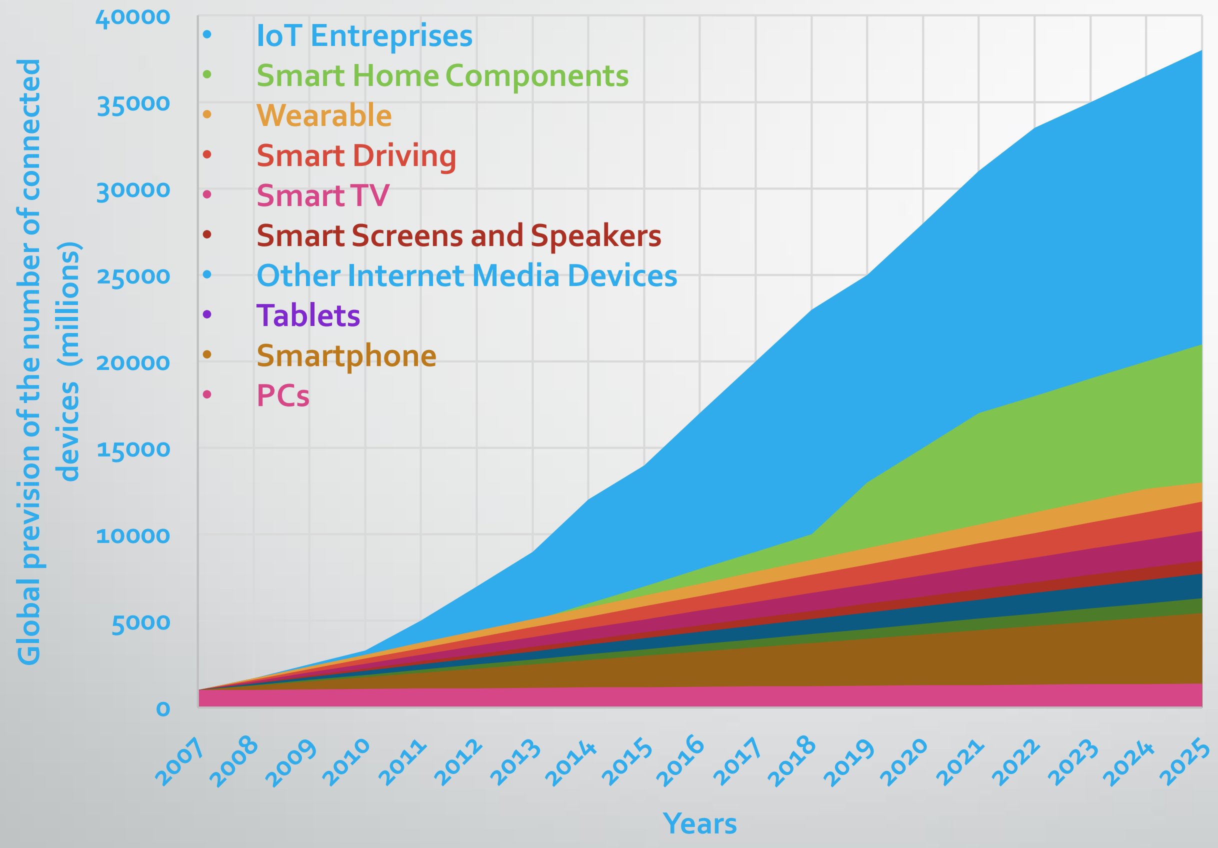
Mm-wave Antenna-System Designs dedicated to high-data rate communications

Cyril Luxey

Polytech'Lab,
University Nice Sophia Antipolis, FRANCE

Context of our research work

The future needs of the global mobile data traffic induces the massive arrival of new connected devices



Consequences

The global mobile data traffic will rise to 600 exabyte/month in 2025

Challenge

Develop wireless links targeting high data rates communications

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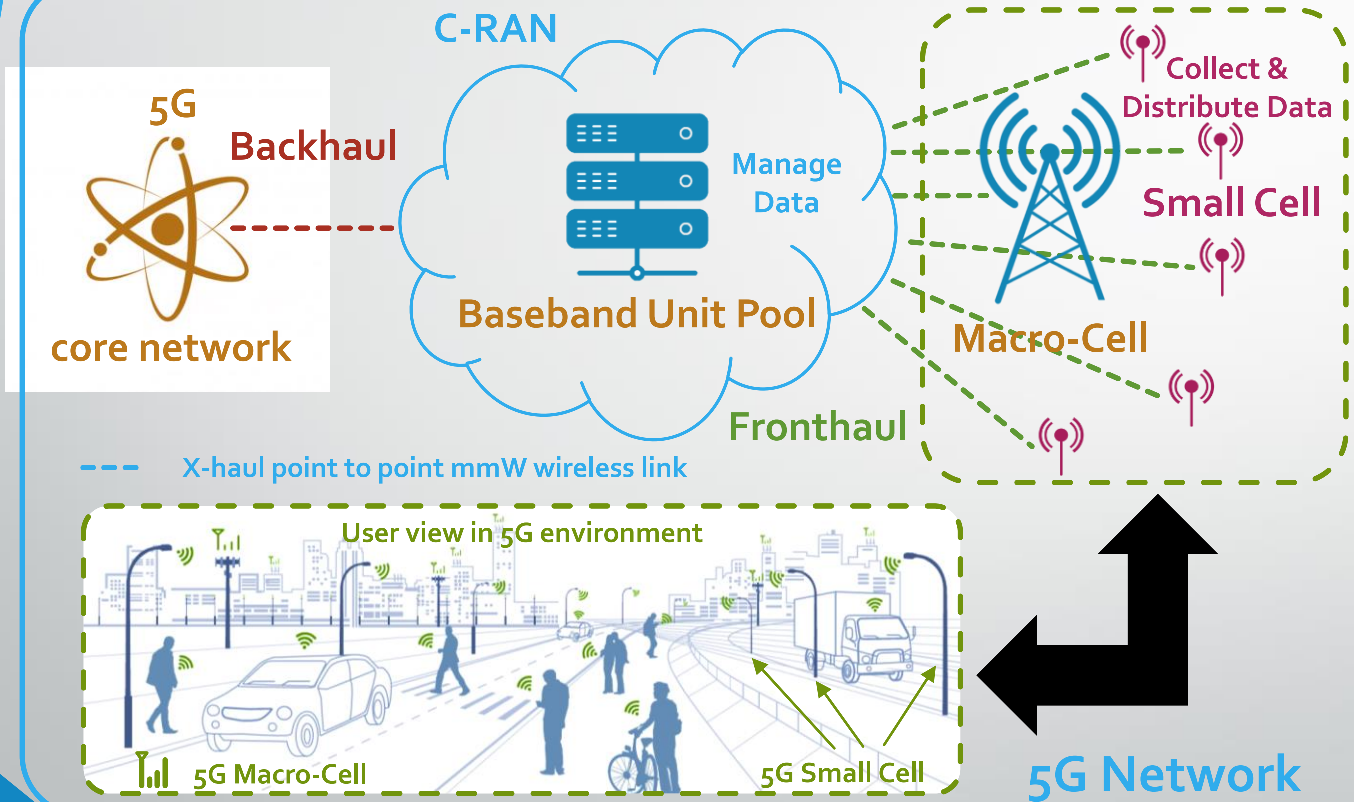
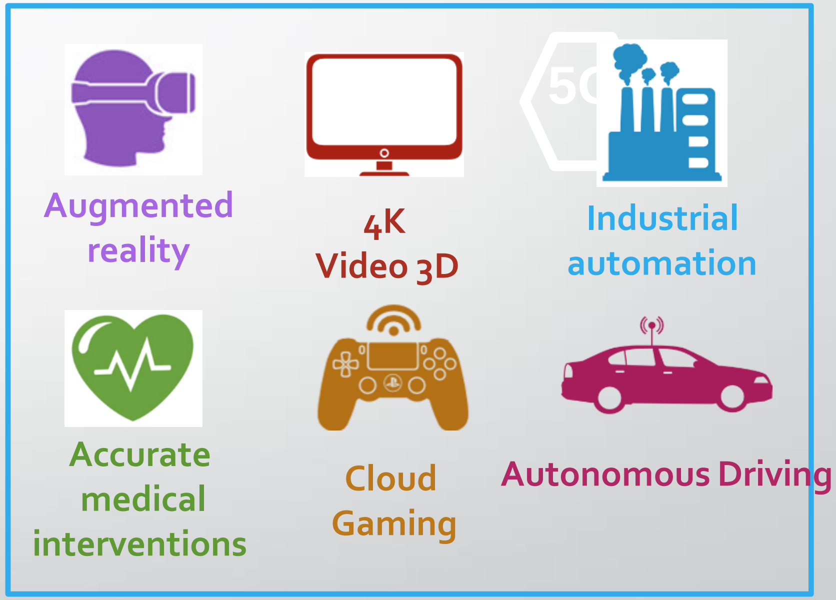
Context of our research work

To address this data challenge a progressive 5G roll out is being planned by telecom industries since the beginning of 2020



5G Network

5G Applications



Data rate up to 10 Gbit/s peak for the users
Data rate up to 40 Gbit/s for the BST

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POLYTECH NICE-SOPHIA POLYTECH'LAB

Context of our research work

In order to support the 5G network and applications roll out, our research work, since 2010, has been concentrated on two main applications:

- Communications between small devices over few meters for kiosk downloading or docking stations wireless links

→ WiGig (60 GHz), D-band (120 GHz) and Sub-THz (200-300 GHz)

- Backhaul and fronthaul communications

→ **Mm-wave and THz point-to-point wireless links targeting 40 Gbit/s**

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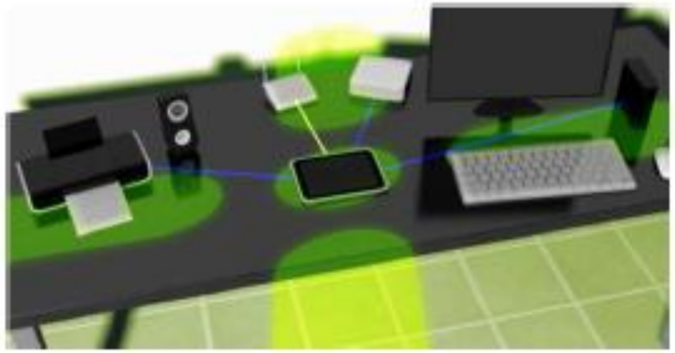
Context of our research work

- Since *data consumption* is going *higher* and higher, short distance (< 3m) *high speed wireless* solution is a *key differentiator* (cable replacement):

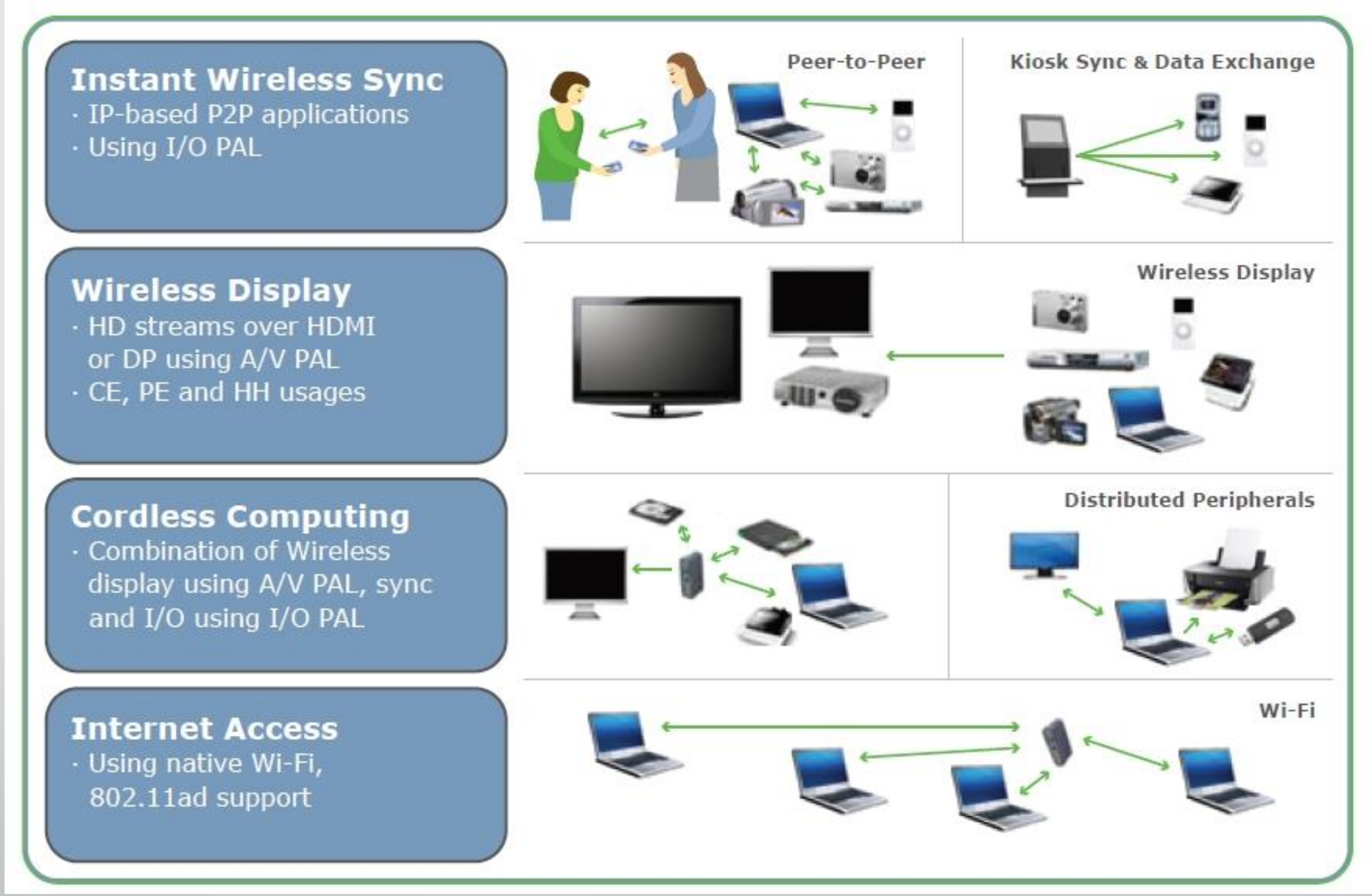
Short distance ad hoc link:



http://www.theverge.com/2013/1/14/3875308/wigig-gets-official-standards-for-short-range-high-speed-wireless

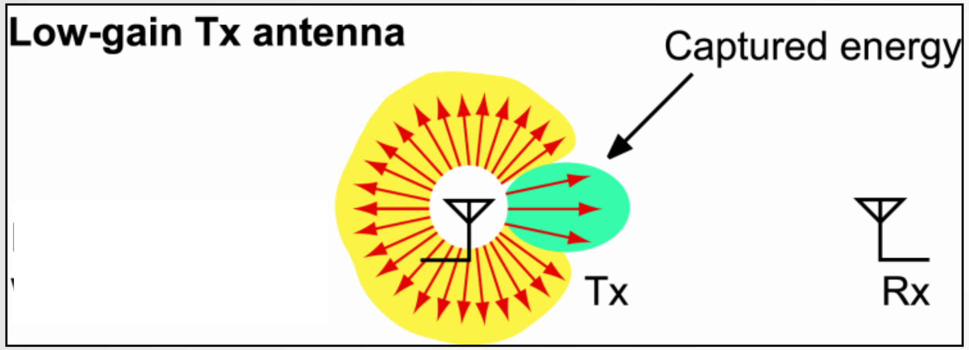
Cloud based Sync. & delivery services:

Context of our research work

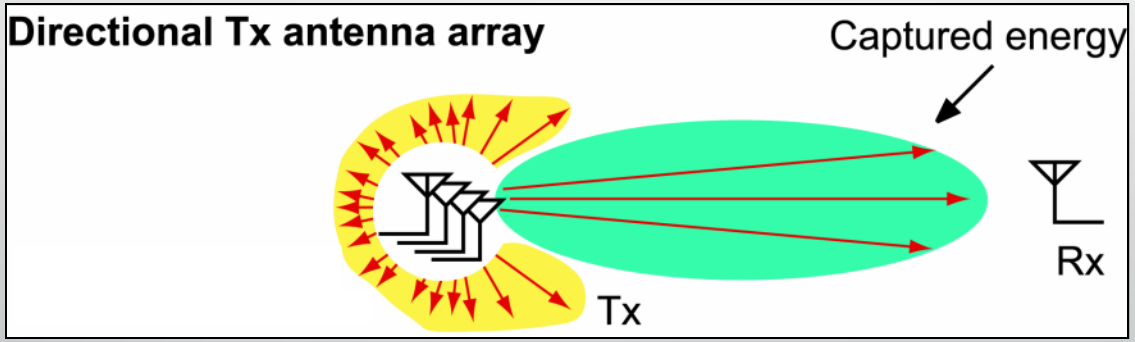


Context of our research work

Line-of-Sight communications (1m to 2m) → **5-dBi gain antenna**

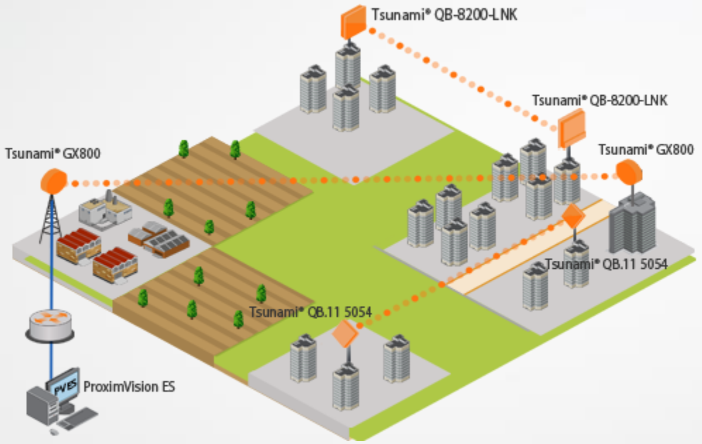


Line-of-Sight communications (2 to 5m) → **10-dBi gain antenna** → Antenna array



Context of our research work

Challenge of Wireless backhaul / fronthaul networks

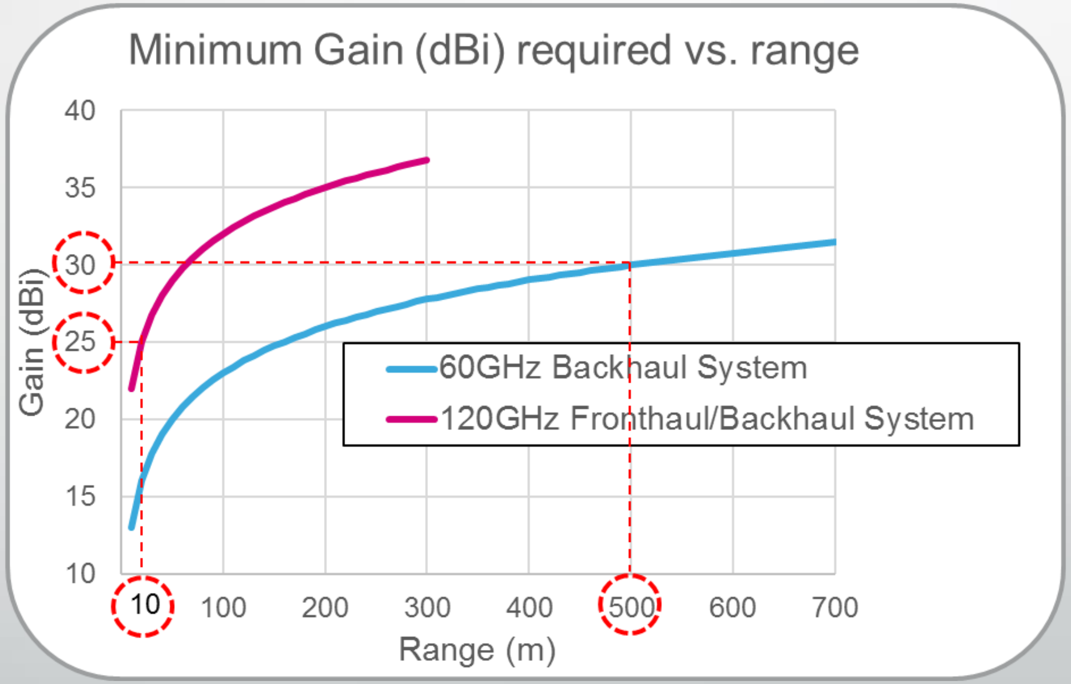


- Densification of the network (Smalls cells x 10) implies a strong pressure on backhaul links.
- 2 solutions:
  - Optics fibers installation is too expensive and cannot be set everywhere.
  - Point-to-point mmW wireless link is the most attractive solution.
- R&D at D Band (110 - 140 GHz): wide bandwidth (> 20 GHz) → 20 Gbit/s
- Sub-THz frequencies could enable wider bandwidth & higher data rates → 40 Gbit/s

Context of our research work

- 60/120GHz High Gain Antenna Specifications

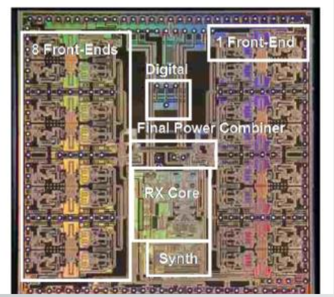
- Since the output power level is limited, the transmission range of the system mainly depends on the *gain of the antenna*.



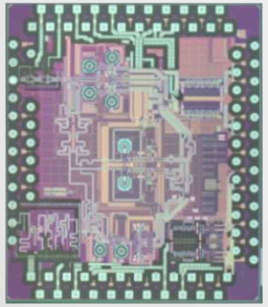
Context of our research work

- Our research work investigated silicon-based technical solutions
- Several *chipset* solutions demonstrated the possibility to use *silicon technology* to address mm-Wave high-data rate transmissions

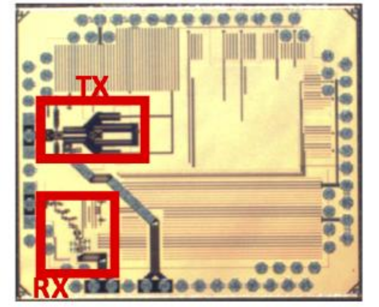
IBM / Mediatek



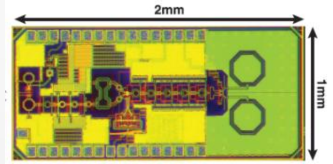
ST



Stanford



Berkeley



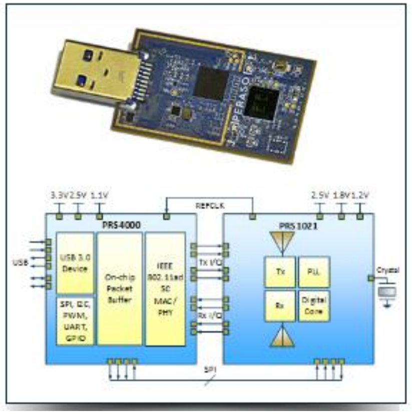
V-band	D/F-band	J-band
57-66 GHz	120-140 GHz	200-280 GHz
15%	15%	34%
1-5 Gbps	**10 Gbps**	**40 Gbps**

- *The main challenge* concerns *an efficient Circuit/Antenna combination*
  - ✓ Low-loss mmW packaging technology
  - ✓ Low-cost mmW packaging technology
  - ✓ Assembly strategy compliant with industrial constraints

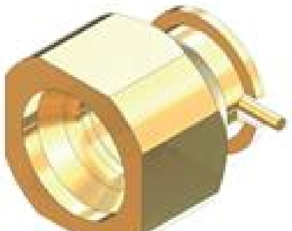
Context of our research work

- For example, the availability of cost-effective silicon mmW chipsets will not be enough in order to reduce the cost of backhaul / fronthaul links

60 GHz BiCMOS chipset ~5$
Peraso PRS1021 (>100 000 parts)



SMPM connector ~15$
67 GHz board connector



V band antenna ~1000$

- So, low-cost high-gain mmW antenna solution is a key enabler in order to support the development of cost effective backhaul/fronthaul links that can leverage the integration capability and cost effectiveness of silicon technologies.

Outline

- SoC or SiP IC/Antenna integration scheme ?
- Low-Gain Antennas in organic packaging technology
- Antenna integration strategies: current status
- High-Gain Antennas in organic packaging & 3D printing technologies
- 10 Gb/s Low-energy point-to-point demo at 120 GHz
- Perspectives
- Conclusion

SoC or SiP IC/Antenna integration scheme ?

- Integrating *60 GHz mm-wave antennas on chip* was the first idea but …

… antennas integrated on *standard or high-end Si CMOS process* (SoC approach) exhibited *poor gain*, clearly not in line with WiGig transmission over few meters (above 5 dBi)

Substrate	Reference	Process	Antenna Type	Gain (dBi)	Size
Low-Resistivity Silicon	**[2]**	Silicon	IFA	-19	2 mm long
	[2]	Silicon	Quasi Yagi	-12.5	1.3 mm long
	[3]	0.18-µm CMOS	Yagi	-10.6	1.1 x 0.95 mm²
	[4]	0.18-µm CMOS	IFA	-15.6	0.28 x 0.27 mm²
	[5]	0.18-µm CMOS	Triangular Monopole	-9.4	1 x 0.81 mm²
	ST/UNS	0.13-µm CMOS	IFA	-2.7	1 x 1 mm²
	ST/UNS	0.13-µm CMOS	Dipole	-7.9	1 x1 mm²
High-Resistivity Silicon	**[6]**	0.15-µm pHEMT	Dipole	3.6	0.9 mm²
	[7]	0.18-µm CMOS	Loop with AMC	4.4	1.8 x 1.8 mm²
	[8]	0.13-µm HR SOI	Double Slot	-5.5	1.2 mm long
	[9]	0.13-µm HR SOI	Interdigitated Dipole	3	NA
	ST/UNS	HR SOI	Folded Slot	3.9	0.8 x 1.7 mm²

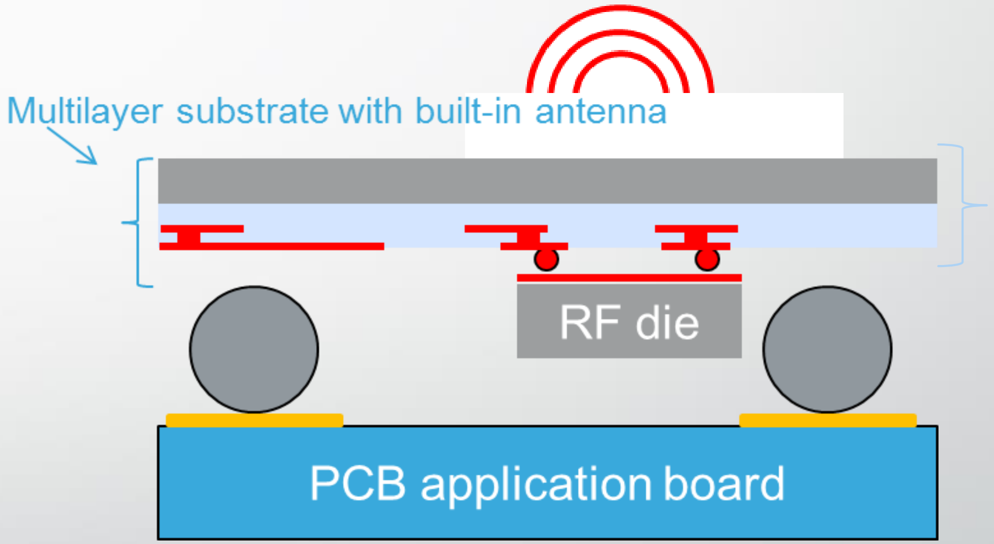
[2] Zhang et al., 2005
[3] Hsu et al., 2008
[4] Guo et al., 2008
[5] Lin et al. 2007
[6] Chen et al., 2009
[7] Bao et al., 2012
[8] Barakat et al., 2011
[9] Barakat et al., 2010

SoC or SiP IC/Antenna integration scheme ?

- *System-in-Package* approach naturally emerged as the solution

Example of a 60 GHz Antenna-in-Package

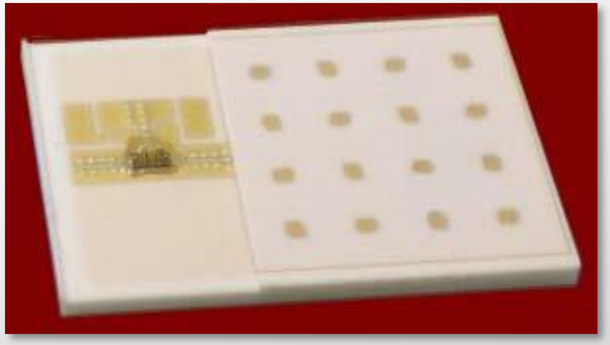
- *Low profile package*
- *Multi-layer build-up*
- *Aperture coupled-Patch Antenna*



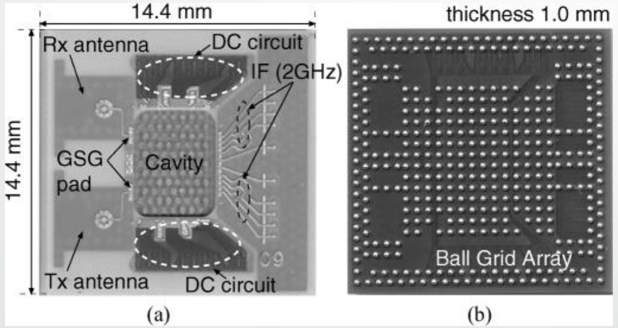
SiP or SoC integration scheme ?

- Mainstream technologies for SiP were glass and multi-layer co-fired ceramics substrates (Low or High Temperature)

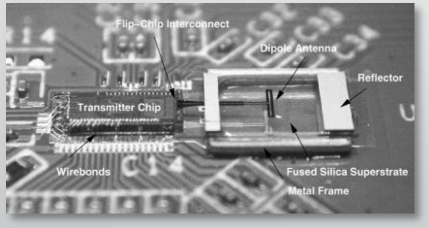
I2R - LTCC



Tokyo Institute of Tech



IBM
Glass Substrate



IBM
Laminated packages

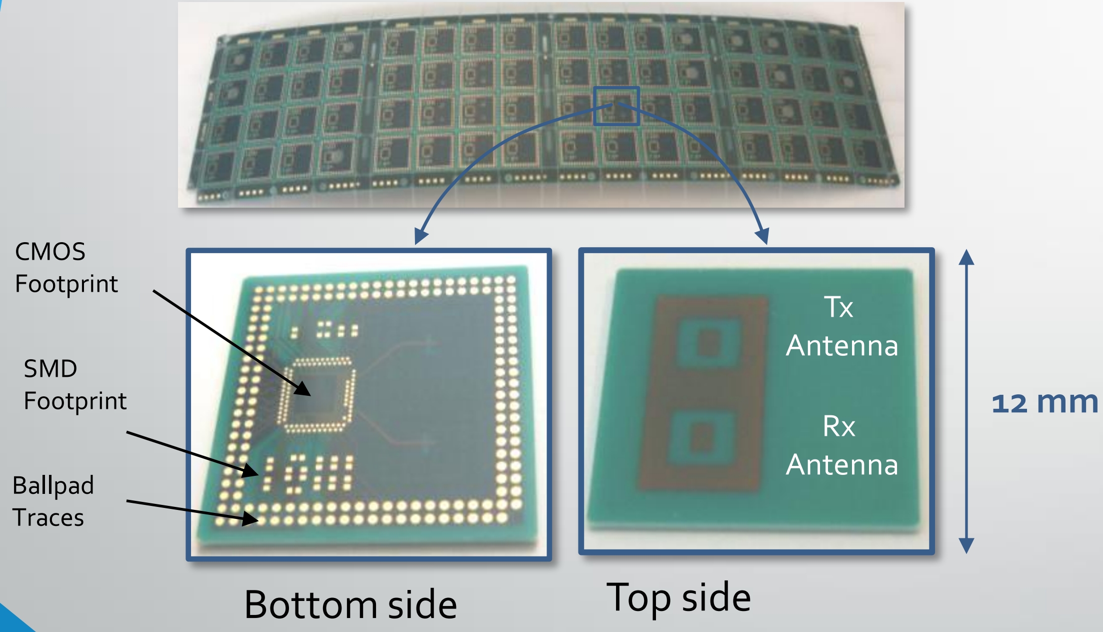
Low-Gain Antennas in organic packaging tech.

- We had to *identify* the appropriate *packaging technology* to support the development of *60 GHz modules* as possible commercial products
- We deeply investigated:
  - HTCC/LTCC
  - Organic Ball-Grid-Array module

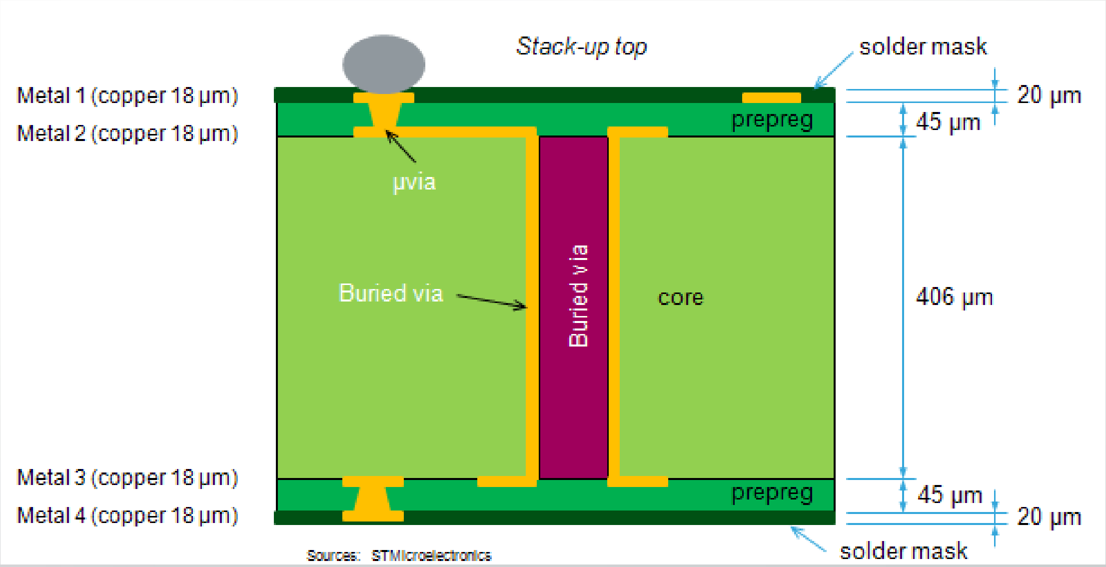
Technology	Design Rules (min width/min space)	Cost
HTCC/LTCC	~100 µm/~100 µm	-
Organic BGA	~35 µm/~35 µm	+

Low-Gain Antennas in organic packaging tech.

- *We* developed a *low-cost* organic *millimeter-wave High-Density Integration (HDI)* packaging *technology*

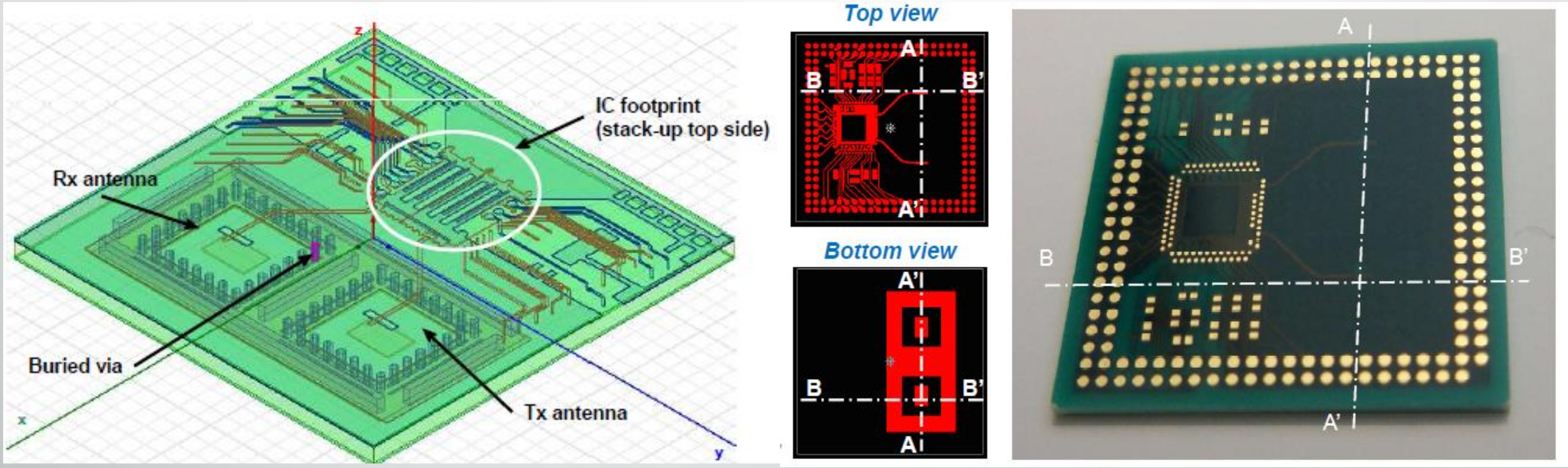


1 prepreg +2 cores +1 prepreg



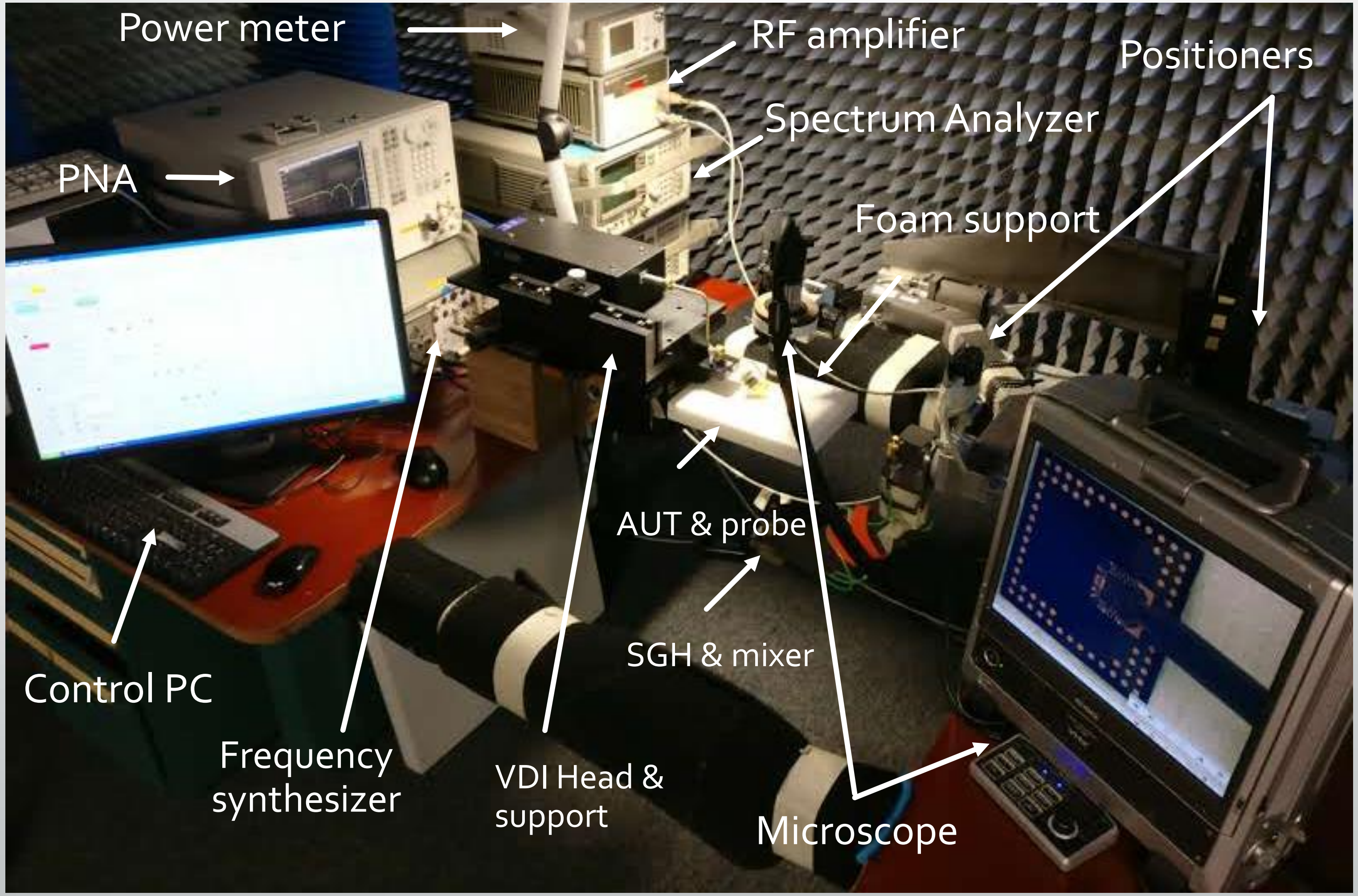
[11] R. Pilard et al., "HDI Organic Technology Integrating Built-In Antennas Dedicated to 60 GHz SiP Solution", IEEE AP-S 2012

Low-Gain Antennas in organic packaging tech.



Low-Gain Antennas in organic packaging tech.

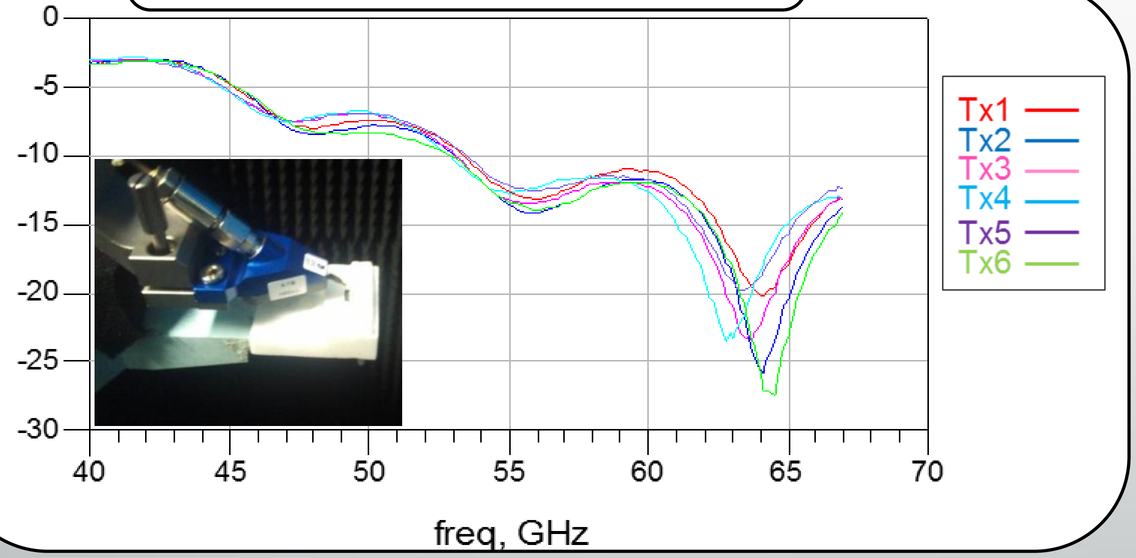
The start of our collaboration with ST was a very good example of *cross-cultural development with the microelectronics world* leveraging both *antenna* & *circuit* communities' *expertise*



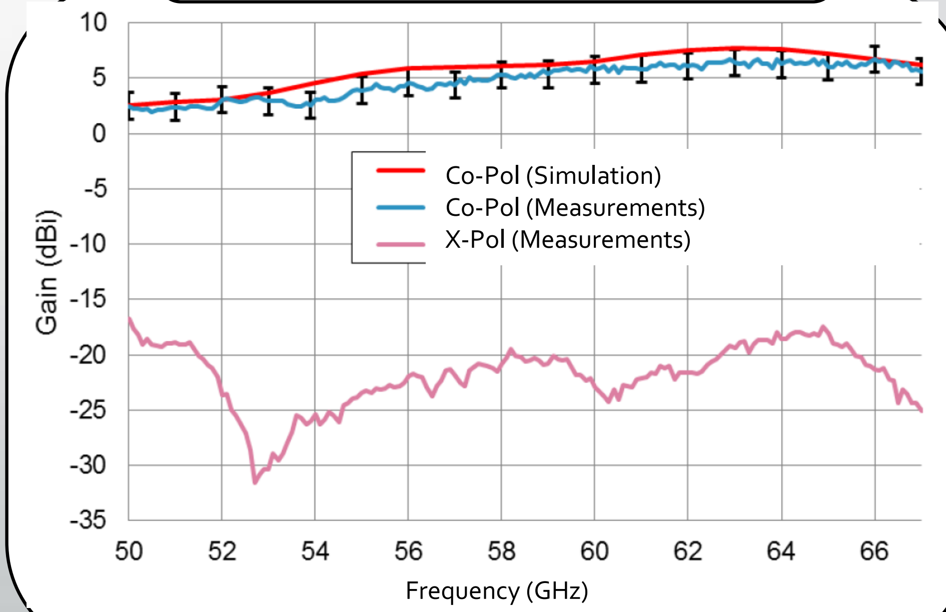
Low-Gain Antennas in organic packaging tech.

- Several modules from *different suppliers* were fabricated and measured showing successful reproducibility tests
- *Antenna performance* were fully *in line* with the 5 dBi Gain *requirement*

S_{11} MATCHING BW
53 GHz – 67 GHz @ -10 dB

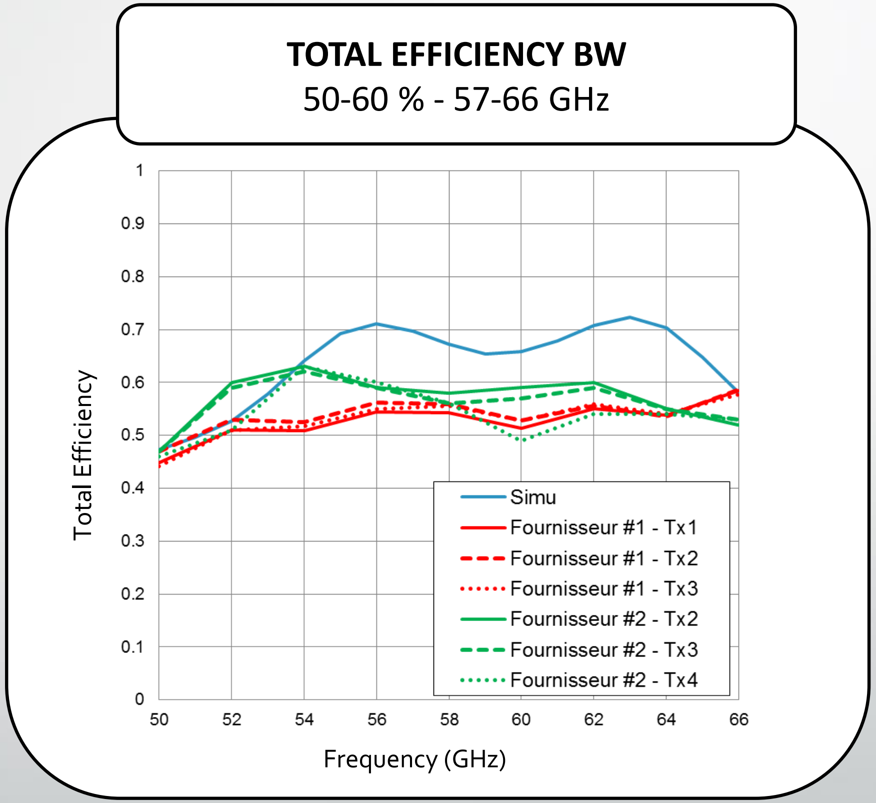


BROADSIDE GAIN BW (> 5 dBi)
57 GHz - 67 GHz



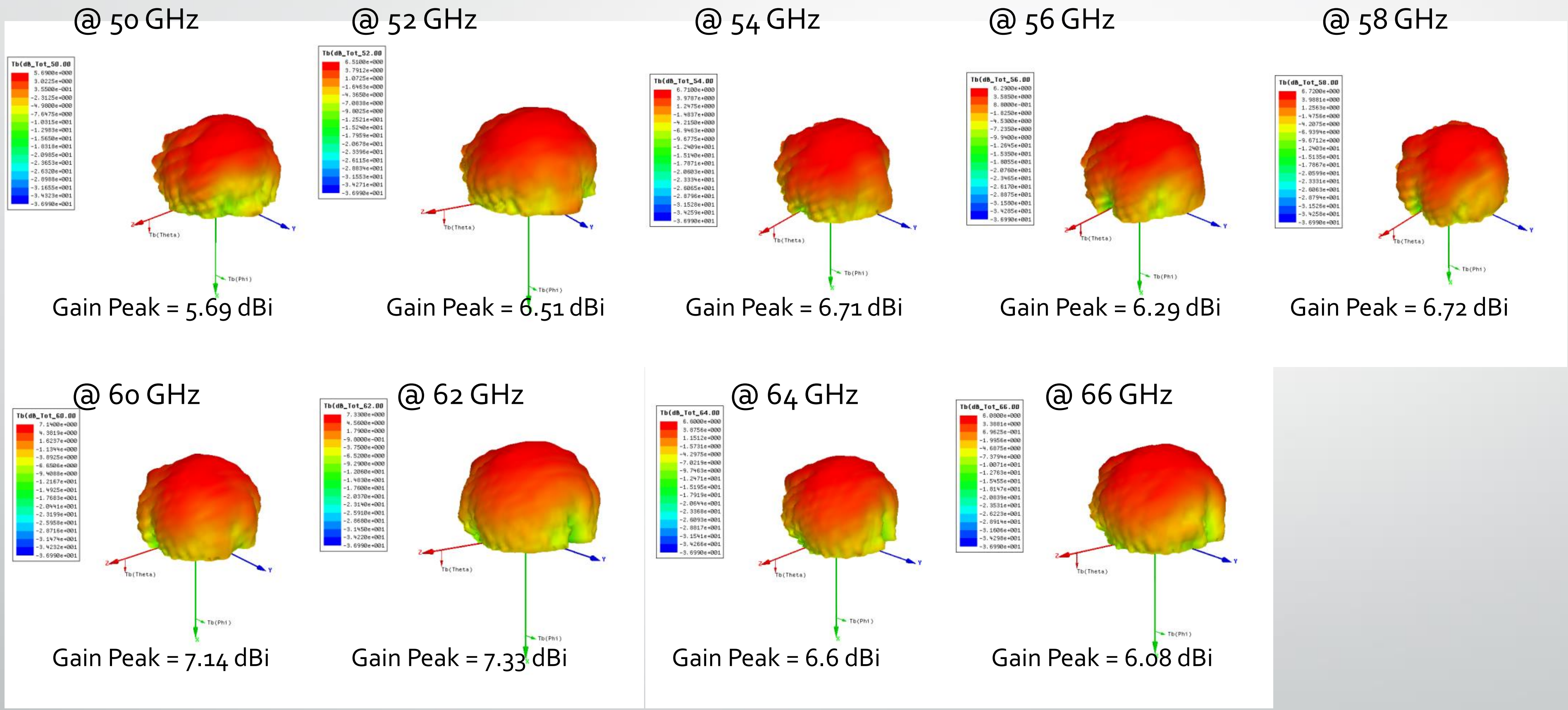
Low-Gain Antennas in organic packaging tech.

- *Organic BGA technology* seems to be the *best compromise between cost/performance/assembly*



Low-Gain Antennas in organic packaging tech.

Total Realized Gains (dBi) – 3D plots



Low-Gain Antennas in organic packaging tech.

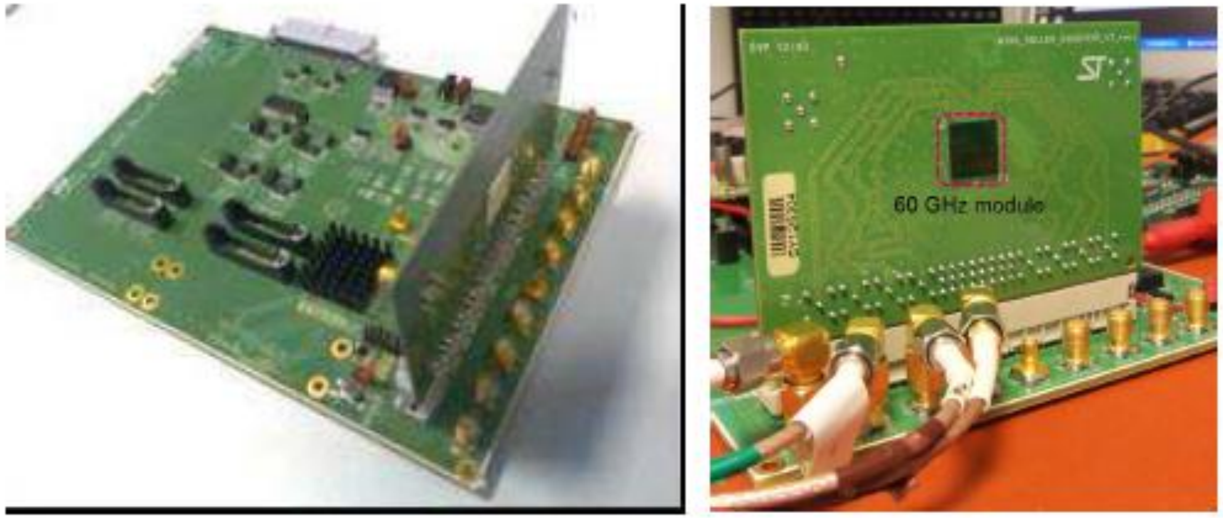


Fig. 8 Low cost 60GHz WiGIG board with Digital Baseband

16 QAM – OFDM
➔ 3.8 Gbps over 1m

SNR around 15 dB

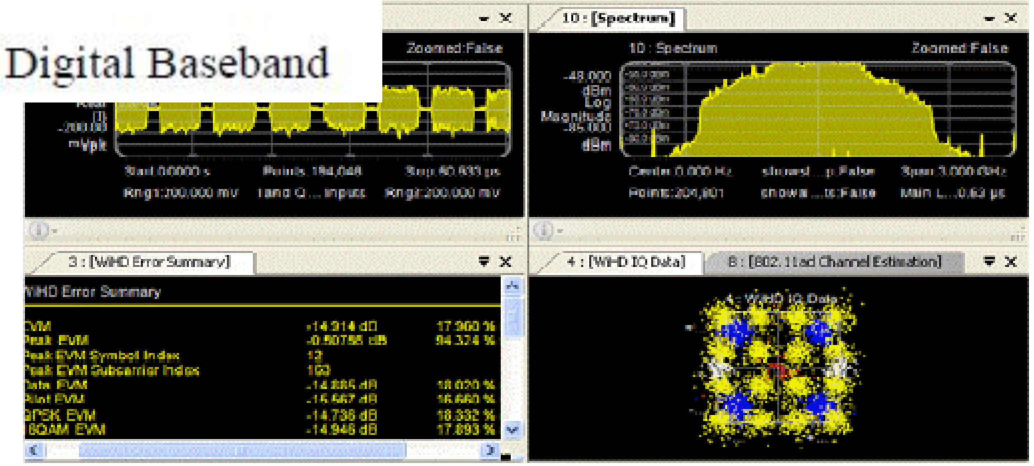
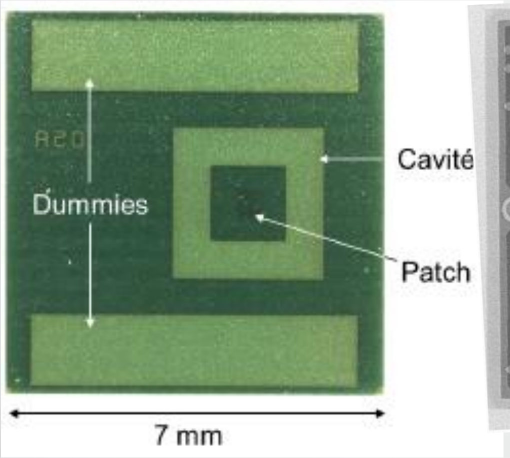
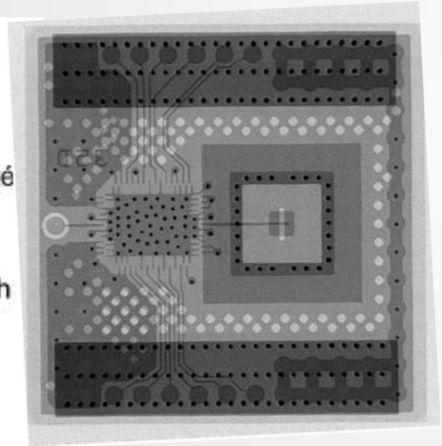


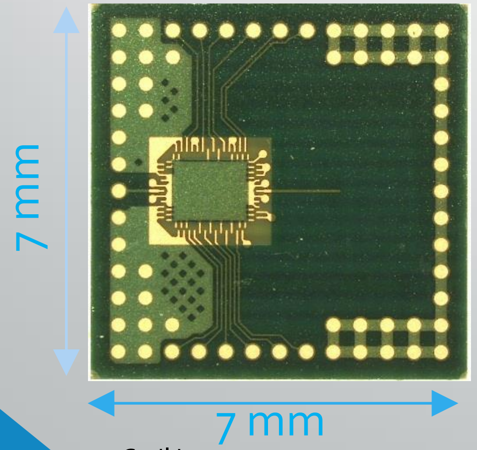
Fig. 9 Measured constellations after demodulation in the HRP2 mode (OFDM-16QAM modulation) with Agilent tools.

Low-Gain Antennas in organic packaging tech.

- 120 GHz organic module for high-data rate links: Single Element







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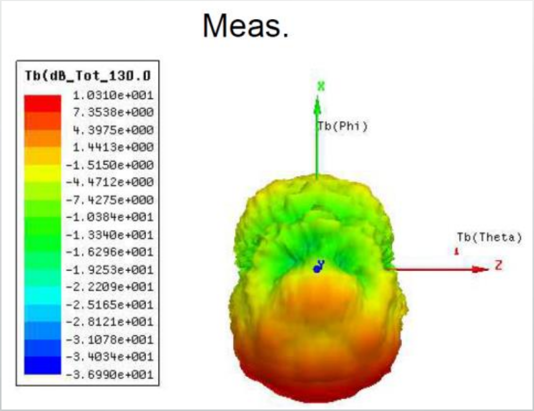
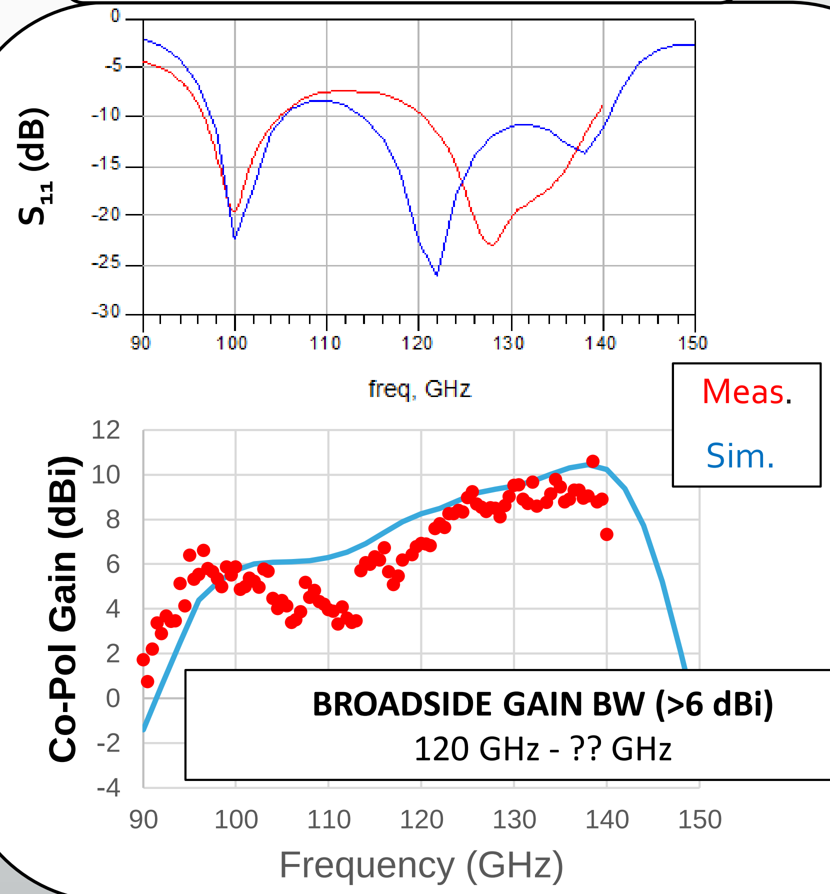


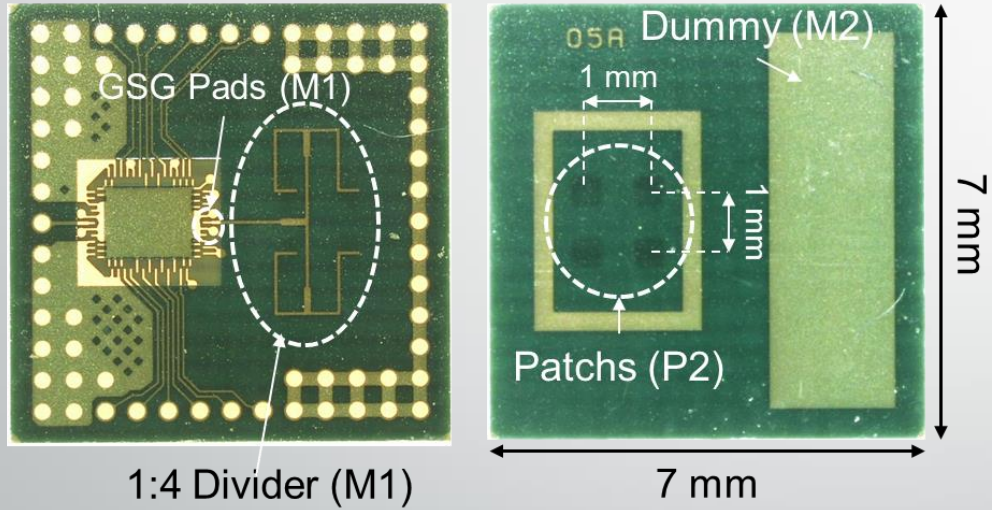
S_{11} MATCHING BW
120 GHz–138 GHz @ -10 dB

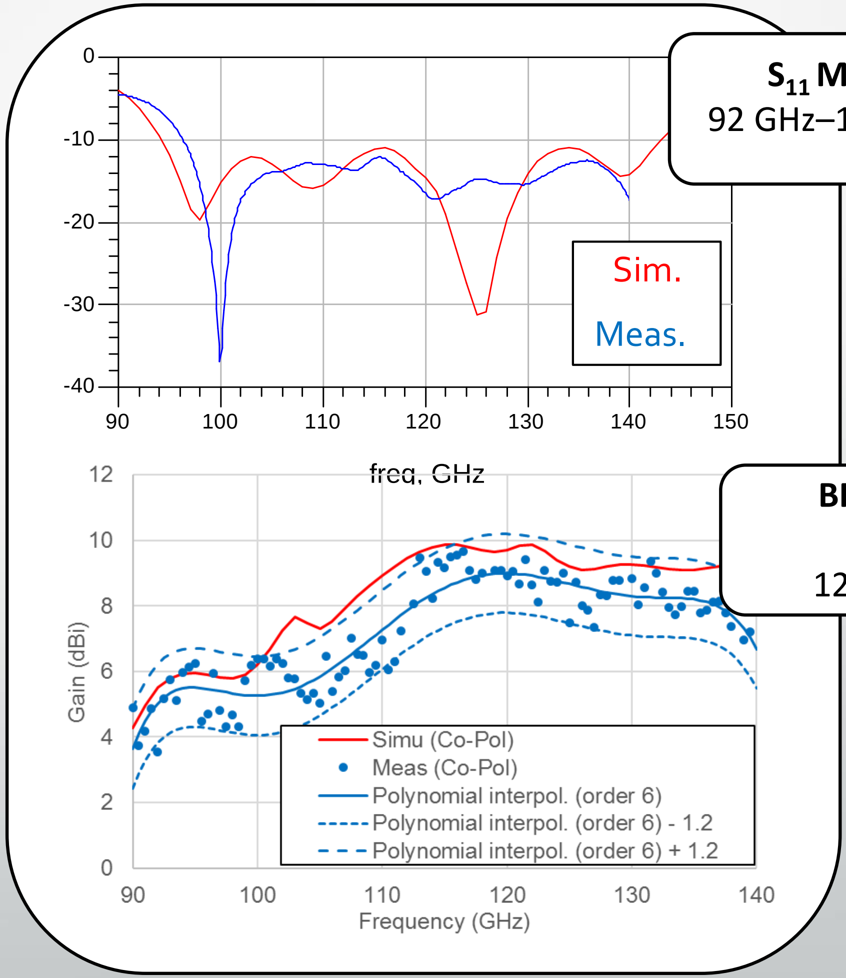


BROADSIDE GAIN BW (>6 dBi)
120 GHz - ?? GHz

Low-Gain Antennas in organic packaging tech.

- 120 GHz organic module for high-data rate links: 2x2 Array of patches





S_{11} MATCHING BW
92 GHz–140 GHz @ -10 dB

BROADSIDE GAIN BW (>8 dBi)
120 GHz - 140 GHz

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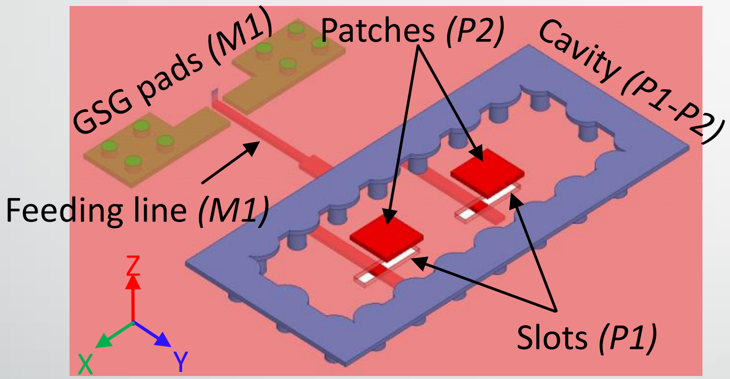
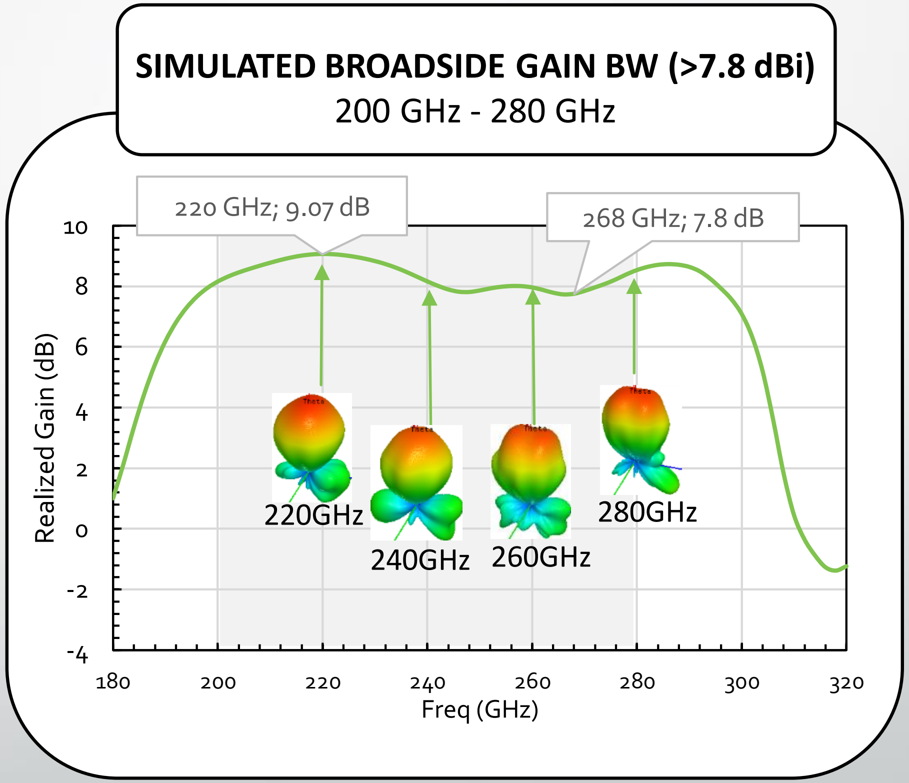
Low-Gain Antennas in organic packaging tech.

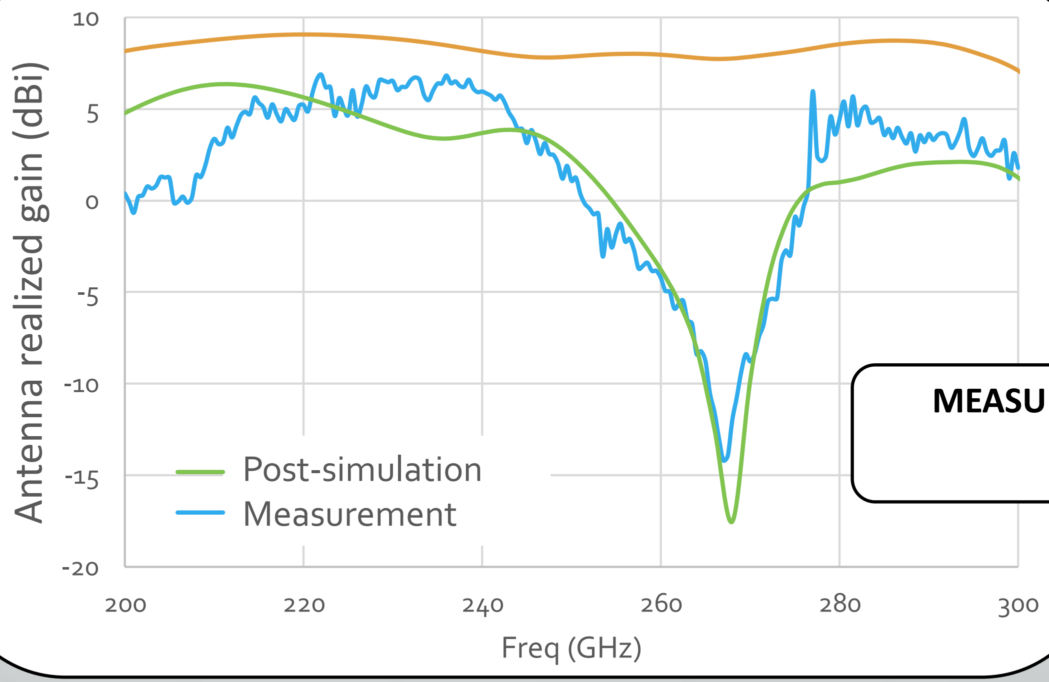
- 240 GHz organic module for high-data rate links: 1x2 Array





Low-Gain Antennas in organic packaging tech.

- 240 GHz organic module for high-data rate links: 1x2 Array



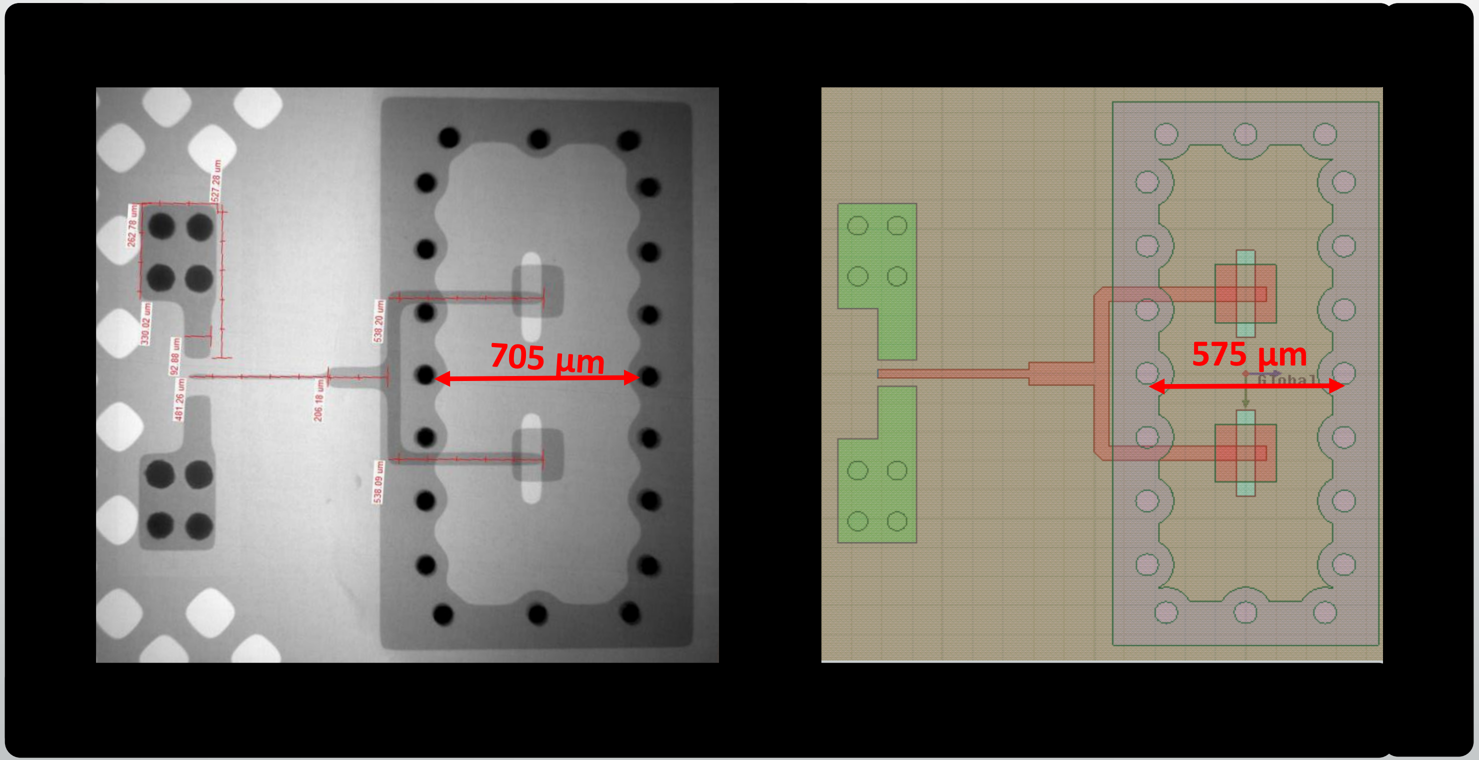
MEASURED BROADSIDE GAIN BW (>5 dBi)
220 GHz - 245 GHz

Low-Gain Antennas in organic packaging tech.

- 240 GHz organic module for high-data rate links: 1x2 Array

Manufactured design ≠ Simulated design

→ We reached the limitations of this technology in terms of drawing rules at 300 GHz

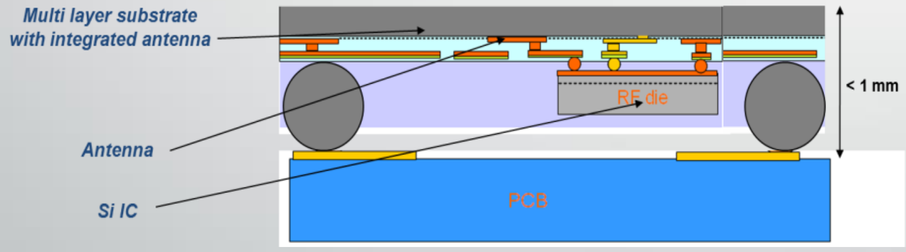


Antenna Integration Strategies:current status

- Today, two industrial integration schemes can be considered for the antenna solution:
  - Antenna-in-Package: targeting high integration level and high performance
  - Antenna-on-board: in order to enable antenna customization according to the use-case of the customer → **HDI PCB or even recently FR4 PCB**

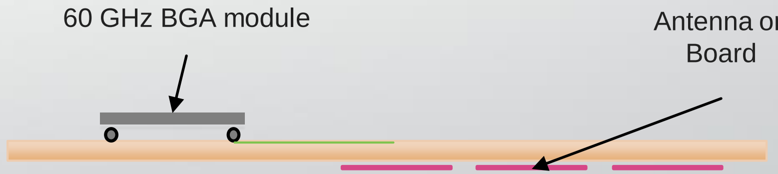
Antenna-in-Package

- Antenna Gain: from 5 to 10 dBi



Antenna-on-Board

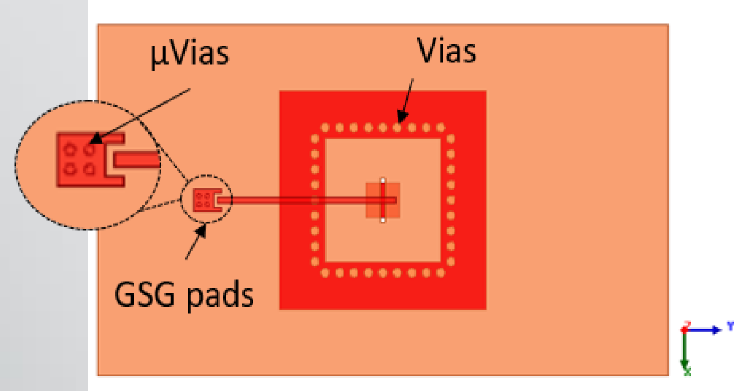
- Antenna Gain: from 5 dBi to 10 dBi

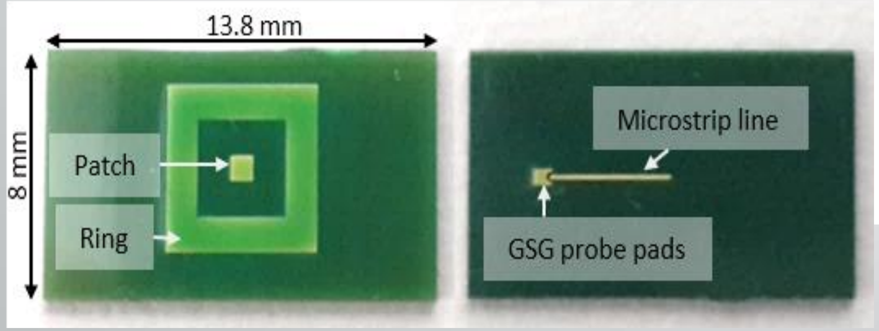


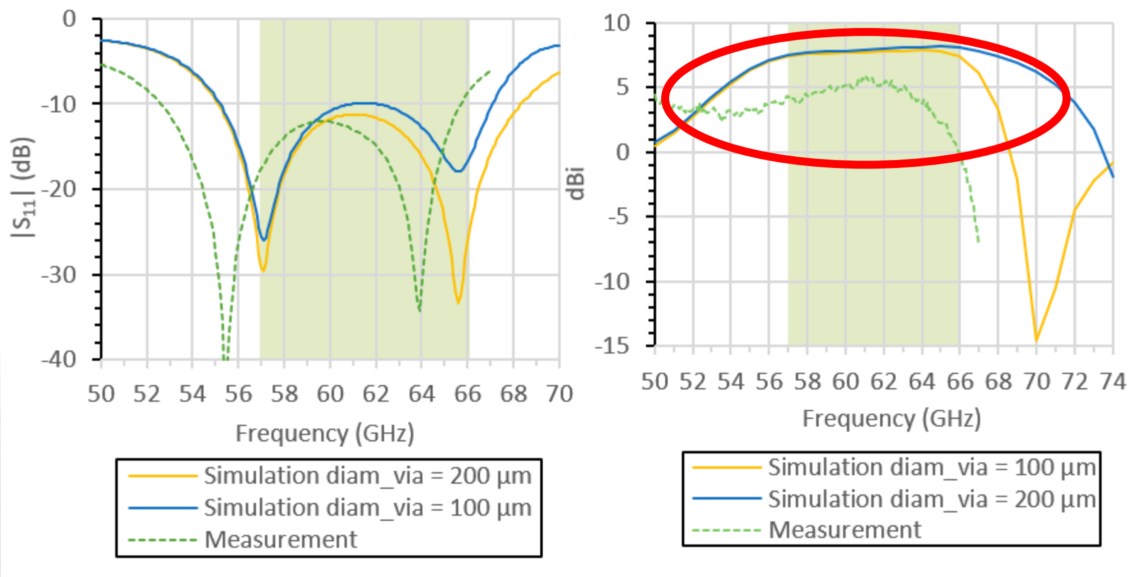
Antenna Integration Strategies:current status

FR4 Standard PCB Technology

- Design rules : 60 (line width) × 75 (space between lines) μm^2





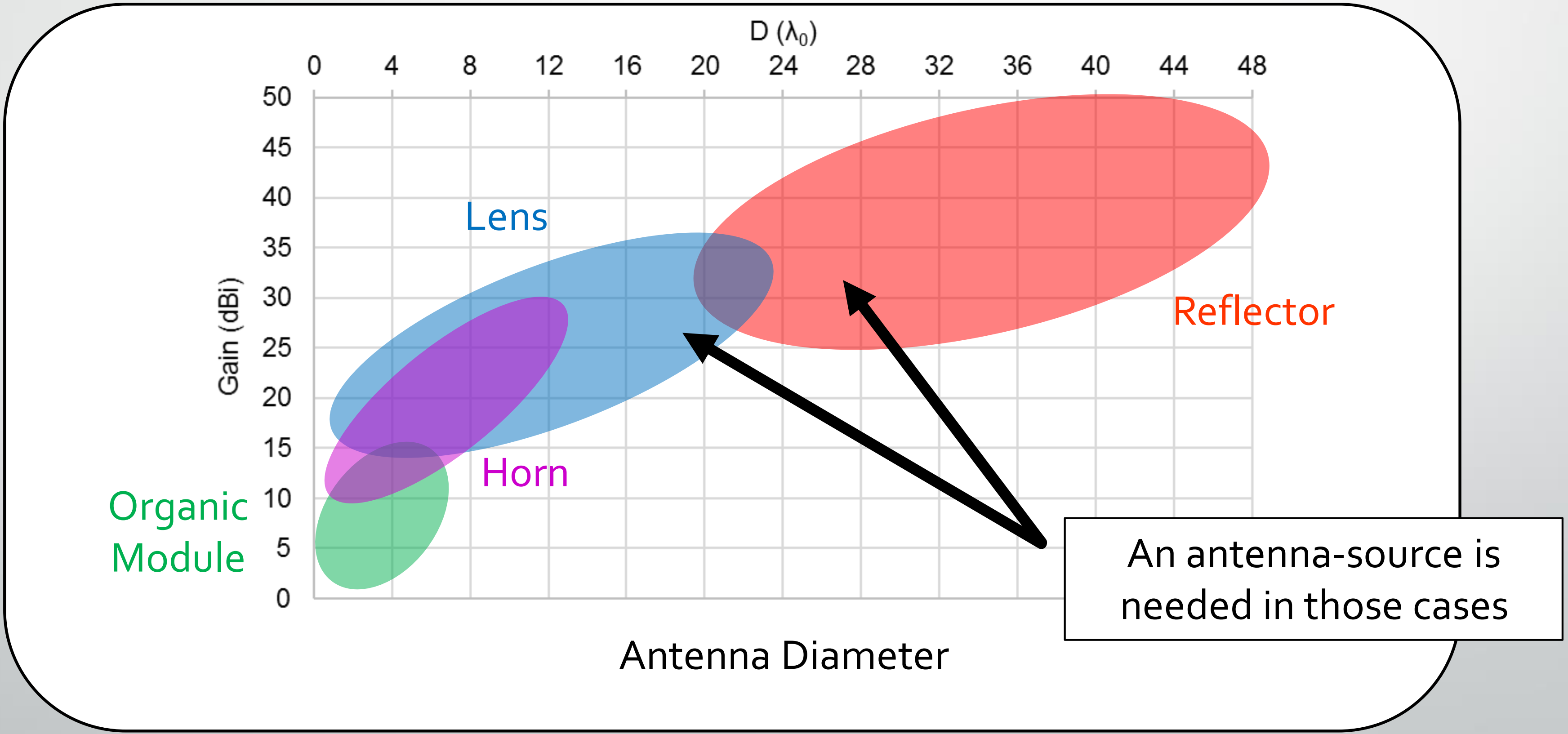


https://www.st.com/en/wireless-transceivers-mcus-and-modules/60-ghz-short-range-rf-transceivers.html

https://blog.st.com/st60/amp/

High-Gain Antennas in organic packaging & 3D printing

- The path towards high-gain antennas for backhaul and fronthaul wireless links



High-Gain Antennas in organic packaging & 3D printing

- What *about* using *3D-printing technology* to fabricate plastic lenses instead of costly Teflon approach ?

	Stereolithography	Selective Laser Sintering	Fused Deposition Modeling
Cost	Expensive	Expensive	Inexpensive
Principal	Solidifies liquid resin	Sinters powdered material	Molten plastic deposition
Surface finishing	smooth	Slightly granular	Rough (dented)
Z axis resolution	Up to 5 µm	Up to 20 µm	Up to 100 µm
XY plane resolution	Up to 30 µm	Up to 300 µm	Up to 200 µm

- Plastic lens fabricated in Fused Deposition Modeling (FDM) :
  - Standard ABS plastic (ε_r = ???)

ε_r and tan δ of the ABS-M30 at 60GHz, 120, 240 GHz ?

High-Gain Antennas in organic packaging & 3D printing

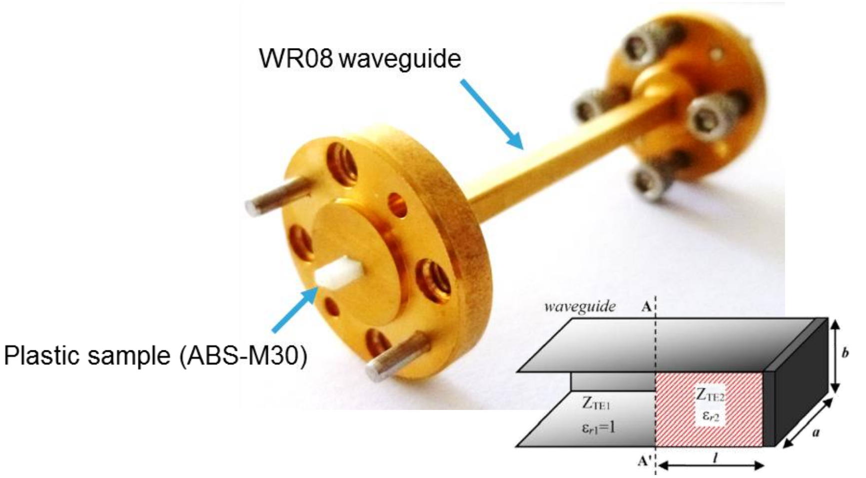
Fabry-Perot Open Resonator at 60GHz

IST/IT lab

TÉCNICO LISBOA

[12] J. R. Costa, et al, "Compact Beam-Steerable Lens Antenna for 60-GHz Wireless Communications", *TAP*, 2009.

Non-resonant waveguide method at 120GHz

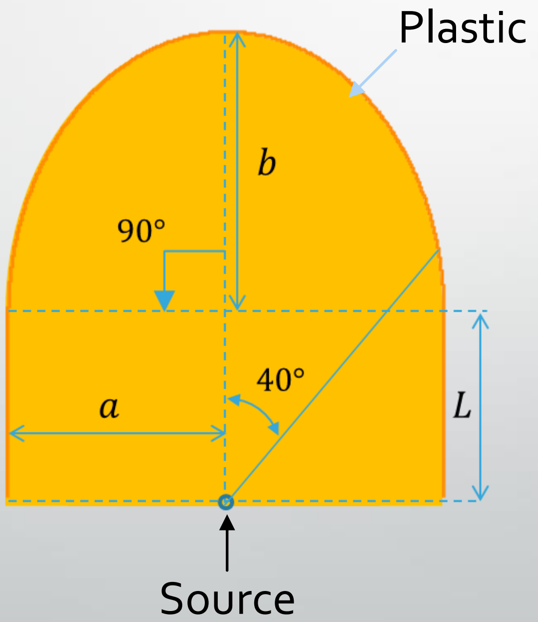


	IST/IT	esa	Our meas.	Teflon
Method	Fabry-Perot Open resonator	Quasi-optical meas. setup	Waveguide method	NA
Freq.	60GHz	137.5GHz	110-125GHz	NA
ε_r	**2.48**	**2.48**	**2.49**	2
$\tan\delta$	0.009	0.008	**0.01**	0.0002

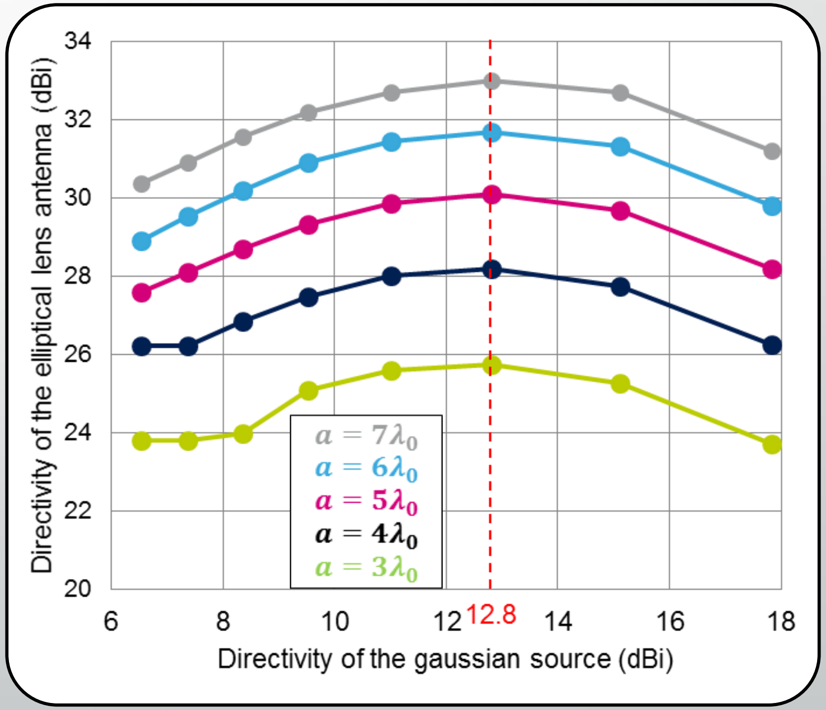
High-Gain Antennas in organic packaging & 3D printing

- In order to obtain the best performance, a *co-design* of the *source with the lens is mandatory*

Elliptical Lens Cross-section

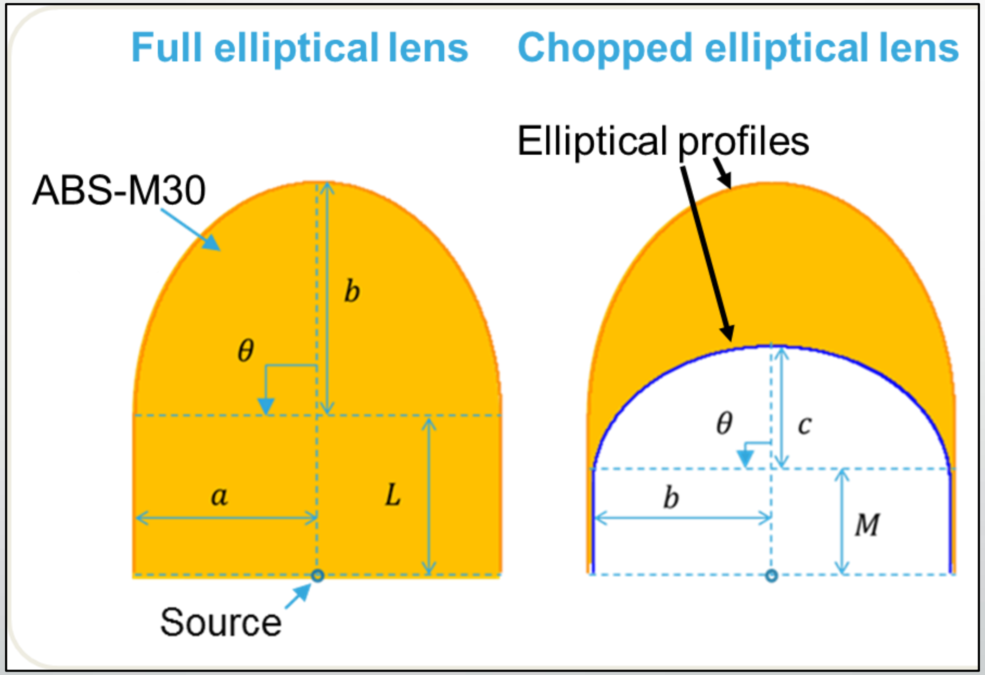


Lens directivity vs. Source directivity



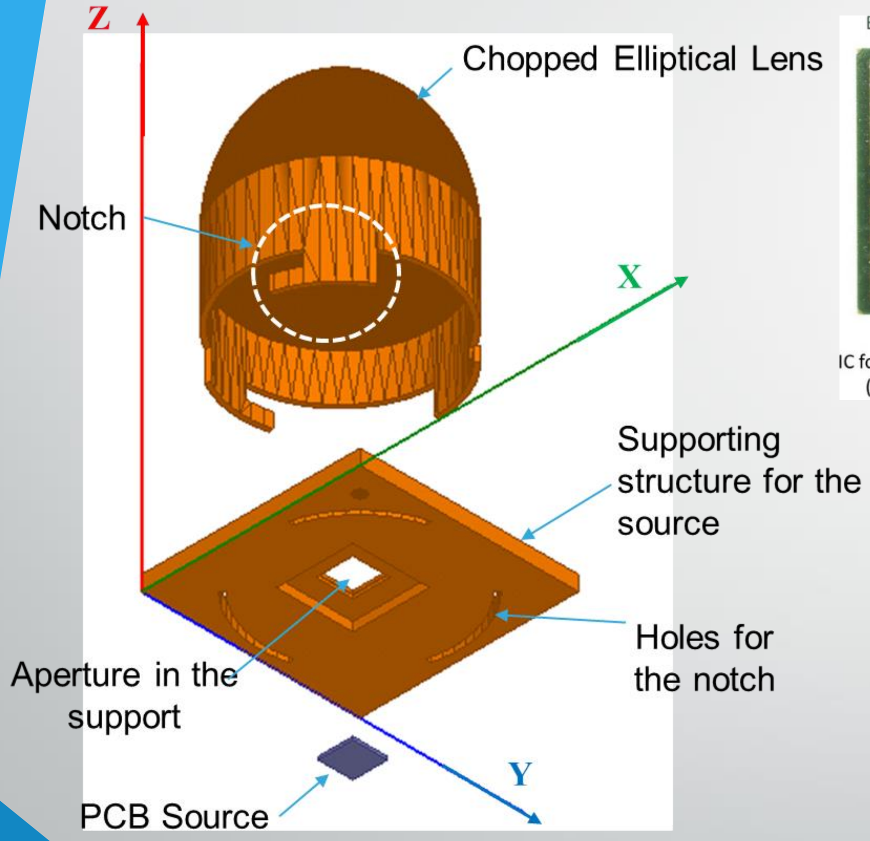
High-Gain Antennas in organic packaging & 3D printing

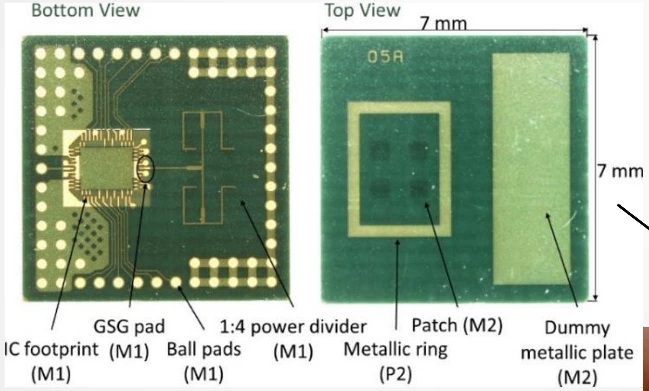
- In order to lower the *dielectric losses*, we designed a *chopped lens*
- Fast optimization using ILASH software tool (GO/PO) + HFSS full-wave verification

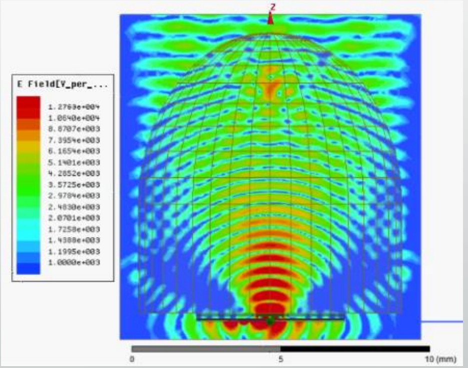


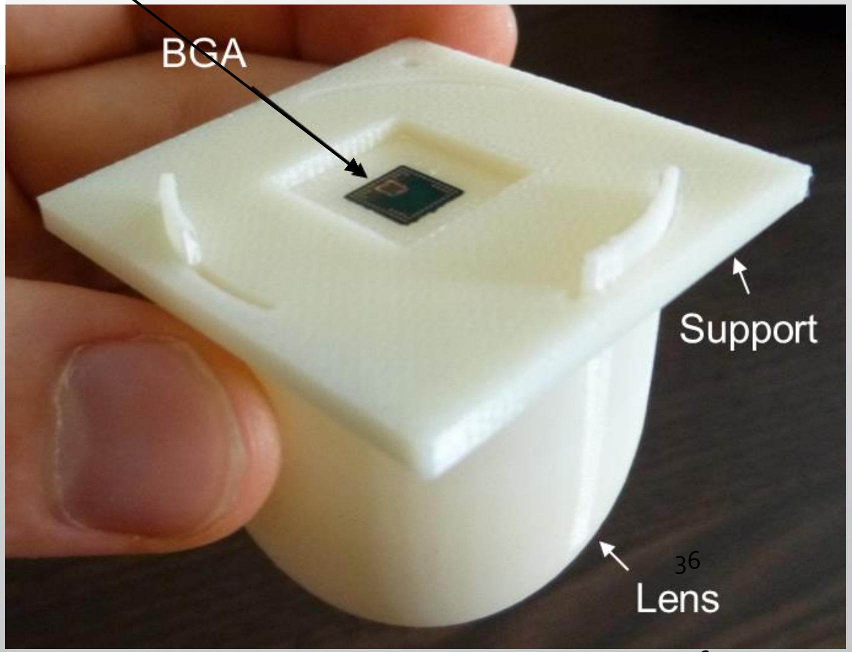
High-Gain Antennas in organic packaging & 3D printing

- 40 mm diameter lens for high-data rate links @ 120 GHz





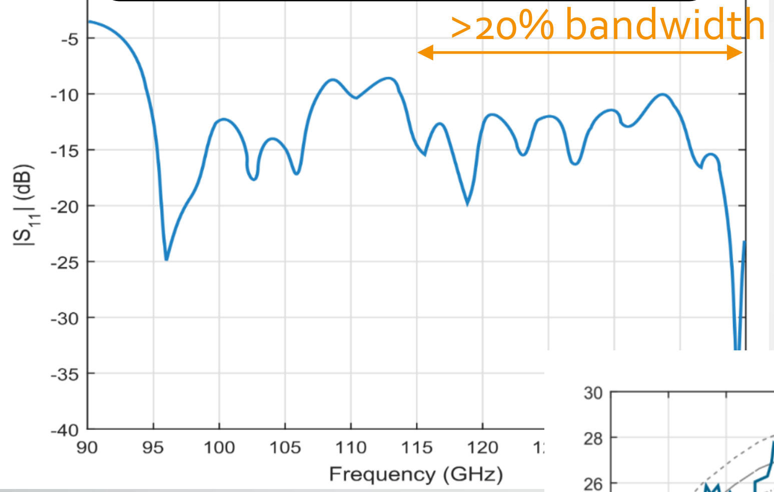


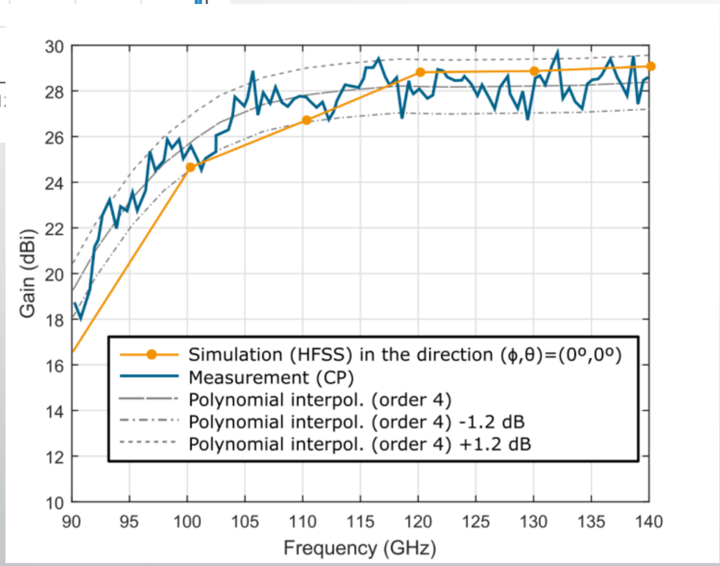


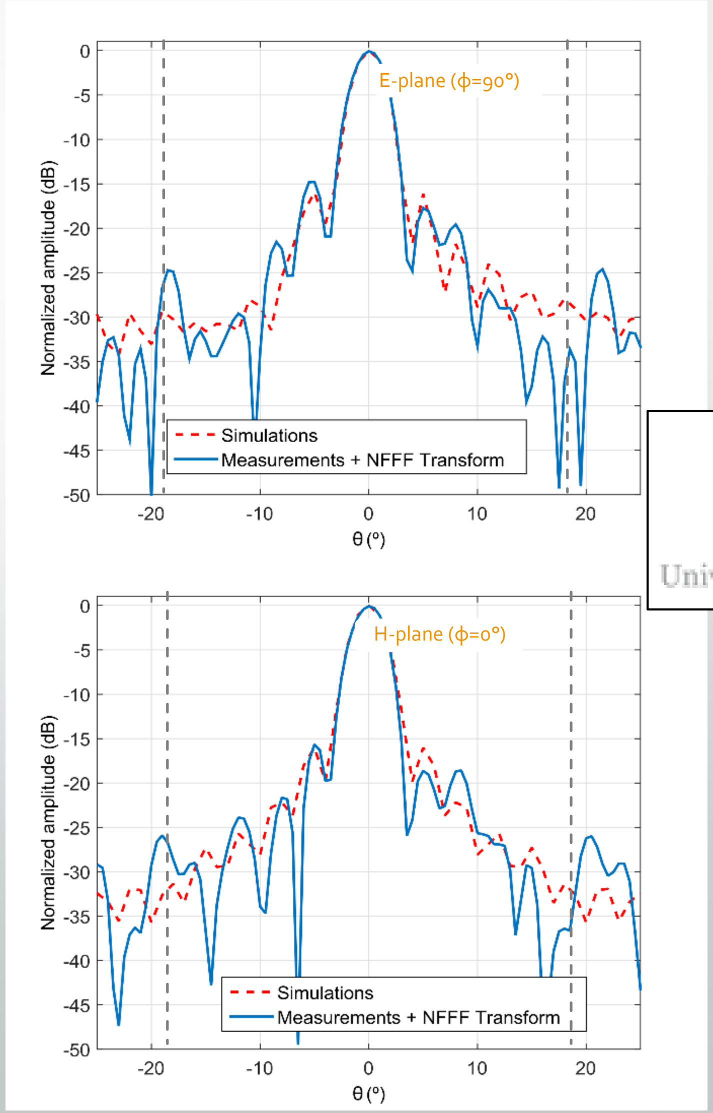
High-Gain Antennas in organic packaging & 3D printing

- 40 mm diameter lens for high-data rate links @ 120 GHz

S_{11} MATCHING BW
112 GHz–140 GHz @ -10 dB







Universidad de Oviedo

SIMULATION:
- FF Gain: **29 dBi**

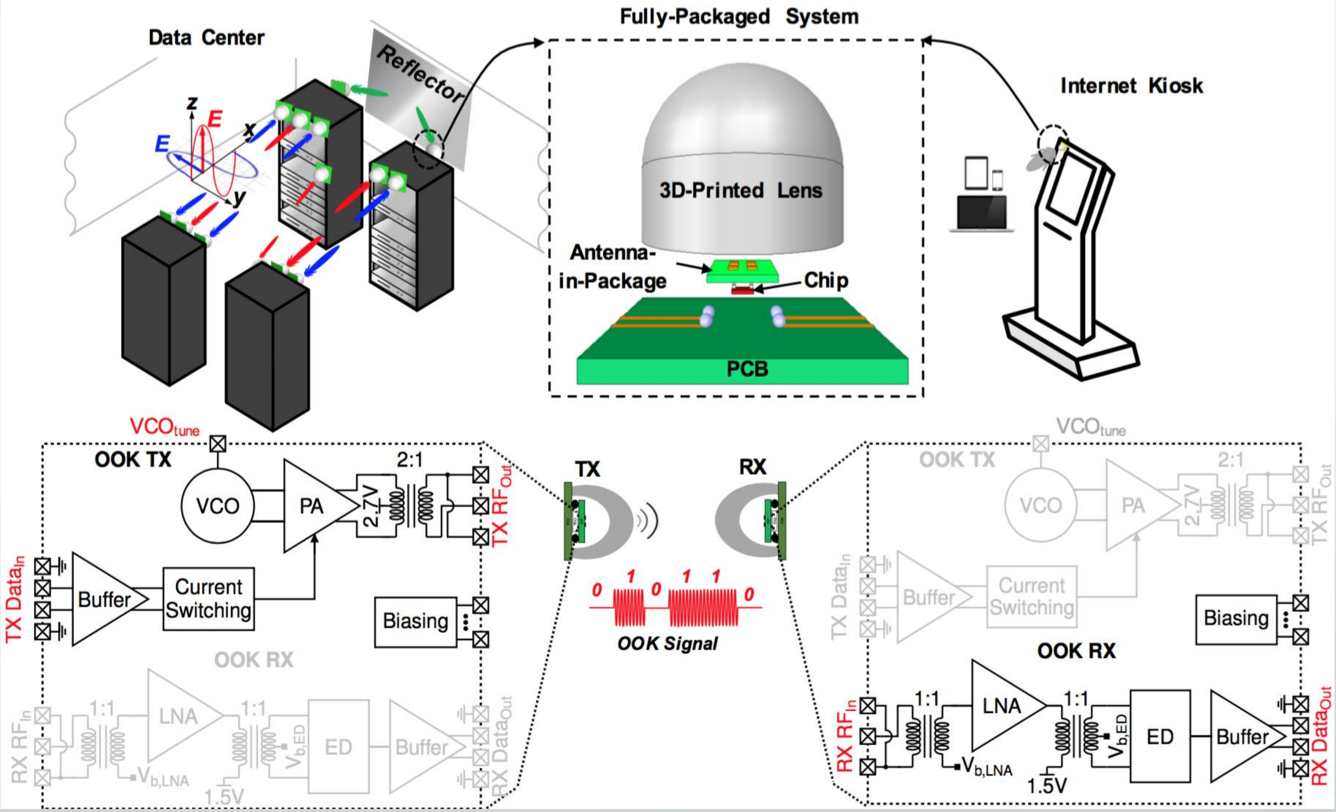
MEASUREMENTS
- FF Gain: **28.5 dBi**

Cyril Luxey

10Gb/s Low-energy Point-to-Point demo @ 120GHz

- Fully-packaged low-cost energy-efficient OOK Tx/Rx device

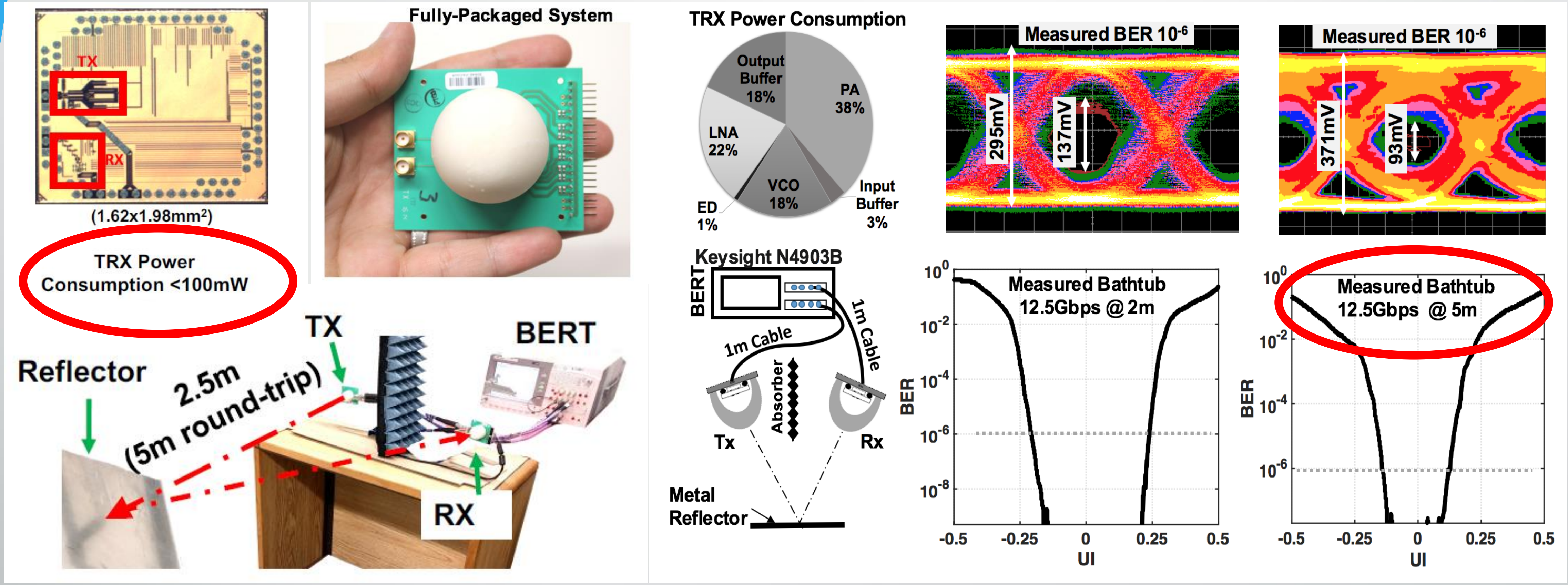
- ST 55nm BiCMOS
- Center frequency: 130GHz
- P_{out} ~ 10dBm
- TX efficiency of 15% → 3x higher than the state-of-the-art



- ST 55nm BiCMOS
- Bandwidth ~ 15GHz
- Receiver sensitivity: -47dBm

[13] N. Dolatsha et al., "*Compact 130GHz Fully Packaged Point-to-Point Wireless System with 3D-Printed 26dBi Lens Antenna Achieving 12.5Gb/s at 1.55pJ/b/m*", IEEE International Solid-State Circuits Conference (ISSCC 2017), February 5-9 2017, San Francisco, USA.

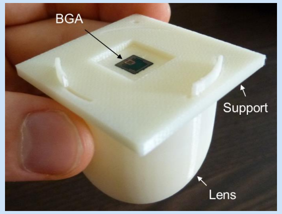
10Gb/s Low-energy Point-to-Point demo @ 120GHz



7.76 pJ/b Energy Efficiency
1.55 pJ/b/m, >40X better than state-of-the-art

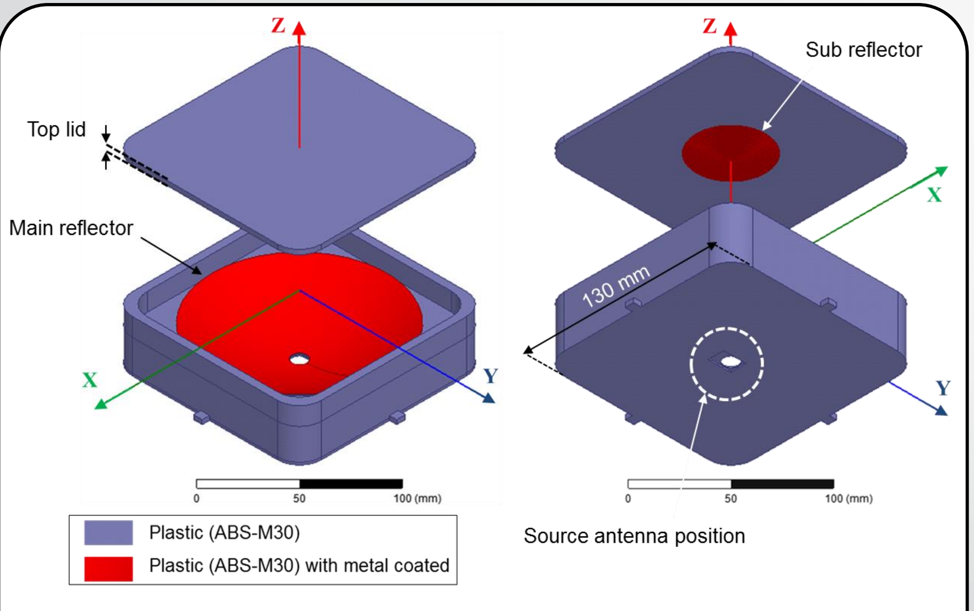
High-Gain Antennas in organic packaging & 3D printing

- 3D Printed Plastic vs. Teflon Lenses

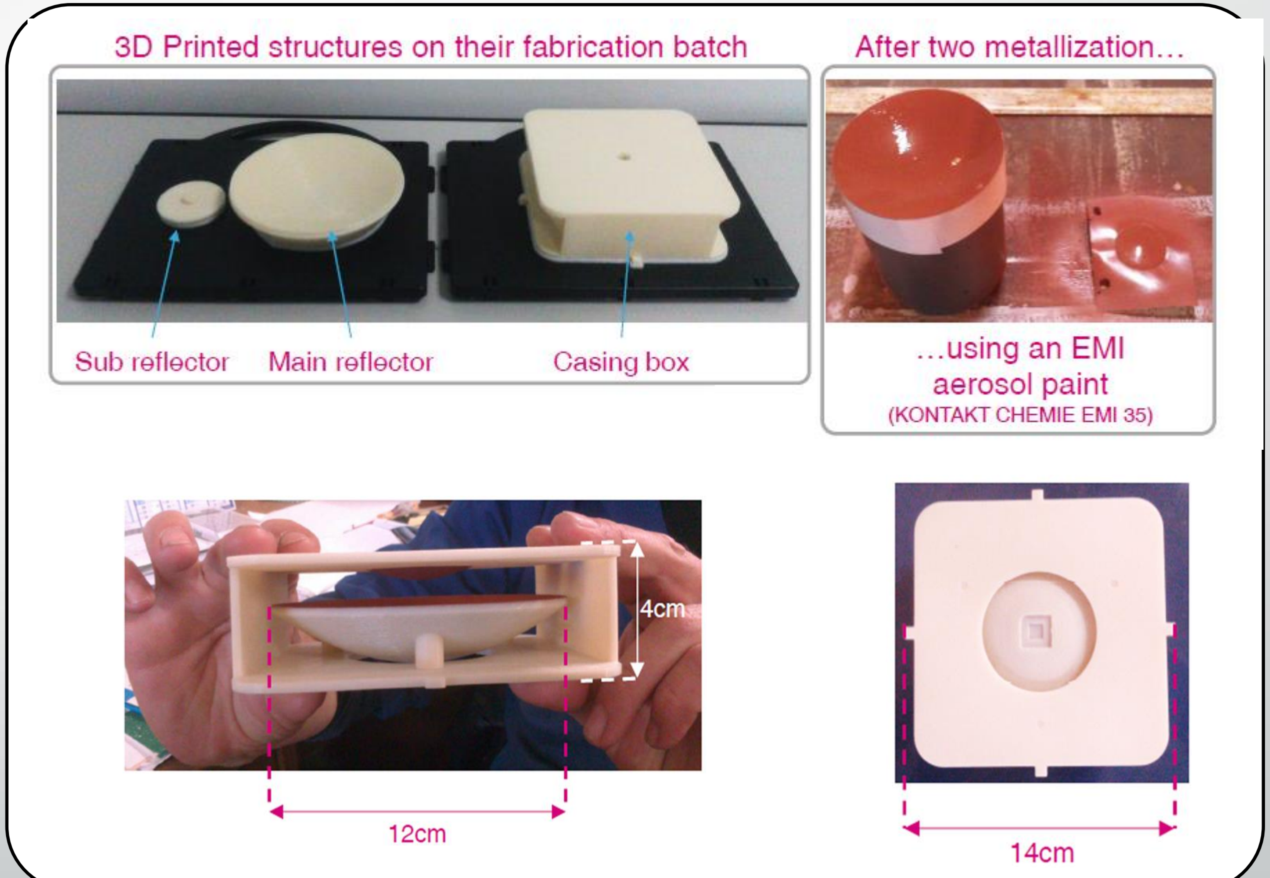
	Teflon Lens	3D Printed Lens
		
Manufacturing time	~1 day	~9 hours
Manufacturing cost/complexity	High	Low
Material cost	High	Low
Lens diameter	25 mm	40 mm

Perspectives

- 120 GHz 3D-printed Cassegrain reflector with plastic casing + BGA source

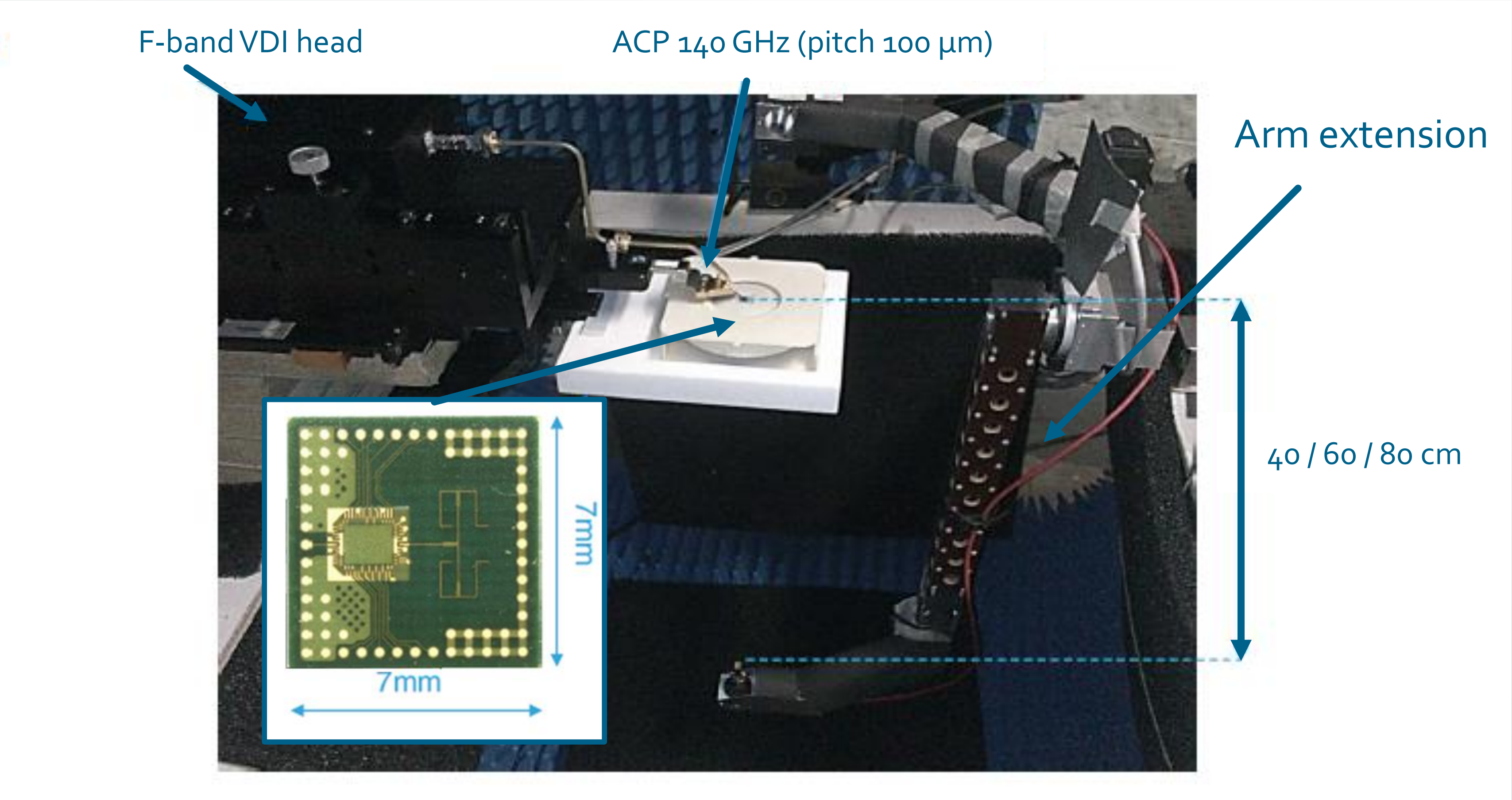


$13 \times 13 \times 3.8 cm^3$



Perspectives

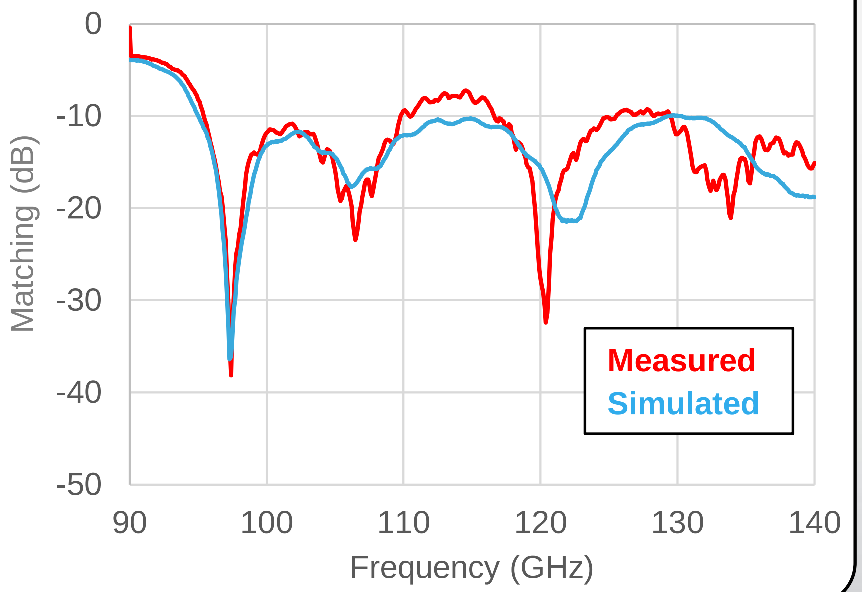
- 120 GHz 3D-printed Cassegrain reflector with plastic casing + BGA source



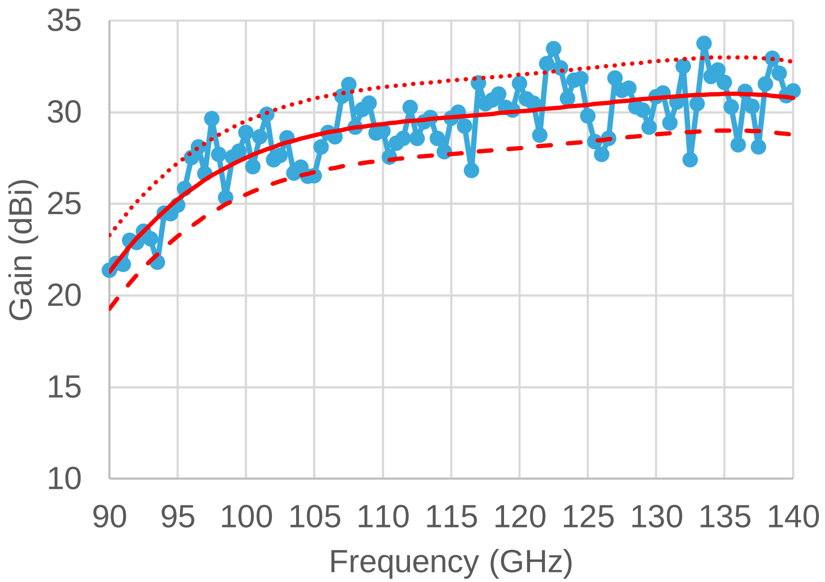
Perspectives

- 120 GHz 3D-printed Cassegrain reflector with plastic casing + BGA source

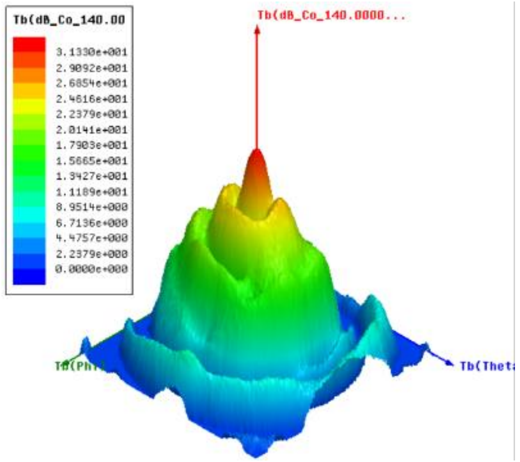
S_{11} MATCHING BW
118 GHz–140 GHz @ -10 dB



BROADSIDE NF GAIN BW (>30 dBi)
120 GHz - 140 GHz

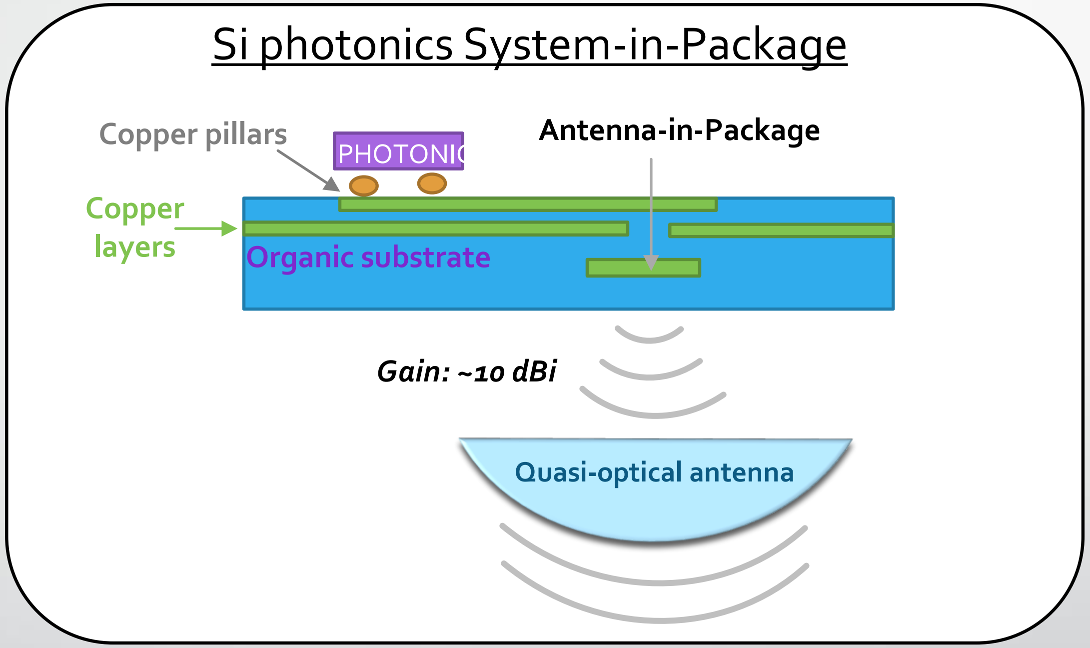


FF GAIN BW 32 dBi
120 GHz - 140 GHz



Perspectives

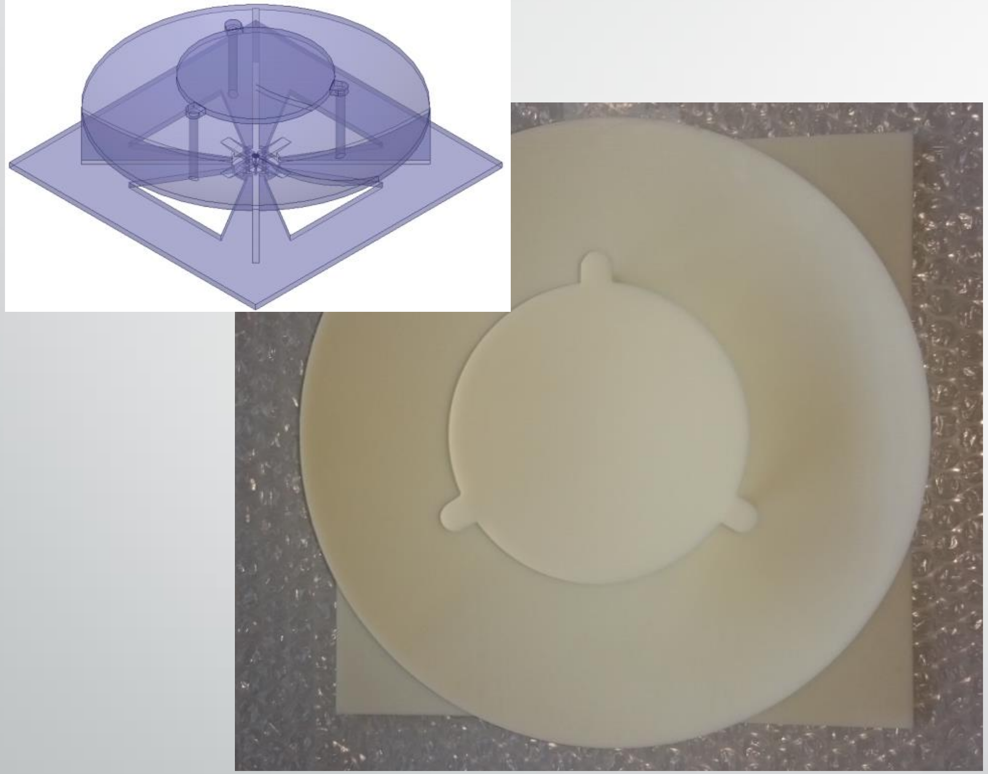
- 300 GHz 50 dBi 3D-printed Cassegrain reflector + BGA source



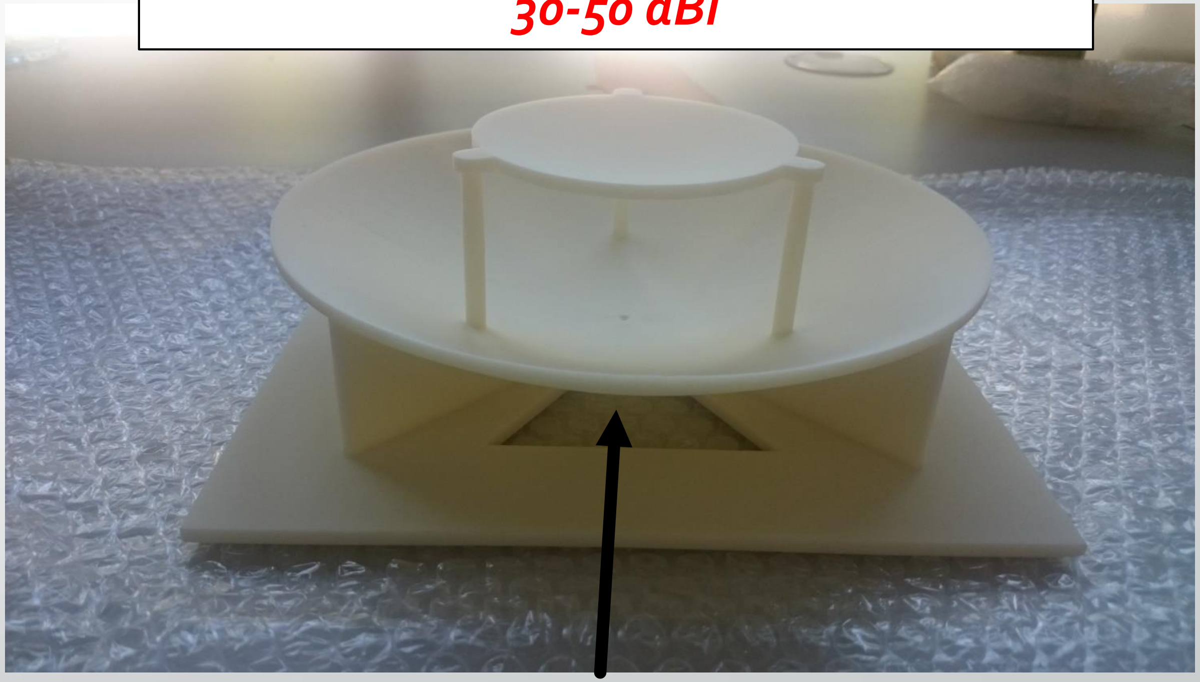
Gain: 30-50 dBi
For 1 to 200 m link

Perspectives

- Design of a 50 dBi Cassegrain at 300 GHz



Antenna Gain needed for 1 to 200m link: 30-50 dBi



Conclusion

- Enabling cost-effective wireless solutions is a key point in order to address future wireless challenges
- Silicon-based technology as CMOS/BiCMOS are suitable even beyond 200 GHz
- Cost-effective packaging with clever IC/antenna integration will continue to be a strong issue

  → Organic laminate technology has proven its suitability up to 300 GHz

  → 3D-printing uses resulted in low-cost plastic-based lenses and reflectors

- From R&D point of view, moving to higher than 300 GHz will require aggressive design rules exceeding today's capability of organic substrate technology

→ Some innovation will be needed here

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cyril.luxey@unice.fr

Questions … and maybe Answers