poor RF performance.

- The evolution was to use an elliptical aperture for meeting better the foreseen swept volume



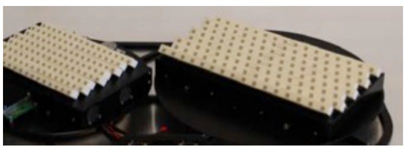
- PROS:
  - ✓ Simple antenna solution;
  - ✓ Quite good RF performance.
- CONTRAS:
  - ✓ Quite large horizontal swept volume;
  - ✓ No 3th axis.

Satcom OTM:Technology evolution step by step

- The array aperture is subdivided in two sub arrays of patches. The overall antenna height may profit from that.
- Azimuth& elevation mechanically steered

- PROS:
  - ✓ Better RF performance at higher scan angles;
  - ✓ Lighter solution.
- CONTRAS:
  - ✓ Phasing network to align RF signals;
  - ✓ Blocking effects.

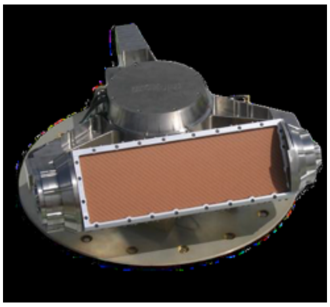
- The array aperture is subdivided more and more in small sub-arrays of radiating elements. The overall antenna height may be reduced a lot
- Azimuth and elevation mechanically steered



- PROS:
  - ✓ Better RF performance at higher scan angles.
- CONTRAS:
  - ✓ Complex phasing network to align RF signals;
  - ✓ Less blocking effects;
  - ✓ Poor RF performance at low elevation angles.

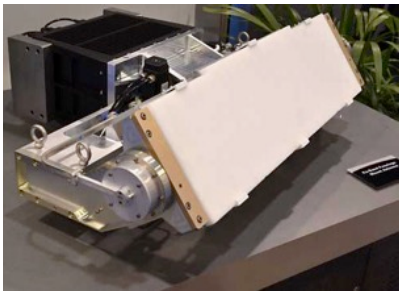
Satcom OTM:Technology evolution step by step

- The array is fed by a low losses BFN.
- Azimuth&elevation mechanically steered



- PROS:
  - ✓ Compact solution;
  - ✓ Quite good RF performance.
- CONTRAS:
  - ✓ No 3rd axis;

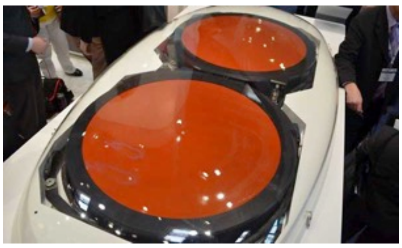
- The array is split into two subarray(one for Tx the other for Rx).
- Cross axis beam scanning is electronically implemented
- Azimuth&elevation mechanically steered



- PROS:
  - ✓ Less compact solution;
  - ✓ Quite good RF; performance
  - ✓ Cross axis handling.
- CONTRAS:
  - ✓ BFN complexity
  - ✓ Reduced RF performance.

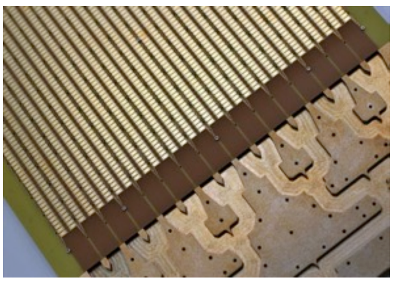
Satcom OTM:Technology evolution step by step

- Two flat arrays (one for Tx the other for Rx)
- Azimuth&elevation mechanically steered (elevation scanning, by converting the horizontal scanning into the vertical scanning)



- PROS:
  - ✓ Very low profile & compact antenna solution;
- CONTRAS:
  - ✓ Poor RF performance at low elevation angles;
  - ✓ No 3rd axis.

- A flat array feeds a metamaterials layer
- No mechanical movements are foreseen.
- Beam deflection is performed via a “TV screen like” matrix

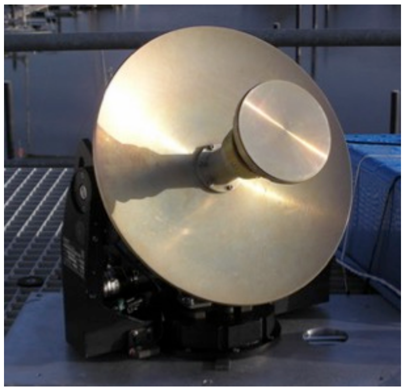


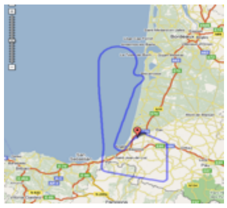
- PROS
  - ✓ The most compact and low height solution;
  - ✓ Quite light (?);
  - ✓ Potentially 3 axes.
- CONTRAS
  - ✓ Poor RF performance at all the scanning angles

Satcom OTM: in house developments

➢ **YEAR 2004**

- **Wideband transmit / receive Ku-band airborne antenna:**
  - compact system for easy accommodation on aircraft;
  - dual shaped reflector antenna;
  - very stable structural layout;
  - simple pointing system;
  - complies with RTCA DO-160 D radiated emission limits;
  - fully qualified manufacturing.

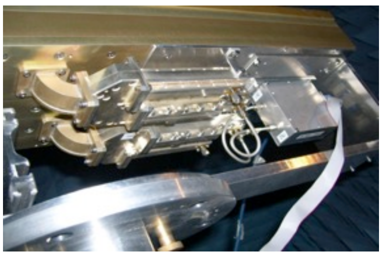




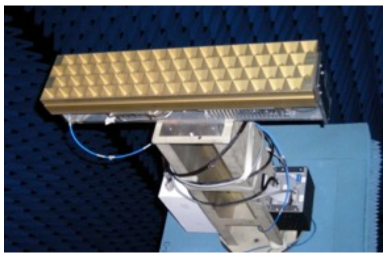
Satcom OTM: in house developments

➢ **YEAR 2006**

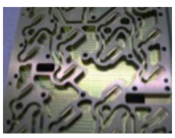
Ku-Band T/R Low-profile Antenna With Polarization Adjustment



Ku-band Tx/Rx antenna: back view



Ku-band Tx/Rx antenna: front view



Low losses BFN

Antenna size:
600 mm X 160 mm X 65 mm

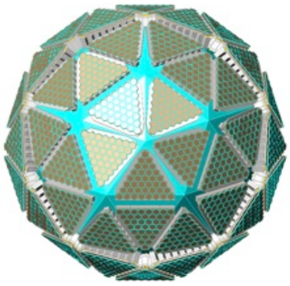
US Patent P500033-US-NP

Satcom OTM: in house developments

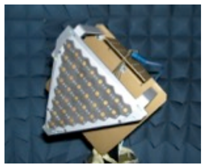
➢ **YEAR 2008**

An example of a full Phased Array approach

- ESA study for a Full Phased Array able to scan the antenna beam within an hemisphere including:
  - design of an active Tx/Rx K_u-band antenna;
  - manufacturing of a 5-active feed demonstrator.
- The system allows:
  - to track the linear polarization
  - to steer beam (+/- 180° el.; 0°/ 360°Az.);
  - To use used both in Tx and Rx through a dual-band self-diplexing patch.



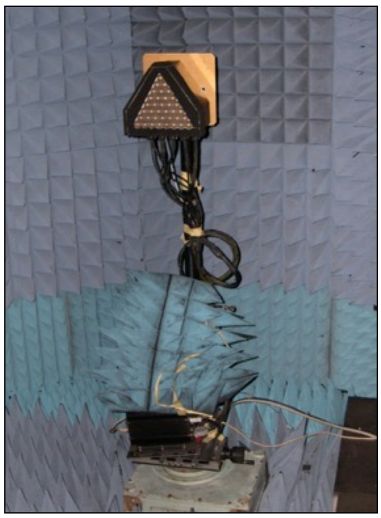
- PROS:
  - ✓ No rotating parts;
  - ✓ No key-hole issues.
- CONTRAS:
  - ✓ Poor RF performance (especially at low elevation angles) compared with the antenna complexity;
  - ✓ Extremely complex and costly.



Satcom OTM: in house developments

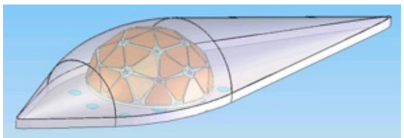
An example of a full Phased Array approach (cont.)

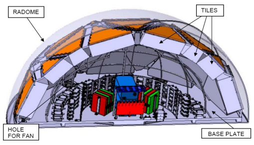
Active T/R Unit



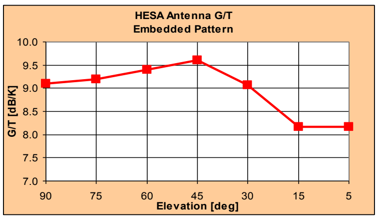
Satcom OTM: in house developments

An example of a full phased array approach (cont.)





Achieved antenna RF performance



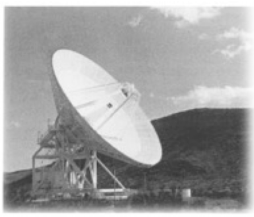
Requirements	Antenna
Radiation gain pattern over RF band	In agreement with (*)
Operative antenna field of view	0° < φ < 360° 0° < θ < 90°
G/T over RF band, in the entire field of view and for every selectable polarization	> 8 dBK^{-1}
EIRP over RF band, in the entire field of view	> 43 dBW
Number of beams	1
Cross polarization discrimination (including pointing error)	> 15 dB

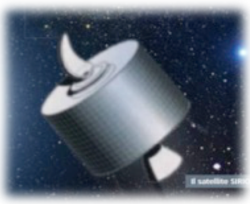
Antenna Diameter	840 mm
Antenna Height	390 mm
Mass	95 Kg
Number of Tile	40
Number of Radiating Element per Tile	36
Total Number of Radiating Element	1440
Tile turned-on per beam	14
Radiating Element turned-on per beam	504

Satcom OTM: in house developments

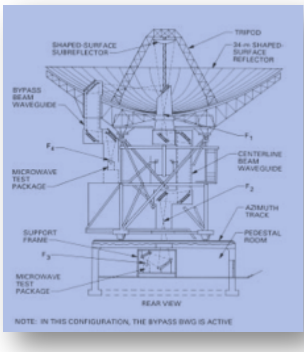
- **YEAR 2009**

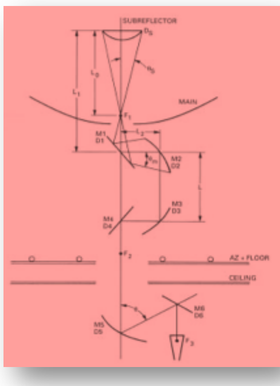
Birth of “Beam Waveguide” concept applied to Satcom OTM





Sirio satellite

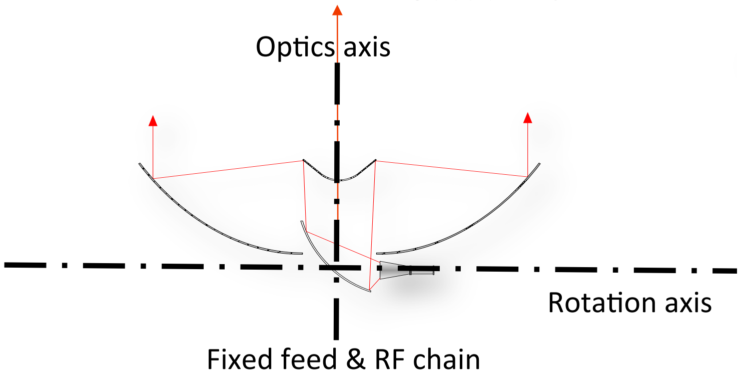


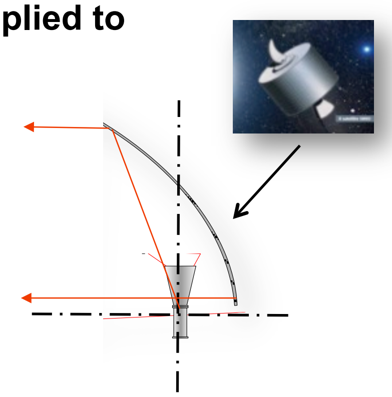


Example of guided RF energy through confocal mirros

Satcom OTM: in house developments

Birth of "Beam Waveguide" concept applied to Satcom OTM



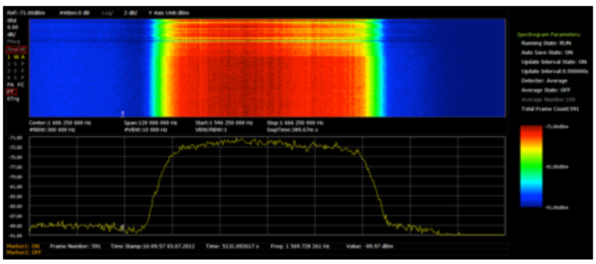


- 3 confocal/shaped mirrors for an almost compensated optics

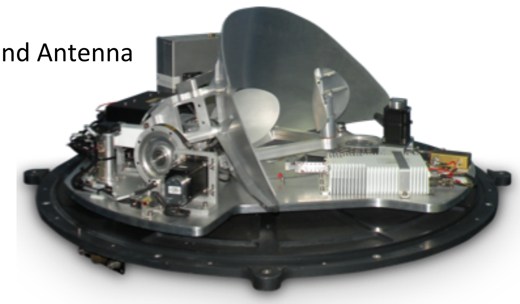
Satcom OTM: in house developments

First example of "Beam Waveguide" concept applied to Satcom OTM

Ka Band railway radome under test by using KASATSatellite



- Train-Sat Ka-band Antenna



- PROS:
  - ✓ Fixed RF chain(s);
  - ✓ Very low losses;
  - ✓ Robust and stable;
  - ✓ Simple and flexible;
  - ✓ Ready to be a bi-band solution.
- CONTRAS:
  - ✓ Significant aperture blockage ;
  - ✓ Limitations in the maximum ratio between horizontal and vertical dimensions.

Satcom OTM: in house developments

➢ **YEAR 2010**

Second example of "Beam Waveguide" concept applied to Satcom OTM: Ku/Ka bands JADA antenna

Rx	
G/T	9.0 dB/K @ 11.7 GHz
Polarization	Linear H or V
cross polarization product	Better than 15dB
RF frequency	10.95 GHz to 12.75 GHz
IF frequency	950 to 2000 MHz
Tx	
EIRP	45 dBW (with 40W BUC)
Polarization	Linear H or V
cross polarization product	Better than 20dB
RF frequency	13.75 to 14.5 GHz
IF frequency	950 to 1700 MHz

Rx	
G/T	9.5 dB/K @ 20.7 GHz
Polarization	Circular RHCP or LHCP
cross polarization product	Better than 25dB
RF frequency	19.20 GHz to 20.20 GHz
IF frequency	950 to 1950 MHz
Tx	
EIRP	50 dBW (with 40W BUC)
Polarization	Circular RHCP or LHCP
cross polarization product	Better than 25dB
RF frequency	30.0 to 31.0 GHz
IF frequency	1000 to 2000 MHz

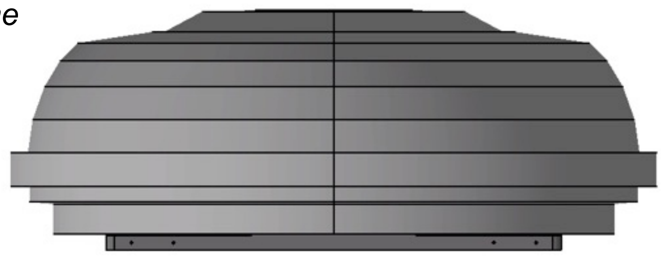
- Two axes Ku/Ka bands antenna with polarization control

Satcom OTM: in house developments

➢ **YEAR 2012**

Third example of "Beam Waveguide" concept applied to Satcom OTM: Enhanced JADA antenna

Antenna Swept Volume



- Enhanced reflector antenna: 800x290mm radiating aperture dimensions

Mechanical	
Antenna Swept Volume	Maximum height: 350 mm Maximum circular diameter: < 1000 mm

Satcom OTM: in house developments

Third example of “Beam Waveguide” concept applied to Satcom OTM: Enlarged JADA antenna (cont.)

Ku-Band

Rx	
G/T	12.0 dB/K @ 11.7 GHz
Polarization	Linear H or V
cross polarization product	Better than 15dB
RF frequency	10.95 GHz to 12.75 GHz
IF frequency	950 to 2000 MHz
Tx	
EIRP	48 dBW (with 40W BUC)
Polarization	Linear H or V
cross polarization product	Better than 20dB
RF frequency	13.75 to 14.5 GHz
IF frequency	950 to 1700 MHz

Ka-Band

Rx	
G/T	13.5 dB/K @ 20.7 GHz
Polarization	Circular RHCP or LHCP
cross polarization product	Better than 25dB
RF frequency	19.20 GHz to 20.20 GHz
IF frequency	950 to 1950 MHz
Tx	
EIRP	53 dBW (with 40W BUC)
Polarization	Circular RHCP or LHCP
cross polarization product	Better than 25dB
RF frequency	30.0 to 31.0 GHz
IF frequency	1000 to 2000 MHz

- Expected antenna RF performance

Satcom OTM: in house developments

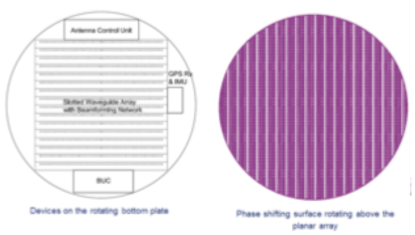
➢ **YEAR 2015**

Metamaterial antenna system (developed in parallel) to cope with ground Satcom OTM

- Two flat arrays (one for Tx the other for Rx);
- Azimuth&elevation mechanically steered;
- Elevation beam steering, by rotating a phasing surface.

- PROS:
  - ✓ Compact and simple;
  - ✓ Low losses antenna solution;
  - ✓ Low weight.
- CONTRAS:
  - ✓ Poor RF performance at low elevation angles.

Mechanical steering baseline solution



Satcom OTM: in house developments

➢ **Coming YEARS**

New antenna layouts for 2.0 Space Engineering Satcom OTM

- **New generation of S.E. antennas for mobile application (especially for aircrafts) should exhibit:**
  - One single aperture for both Tx & Rx sections;
  - Horizontal/vertical/cross axis scanning capabilities;
  - Polarization control as simple as possible;
  - Low losses between the antenna aperture and the Front-End input port;
  - Easy handling of two frequency bands;
  - Reduced weight (through the exploitation of carbon fiber/fiber glass/etc. materials);
  - Reasonable cost;
  - Quite good filling factor (*FF is defined as the ratio between the effective antenna aperture and the antenna swept volume*)
  - Simple antenna layout

S.E. Antenna designer

Conclusions

- A brief overview has been carried out on the evolution of the antennas for Satcom OTM applications. The main aspects come out from the analysis are the following:
  - ✓ No room for really flat antennas (either mechanically or electronically steered), in case a good satellite link is requested at very low elevation angles;
  - ✓ Conformal Arrays, fully electronically steered, might exhibit acceptable RF performance at very low elevation angles. Nevertheless they still exhibit high costs and complexity;
  - ✓ Mechanically steered arrays might be a reasonable answer, provided RF BFN does not introduce too many losses;
  - ✓ Mixed solutions (mechanical/electronic) might handle the 3rd axis issue, but reducing its RF performance and increasing the antenna complexity;
  - ✓ Simple polarization handling capability is highly recommended;
  - ✓ High RF power handling, for military application, would be very much appreciated.

GaN based, passively cooled L-Band SSPA for Avionics

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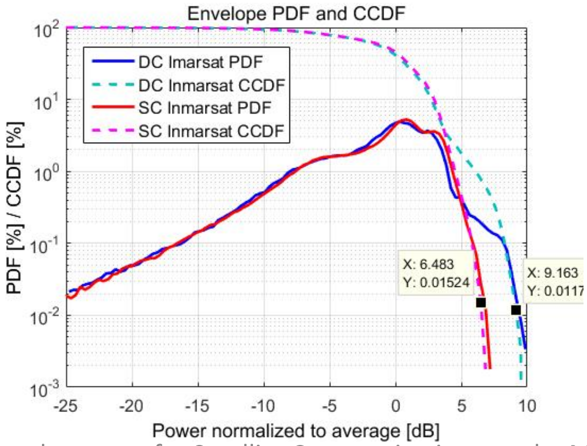
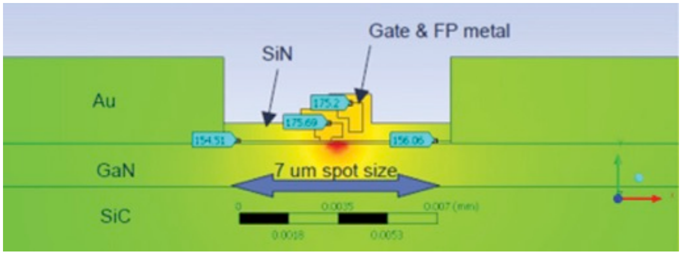
Motivation – complex signals

- **Aeronautical SatCom terminals employ new communication standards**
  - FANS system based on BGAN (INMARSAT), and ANTARES
  - Complex modulated signals with high PAPR (CDMA or QAM)
  - Linearity requirements dictate large back-off from the output PA
  - Low average efficiency and increased thermal dissipation



Motivation – Cooling

- **Limited available room and restrictions on air cooling due to noise**
  - Air cooling systems also prohibitively expensive
  - Heat sink size reduction required to fit into the limited and highly variable available space
- **Existing GaAs or LDMOS technology unable to meet such requirements or are very expensive**
- **GaN technology allows compact heat sink and passive cooling (high junction temperature → 225 C @ MTTF > 200 years)**
- **GaN technology allows for very linear amplifier designs when combined with a low cost digital lineariser**



Project Outline

- **Technology Description**
  - GaN based, passively cooled linearised L-band SSPA for avionics
- **Technology Elements**
  - State-of-the-art GaN device
  - Asymmetrical Doherty power amplifier
  - Digital Pre-distortion
  - Crest Factor Reduction (if needed)
  - COTS Transceiver
- **Program Objectives**
  - Design and implement a demonstrator of a linearised highly efficient Doherty HPA for future avionic SATCOM terminals
  - Build up expertise and prove GaN technology for future radio products

Product CTQs:
- Passive cooling (SWaP reduction – flexible installation)
- Power efficiency > 47% (SWaP reduction)
- Supported waveforms: Inmarsat, Antares
- Number of simultaneous carriers: 2 desirable

Project Consortium

Technology Org: Honeywell Advanced Technology Europe ET
Customer: European Space Agency – ARTES 5.1

Honeywell International
Project management, system design, RF HW design, implementation and verification

LKE
Thermal and mechanical aspects

UCD
Lineratization and device modeling

MACOM EIR+UK
GaN support

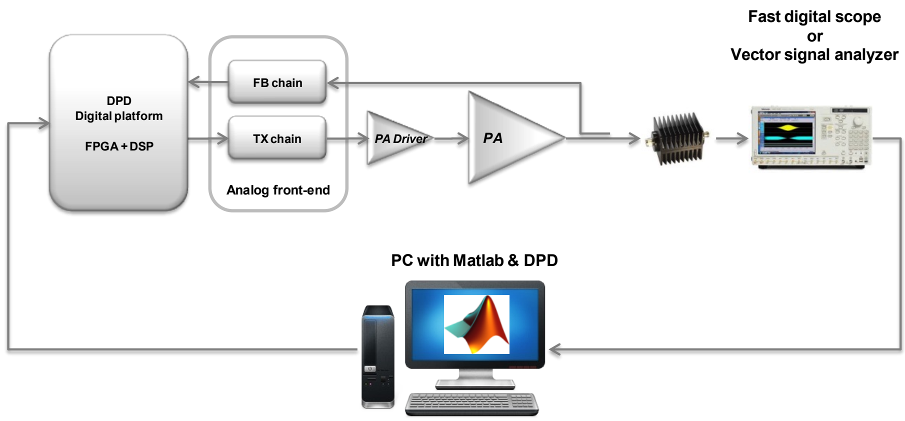
Requirements (Electrical)

	REQUIRED	OPTIONAL
Supported Waveforms	Inmarsat	Iridium, Antares
Number of carriers	One (100% Duty Cycle)	Two (100% + 10% Duty Cycle)
Frequency	Inmarsat: 1626.5-1660.5 MHz Alphasat: 1668-1675 MHz	Iridium: 1610-1626.5 MHz Antares: 1646.5 – 1656.5 MHz
Output Power	14.5W (nom.) / 64.6 W (peak)	16 W (nom.) / 257 W (peak) (with 10% DC second carrier)
Average PAE for modulated signals	> 47%	
Gain	> 45 dB	
Power flexibility	> 6dB (PAE spec not imposed)	
Channel mask	Inmarsat / ETSI (EN 301-473)	
EVM	< 10% (R20T4.5X – 16QAM)	< 5.5% (FR80T5X64 – 64QAM)
Harmonic rejection	< -70 dBc/(4kHz) over 1.675 to 18 GHz (ARINC 731)	
Return loss	Input: < -9.5 dB (ARINC 741) Output: < -15 dB	Input: < -15 dB

Requirements (Physical & Other)

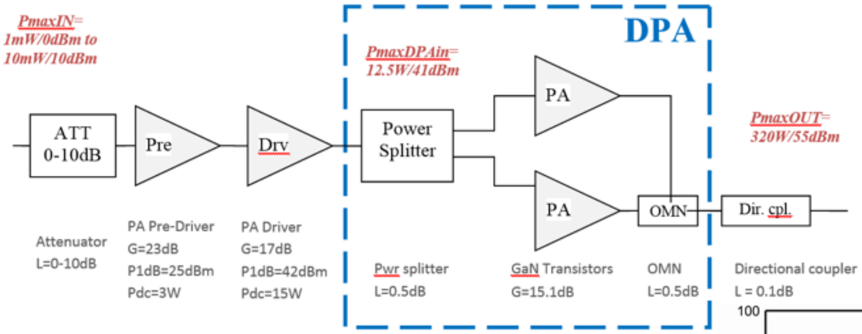
	Requirement
Dimensions	Footprint < 200 cm^2
Cooling	Passive
Reliability	10^6 hrs MTTF
Operating Temperature (PA Block only)	-55 C to +70 C
Pressure	9 kPa to 110 kPa (ground to FL55)
Dissipated power	< 36.5 W
Environmental tests	Acc. to DO-160G

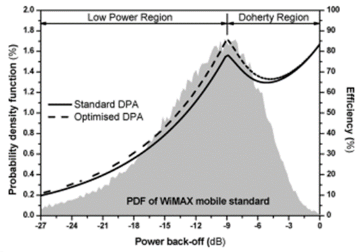
Final demonstrator



- TRL-5 Demonstrator will include:
  - FPGA with DPD implementation (eval. board)
  - Digital to RF convertor (eval. board)
  - Amplifier = Pre-driver + Driver + Doherty PA in one box
    - With heatsink for passive cooling

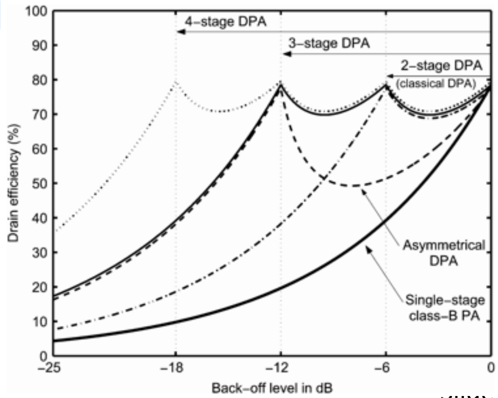
SSPA concept – Doherty PA



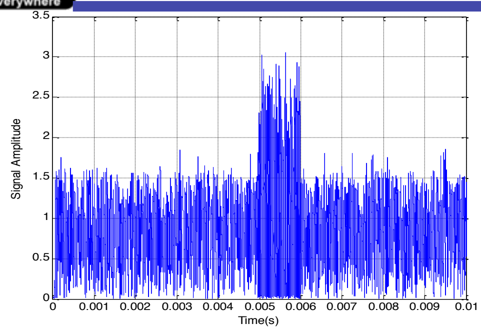


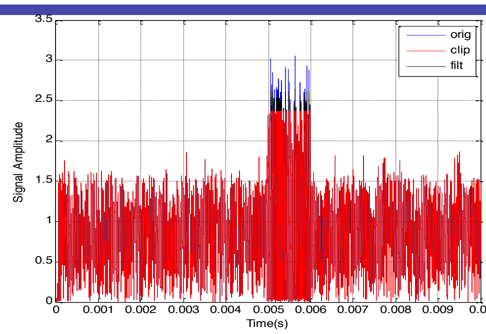
Doherty concept is well proven and flexible

- 60-70% efficiency levels attainable
- Large back-off levels can be achieved by asymmetrical or multi-stage DPAs
- 2-stage symmetrical DPA (6 dB OBO) easy to tune
- Higher number of stages can be tricky

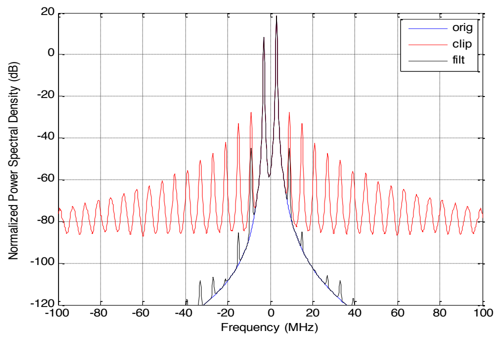


Dual-carrier (Go / No-Go)

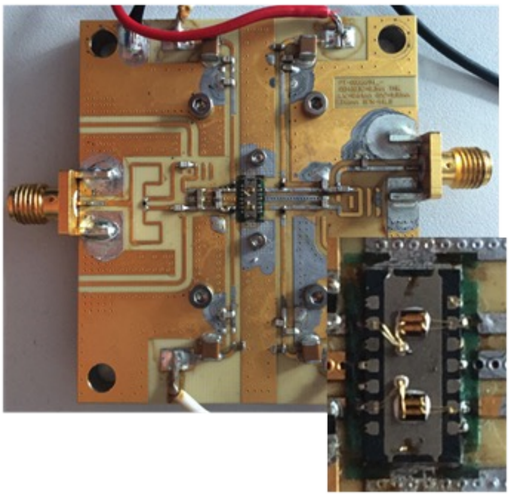




- 3- or more stage Doherty ruled out due to complexity
- Crest factor reduction (CFR) investigated
  - Dual-carrier should raise PAPR by 3-dB when both carriers are at 100% duty cycle
  - Second carrier at 10% duty cycle increases peak but not average → PAPR increase by ~6dB
  - CFR only clips when second carrier present (very high distortion)
- Other methods require more than planned amount of effort



WP2 - Fast-prototype Doherty amplifier

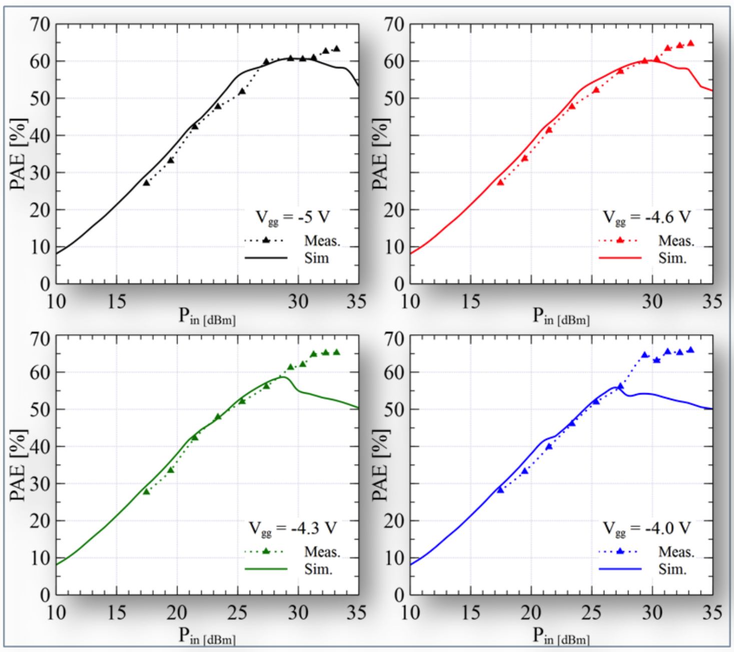


Fast-prototype

MACOM Demo design (2-mm GaN-SiC)

- Customer demo for LTE band
- Optimised for LTE waveform
- Optimised for physical size

Fast-prototype results

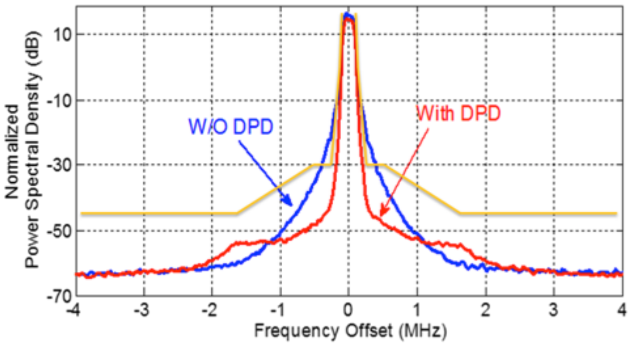


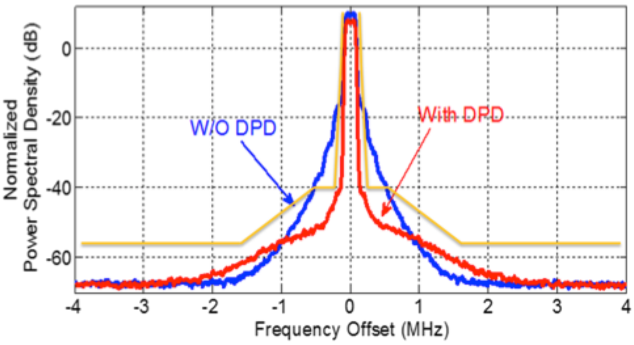
All simulations and measurements performed at 2.7 GHz

Observations:

- ~60% peak efficiency available
- Model does not predict the performance close to saturated power
- Doherty signature behaviour in efficiency not as prominent

Fast-prototype results – ctd’





ANTARES

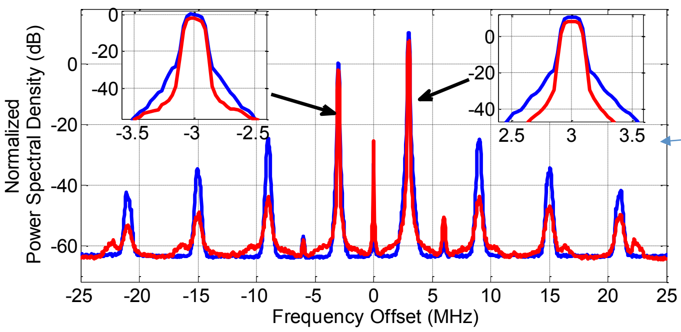
	NMSE (dB)	ACPR (dBc)	Efficiency (%)
No DPD	-14.0	-29.8/-29.6	60.0
DPD (meas)	-40.0	-56.6/-56.1	58.7

P_{out} = +38 dBm (6-dB OBO)

INMARSAT (SINGLE-CARRIER)

	NMSE (dB)	ACPR (dBc)	Efficiency (%)
No DPD	-10.4	-24.7/-24.2	49.7
DPD (meas)	-36.9	-49.6/-48.9	50.0

Dual-carrier INMARSAT



BOTH CARRIERS AT 100% DUTY CYCLE

	NMSE (dB)	ACPR (dBc)	Efficiency (%)
No DPD	-10.9	-22.7/-35.2	30.3
DPD (meas)	-27.6	-47.1/-52.3	30.2

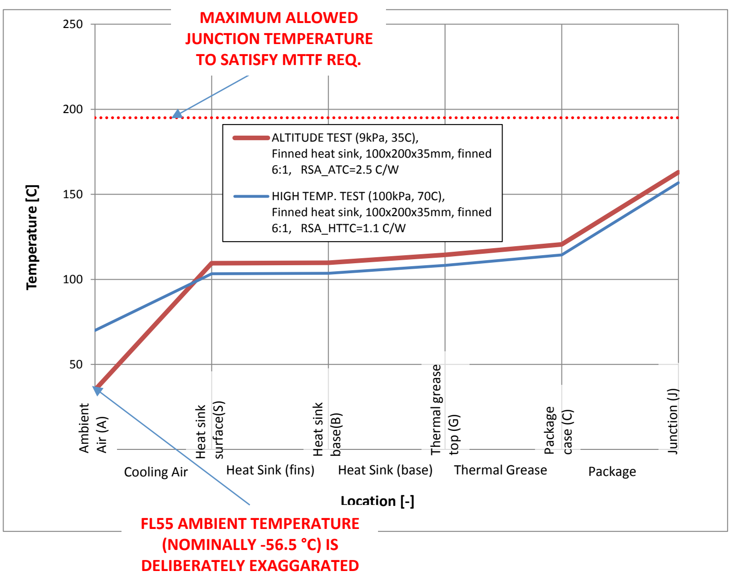
Fast-prototype – potential improvements

Possible improvements over achieved performance

1. Frequency:
   The fast-prototype amplifier operates at 2.7 GHz
   Device, component and PCB losses would be higher at 2.7 GHz compared to the 1.6 GHz band
2. Intended application:
   The fast-prototype amplifier is optimised for operation with LTE signals
3. Harmonic matching and output combiner
   For space saving purposes, the fast-prototype amplifier does not use a l/4 transformer at the output combiner (*simulation study confirmed a classical Doherty combiner improves performance*)
   Better efficiency expected when the input and output are both presented with correct impedances (for highest PAE) at all harmonics.

Conclusion: The fast-prototype GaN technology is a feasible candidate for Phase II Advanced Concept PA. Above improvements will help achieve and exceed project targets.

WP2 - Thermal Analysis & Management



Worst case thermal analysis (on an airport apron in a hot country or at FL55) confirms heat sink size of 100 x 200 mm^2 can cool the amplifier sufficiently –

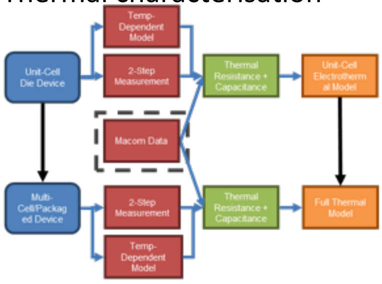
→ MTTF REQUIREMENT CAN BE MET

→ MAXIMUM SIZE REQUIREMENT CAN BE MET

WP3 – Device Characterisation

Electrical characterisation

Thermal characterisation



- MACOM GaN/Si unmatched HEMT
- P_max ~ 100W
- Previously been used in high-efficiency designs covering frequency band of interest
- Difficult to model such a large, packaged device
- Significant parasitic and package effects
- Must build model from single-finger die device and scale up

Phase II and Project Conclusion

- Finalised device model (electrical and thermal) (WP4)
- Advanced concept Doherty PA design that complies with project specifications (WP5)
- Integration with DPD in HW and assembly of final transmitter chain (pre-drivers, driver, PA, DPD etc.) (WP5)
- Full thermal analysis of finalised design (WP5)
- Development of peripheral circuitry and product integration (WP5)
- Test plan and full characterisation (WP5)
- Second iteration if required (WP6)
- Critical evaluation & lessons learned (WP7)
- End of project targeted for Dec 2017

Advanced Digital Predistortion Techniques for Satellite Communications on the Move

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Outline

- Introduction
- Digital Predistortion (DPD) Principle
- Behavioural Modelling of RF Power Amplifiers
- DPD for L-Band GaN PA for Avionics Terminals
- DPD for Multicarrier DVB S2 TWTA
- Conclusion

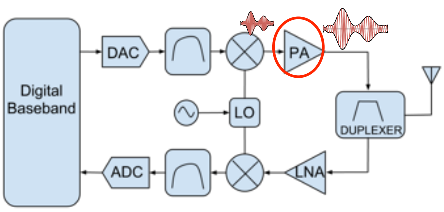
System Requirements/Trends

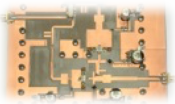
- Future satellite communication systems demand larger capacity
  - Higher data rate, wider signal bandwidth
- Tighter integration, smaller sizes, lower weights
- Power efficiency becomes a big concern
  - For wideband multicarrier non-constant envelope signals: back-off efficiency of power amplifier is very poor
  - Large cooling systems result in big size, heavy weight, and wasting energy
- Digital circuits and modern solid-state device technologies have been significantly advanced in the past decades
  - More and more digital in transceiver design
  - SSPA replacing TWTA

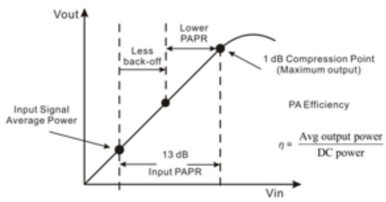



RF Power Amplifiers

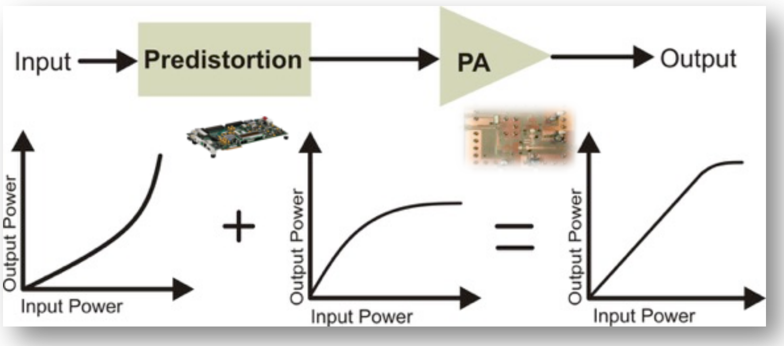
- RF power amplifier (PA) is a unit that strengthens the signal to combat losses in transmission by converting DC electric power to added RF output signal power.
- It consumes a high proportion (over 50%) of the total transceiver energy. It is also a complex nonlinear unit which introduces distortion that can severely limit data capacity.
- High PAPR (peak to average power ratio) signals: very poor power efficiency due to power back-off.
- Challenges: design high-efficiency and high-linearity PAs with very wide operating bandwidths.





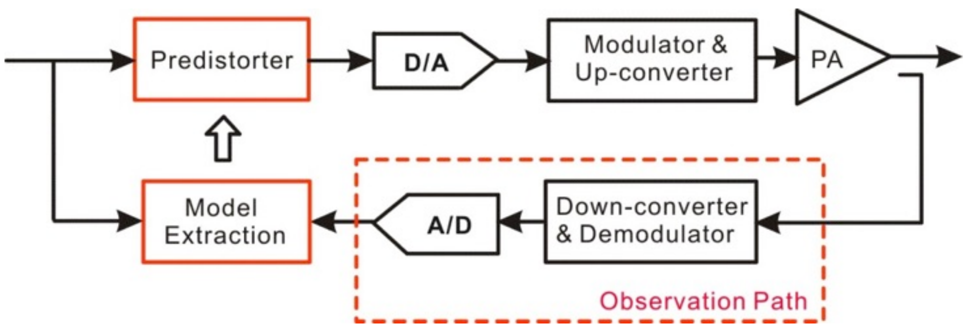


Predistortion Principle



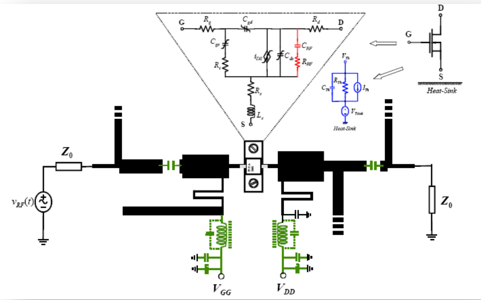
- Compensate distortion in RFPA by inverting its nonlinear behaviour.
- The PA can be operated at high efficiency modes without losing linearity.
- Conventional analog predistorters achieve limited performance.
- Digital predistortion (DPD) becomes more popular: low cost/low power digital implementation and high performance.

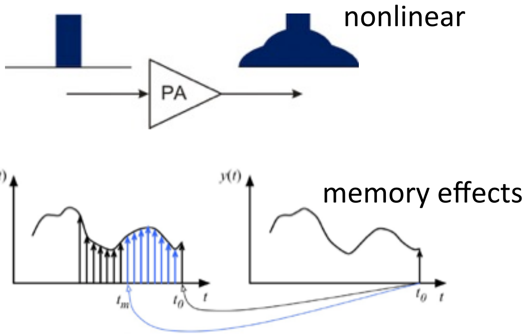
DPD System Architecture



- **Feedback Observation Path**
  - Acquire information from PA output
- **Model Extraction Unit**
  - Find model parameters, can run off-line or occasionally
- **Predistorter Unit**
  - Real-time signal processing

Modelling Challenges





- Accurate model is crucial.
- Simultaneously count nonlinearities and memory effects.
- Discrete time domain and in complex baseband.
- The model must be simple: easy and low cost digital implementation.
- Linear-in-parameters: linear estimation algorithms can be used for model extraction.

Volterra Series

Linear system
with memory

$$y(n) = \sum_{i=0}^{m-1} w(i) \times x(n-i)$$
$$= w(0)x(n) + w(1)x(n-1) + \cdots$$

Nonlinear system
without memory

$$y(n) = \sum_{i=0}^{m-1} a_i [x(n)]^i$$
$$= a_0 + a_1 x(n) + a_2 [x(n)]^2 + \cdots$$

1st-order Volterra kernel

2nd-order Volterra kernel

$$y(n) = \sum_{i=0}^{m-1} h_1(i)x(n-i) + \sum_{i=0}^{m-1}\sum_{j=0}^{m-1} h_2(i,j)x(n-i)x(n-j)$$

3rd-order Volterra kernel

$$+ \sum_{i=0}^{m-1}\sum_{j=0}^{m-1}\sum_{k=0}^{m-1} h_3(i,j,k)x(n-i)x(n-j)x(n-k) + \cdots$$

Volterra Series ⇒ **Nonlinear system** **with memory**

Simplified Models

- Memory Polynomial (MP)
- Generalized Memory Polynomial (GMP)
- Dynamic Deviation Reduction (DDR)

$$y(n) = \sum_{p=1}^{P} h_{p,0}(0,\cdots,0)x^{p}(n)$$

← Instantaneous term

$$+\sum_{p=1}^{P}\sum_{i=1}^{M} h_{p,1}(0,\cdots,0,i)x^{p-1}(n)x(n-i)$$

← 1st order dynamic term

2nd order dynamic term

$$+\sum_{p=2}^{P}\sum_{i_1=1}^{M}\sum_{i_2=i_1}^{M} h_{p,2}(0,\cdots,0,i_1,i_2)x^{p-2}(n)x(n-i_1)x(n-i_2)$$

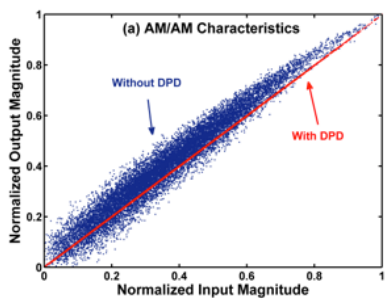
$$+\cdots$$

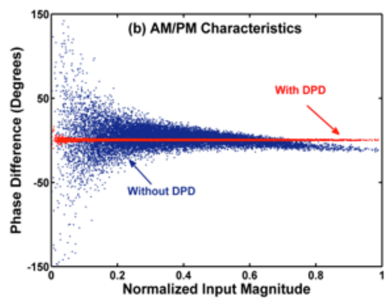
[Zhu, et al,T-MTT, Dec.06]

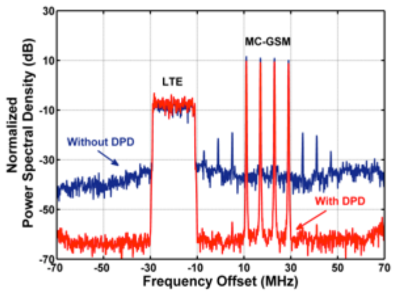
Many simplified versions of Volterra models have been developed in the past years.

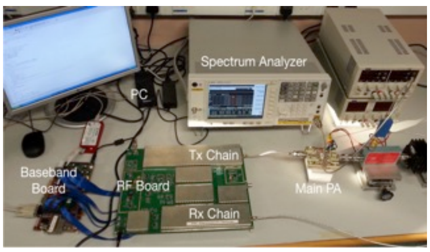
Cellular Signal Test Example

DPD has been widely deployed in terrestrial cellular mobile base stations





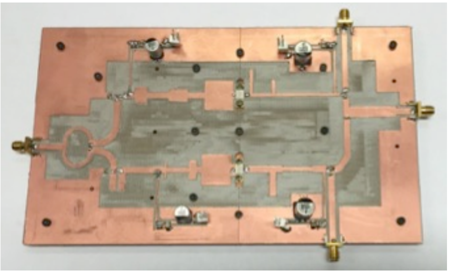




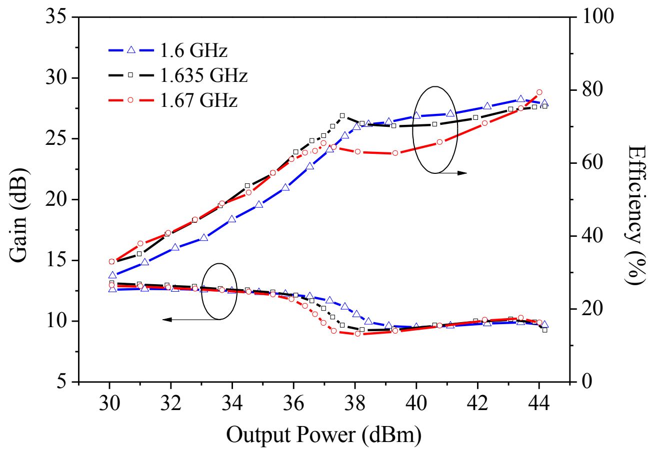
DPD Test Bench in UCD

L-Band GaN Doherty PA

- L-band GaN PA for Avionics Terminals
- Carrier Frequency: 1.60 - 1.67 GHz
- Efficiency: 63-72% @6-dB Back-off
- 75-80% @Saturation
- Output Power: 25Watts

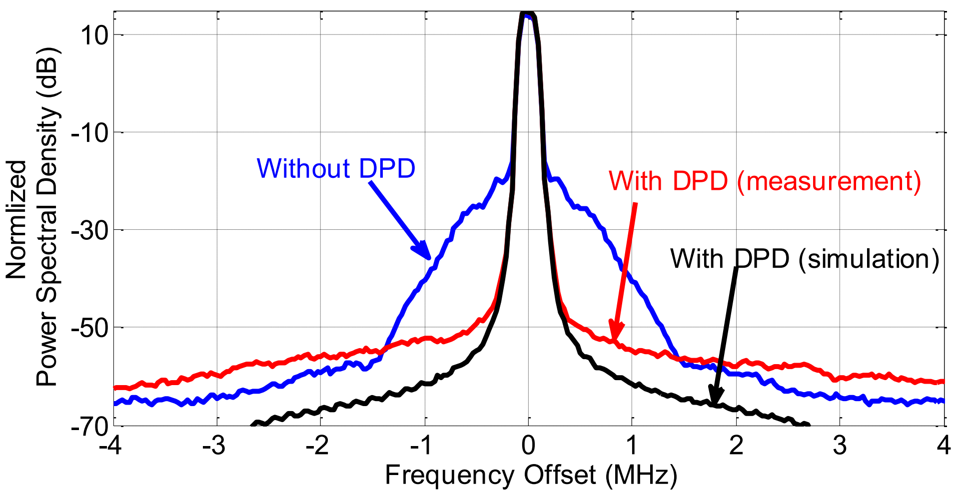


GaN Doherty PA Fast Prototype

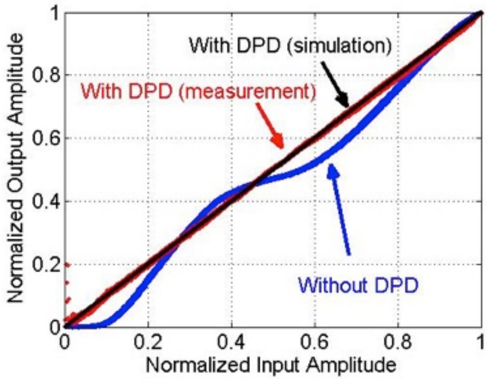


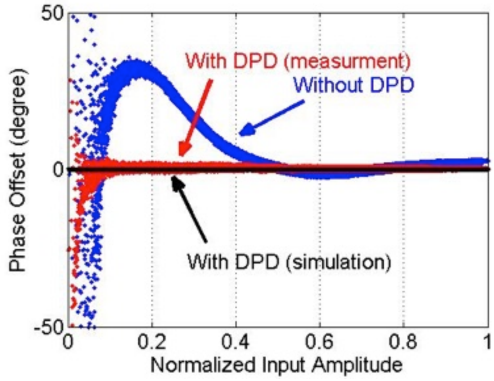
Linearization Performance

ANTARES Signal



Linearization Performance

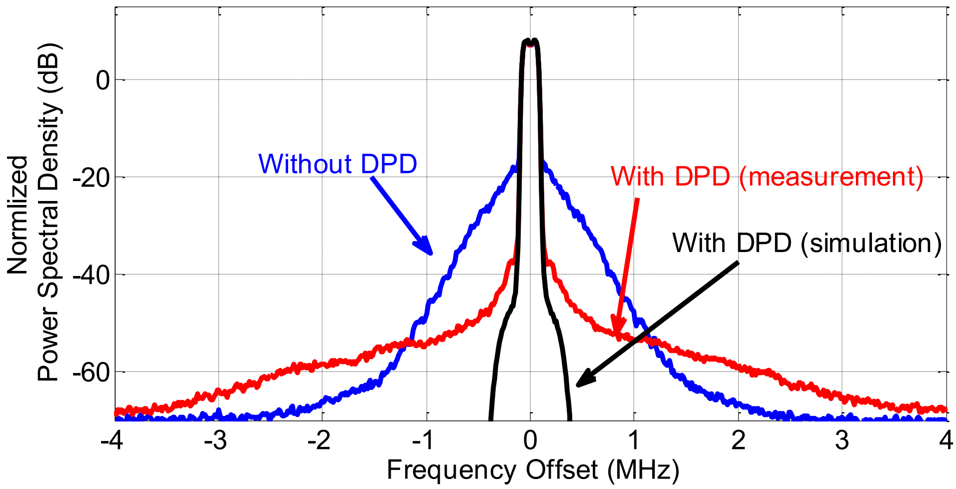




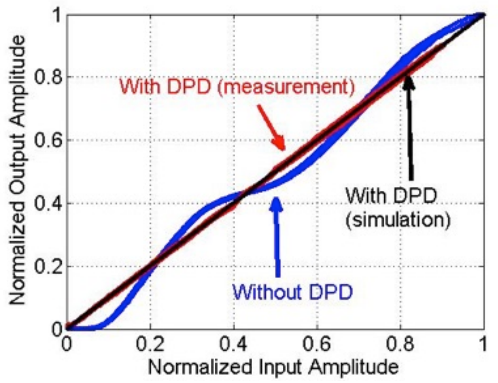
	NMSE (dB)	ACPR Upper (dB)	ACPR Lower (dB)	Efficiency (%)
Without DPD	-20.4	-29.8	-29.6	67.9
With DPD (measurement)	-41.5	-63.4	-62.8	67.9
With DPD (simulation)	-70.7	-76.5	-74.9	67.9

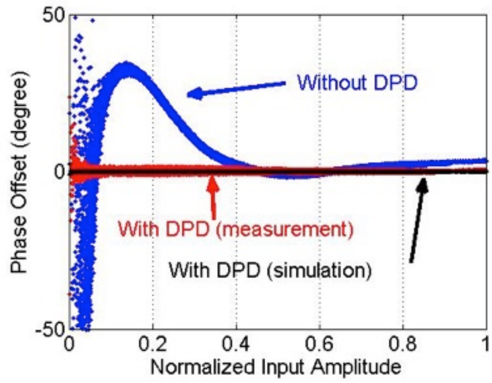
Linearization Performance

INMARSAT Signal



Linearization Performance



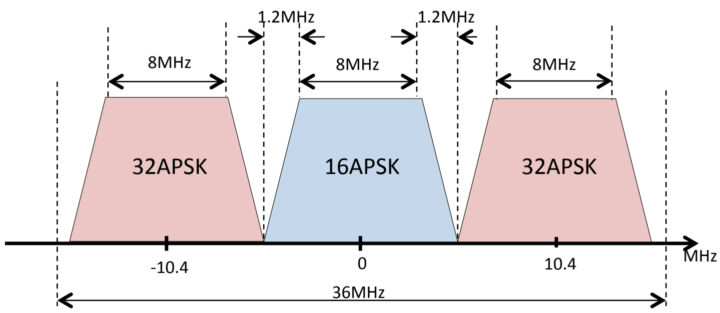


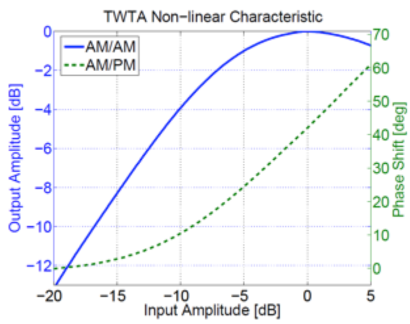
	NMSE (dB)	ACPR Upper (dB)	ACPR Lower (dB)	Efficiency (%)
Without DPD	-19.0	-24.7	-24.2	69.13
With DPD (measurements)	-41.0	-54.7	-55.1	69.05
With DPD (simulation)	-74.7	-74.8	-75.6	69.00

Multicarrier DVB S2 Signals

- 3-carrier signal, 32-APSK/16-APSK/32-APSK
- 8MBaud symbol rate, roll-off = 0.25
- 36MHz Transponder Bandwidth
- Non-linearized TWTA, DVB-S2 standard with IMUX/OMUX configuration
- End-to-end simulation

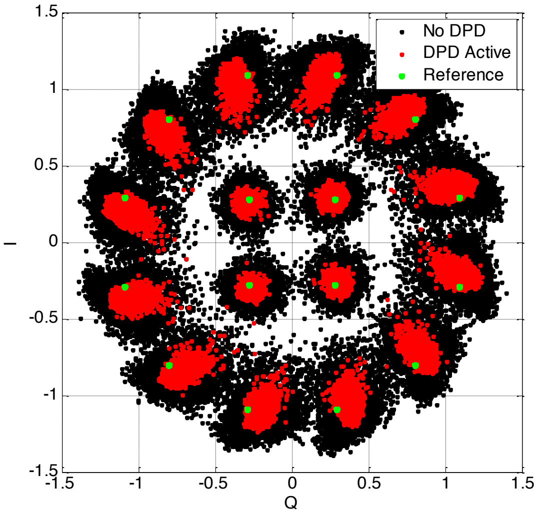
DVB S2 SATELLITE



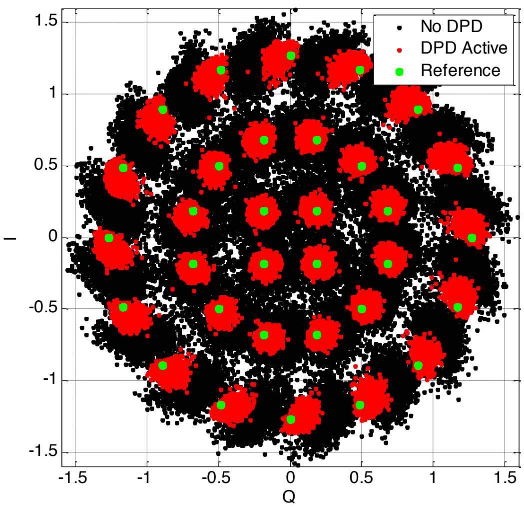


Linearization Performance

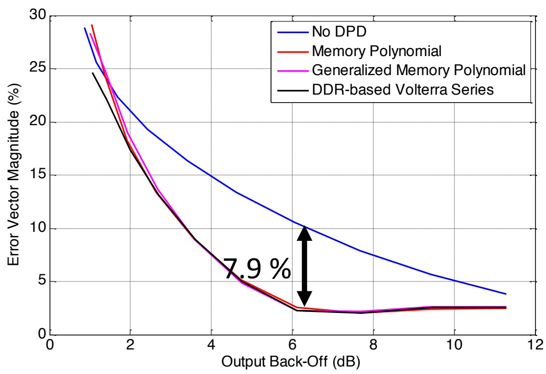
Inner Carrier



Outer Carrier

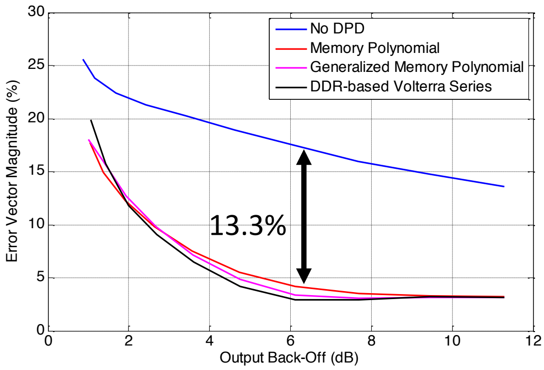


Linearization Performance

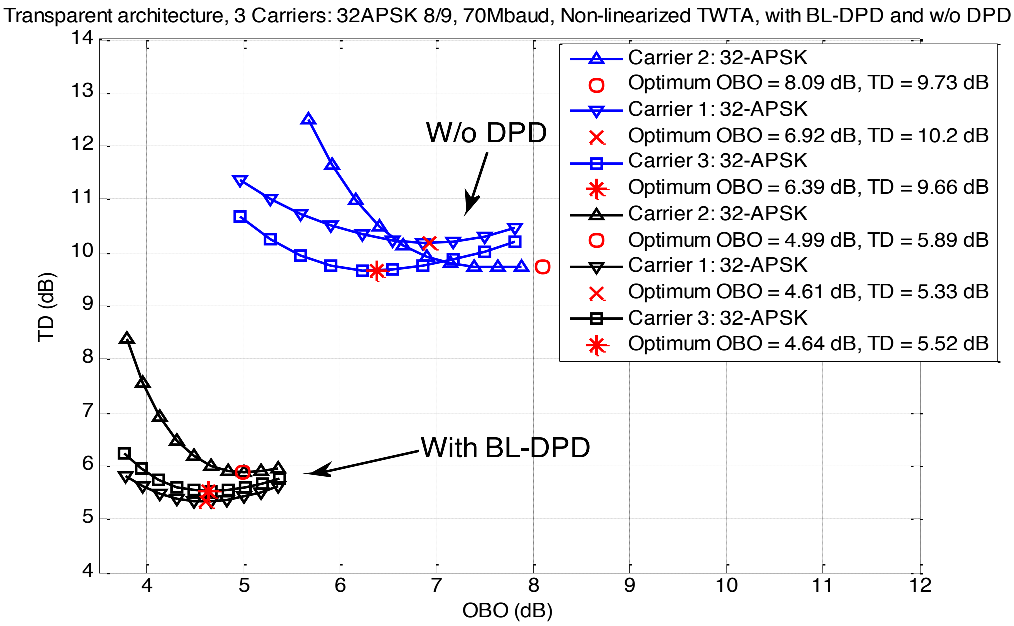


Inner Carrier

Outer Carrier



Linearization Performance



Conclusion

- Future aeronautical communication system design faces new challenges in terms of signal bandwidth, power efficiency, linearity, size/weight, cost, etc.
- Digital predistortion techniques can significantly enhance linearity and enable high power efficiency operation of transmitters.
- Reduce power consumption, enable smaller size, better integration and lower cost.
- Technologies recently developed for terrestrial cellular mobile systems can be transferred to satellite systems with proper modifications.

EuMW 2016
Microwaves Everywhere

46TH EUROPEAN MICROWAVE CONFERENCE 2016
The 46th European Microwave Conference

Millimetre-Wave Technologies for Next Generation Mobile Terminal

Prof. George Goussetis
Prof. Savvas Kosmopoulos
Heriot-Watt University

g.goussetis@hw.ac.uk

EuMW 2016
Microwaves Everywhere

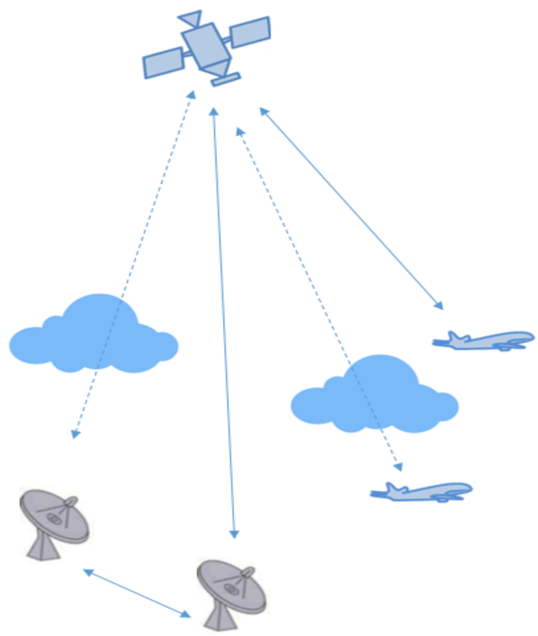
MM-wave Satellite Communications

Ka-band
- FSS
- SOTM

Q/V-band
- Gateway links
- Aeronautical …?

Advantages
- Bandwidth & throughput
- Smaller apertures

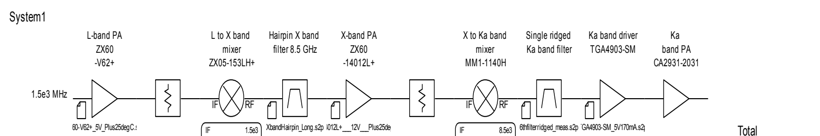
Challenges
- Fading
- Cost



Technology challenges

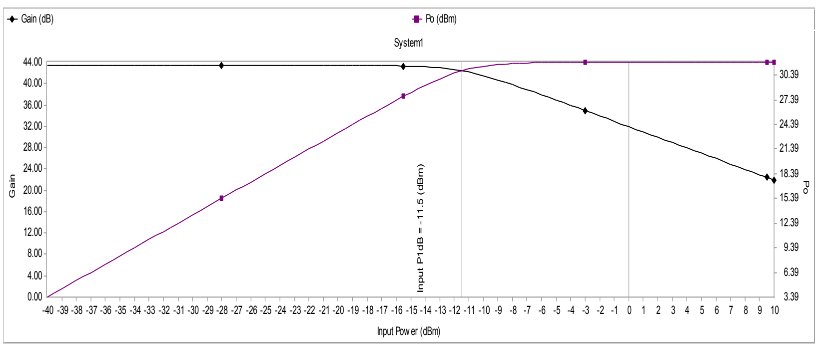
- Propagation and fading beyond 30 GHz
- ACM: Link level analysis, verification and component specification
- Fading: Dual-band terminal architectures
- Front-end integration
- Power amplification
- Passive components
- Packaging
- Beam steering “flat” antenna

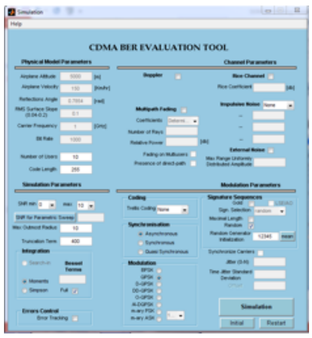
Link level evaluation & System design

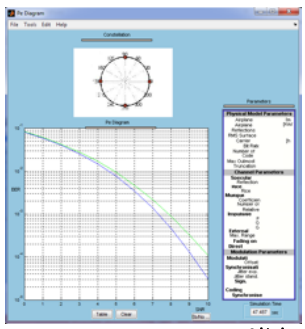


	L-band PA		L to X band mixer	Hairpin X band filter	X-band PA		X to Ka band mixer	Single ridged Ka band filter	Ka band driver	Ka band PA	Total
NF (dB)	5.10	3.00		1.19	5.35	3.00		0.49	12.00	4.00	9.29
Gain (dB)	15.42	-3.00		-1.19	12.18	-3.00		-0.49	14.36	22.26	42.58*
OIP3 (dBm)	33.40				29.20				27.00	41.00	40.08
Gain+ (dB)	15.42	12.42	6.52	5.32	17.51	14.51	6.45	5.96	20.31	42.58	42.58
Po (dBm)	3.52	0.52	-5.38	-6.58	5.61	2.61	-5.45	-5.94	8.41	30.68*	30.68*
Pdc (W)	.41	0	0	0	.744	0	0	0	.85	13.2	15.2

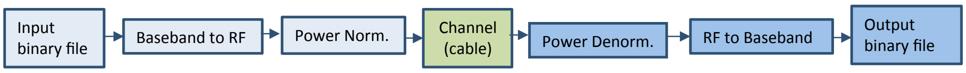
Input Pwr (dBm)	-11.90	System Temp (K)	290.00	IM Offset (MHz)	.025
DC Voltage (V)	5	DC Current (mA)	252	DC Pwr (W)	1.26
DC Voltage (V)	12	DC Current (A)	1.162	DC Pwr (W)	13.94
Total DC Pwr (W)	15.2				

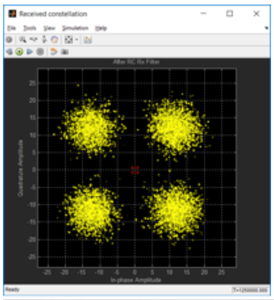


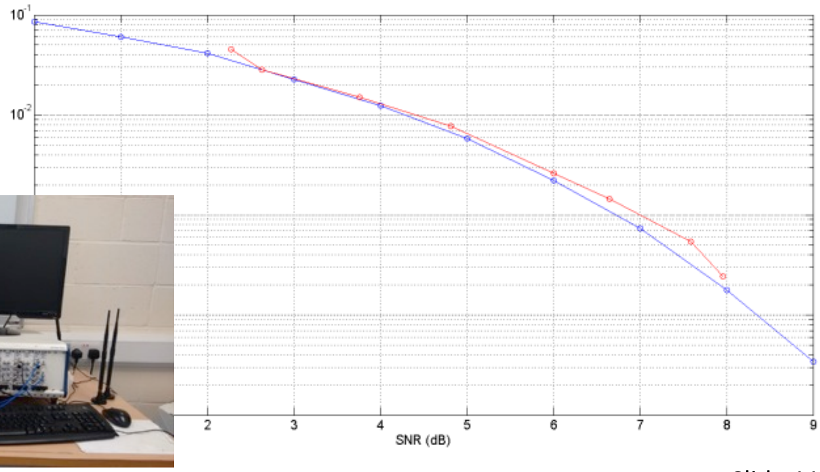




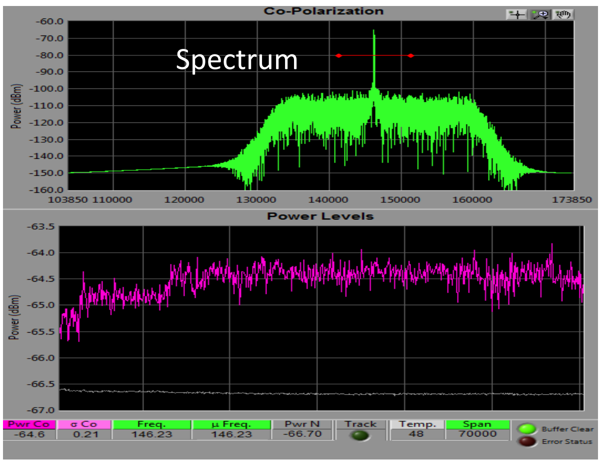
Link level evaluation: Testbed verification

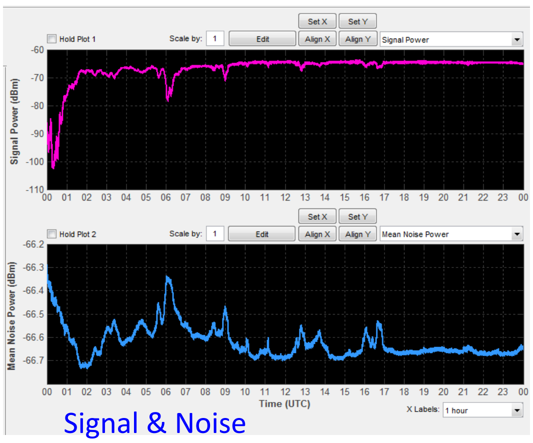


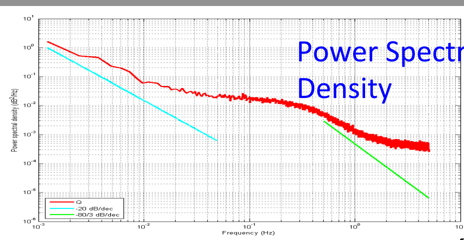




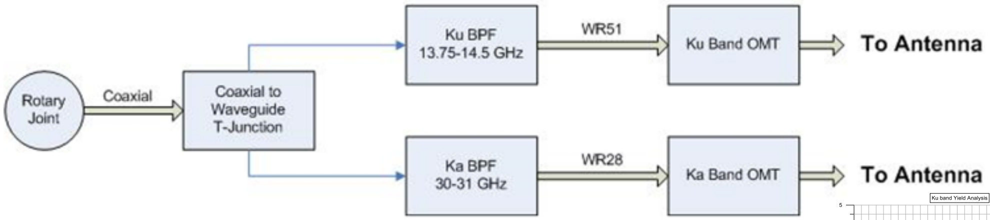
Q-band propagation

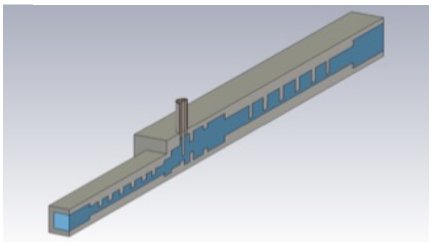


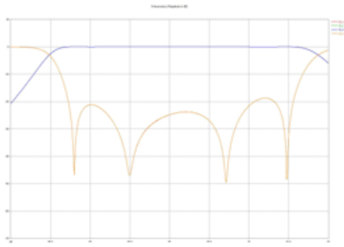


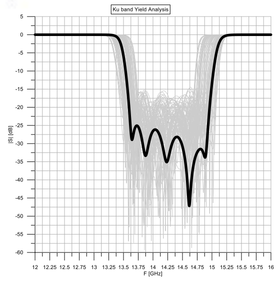


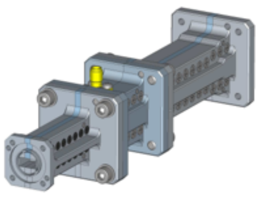
Dual-band terminal and Ku-/Ka- Tx/Tx Diplexer

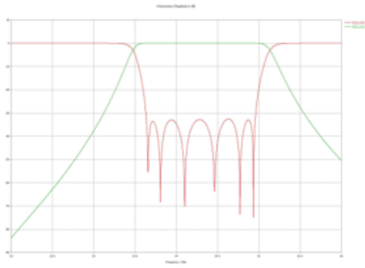






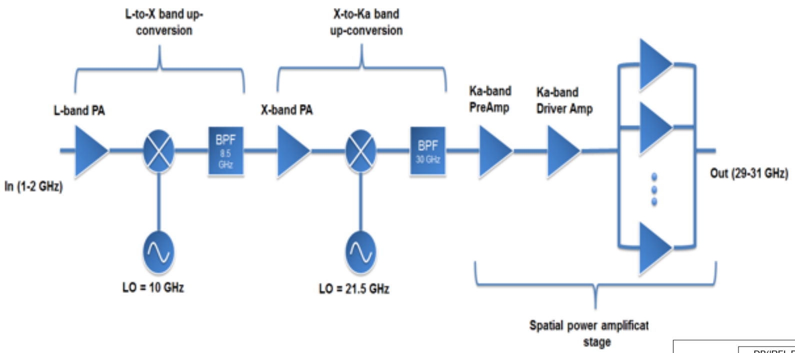




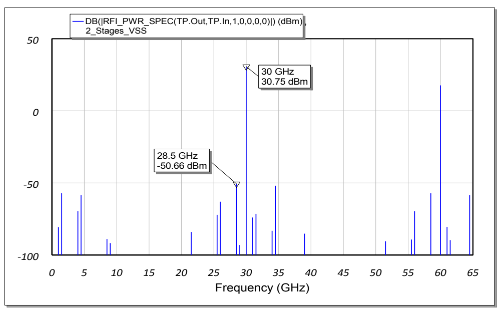


Robust design to ±30µm statistical variation

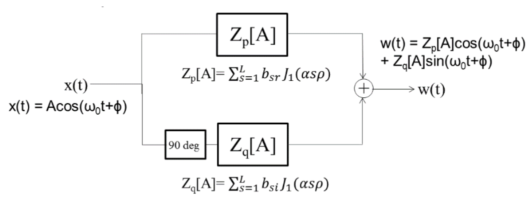
L- to Ka-band Converter

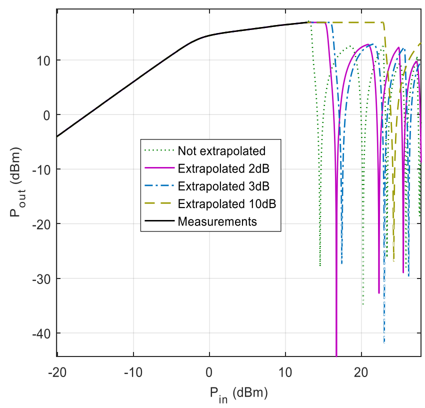


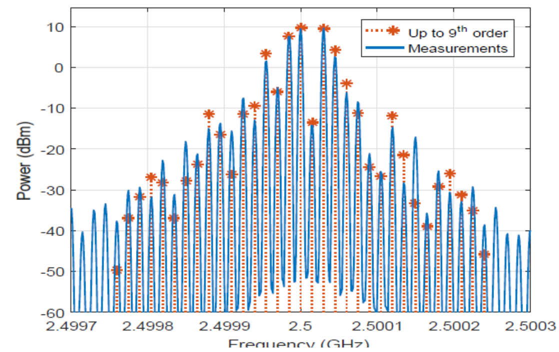
Parameter	Units	Requirement	Note
Operating Frequency Band	GHz	29-31	
Power Output (P1dB)	Watt	30	
Input Power	dBm	-15 to +5	
Gain	dB	40	
Gain Flatness	dB	<0.4	TBC
Gain Slope	dB/MHz	<0.02	TBC
Gain variation over temperature	dB	±2	TBC
Gain stability	dB/24h	±0.25	TBC
Noise Figure	dB	<20	
P1dB	dBm	4.77	
TX maximum power (Psat)	dBm	46	
OIP3	dBm	> 47.5	TBC
Input RL	dB	>15	TBC
Output RL	dB	>15	TBC
Spurious	dBc	-60	
HPA DC Supply	Vdc@A	4.5 V@5.6 A	Needing of stabilized voltage
Power Consumption	Watt	<500	TBC
Operating Temperature	°C	-40 to 60	TBC

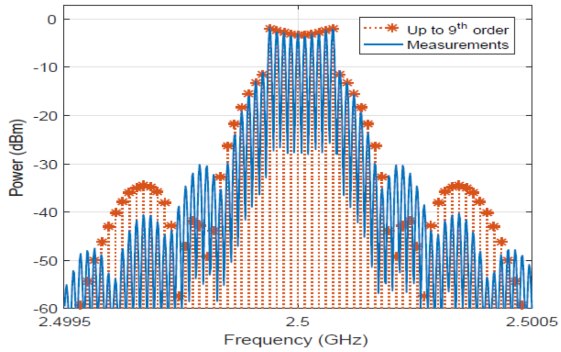


From AM/AM to IMDs

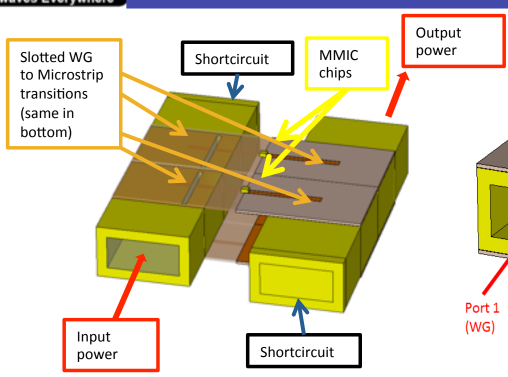


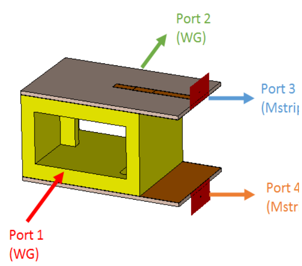


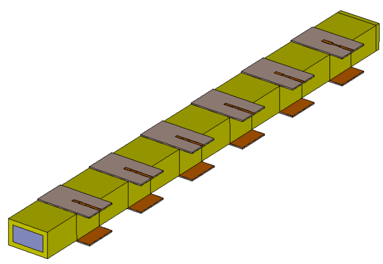


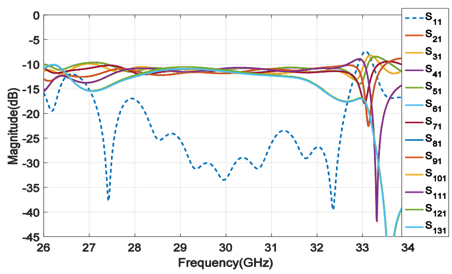


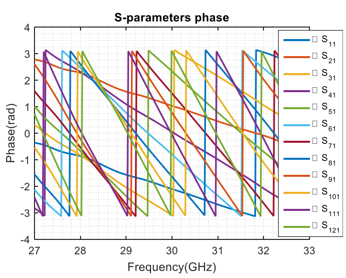
Ka-band power combiner

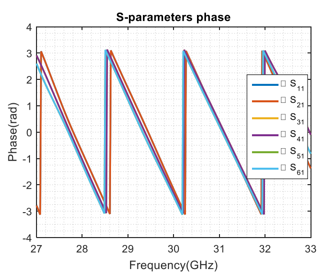




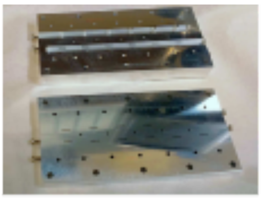


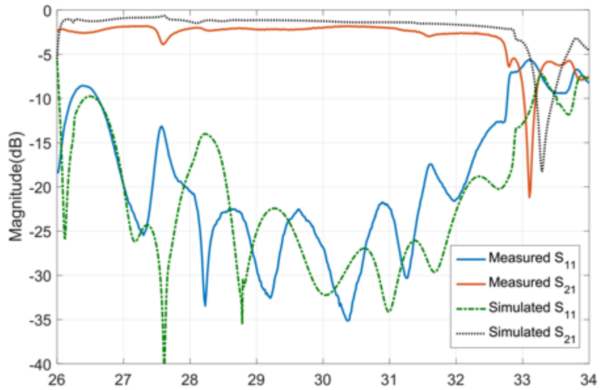


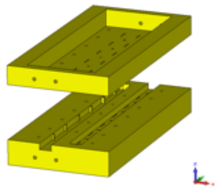




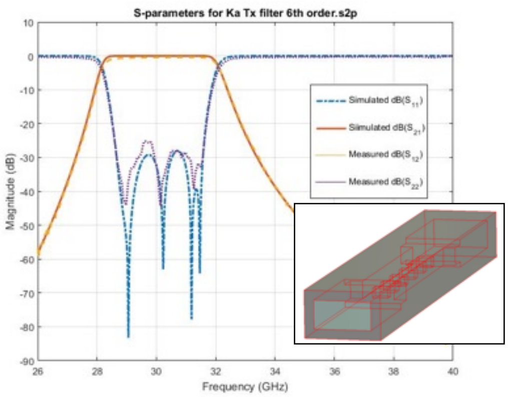
Ka-band Power combiner

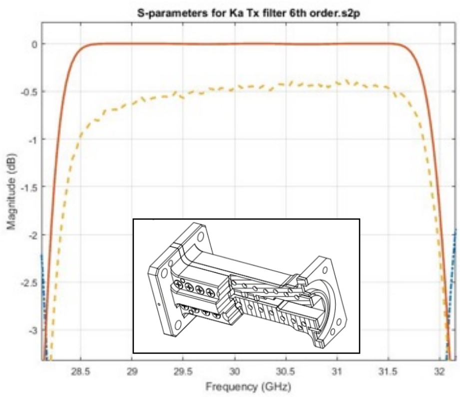


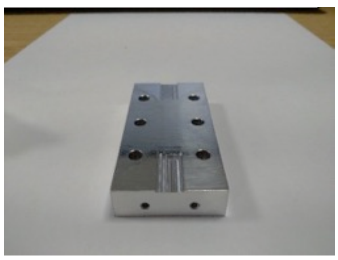




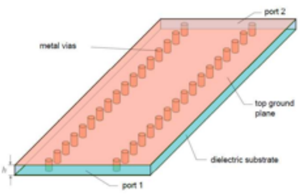
Passive components: Ka-band Waveguide Filter

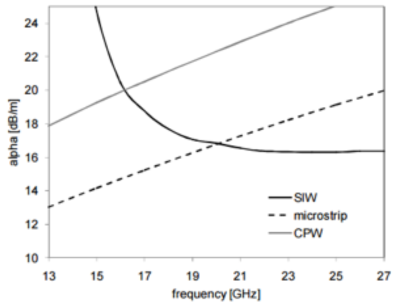


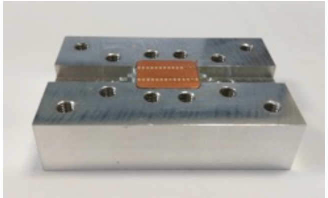


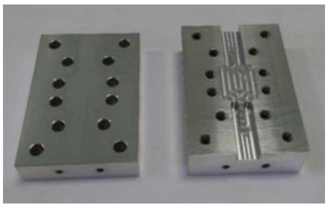


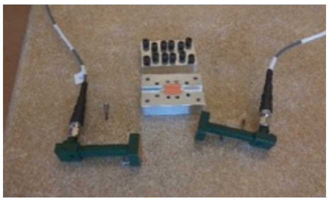
Packaging

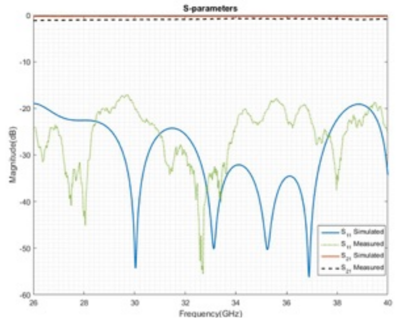


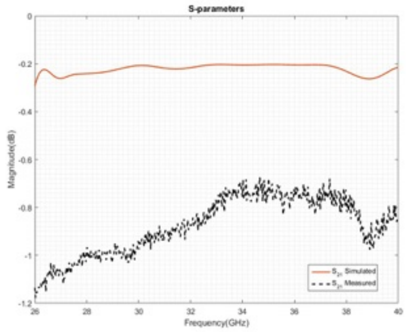




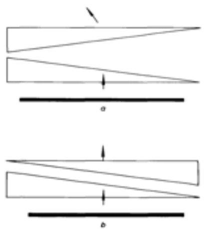








Innovative antenna solutions



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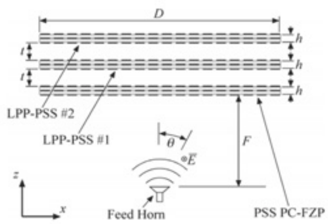

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