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FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT OF INFORMATION TECHNOLOGY
IDLAB - ELECTROMAGNETICS

Opto-Electronic Antenna Systems for Next-Generation Wireless Applications

Olivier Caytan, Laurens Bogaert, Thomas Deckmyn, Quinten Van den Brande, Igor Lima de Paula, Dennis Maes, Johan Bauwelinck, Guy Torfs, Bart Kuyken, Gunther Roelkens, Piet Demeester, Sam Lemey, Dries Vande Ginste and Hendrik Rogier

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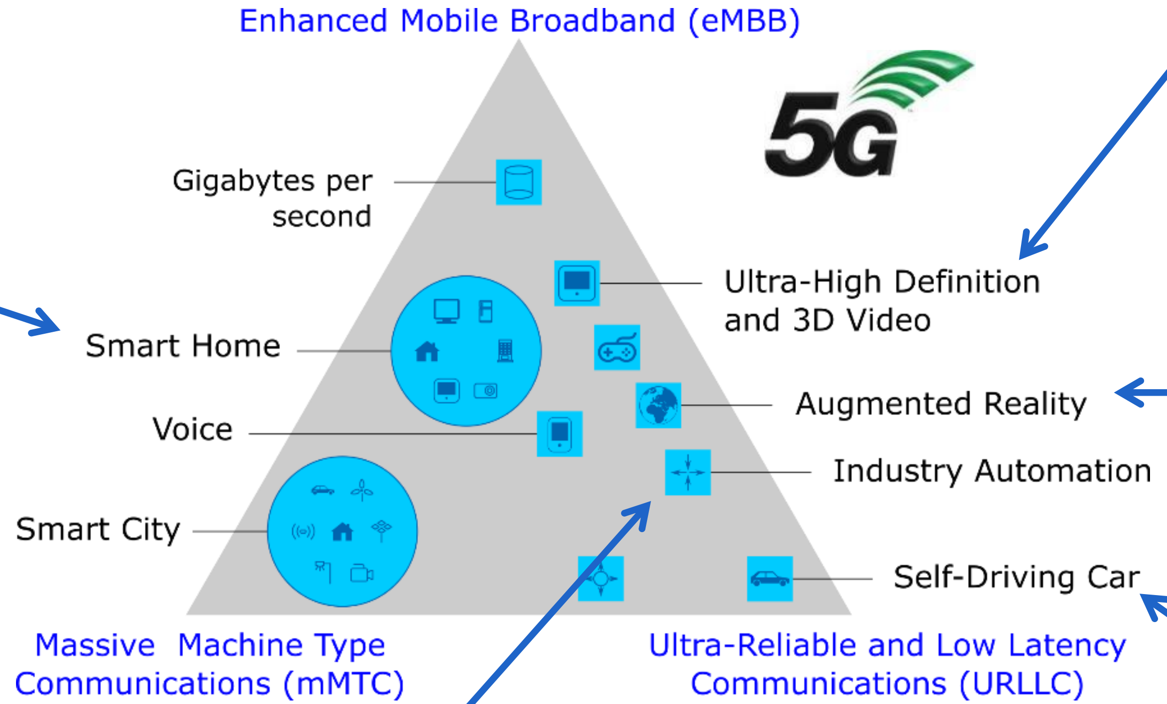
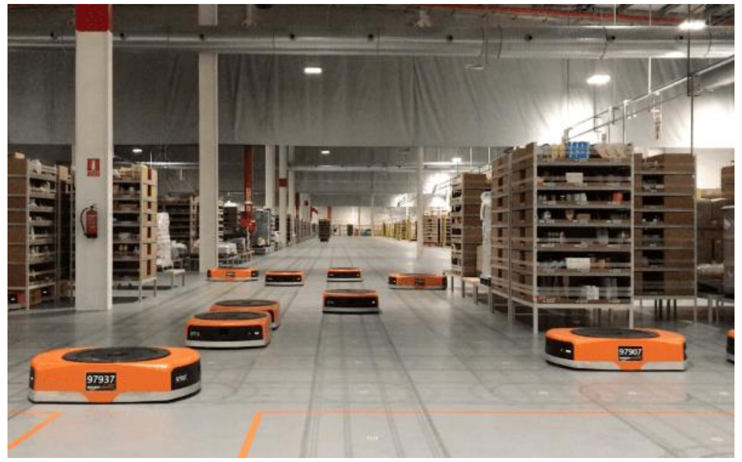
Overview

Introduction

5G Networks

- Unprecedented data rate
- Ultra-low latency
- User density
- Multiple usage scenarios





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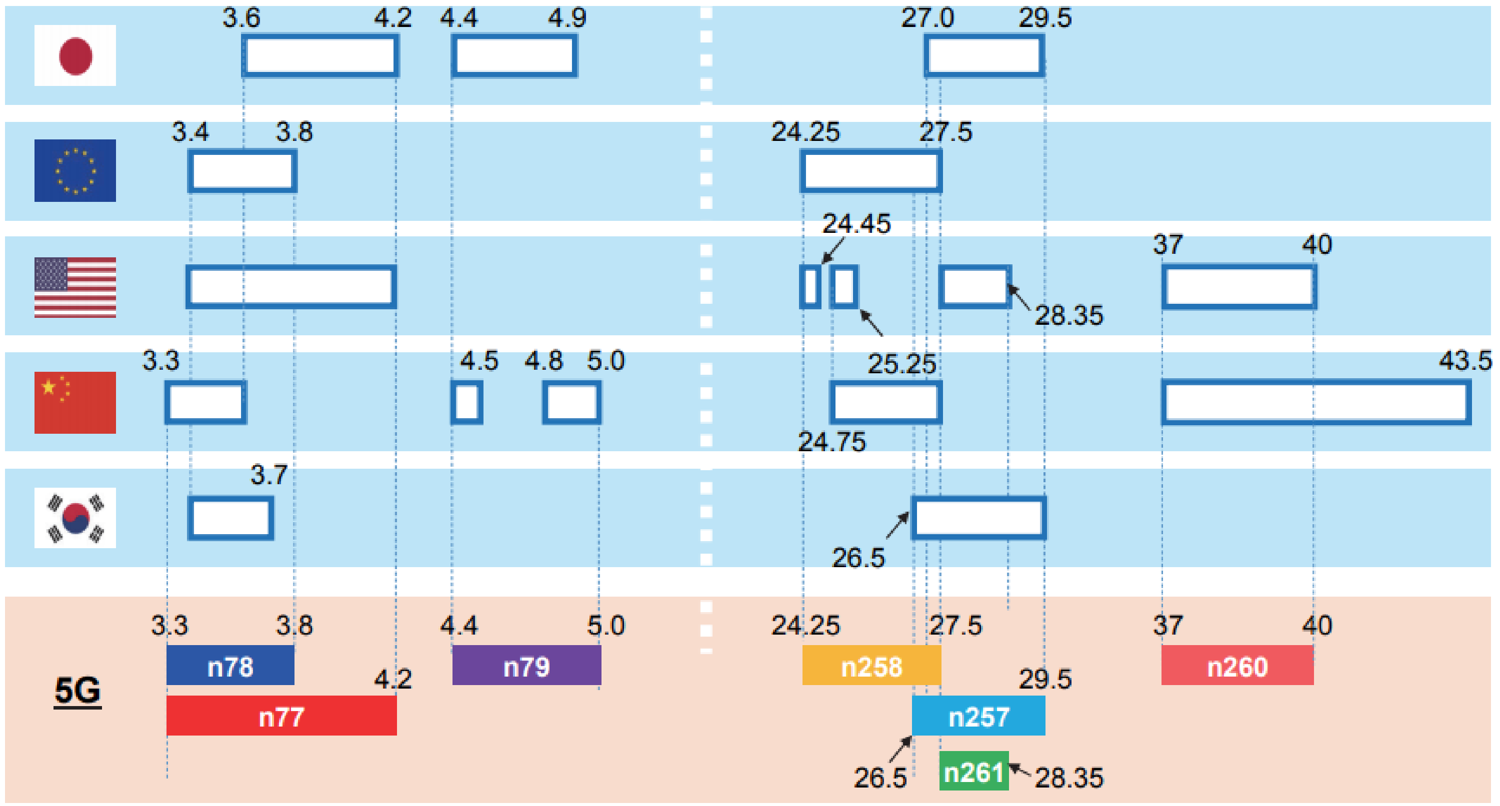
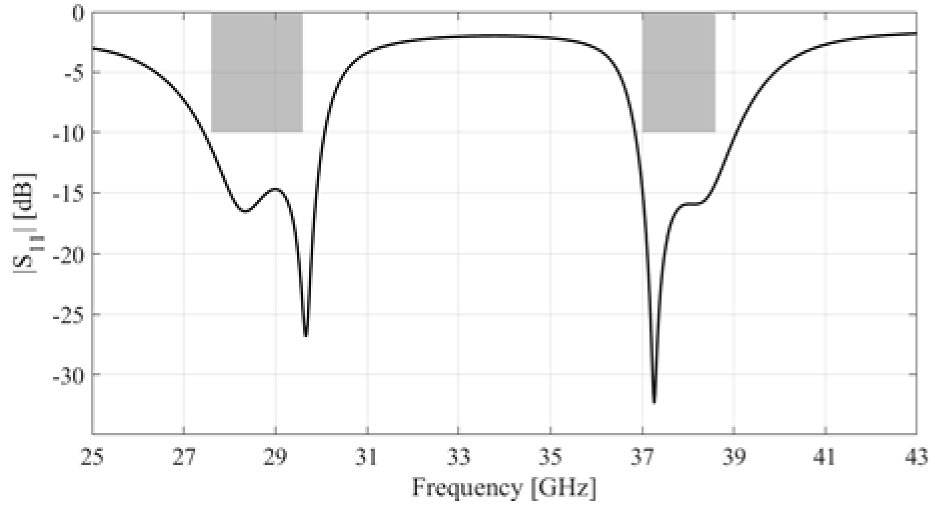
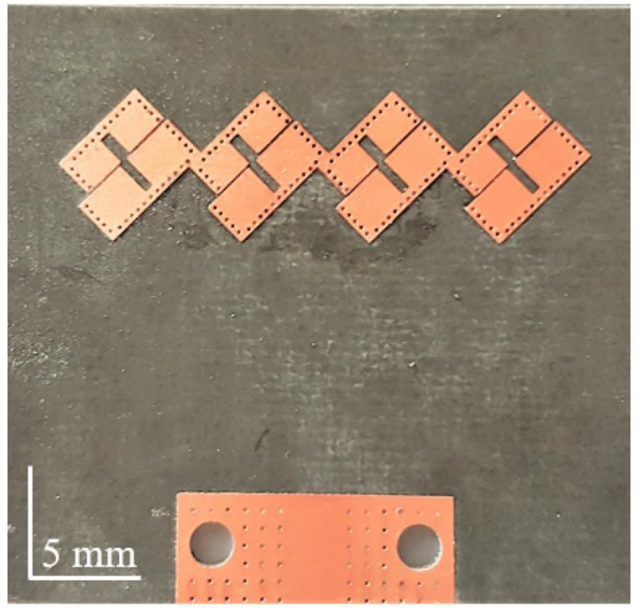
5G Dedicated Antenna Design

- Wideband and Multiband
  - Sub-6 GHz bands
  - Emerging mm-wave bands
- Multi-antenna deployment
  - Propagation losses
  - Beam steering (~ λ/2)
  - Large-scale spatial multiplexing







28/39 GHz Dualband 1x4 Linear Array

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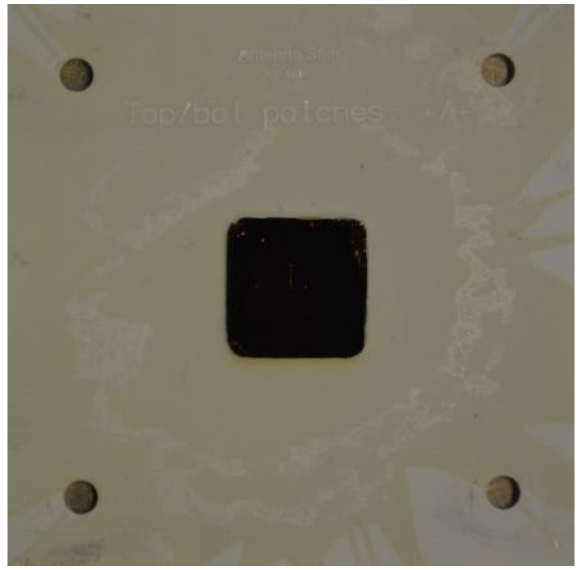
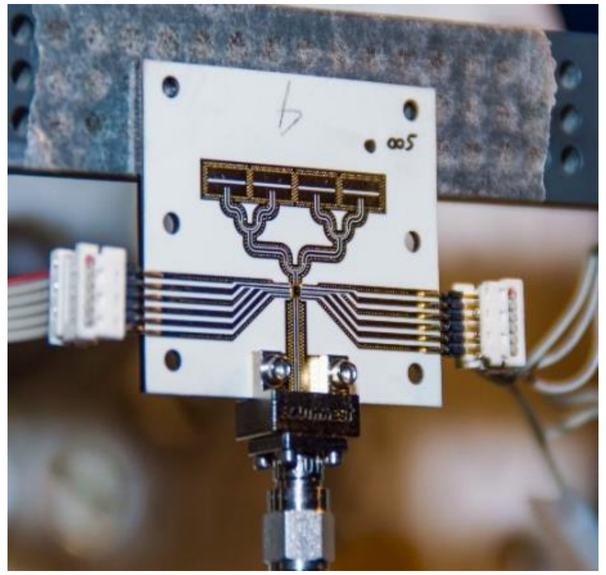
5G Dedicated Antenna Design

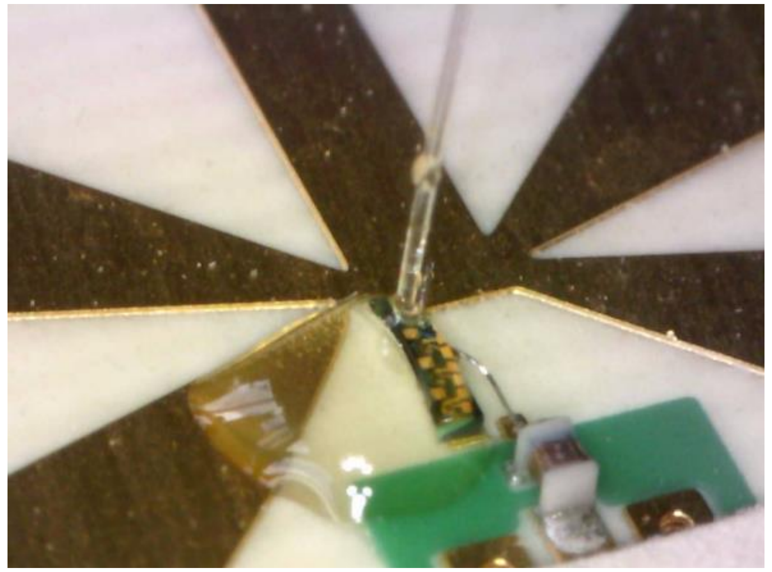
- Our approaches
  - Novel methodologies for performance, cost-effectiveness and compactness
  - Antenna/transceiver co-design
    - Avoid high interconnection losses
    - Compact, reliable and maximum performance
    - e.g. opto-electronic antennas



Hybrid on-Chip/on-PCB Antenna



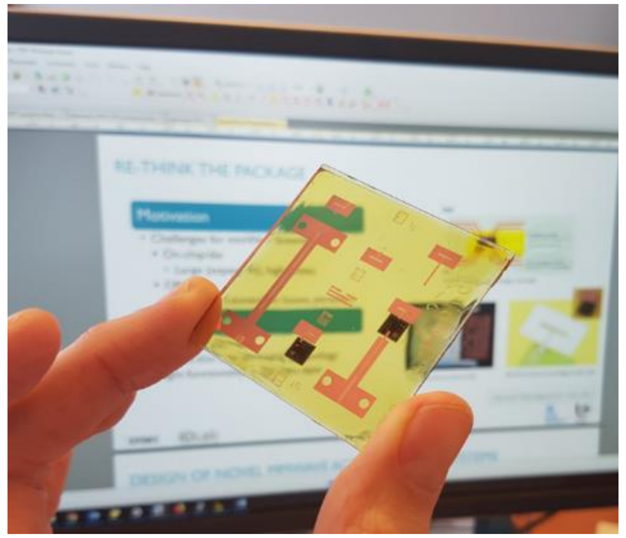
Antenna/Amplifier co-design



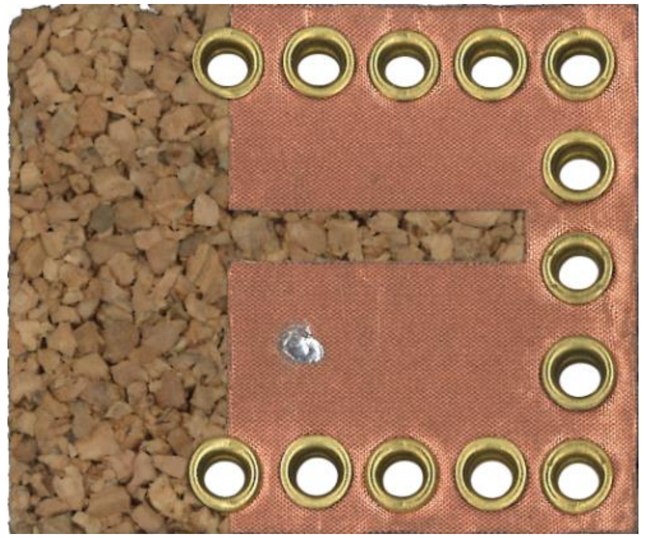
Antenna/Photodetector co-design

Novel methodologies for performance, cost-effectiveness and compactness

1. High, robust performance
   - Energy efficiency, gain, bandwidth
2. Cost-effective
   - Standard manufacturing
3. Compact footprint
   - User Equipment integration
   - Multi-antenna deployment (~ λ/2)
4. Novel substrates
   - Performance
   - Cost-effective/aesthetic integration



Glass substrate



Biodegradable substrates

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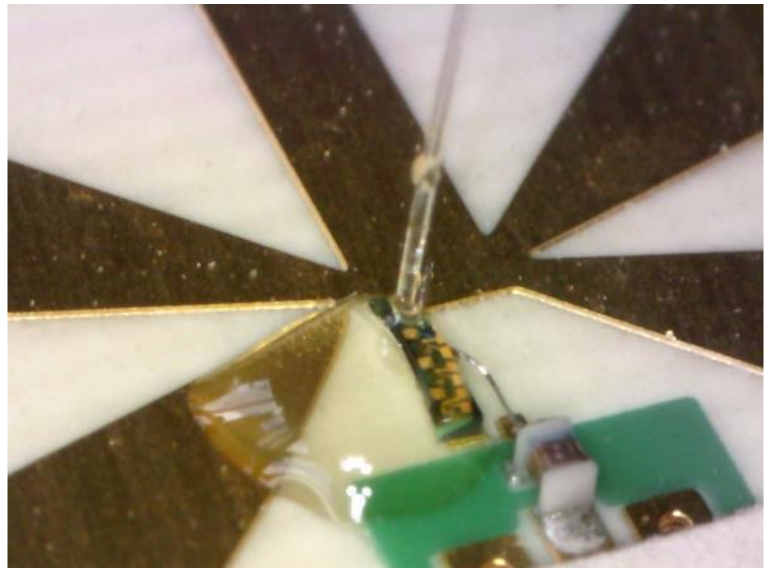
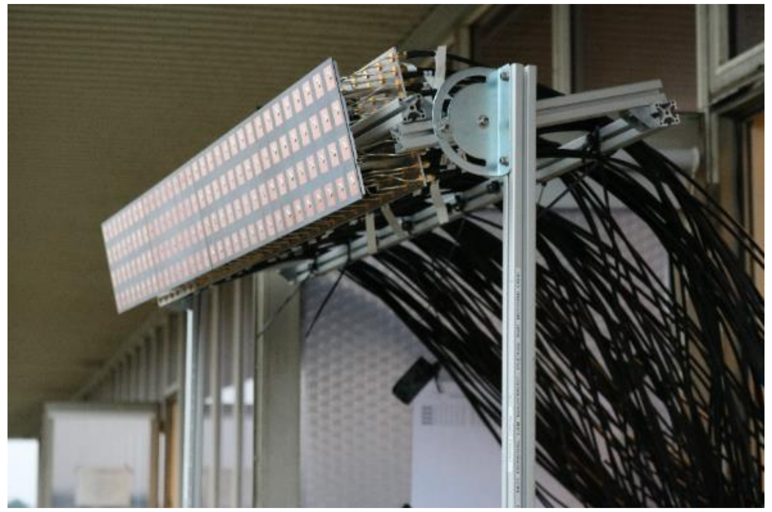
Opto-Electronic Antennas

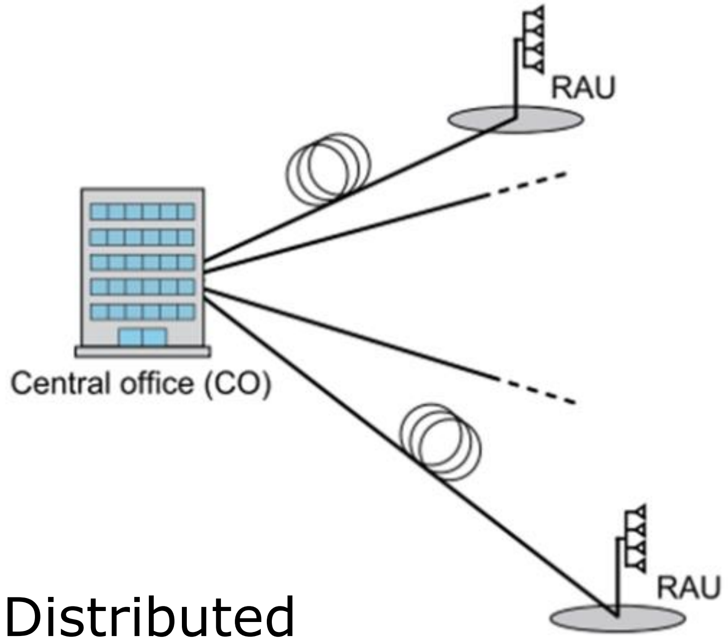
- Antenna co-designed with opto-electronic transducer
- Optical routing to co-located or distributed antennas
  - + Wideband
  - + Low-loss
  - + No EMI/EMC issues, low crosstalk
  - + Beam-squint-free array steering



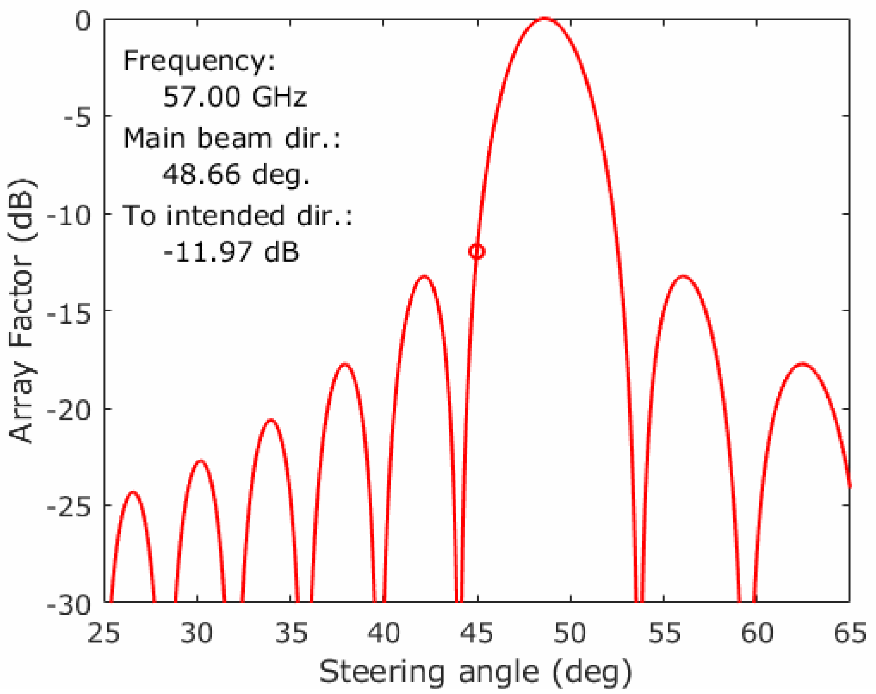
Antenna/Photodetector co-design



Massive MIMO array with electrical routing



Distributed Antenna System



1x32 Linear Array in 60 GHz band (0.6λ spacing) exhibiting beam-squint

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Sub-6 GHz Passive Downlink Opto-Electronic Antennas

ATTO Ultra-High Capacity Wireless Networking

G. Torfs, H. Li, S. Agneessens, J. Bauwelinck, L. Breyne, O. Caytan, W. Joseph, S. Lemey, H. Rogier, A. Thielens, D. Vande Ginste, J. Van Kerrebrouck, G. Vermeeren, X. Yin and P. Demeester, "ATTO: Wireless Networking at Fiber Speed," in *Journal of Lightwave Technology*.

Fiber-like connectivity to humans/robots in a factory-of-the-future

- High user density
- Large bandwidth
- Low latency
- High reliability

Solution

- Large number of *atto*-cells
- Floor-integrated opto-electronic antennas
- Radio over Fiber (RoF) interconnection

➔ Extreme low cost and power

***atto*-cell served by opto-electronic antenna**

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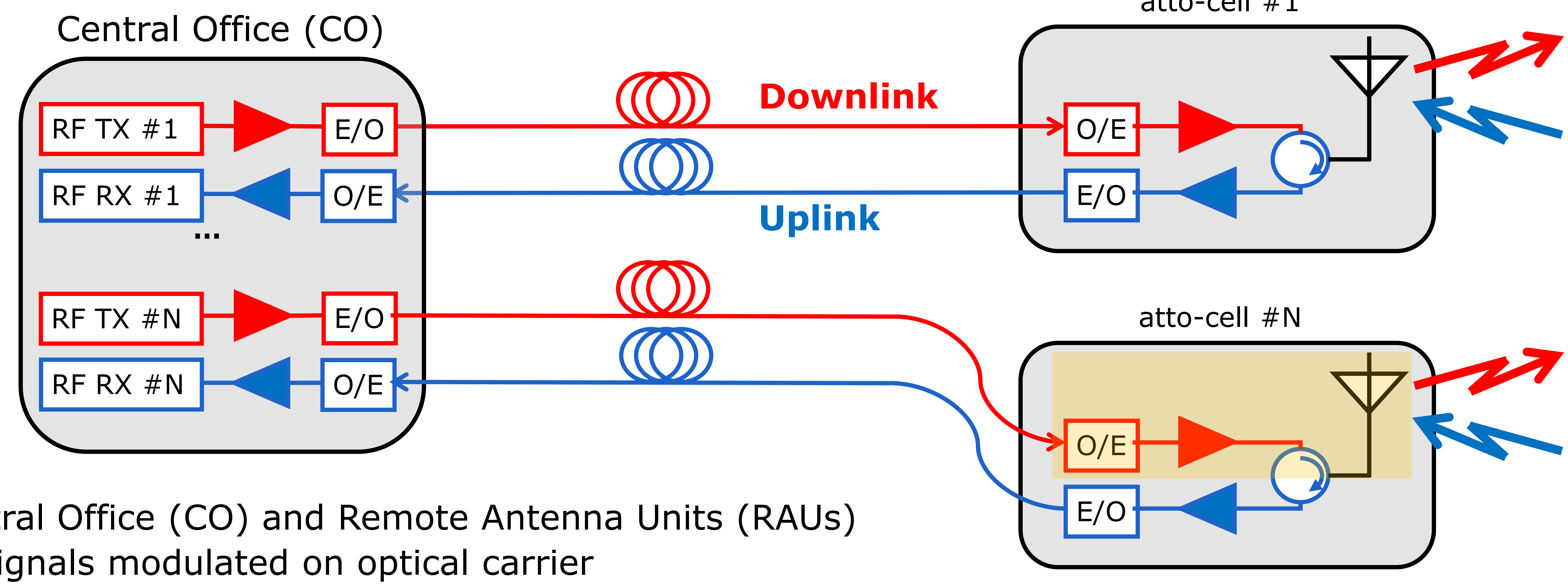
Radio-Frequency-over-Fiber (RFoF) interconnection



- Central Office (CO) and Remote Antenna Units (RAUs)
- RF signals modulated on optical carrier
  + Wideband and low-loss
  + No EMI/EMC issues
  + Low complexity, cost-effective and flexible
  – High-speed photodetectors and optical sources required

Focus on downlink direction

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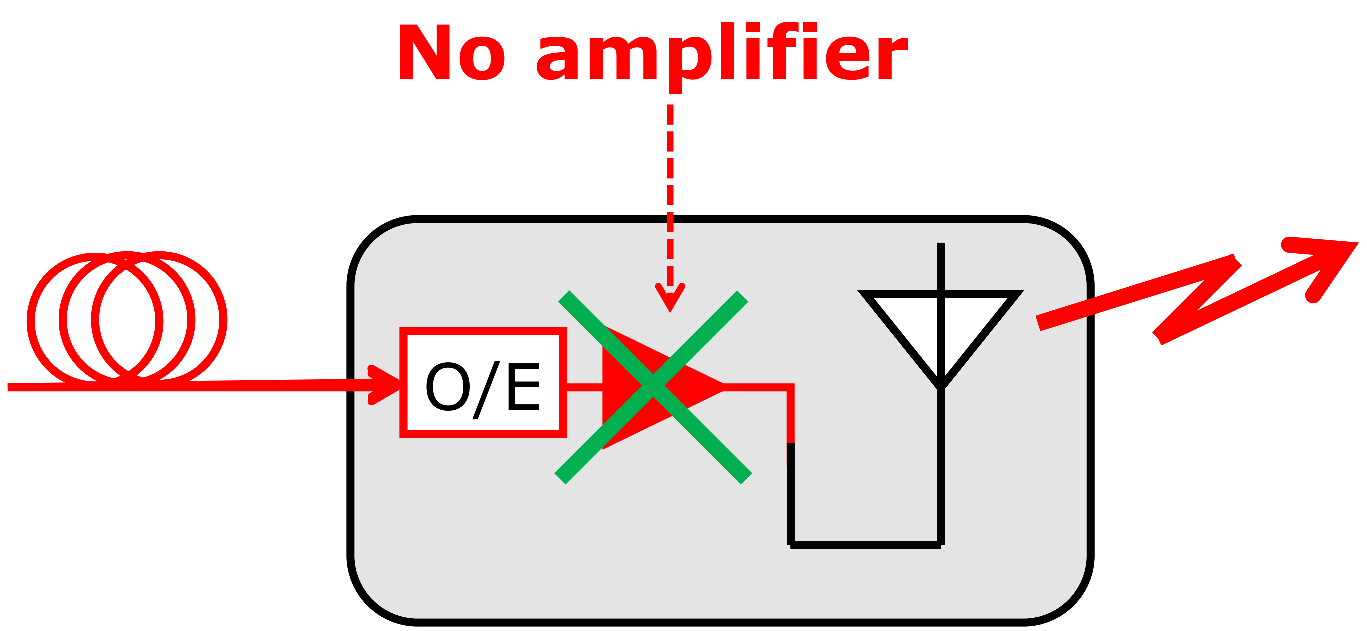
Passive Downlink Opto-Antenna: Design Goals

- Passive opto-electronic conversion
  - No additional active components (amplifiers)
- Wideband and efficient opto-electronic conversion
  - Optimized for operation in specified frequency band
  - Lossless impedance matching
- Low-profile and efficient antenna
- Cost-effective unit
  - 850 nm multi-mode fiber
  - Vertical-cavity surface-emitting laser (VCSEL)
  - Standard PCB fabrication process



Passive Downlink “Opto-Antenna”

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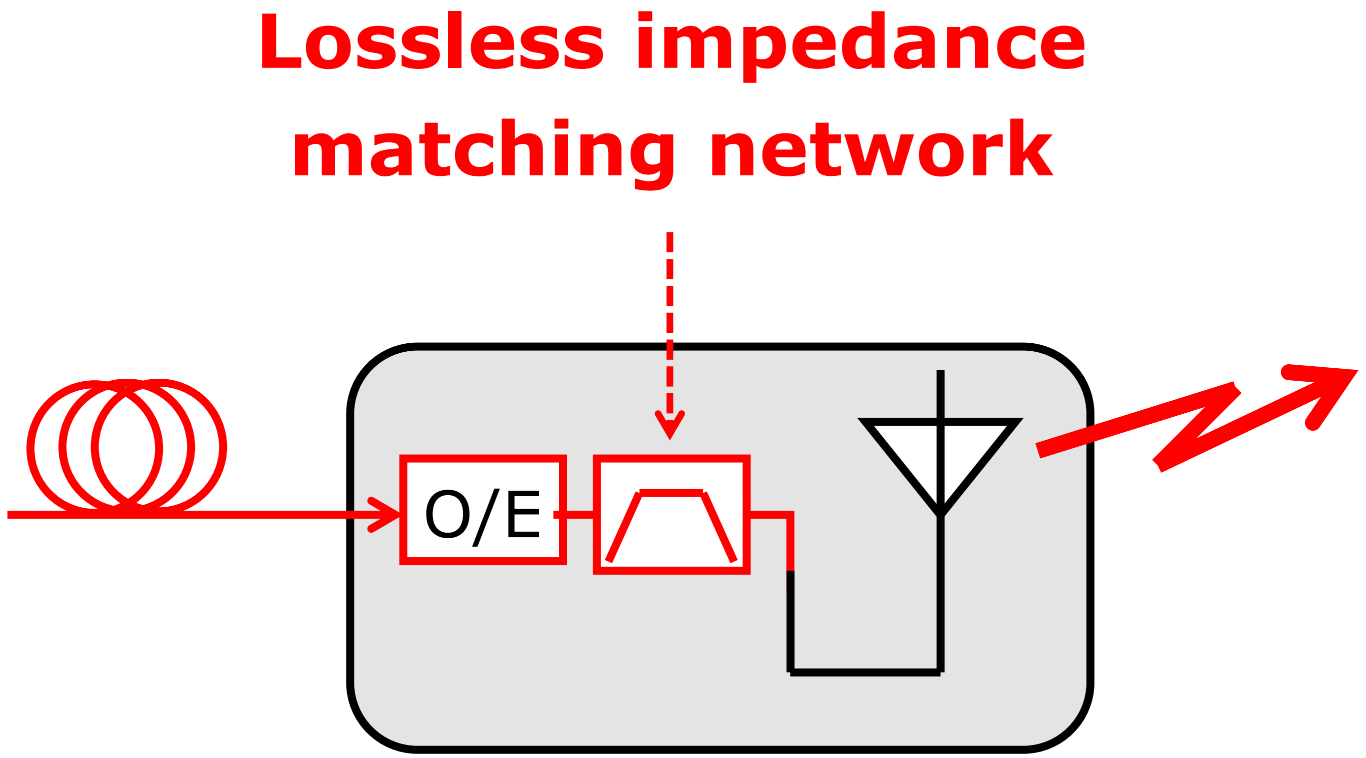
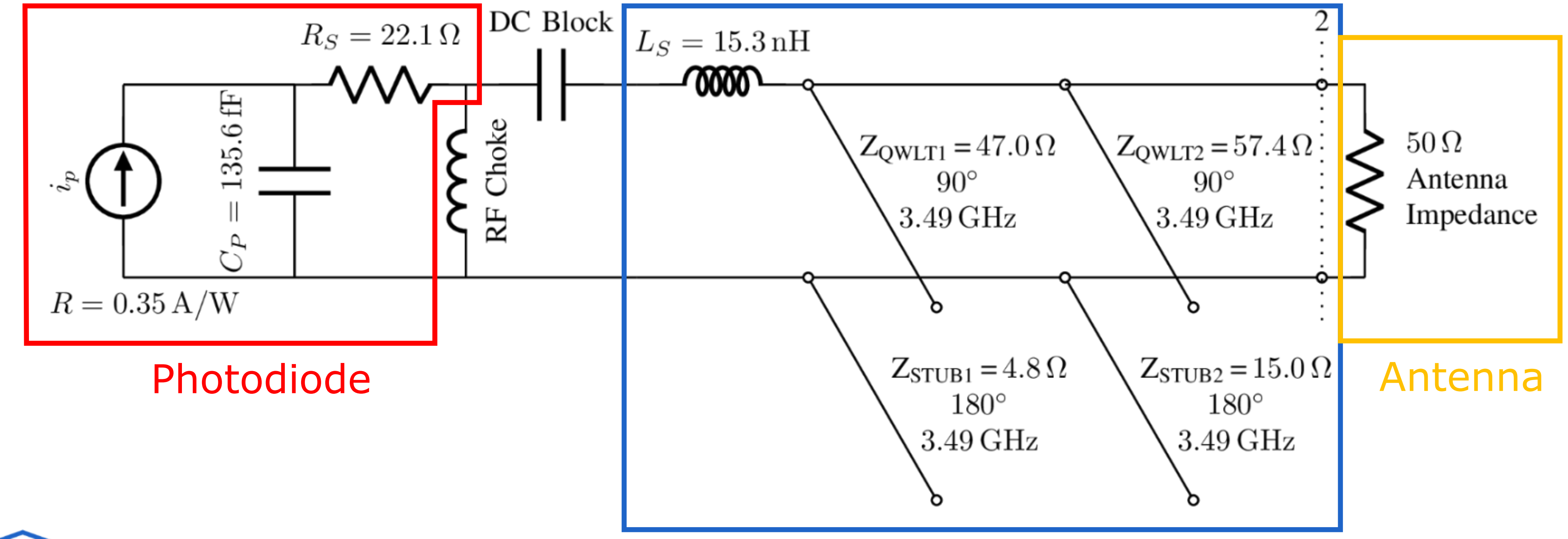


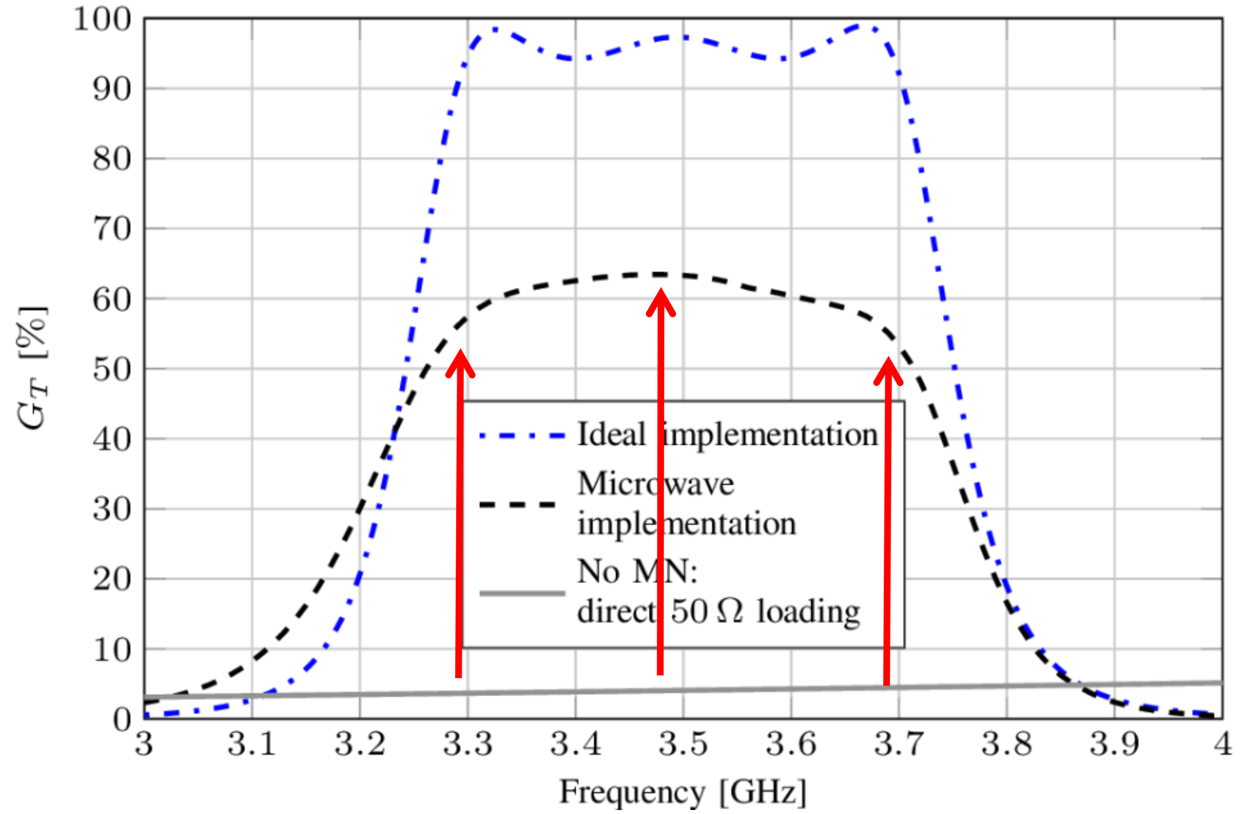
Passive Downlink "Opto-Antenna"

Passive Downlink Opto-Antenna: 3.50 GHz Design

O. Caytan, L. Bogaert, H. Li, J. Van Kerrebrouck, S. Lemey, G. Torfs, J. Bauwelinck, P. Demeester, S. Agneessens, D. Vande Ginste, and H. Rogier, "Passive Opto-Antenna as Downlink Remote Antenna Unit for Radio Frequency over Fiber," in *Journal of Lightwave Technology.*

- Third order Chebyshev impedance matching network
  - 3.30 – 3.70 GHz band (11 %)
  - Generator = photodetector
  - Load = 50 Ω antenna
- Mixed lumped/distributed implementation





> 10 x extracted power as compared to standard technique

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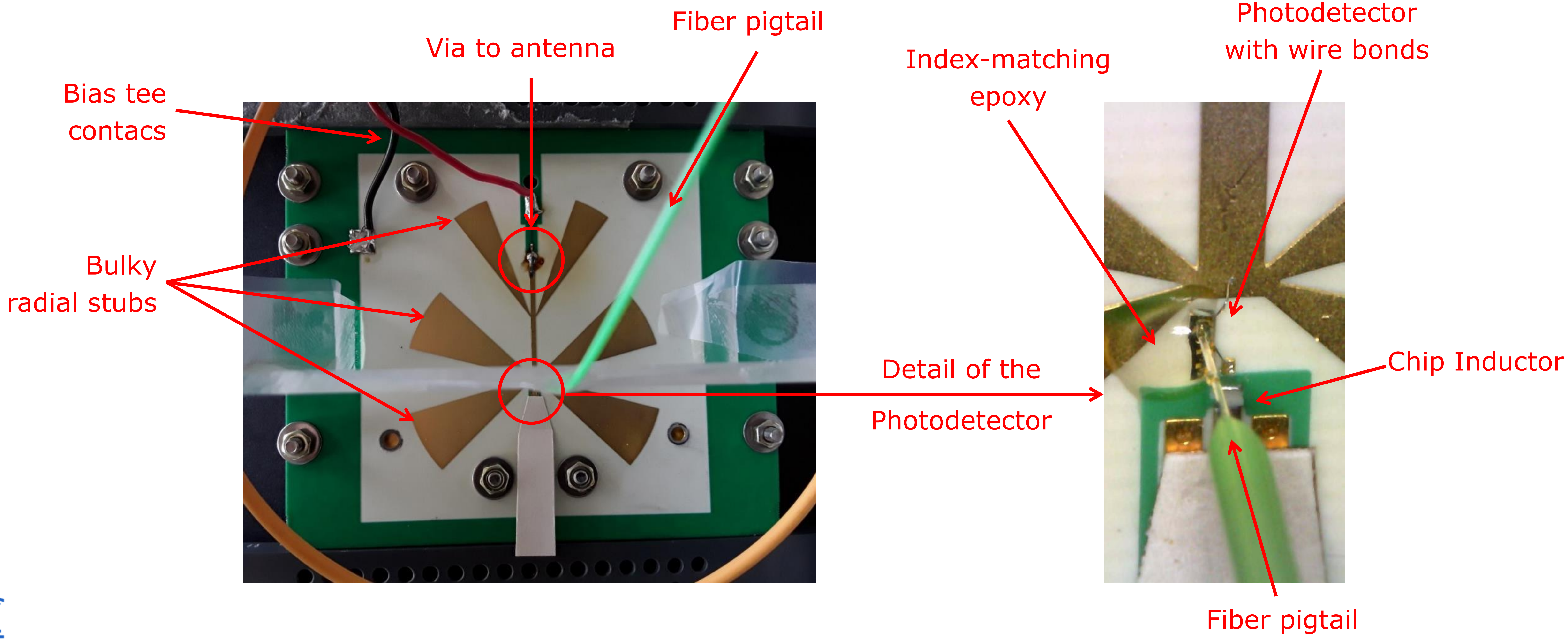
- Microwave implementation prototype



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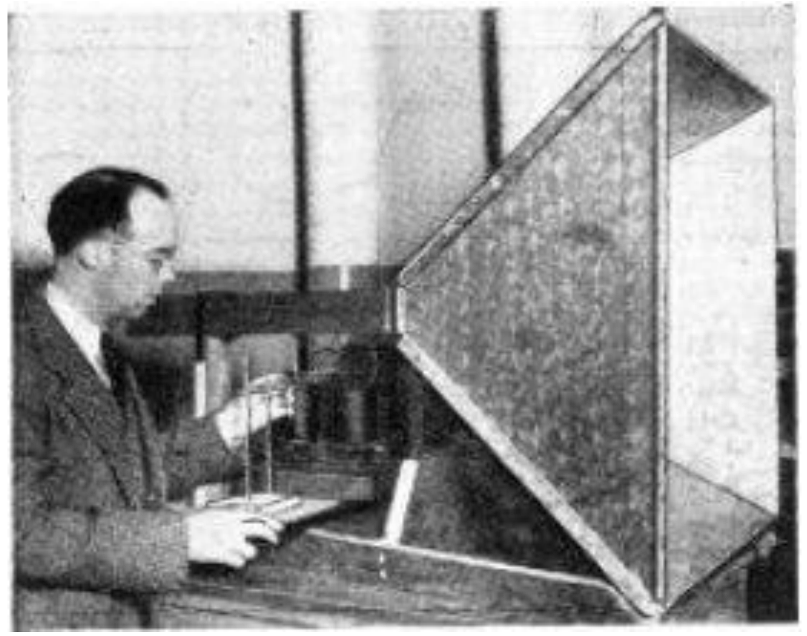
Air-Filled Substrate-Integrated-Waveguide (AFSIW)

Q. Van den Brande, S. Lemey, J. Vanfleteren, and H. Rogier, “Highly-Efficient Impulse-Radio Ultra-Wideband Cavity-Backed Slot Antenna in Stacked Air-Filled Substrate-Integrated-Waveguide Technology,” in *IEEE Transactions on Antennas and Propagation*.

- Metallic waveguide filled with air
  … integrated in a multi-layer PCB
  - + Low propagation loss
  - + High electrical shielding
  - + Low-profile

- Devices
  - Waveguide transitions
  - Filters
  - Phase shifters
  - **Low-profile, efficient antennas**



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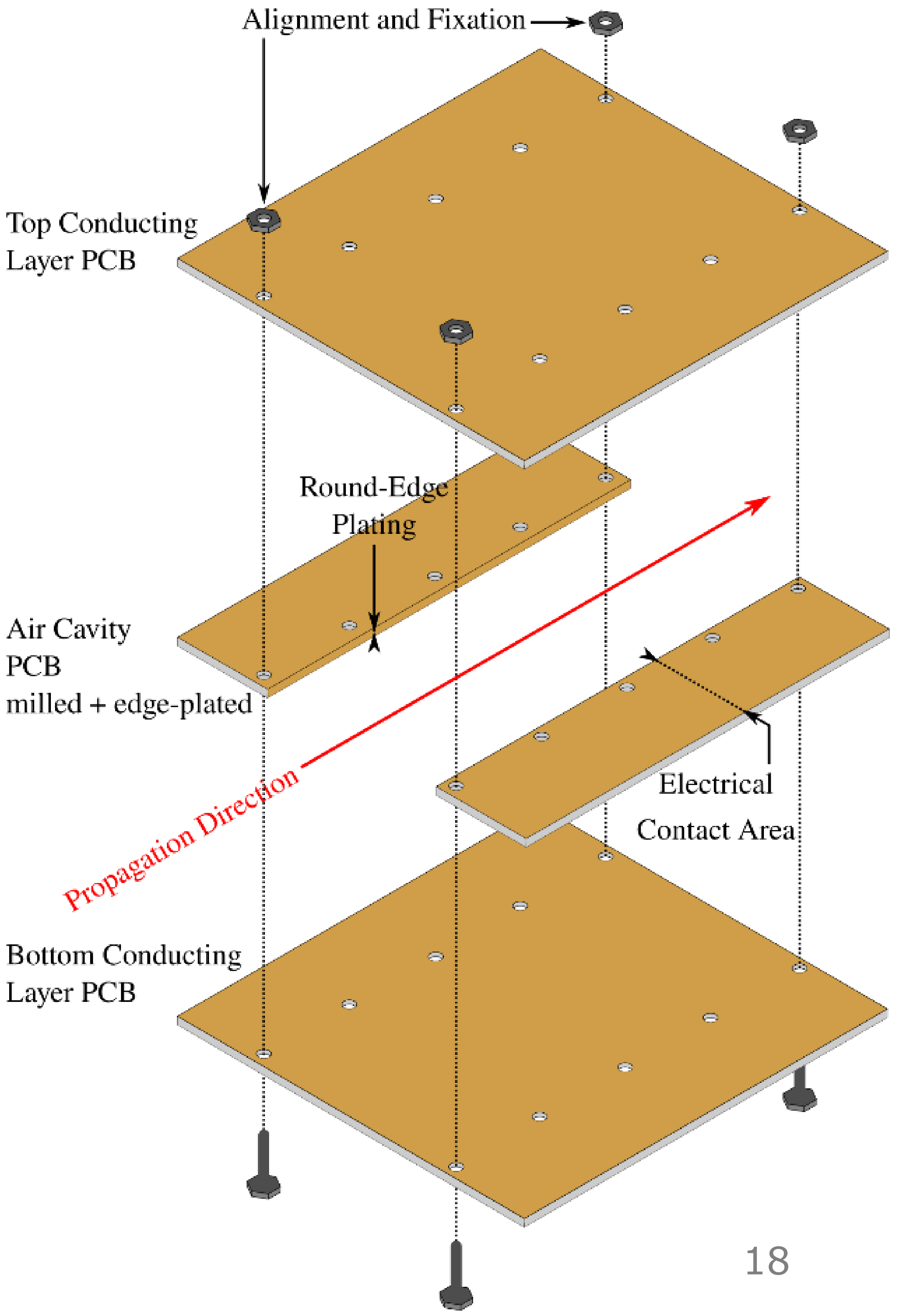

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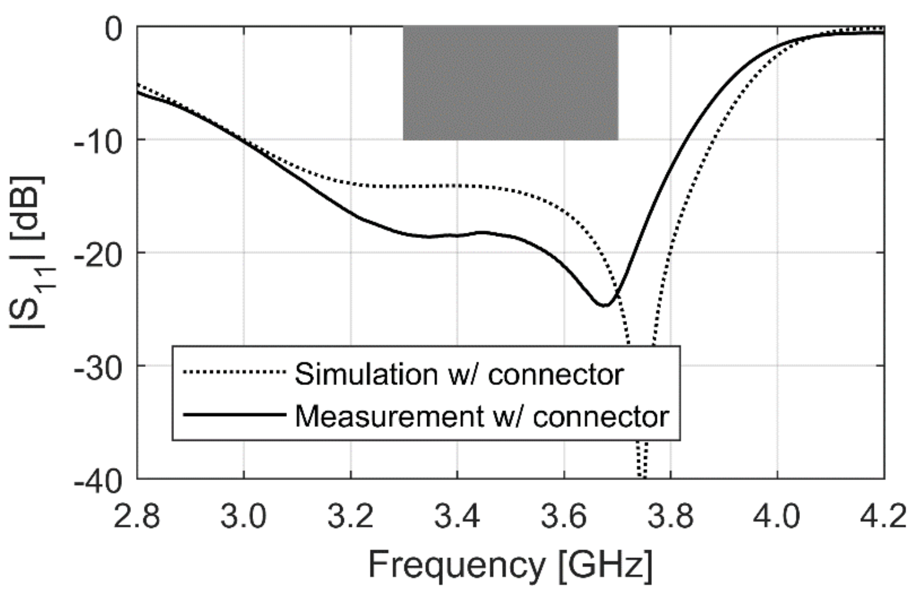
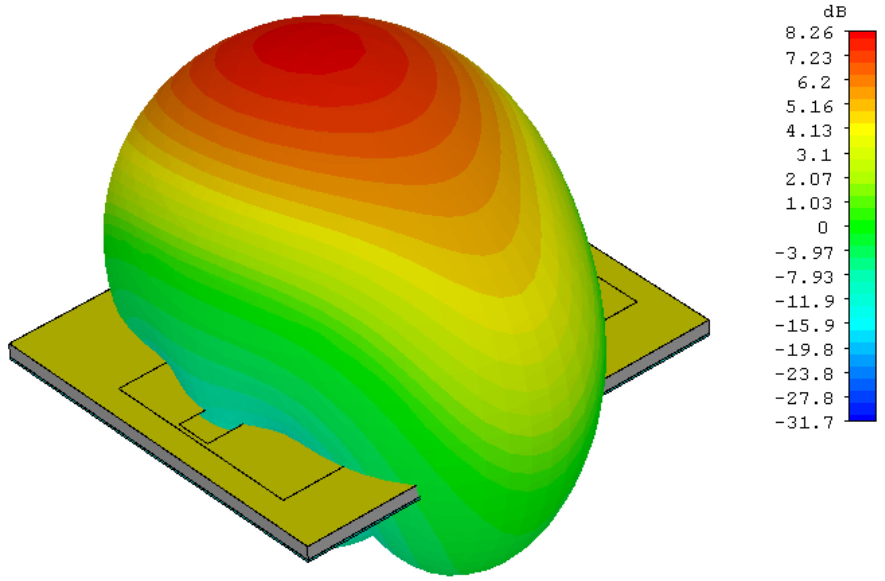
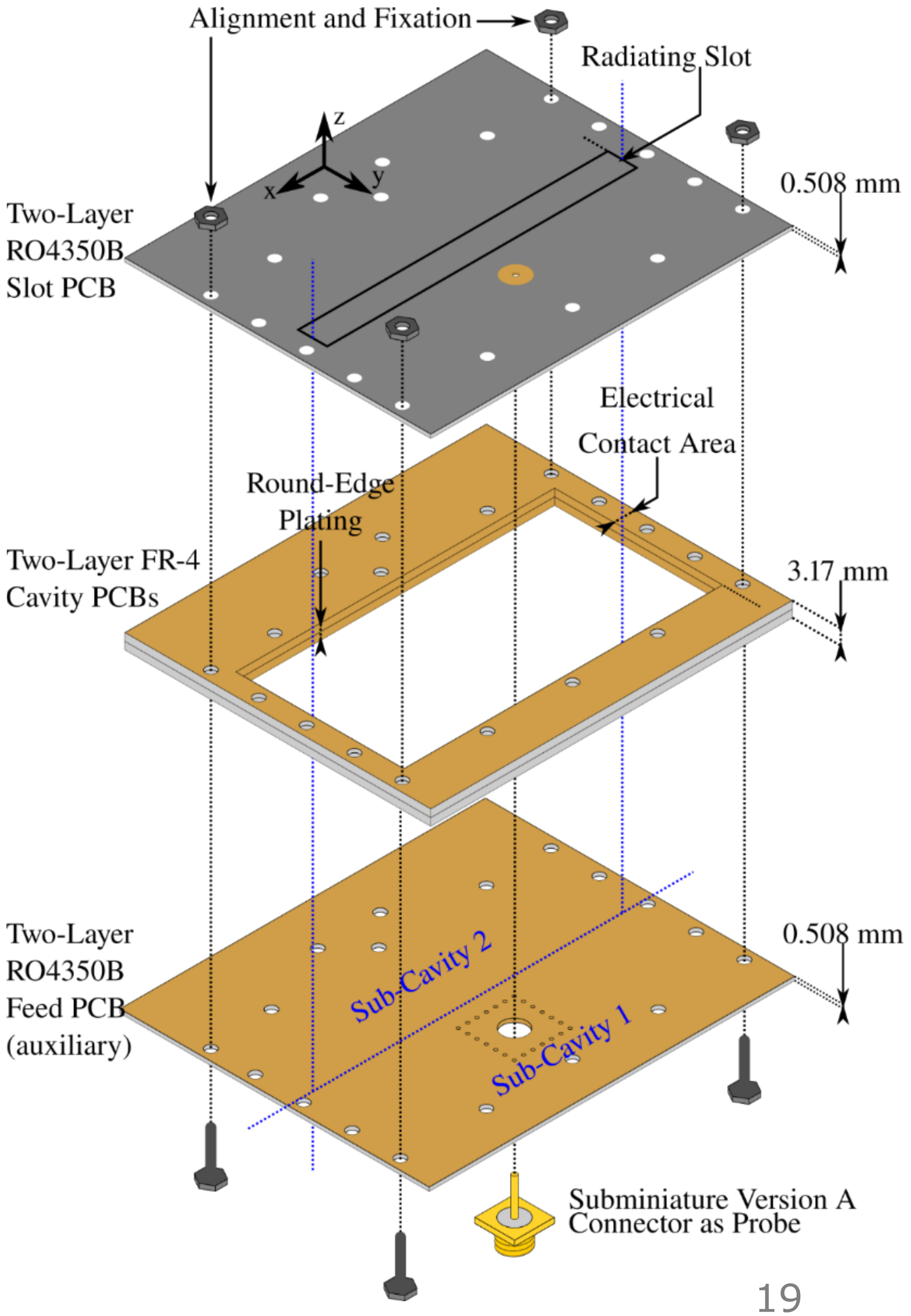
- AFSIW Cavity-Backed Slot Antenna
  - Coupled half-mode sub-cavities
    - ⇒ Bandwidth ↑
  - Air substrate
    - ⇒ Radiation efficiency ⇈ (approaching 100 %)
    - ⇒ Impedance bandwidth ↑
  - Directive radiation with linear polarization
  - High antenna / integration platform isolation







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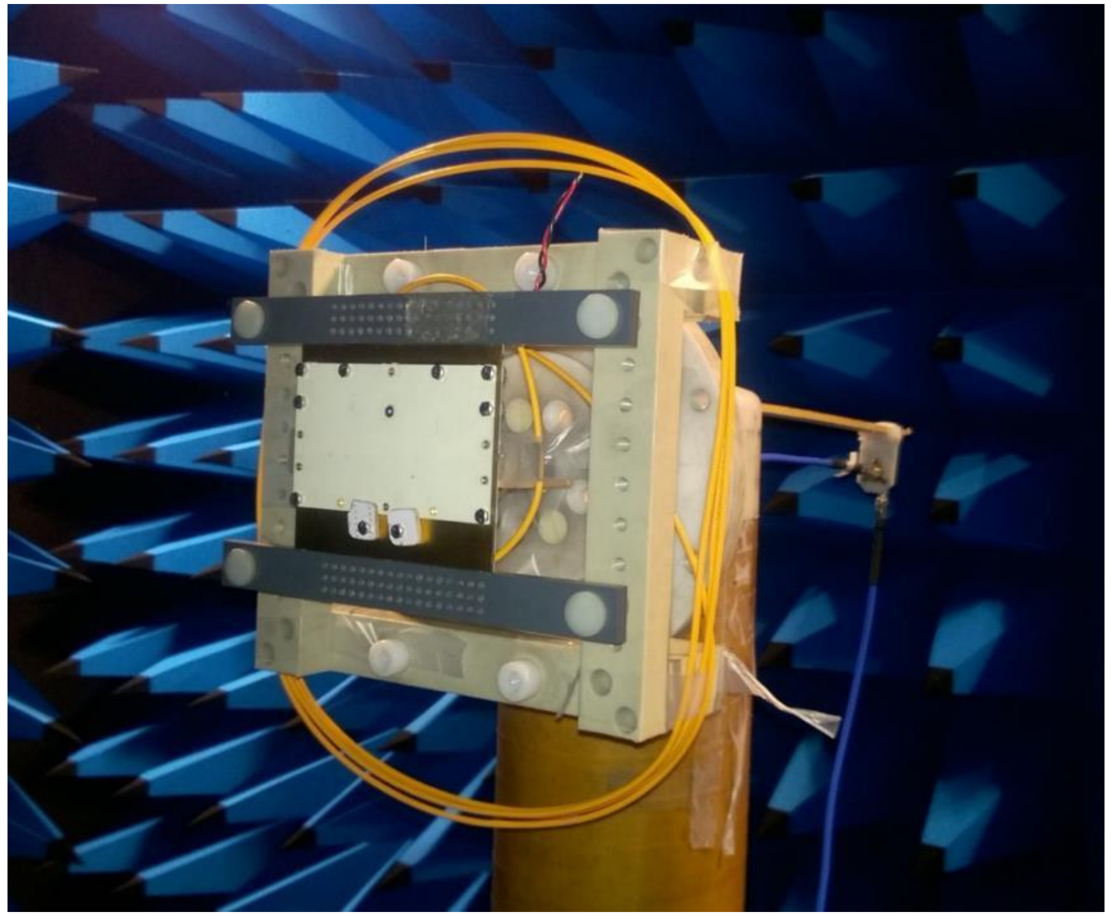
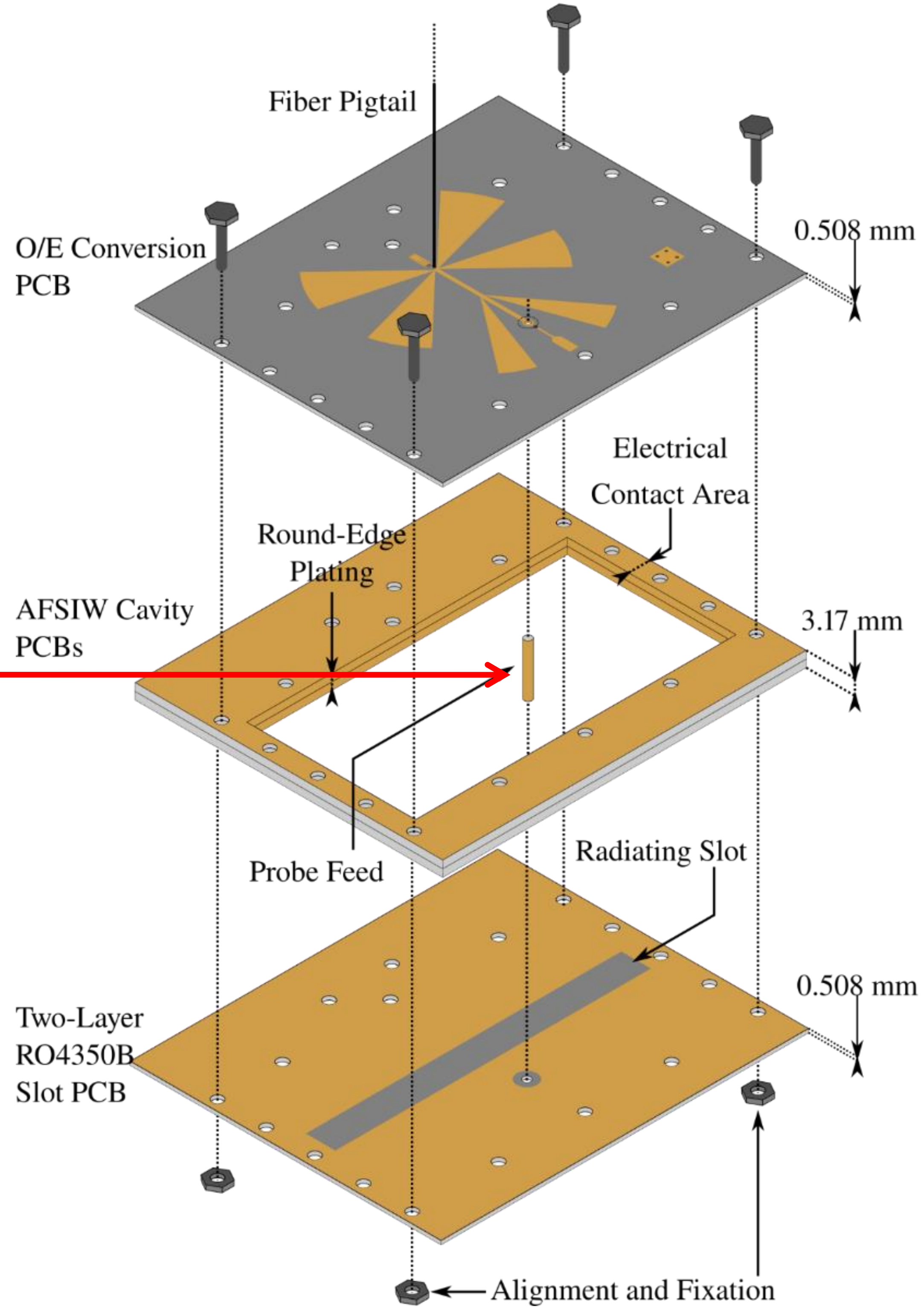
- Full opto-electronic antenna assembly
  1. Photodetector & Matching Network
  2. AFSIW Cavity-Backed Slot Antenna



O/E conversion circuit prototype →

Connecting Probe →

AFSIW Cavity-Backed Slot Antenna →



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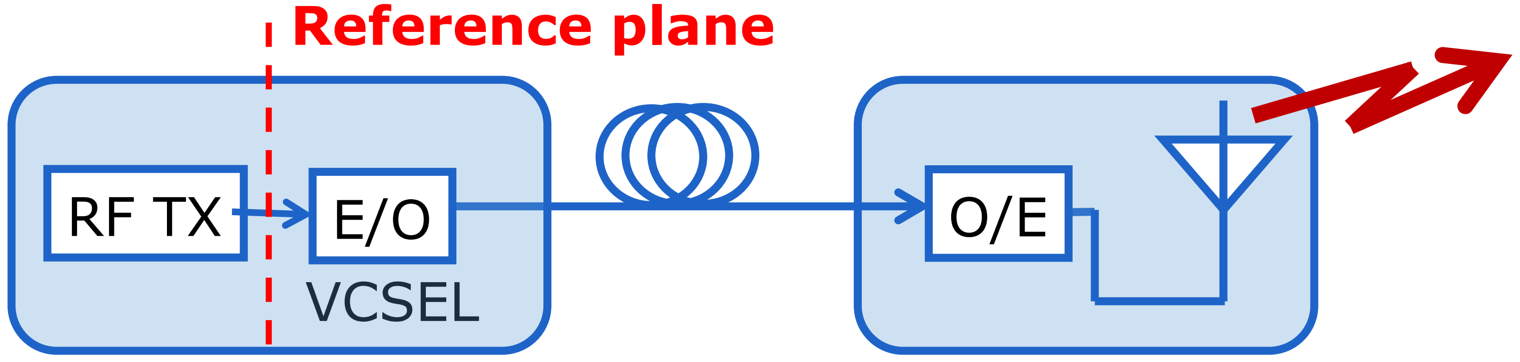
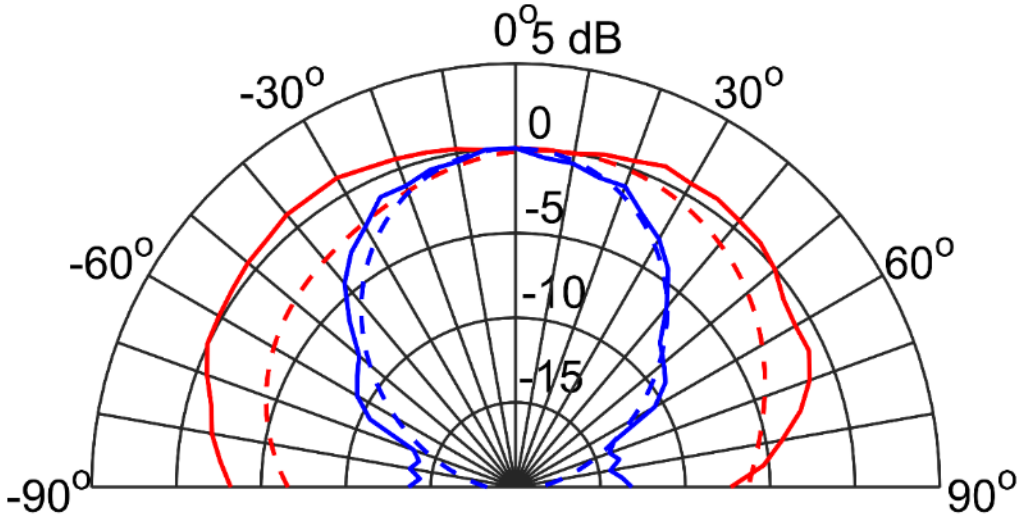
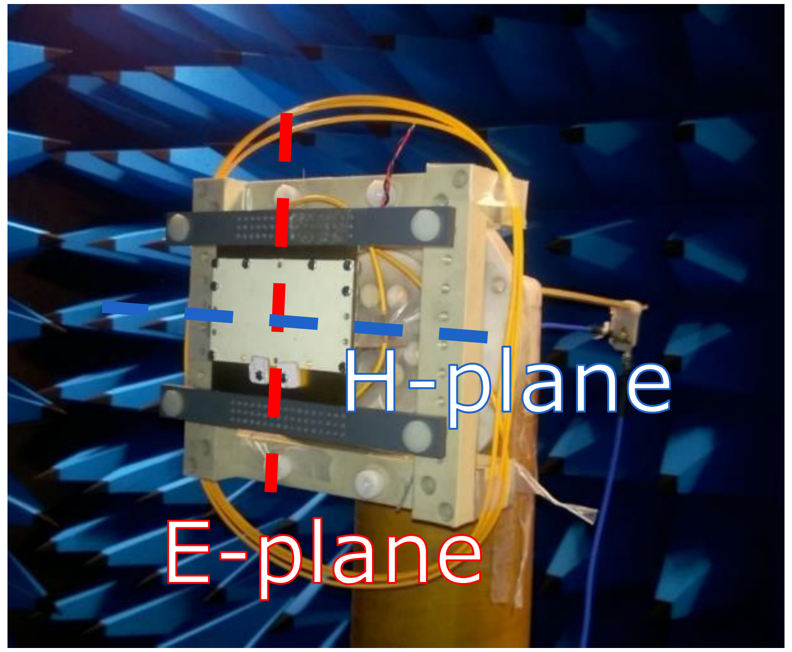
- Prototype measurements
  - Directive linearly polarized antenna
  - Boresight gain -0.2 dBi, cross polarization < -28 dB
  - −3 dB gain bandwidth of 500 MHz
  - Good performance prediction by model

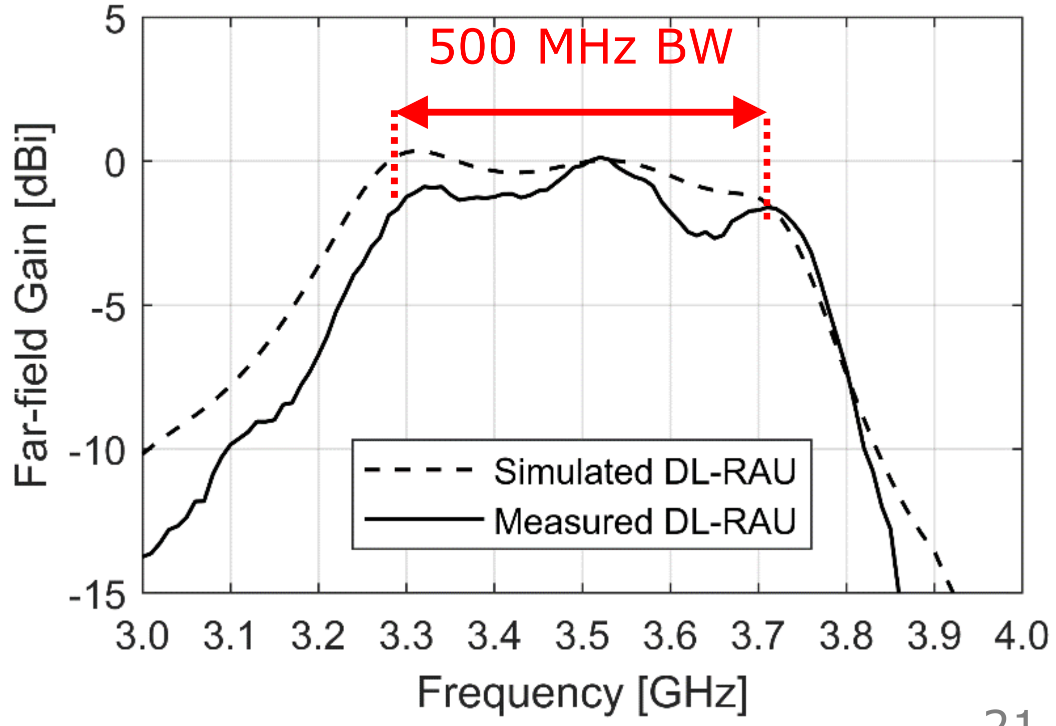




Far-field radiation patterns at 3.50 GHz:
E-plane (red) and H-plane (blue)
Measurement (solid) and simulation (dashed)



DL-RAU prototype in anechoic chamber



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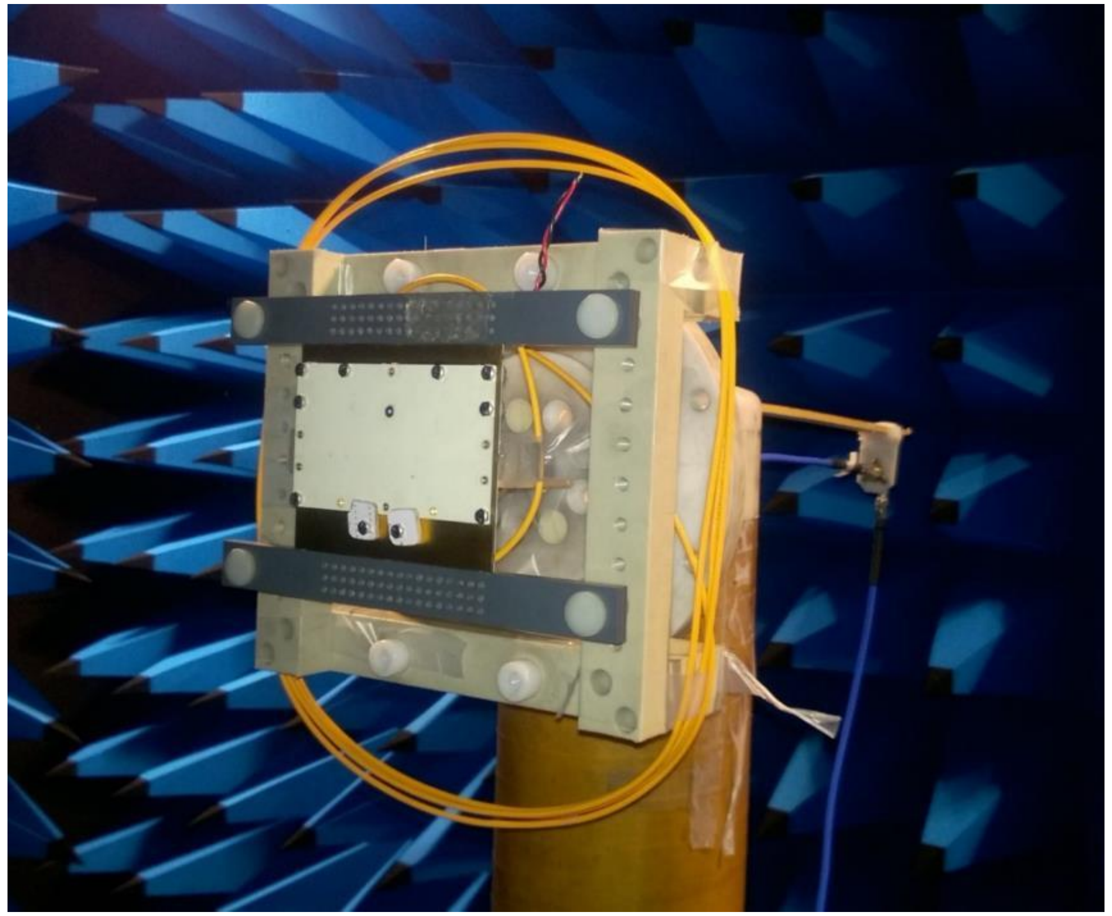
Conclusion

Lossless impedance matching network to enhance transferred power from photodetector to antenna tenfold



Passive Downlink Opto-Antenna: Compact 5.50 GHz Design

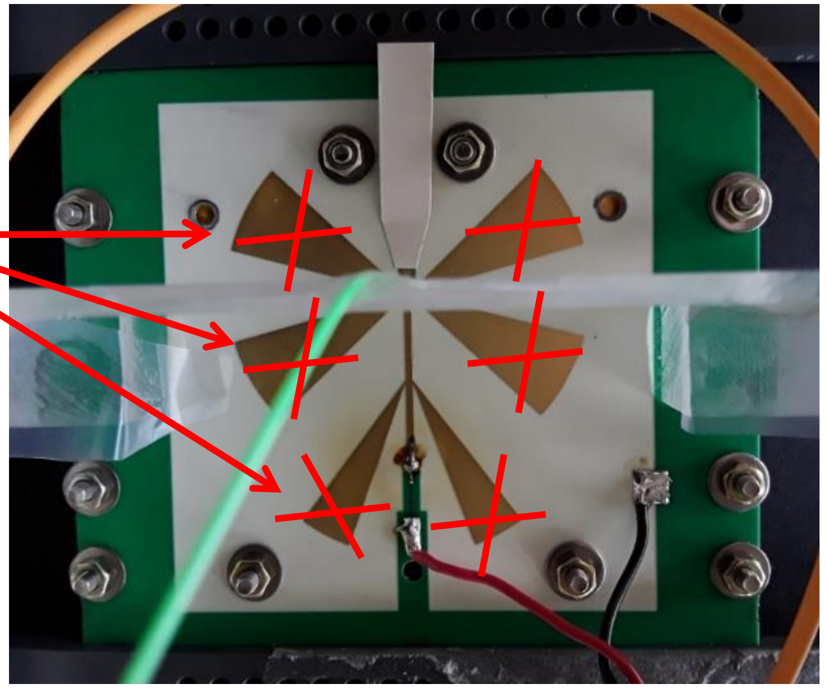
O. Caytan, L. Bogaert, H. Li, J. Van Kerrebrouck, S. Lemey, S. Agneessens, J. Bauwelinck, P. Demeester, G. Torfs, D. Vande Ginste, and H. Rogier, "Compact and wideband transmit opto-antenna for radio frequency over fiber," in *Optics Express.*

- Compact design without electrically large matching network

  → true co-design is key

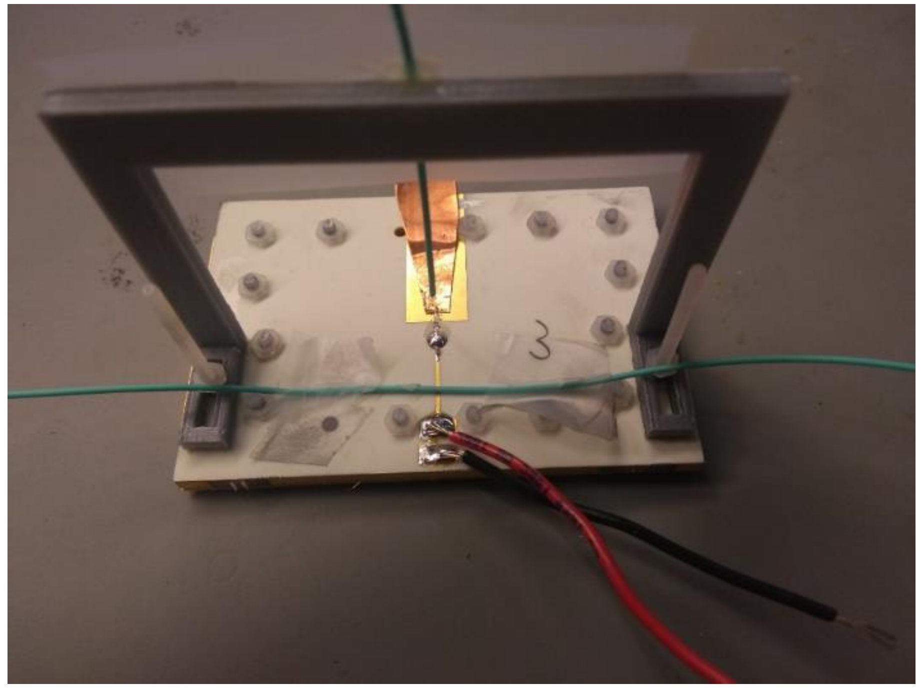
- 5.10 GHz – 5.90 GHz band (14.5 %)

radial stubs eliminated



External matching network

➔



Compact 5.50 GHz Opto-Antenna

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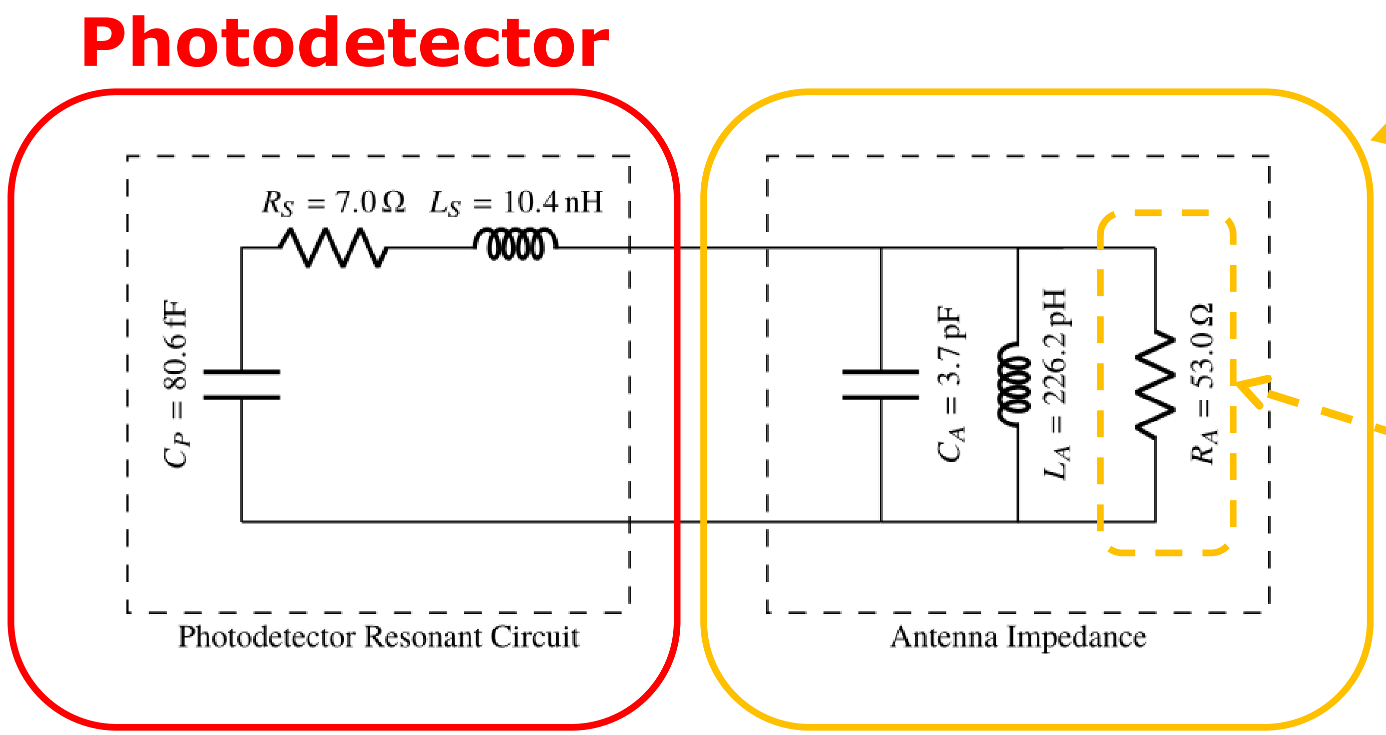

Compact design
Antenna = RLC resonator
Q=6.8 f_{res} = 5.49 GHz

Previous design
Antenna = matched to 50 Ω
LC = open shunt radial stubs

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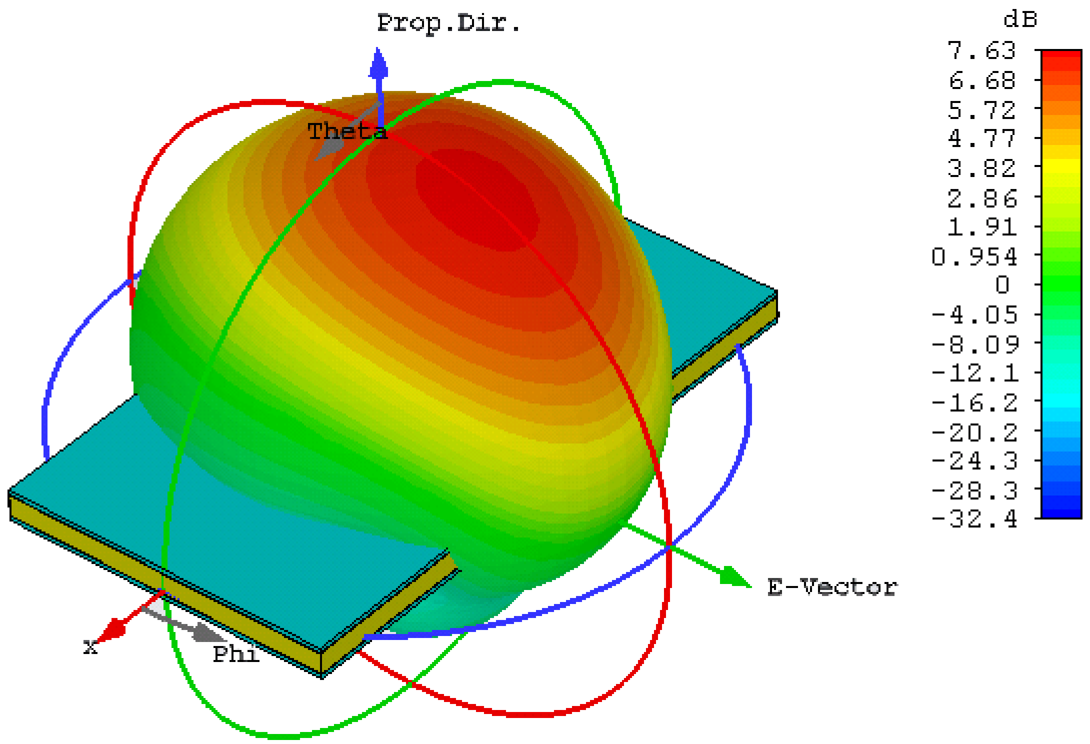
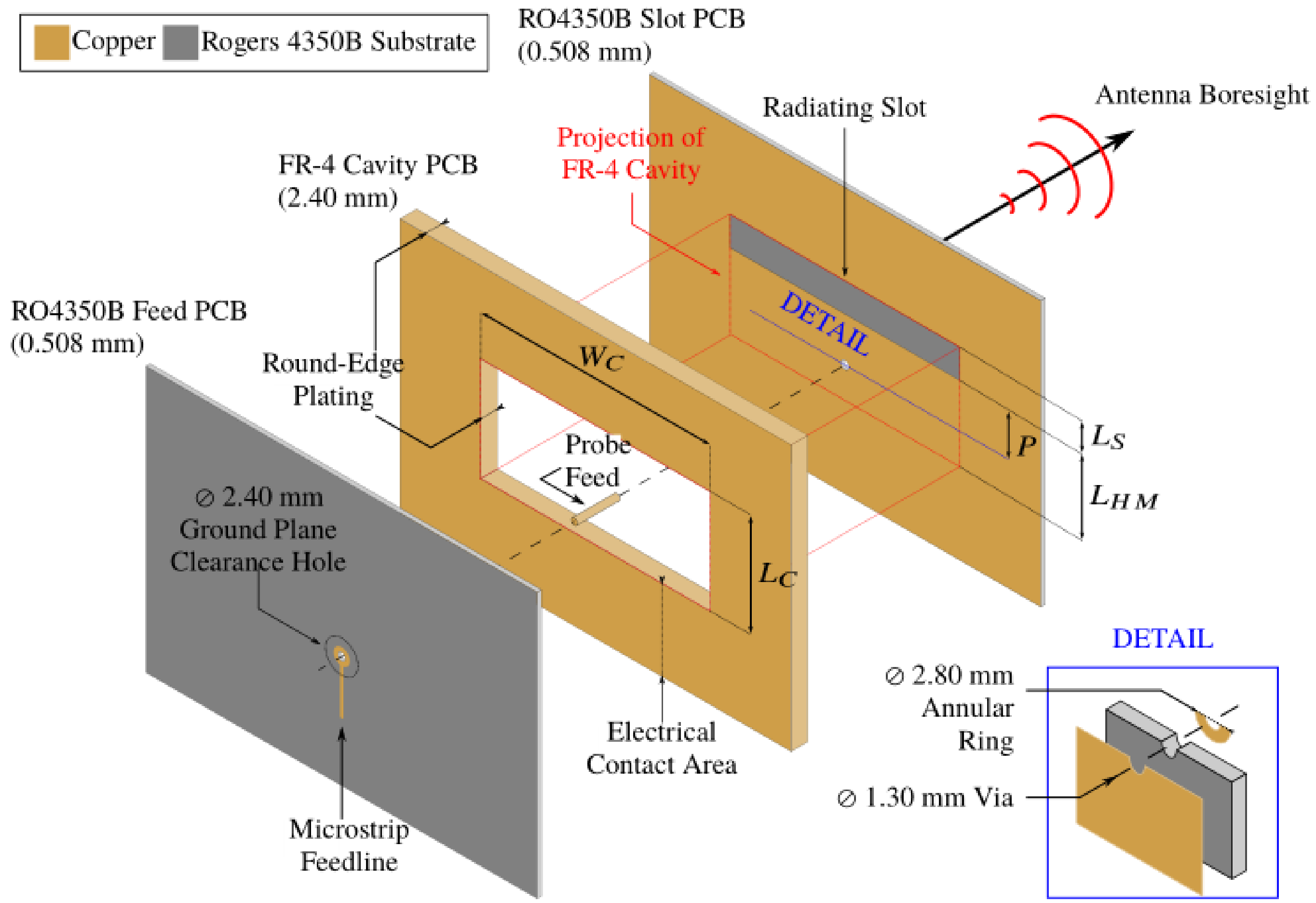
- Single half-mode AFSIW cavity matching photodetector impedance
  - Codesign results in more compact antenna topology
  - Similar performance to coupled half-mode antenna (approaching 100 % efficiency)





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- Full opto-antenna assembly
  1. O/E conversion circuit
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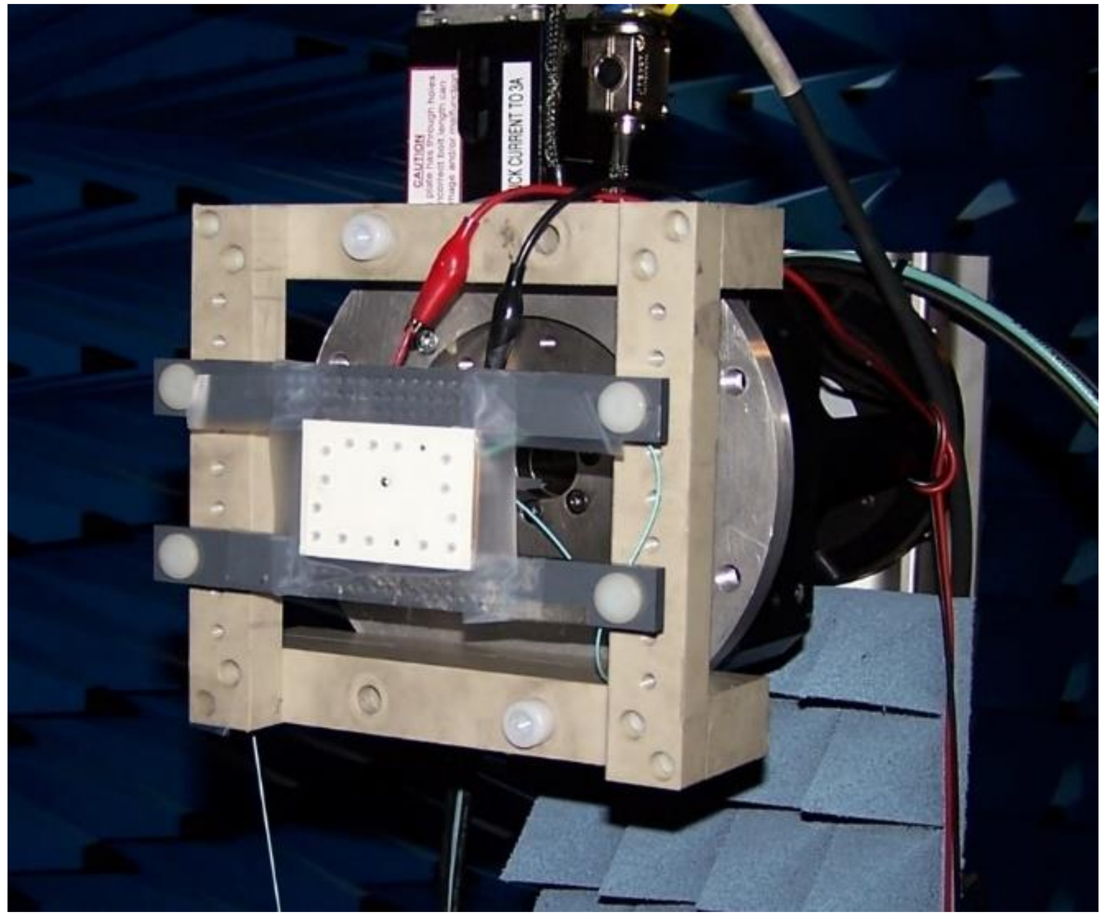

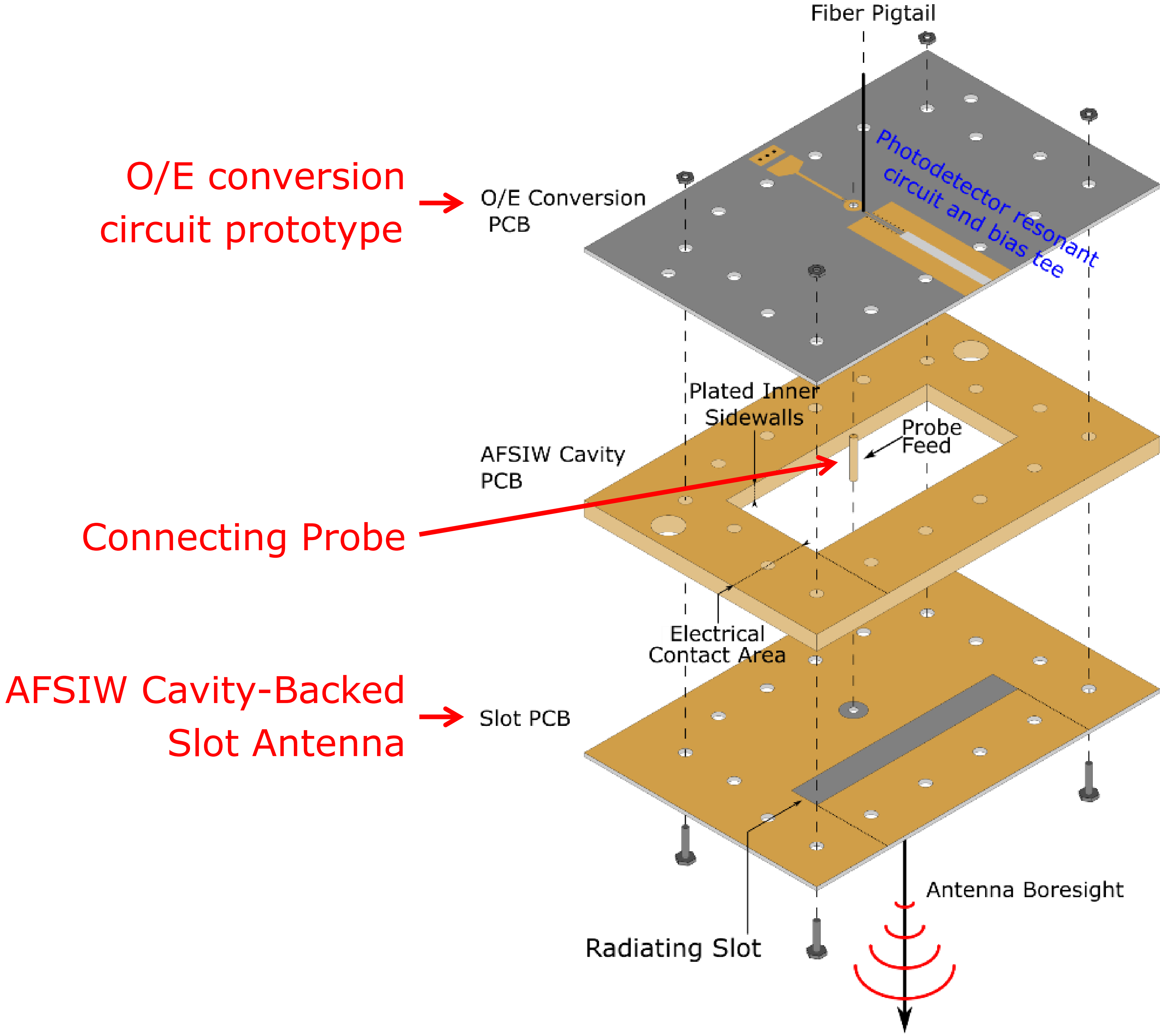

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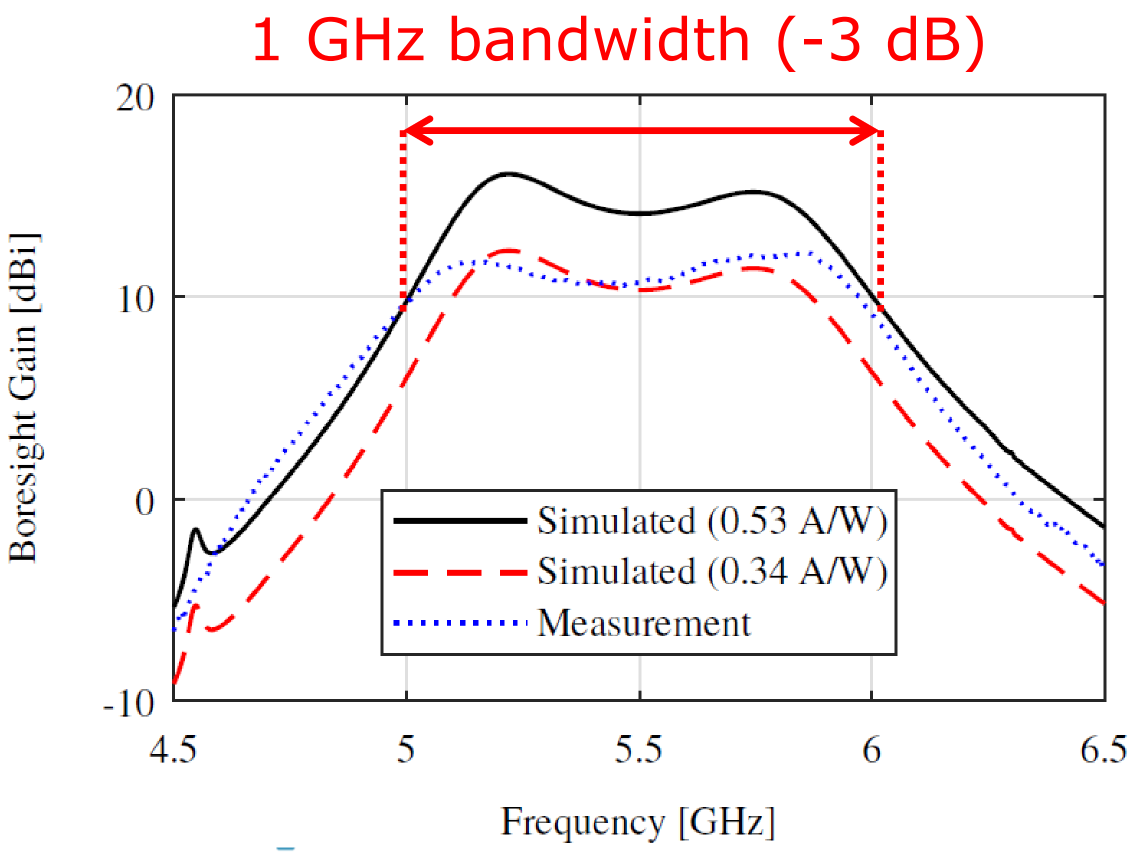
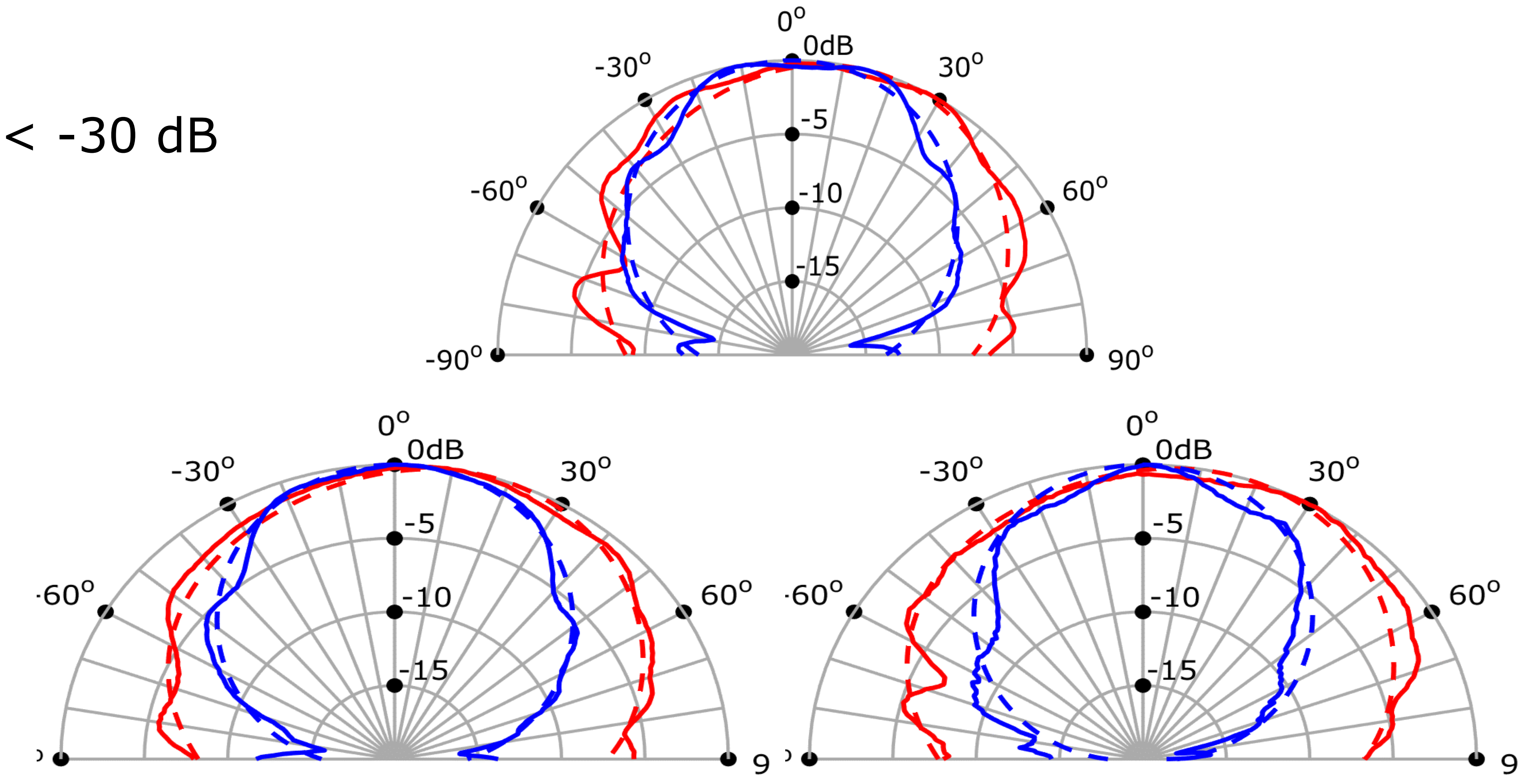
- Prototype measurements **(normalized w.r.t. laser)**
  - Directive linearly polarized antenna
  - Boresight gain 10.5 dBi, cross polarization < -30 dB
  - −3 dB gain bandwidth of 1 GHz
  - Good performance prediction by model





Far-field gain patterns at 5.15 GHz (top), 5.5 GHz (bottom left) and 5.85 GHz (bottom right)
E-plane (red) and H-plane (blue)
Measurement (solid) and simulation (dashed)

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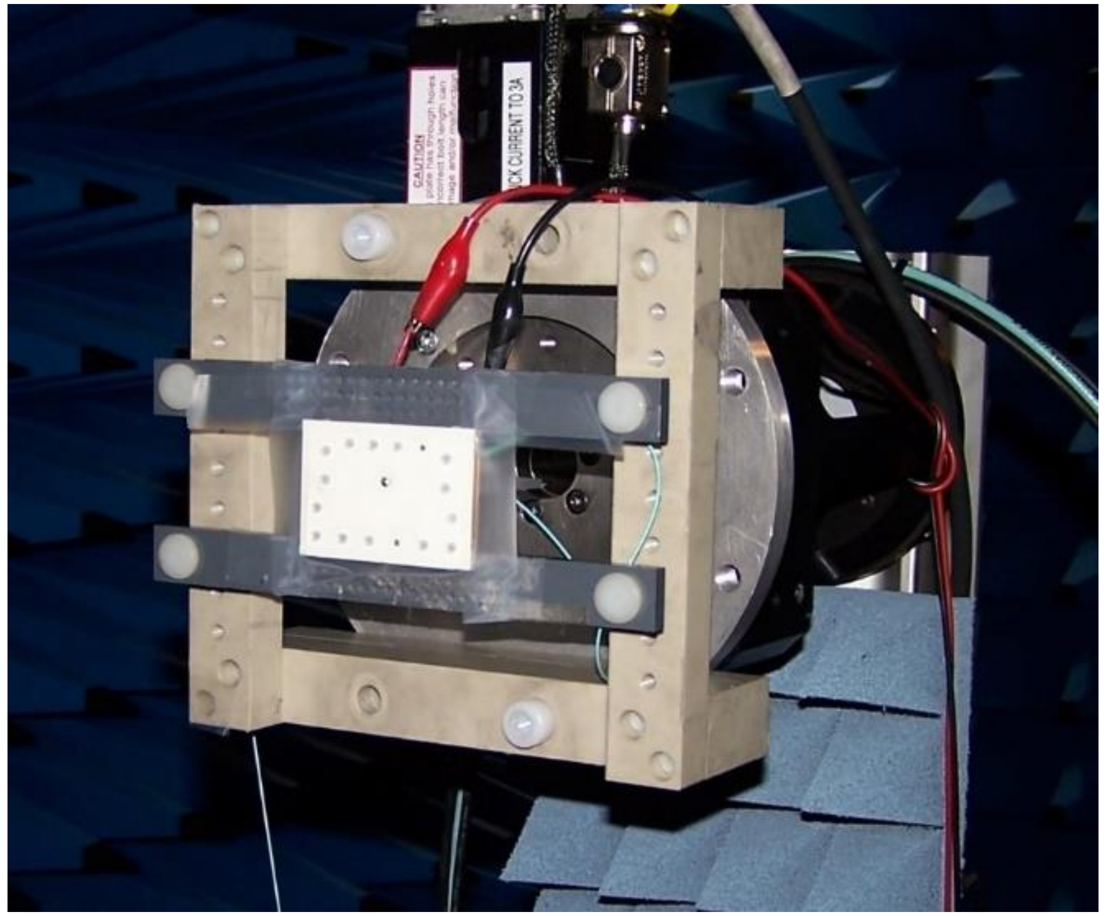
Passive Downlink Opto-Antenna: Compact 5.50 GHz Design

O. Caytan, L. Bogaert, H. Li, J. Van Kerrebrouck, S. Lemey, S. Agneessens, J. Bauwelinck, P. Demeester, G. Torfs, D. Vande Ginste, and H. Rogier, "Compact and wideband transmit opto-antenna for radio frequency over fiber," in *Optics Express.*

Conclusion

Thorough co-design eliminates bulky matching network
and associated losses and spurious radiation
while resulting in a more compact antenna topology

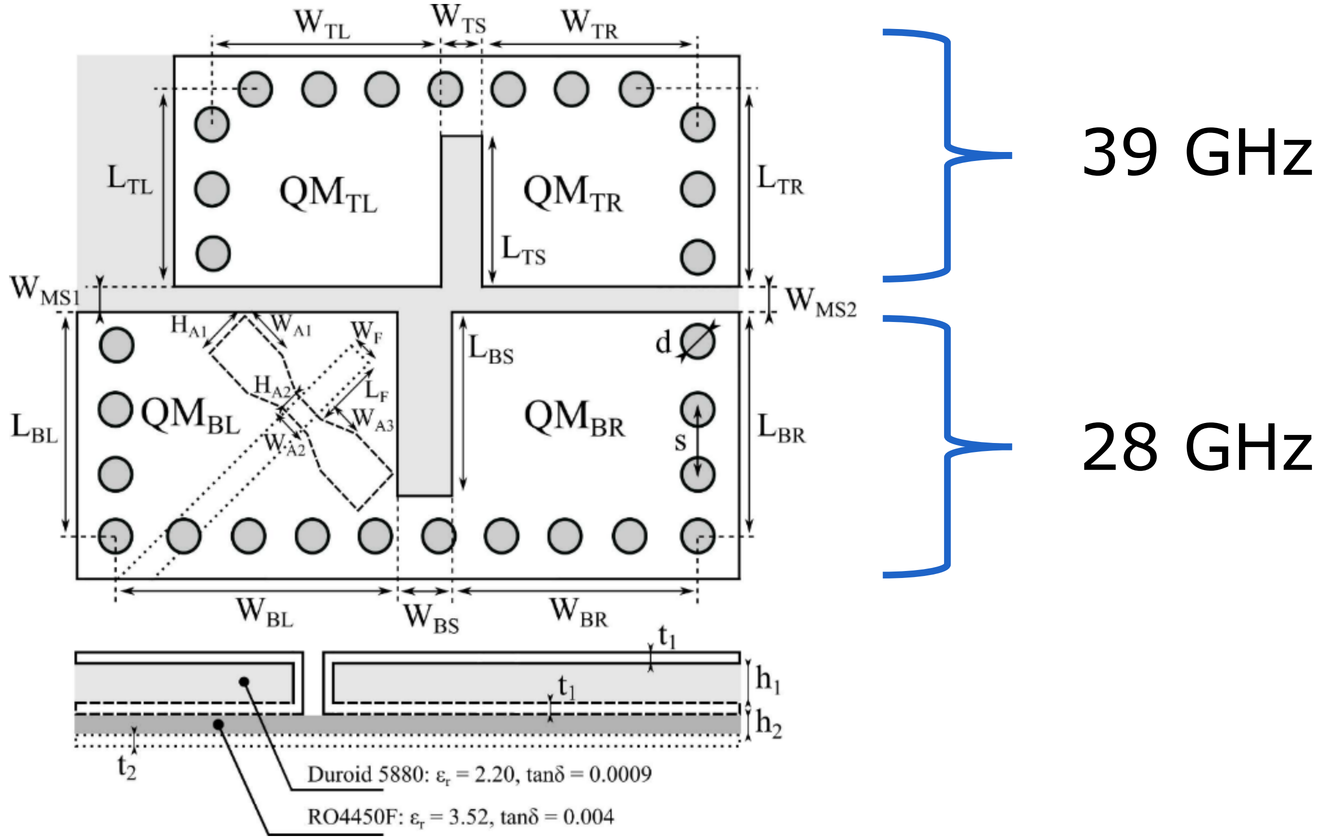


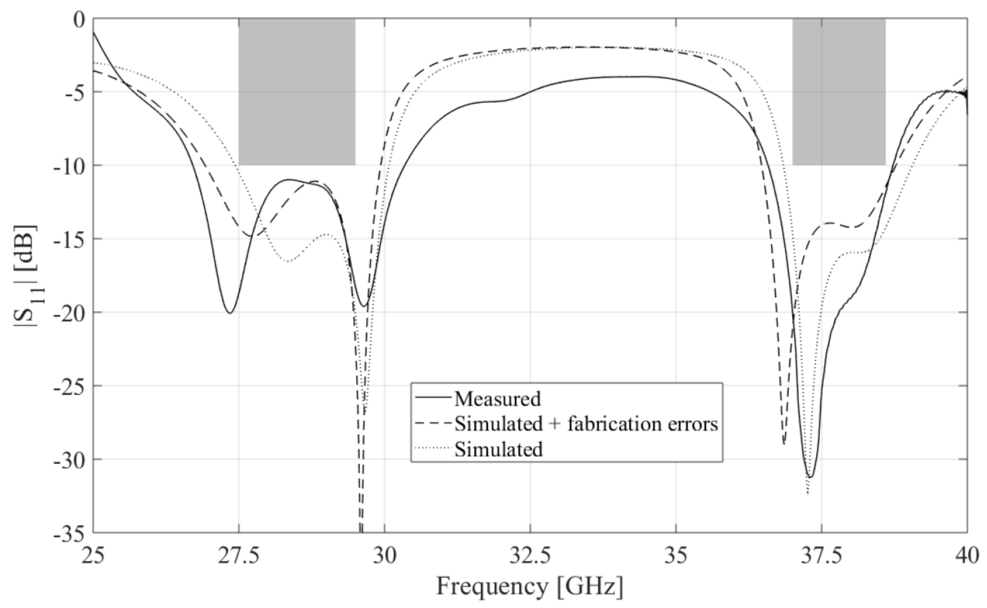
Millimeter-Wave Antennas

28/38 GHz Dual 5G-Band 1x4 Linear Array

T. Deckmyn, M. Cauwe, D. Vande Ginste, H. Rogier, and S. Agneessens, “Dual-Band 28/38 GHz Coupled Quarter-Mode Substrate Integrated Waveguide Antenna Array for Next-Generation Wireless Systems,” in *IEEE Transactions on Antennas and Propagation.*

- Wideband and dual 5G-band performance
  - 28 GHz band: 27.5 GHz – 29.5 GHz
  - 39 GHz band: 37 GHz – 38.6 GHz
  - Four coupled QMSIW cavities with single feed
- Compact, low-profile and cost-effective
  - dimensions ~λ/2 ➔ array implementation
  - 508 µm Rogers Duroid 5880 laminate antenna layer
  - 100 µm Rogers RO4450F feeding layer





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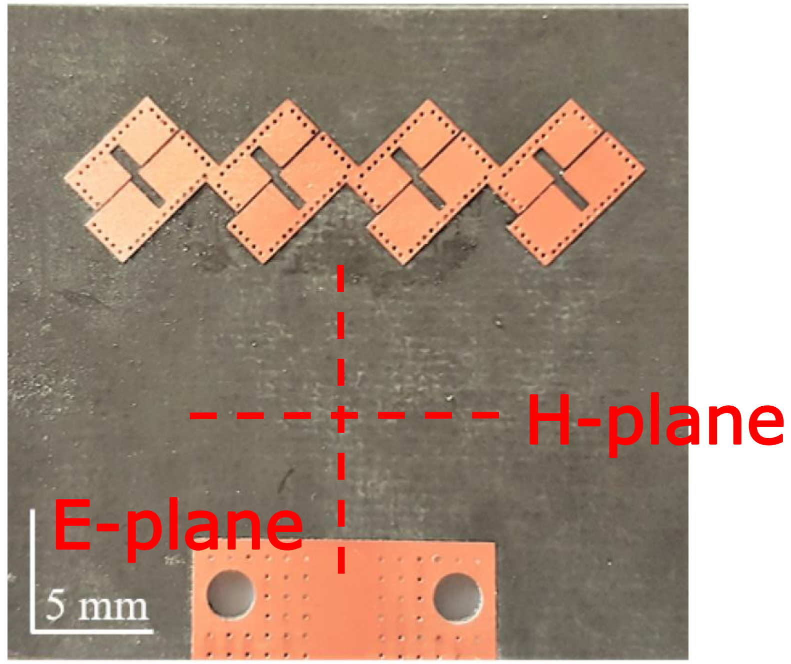
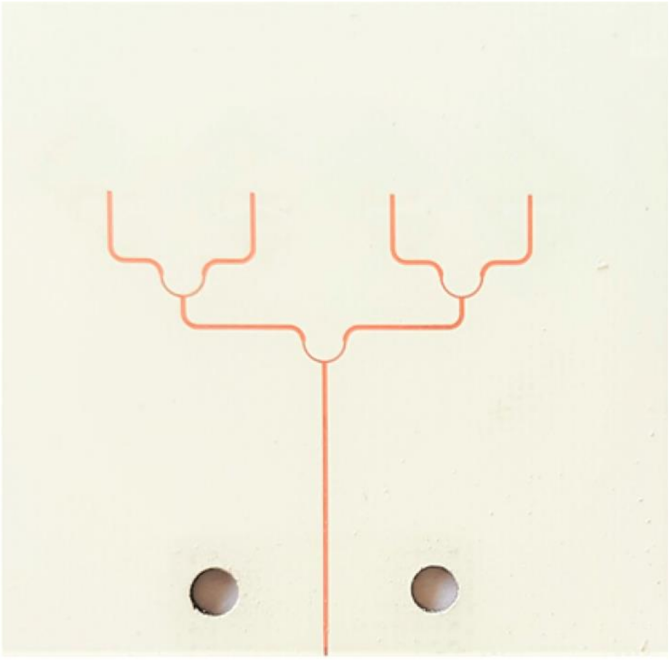


top: 1 by 4 linear array



bottom:
corporate feed network

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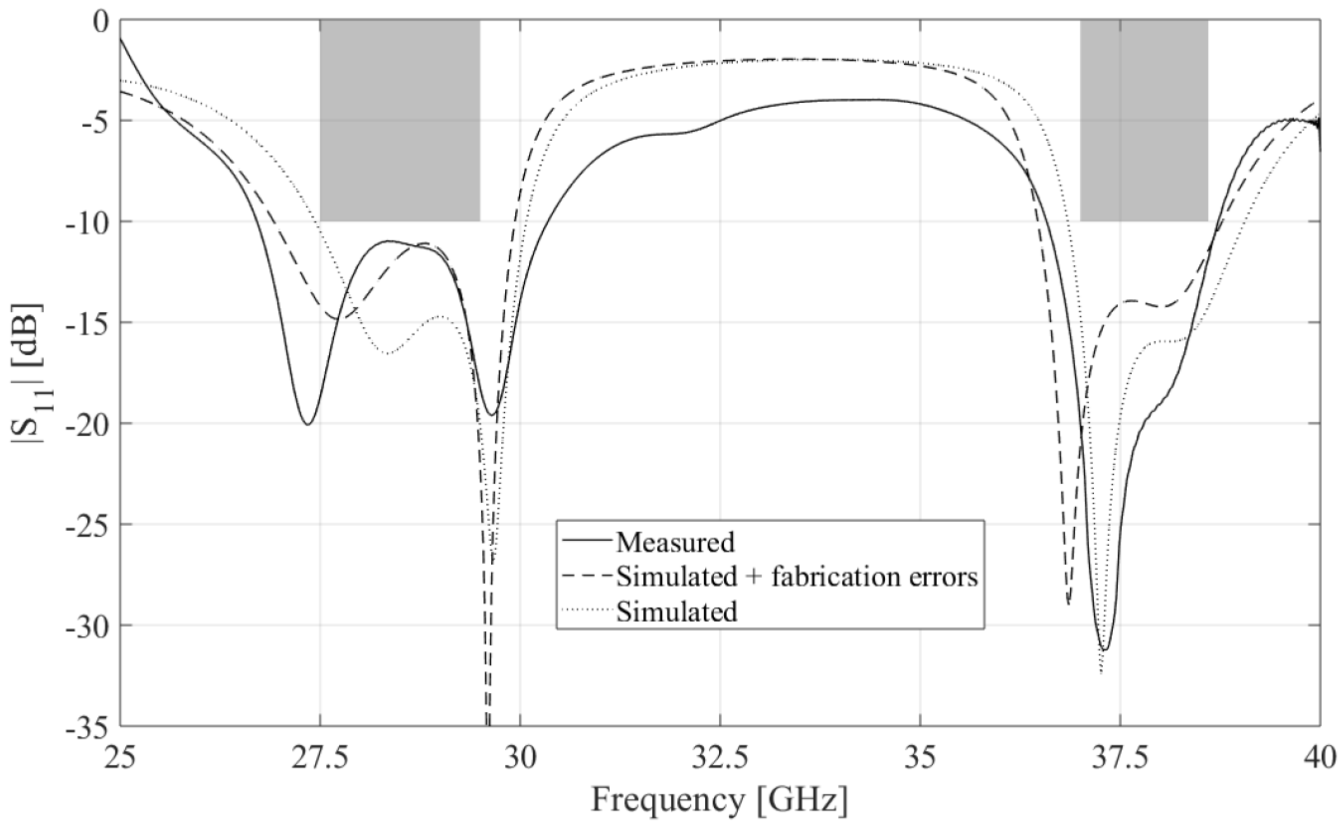
- High and robust performance

Frequency band	Bandwidth [GHz]	Gain [dBi]	Radiation efficiency [%]	H-plane beamwidth [°]
28 GHz	3.65	10.1	75.8	25
38 GHz	2.19	10.2	70.7	20

Measured array performance metrics



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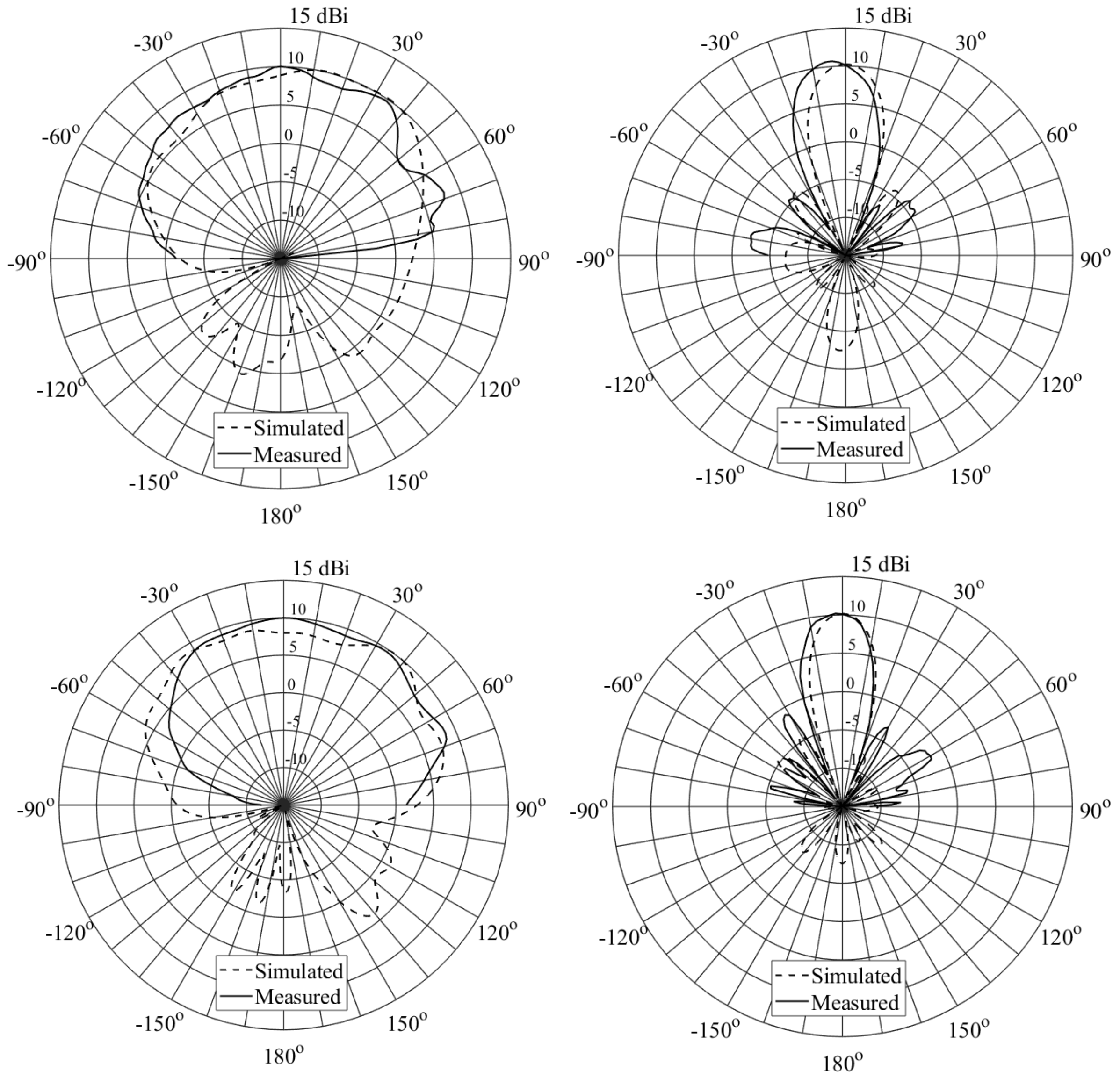

Far-field gain pattern in the
28 GHz (top) and 39 GHz (bottom) bands.
E-plane (left) and H-plane (right)
Measurement (solid) and simulation (dashed)

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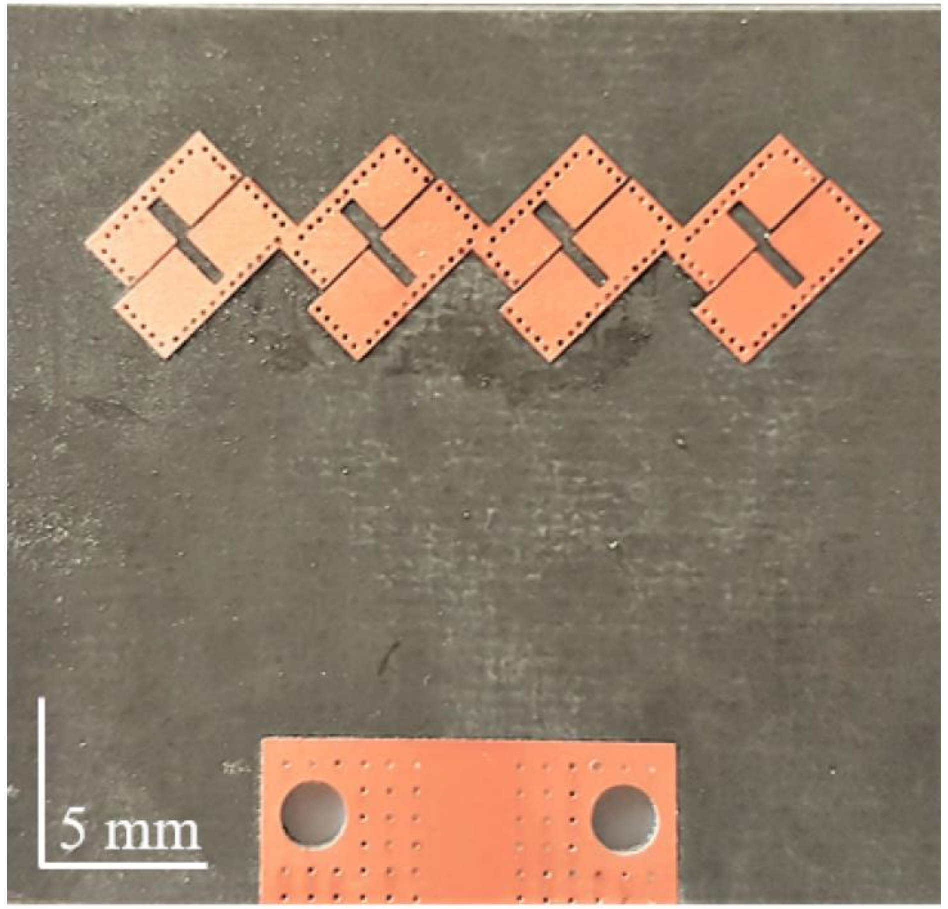
Conclusion

Wide-, multiband and efficient performance in a compact footprint
by means of multi-mode cavity with cost-effective manufacturing processes



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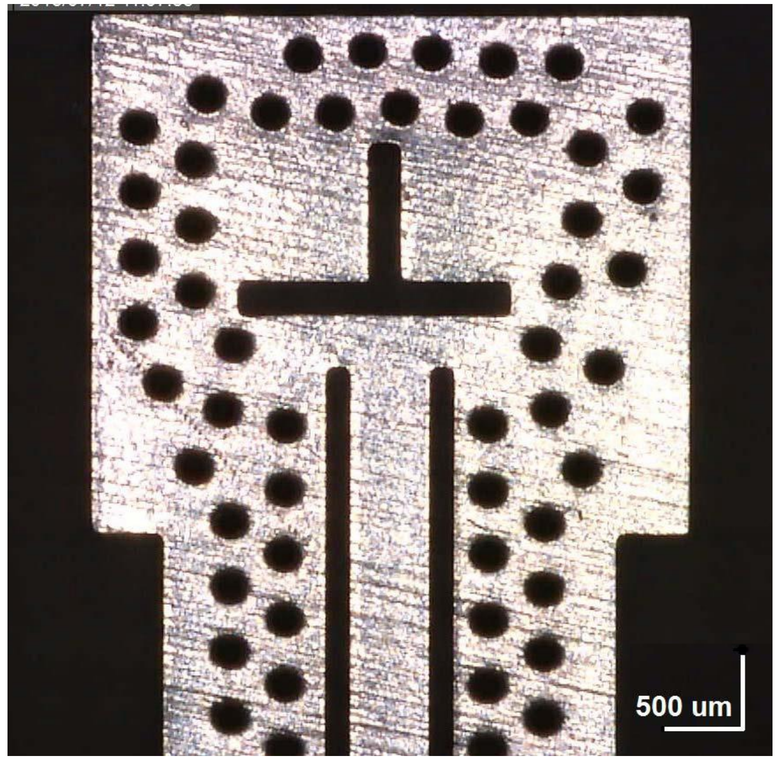
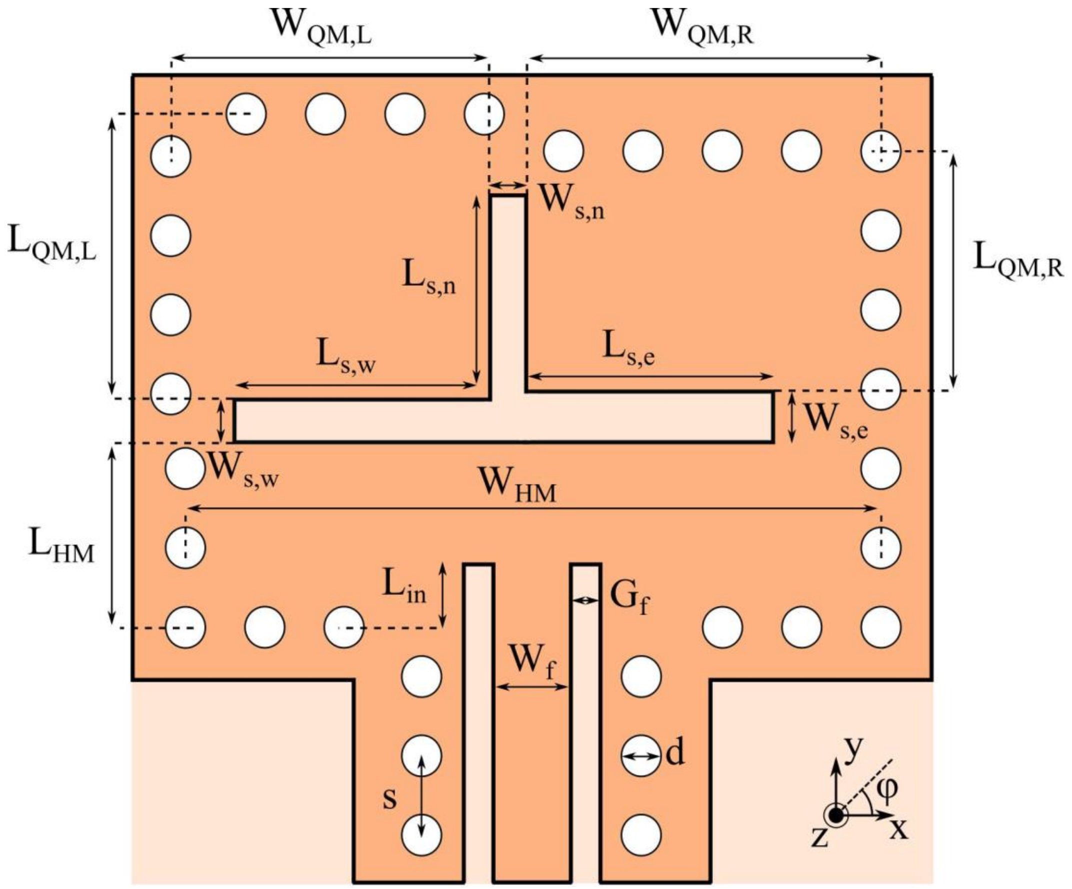
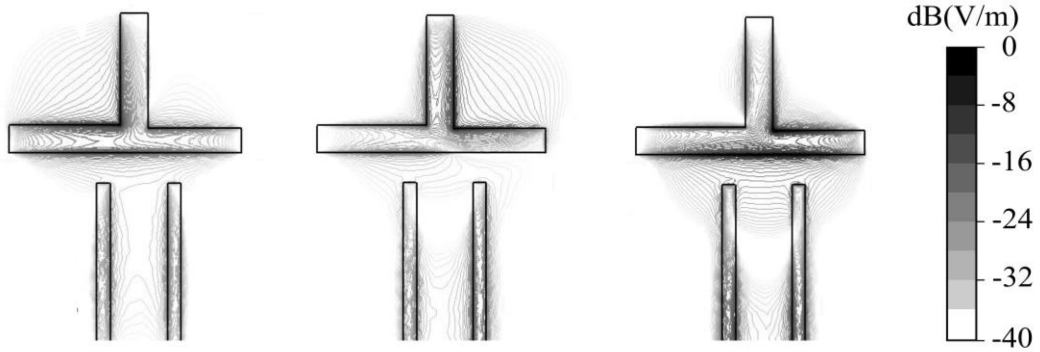
60 GHz Coupled Half/Quarter-Mode SIW Antenna

T. Deckmyn, S. Agneessens, A. C. F. Reniers, A. B. Smolders, M. Cauwe, D. Vande Ginste and H. Rogier, "A Novel 60 GHz Wideband Coupled Half-Mode/Quarter-Mode Substrate Integrated Waveguide Antenna," in *IEEE Transactions on Antennas and Propagation.*

- Wideband performance in compact footprint
  - Coupling of HMSIW and two QMSIW cavities
  - 60 GHz band: 57 GHz – 64 GHz
  - Single grounded coplanar waveguide feed
  - Integrated on single 508 μm Rogers 4350B laminate







Simulated normalized electric field distribution at 57.5 GHz, 60.4 GHz and 63 GHz

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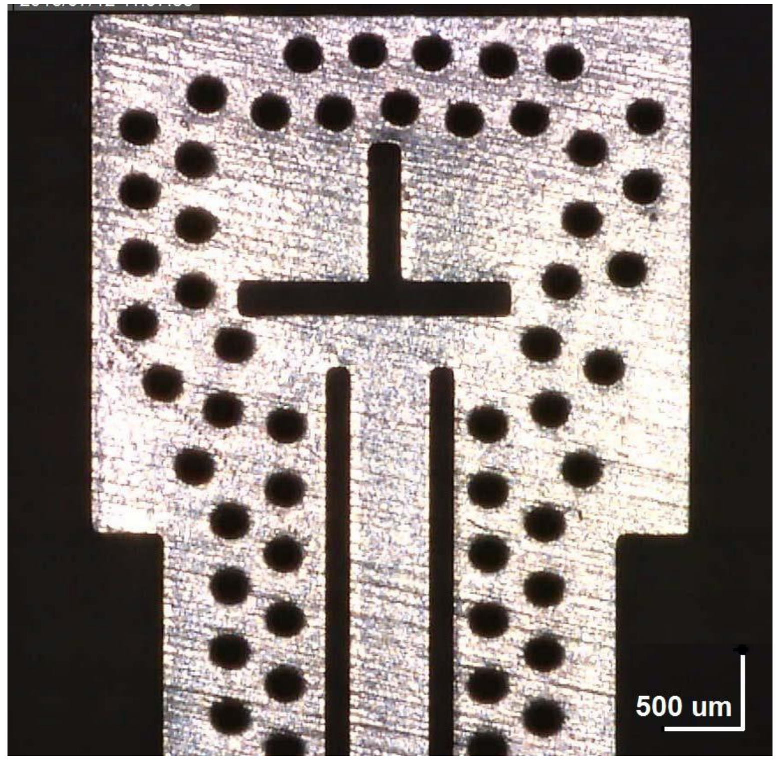
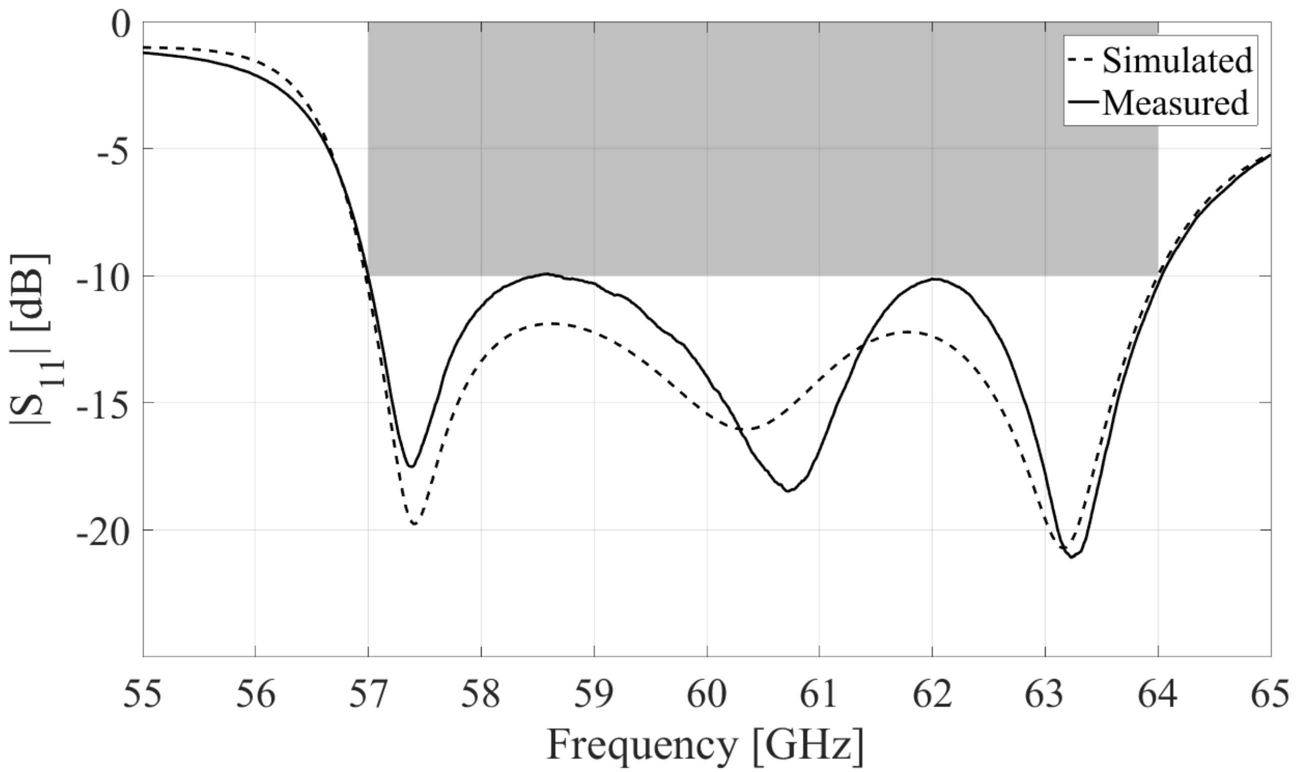
- Wideband performance in compact footprint
  - Measured impedance bandwidth of 7 GHz (11.7 %)
  - Stable gain > 5.1 dBi; radiation efficiency > 65 %
  - High antenna/platform isolation

Frequency [GHz]	Gain [dBi]	Radiation efficiency [%]
57.5	5.92	65.8
61	6.32	67.7
63	5.14	67.5





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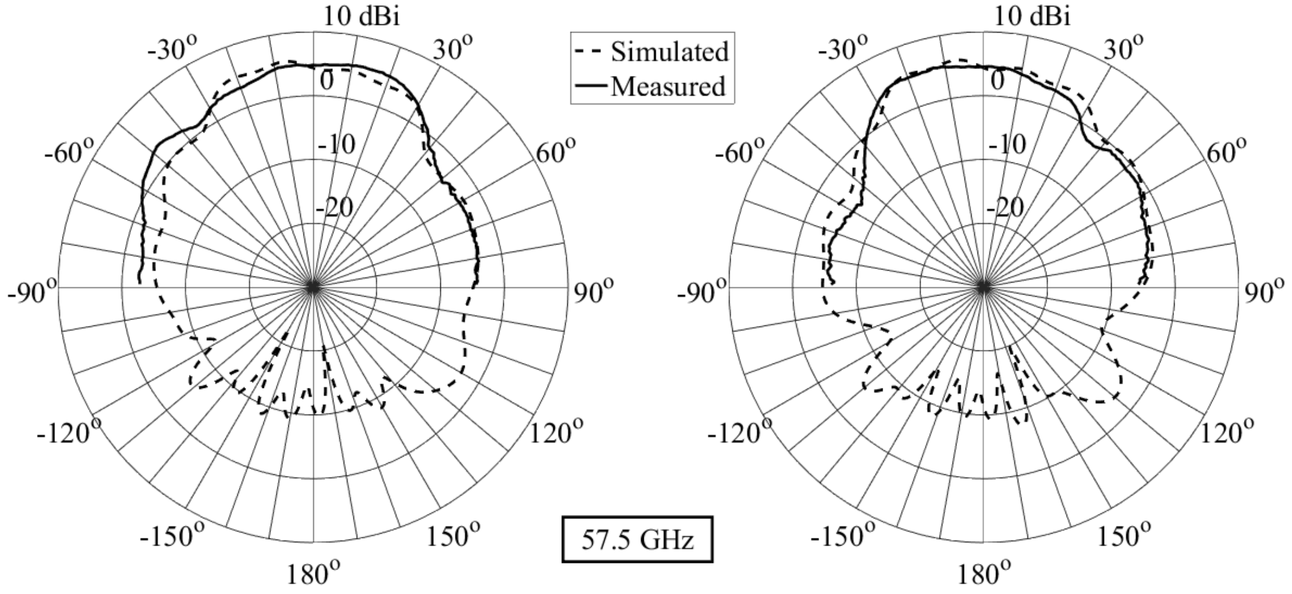

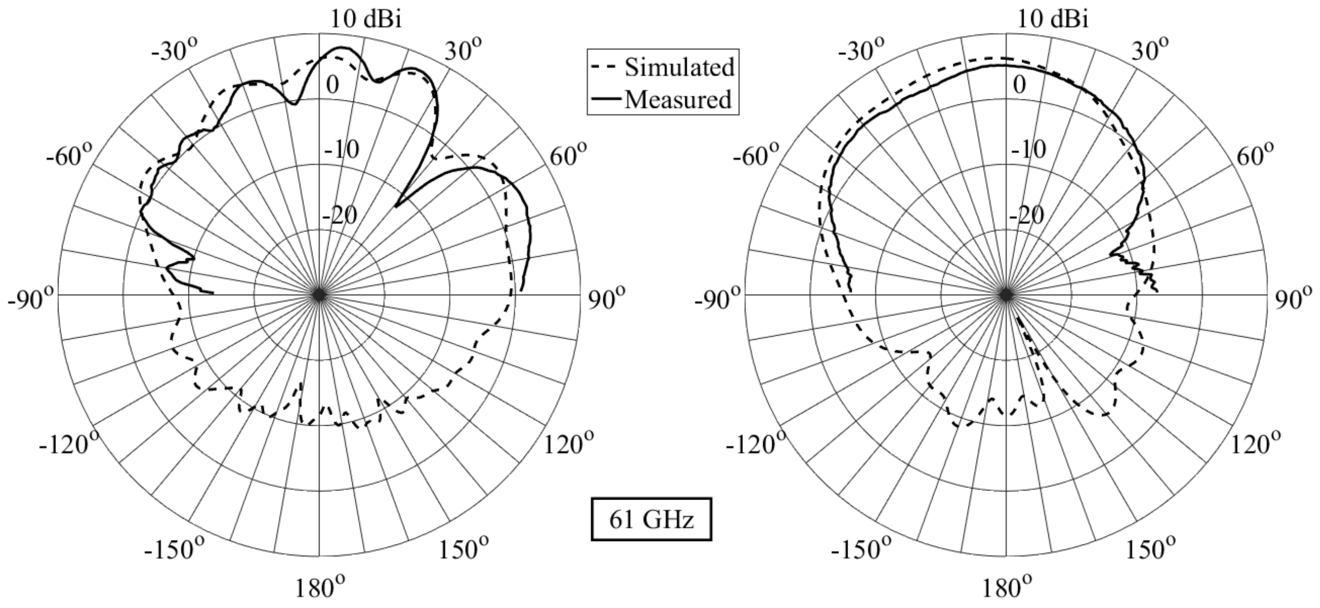

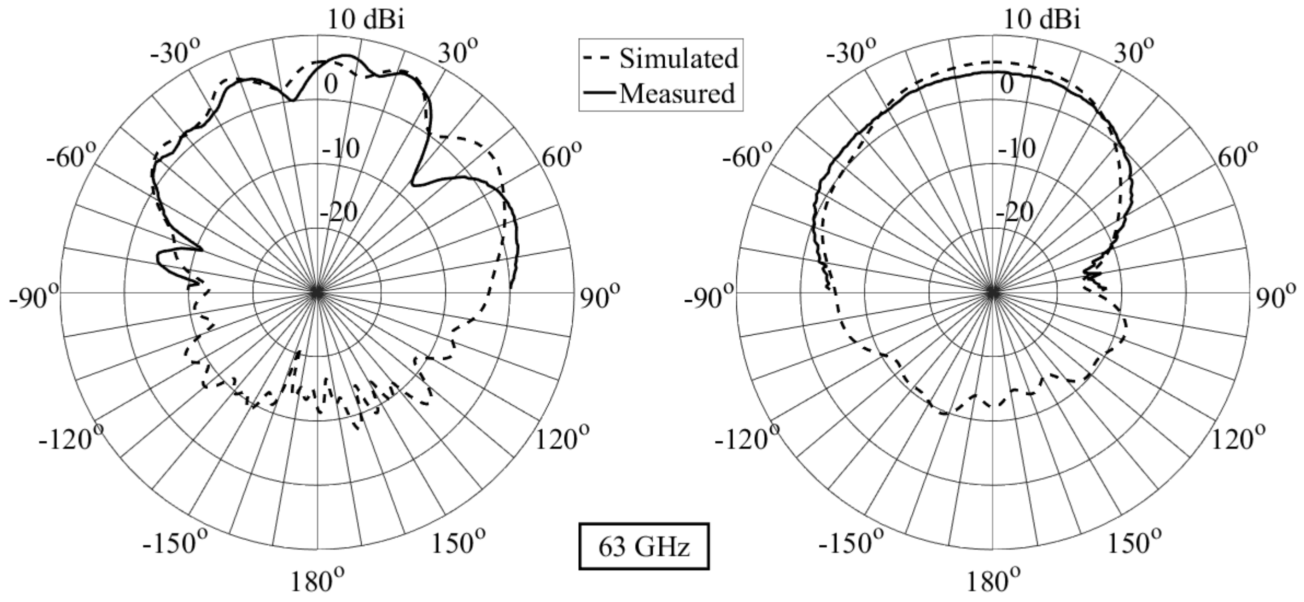

Far-field gain pattern at 57.5 GHz (top), 61 GHz (bottom left) and 63 GHz (bottom right).
E-plane (left) and H-plane (right); Measurement (solid) and simulation (dashed)

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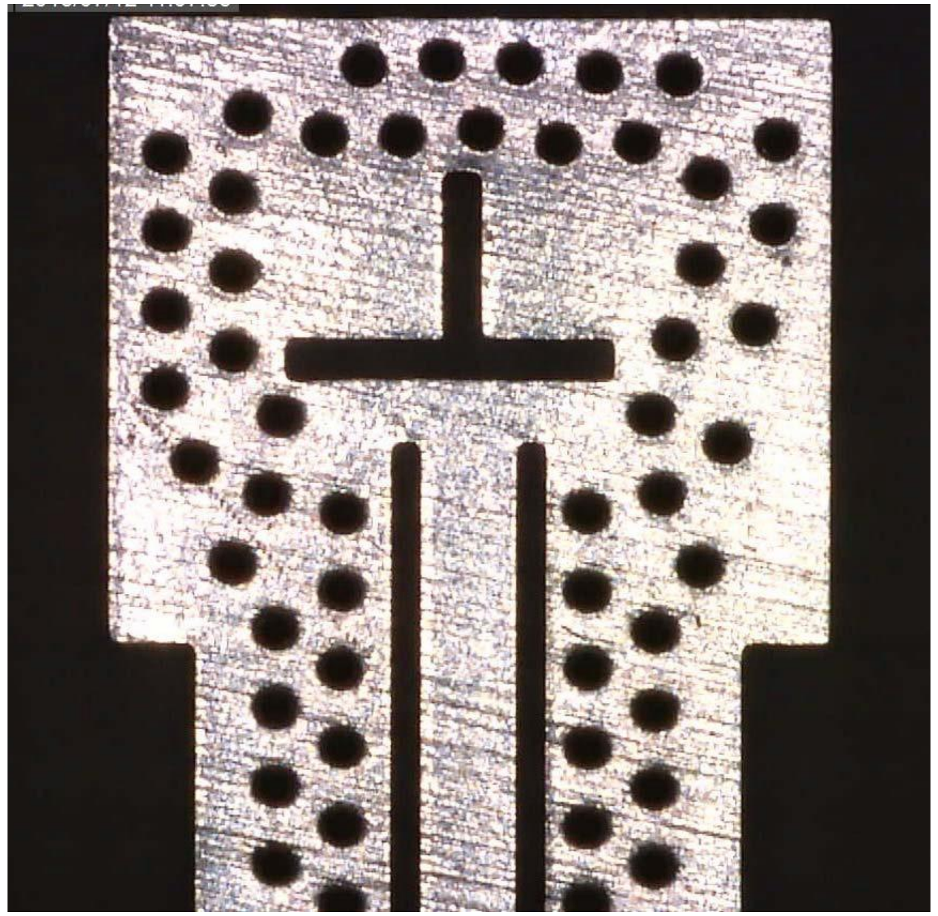
Conclusion

Wideband and efficient performance at 60 GHz in a compact footprint
by means of multi-mode cavity with cost-effective standard PCB manufacturing

Novel topology enhances cost-effectiveness, size and performance simultaneously



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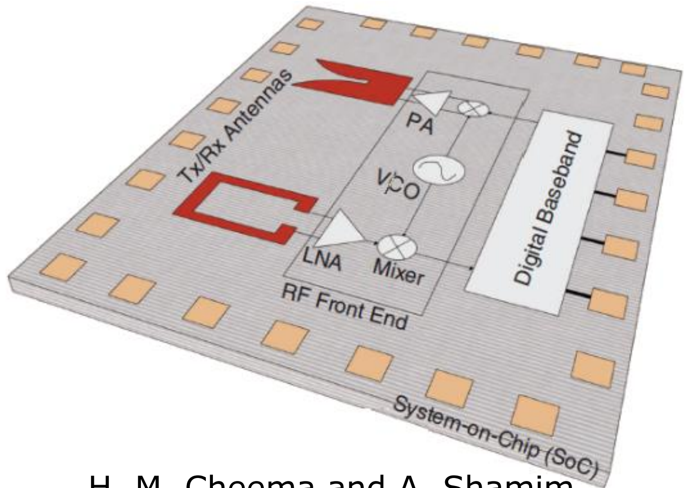
Hybrid On-Chip/In-Package Antenna Integration



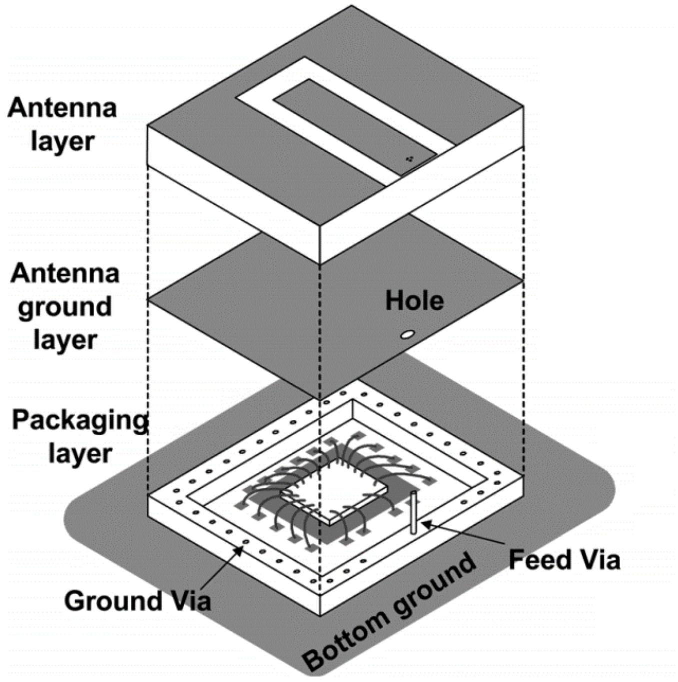
H. M. Cheema and A. Shamim, "The last barrier: on-chip antennas," in *IEEE Microwave Magazine.*

Antenna On-Chip

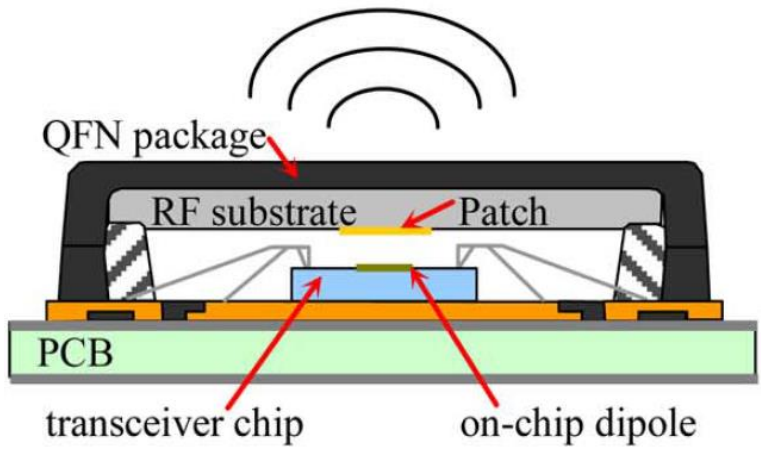
- \+ Close Integration
- – Low Performance
- – Low Efficiency

Antenna In-Package

- – Lossy Interconnection
- \+ High Performance
- \+ High Efficiency



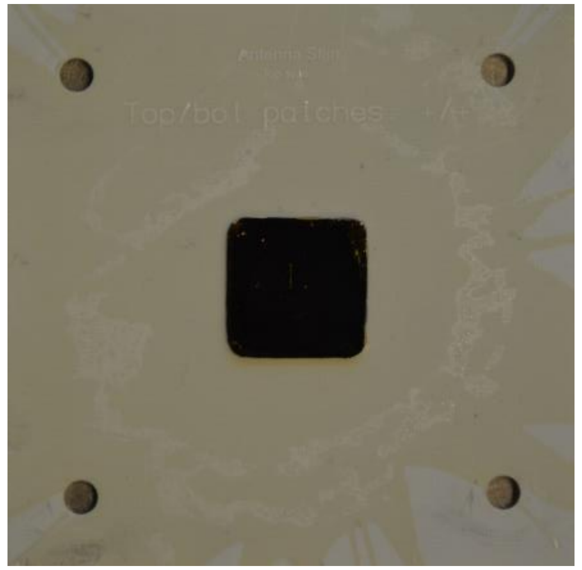
S. Wi et al., "Package-Level Integrated LTCC Antenna for RF Package Application," in *IEEE Transactions on Advanced Packaging.*



J. A. Zevallos Luna, L. Dussopt and A. Siligaris, "Hybrid On-Chip/In-Package Integrated Antennas for Millimeter-Wave Short-Range Communications," in *IEEE Transactions on Antennas and Propagation.*

Hybrid Antenna On-Chip/In-Package

- \+ Close Integration
- \+ High Performance
- \+ High Efficiency



Hybrid on-Chip/on-PCB Antenna

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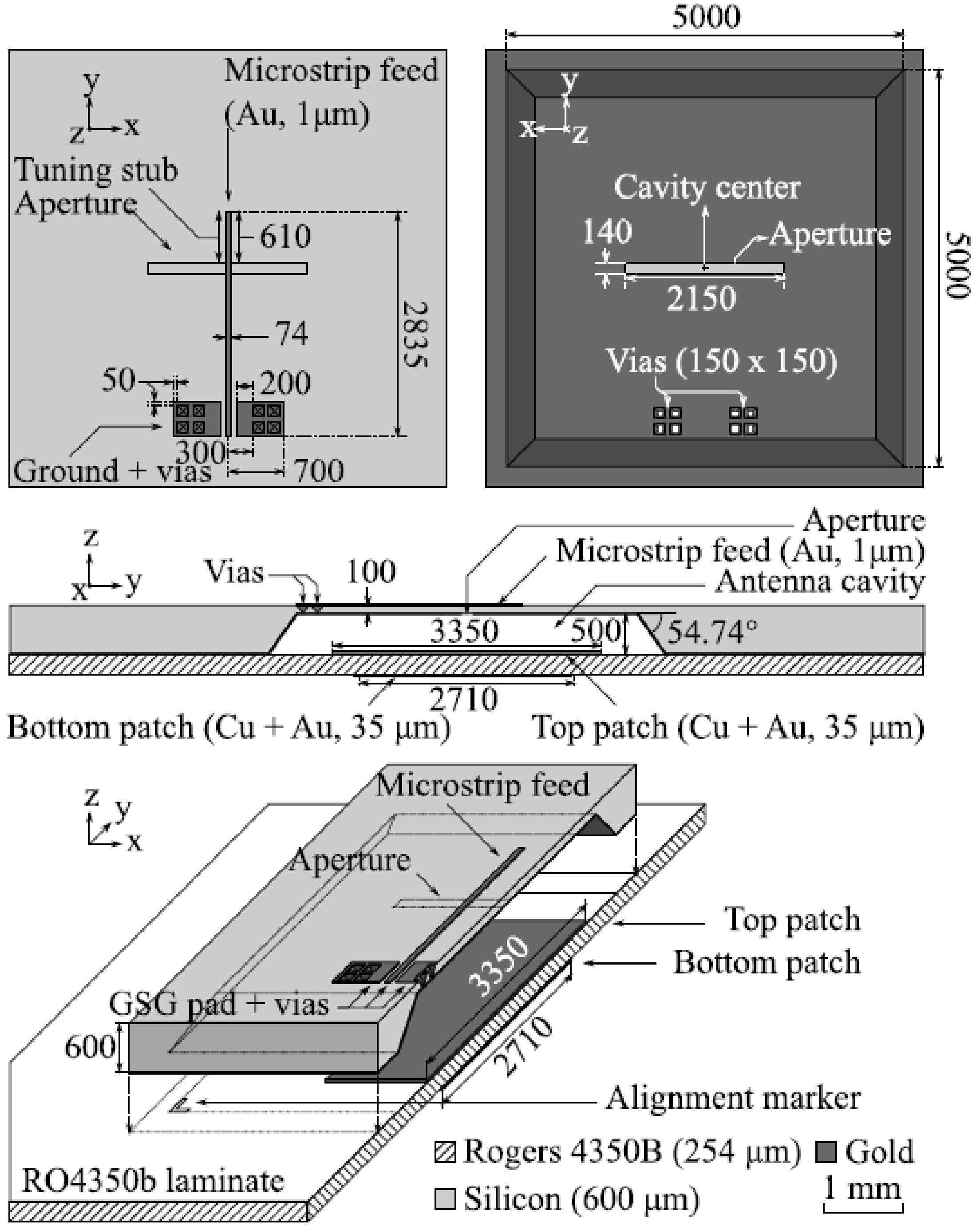
28 GHz Highly-Efficient AFSIW Hybrid On-Chip Antenna

Q. Van den Brande, S. Lemey, S. Cuyvers, S. Poelman, L. De Brabander, O. Caytan, L. Bogaert, I. Lima De Paula, S. Verstuyft, A. C. F. Reniers, B. Smolders, B. Kuyken, D. Vande Ginste and H. Rogier, "A Hybrid Integration Strategy for Compact, Broadband and Highly Efficient Millimeter-Wave On-Chip Antennas," in *IEEE Antennas and Wireless Propagation Letters.*

- Hybrid integration strategy
  - Feed structure on chip
  - Radiating elements on PCB
- State-of-the-art performance
- Standard Si processing techniques
- High isolation from active electronics
  - Front-to-back-ratio of 20.3 dB



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#	Technique	f [GHz]	BW [%]	η [%]	A [λ x λ]
1	μMachining	135	8.9	80	0.81 x 0.81
2	μMachining	60	11.8	90	0.61 x 0.95
3	μMachining	143	13.9	76	0.95 x 0.95
4	μMachining	34.5	4	95	1.15 x 1.15
5	Superstrate	93	8.5	50	0.70 x 0.50
6	AiP	143	6.9	89	0.38 x 0.38
7	AiP	60	8.8	85	2.60 x 2.60
8	AiP	29	5	N.A.	0.23 x 0.23
9	Hybrid	60	12.6	73	0.33 x 0.16
10	Hybrid	68	5.7	97	0.16 x 0.28
This	**Hybrid**	**28.5**	**13**	**91**	**0.49 x 0.49**

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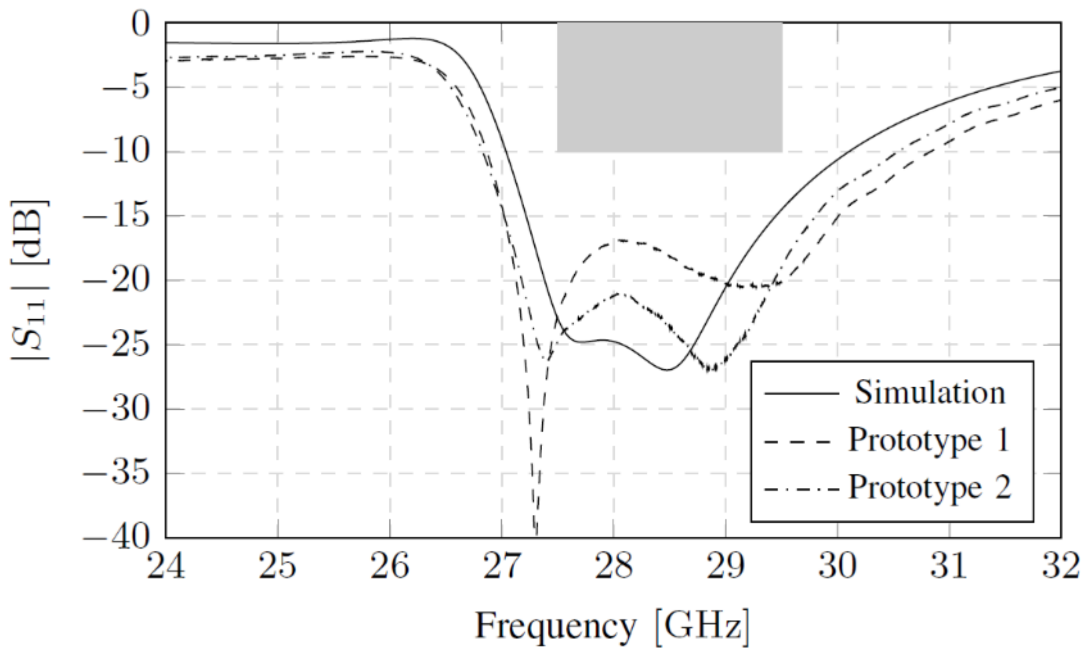

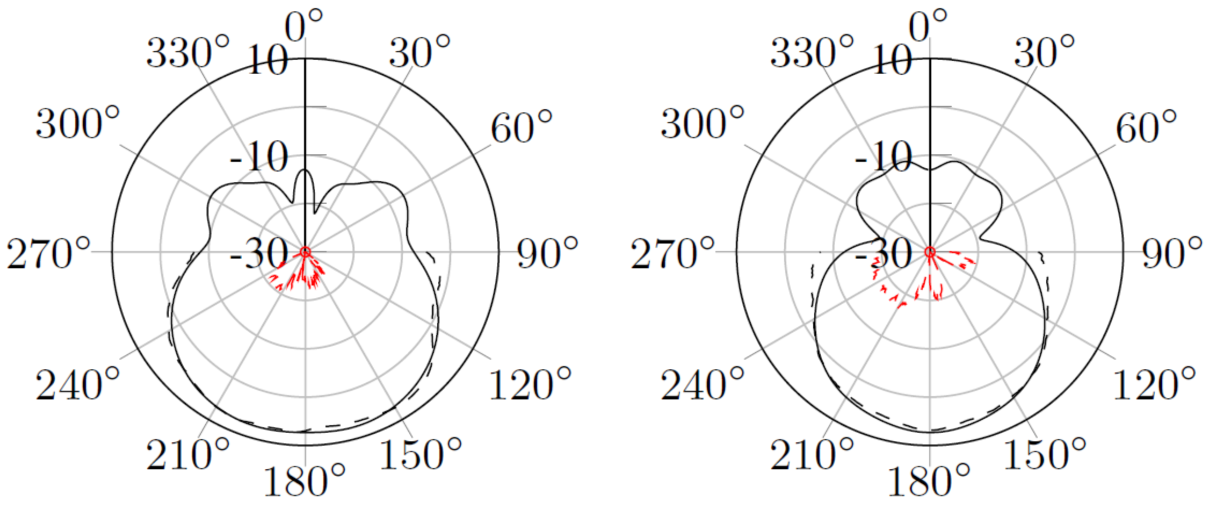

Far-field gain pattern at 28.5 GHz
E-plane (left) and H-plane (right)
Measurement (dashed) and simulation (solid)

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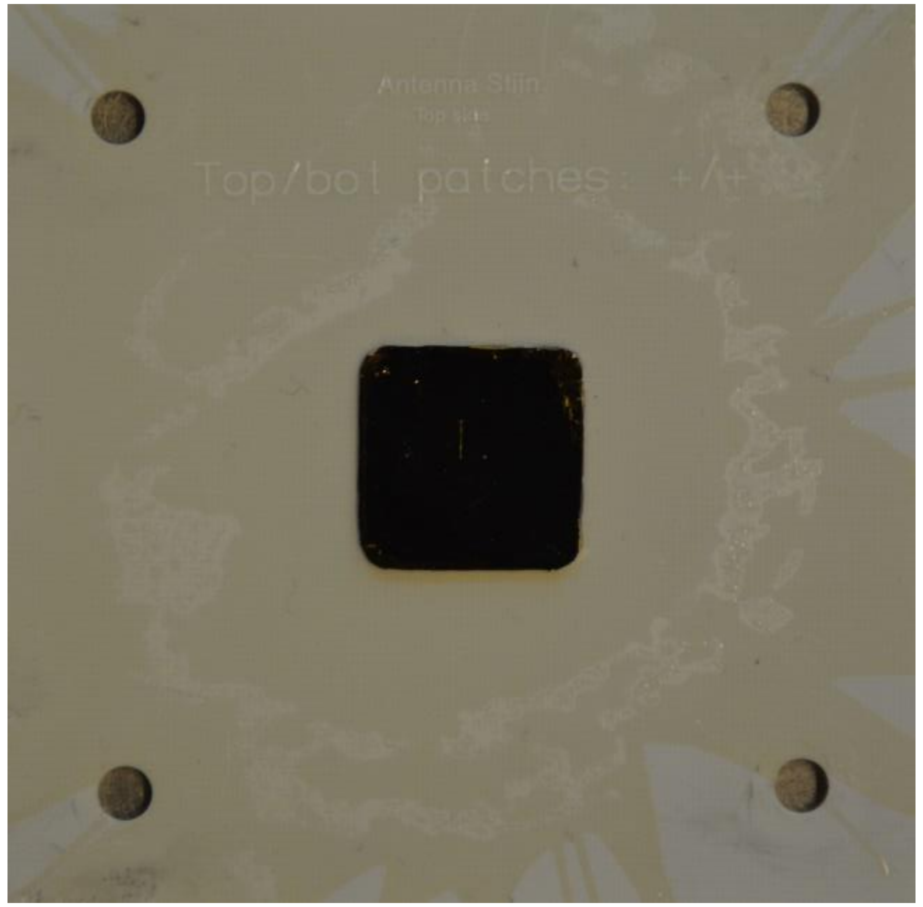
Conclusion

Wideband, highly efficient and compact antenna/chip integration
by means of hybrid strategy



Conclusion

Conclusion

- 5G-dedicated antenna design very demanding
- Novel methodologies for performance, cost-effectiveness and compactness
  - 28/38 GHz dual-band antenna
  - 60 GHz wideband antenna
  - 28 GHz hybrid on-chip/on-PCB antenna integration
- Antenna/transceiver co-design
  - Compact passive opto-electronic antenna

FACULTY OF ENGINEERING AND ARCHITECTURE

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