WMJ-3

5G PA Implementation and Integration Aspects

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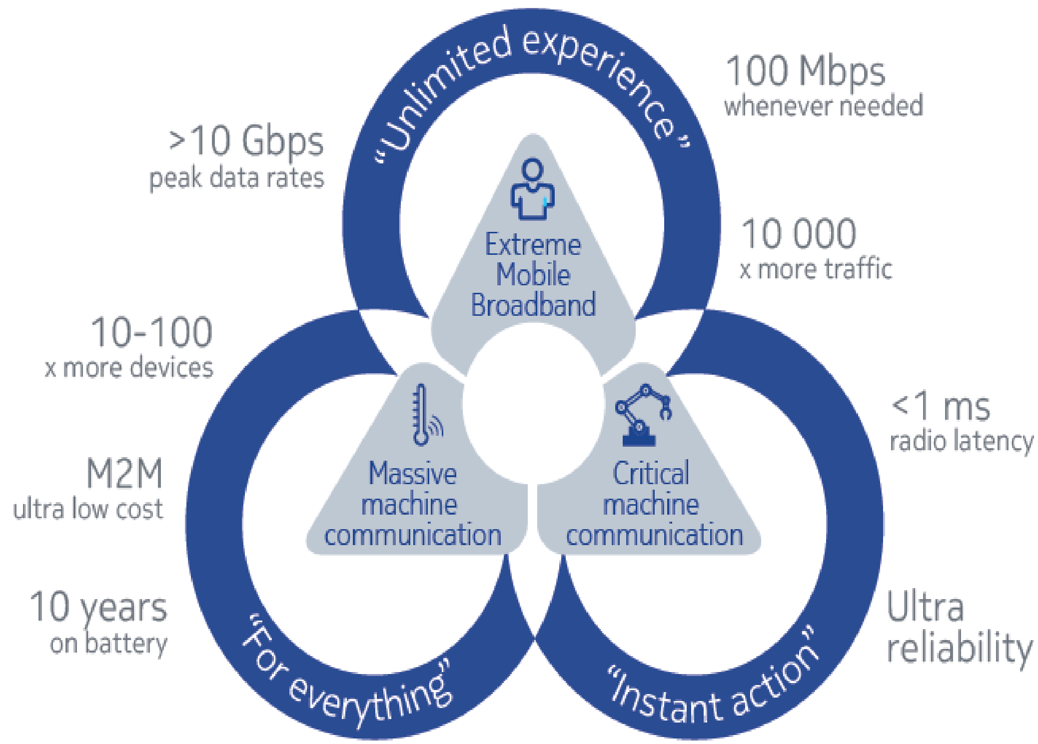
Agenda

- Introduction
- 5G mmWave Link Budget Requirements & Architectures
- mmW Integration Challenges and Techniques
- Techniques for addressing the Mobile Device Power Consumption/Efficiency
- Prototype Front-End Module with single PA
- Summary

What Will 5G Be?

- Highly consistent, ubiquitous data rate and capacity
- Ultra low latency
- Ultra high reliability/resilience
- Ultra low cost, high coverage and reliability
 for M2M services
- Lower energy in infrastructure and terminals
- Architecture for a rapid service launch, support, operation and maintenance
- Scalability for billions of devices
- Utilise all available spectrum



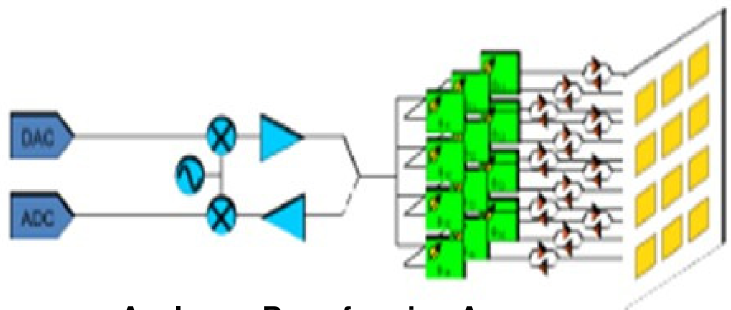
Nokia 5G masterplan_white_paper

5G Communications: People & Things

5G is about Communication, Storage, Processing…

Creation of Sense of Being - through ultra high bit rate and low latency

5G mmWave Link Budget Requirements & Architectures



Analogue Beamforming Array [IMS2016, Flex5G Project]

Analogue beamforming array on mobile device : estimated link budget for 250m coverage NLOS

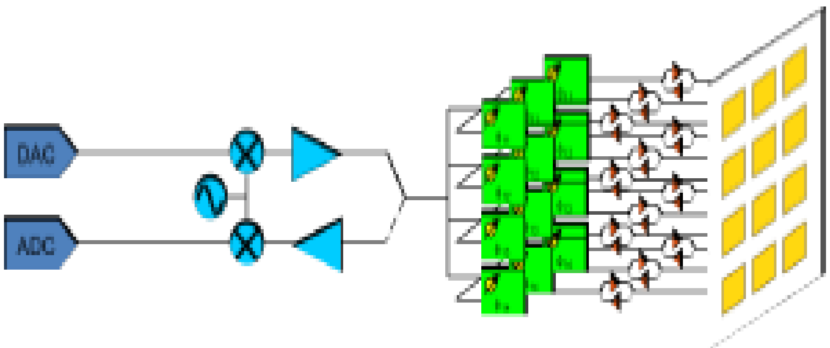
Due to the finite number of antenna elements, a relatively high output power/element is required with high efficiency in order to avoid thermal issues

Required Rx sensitivity at BS receiver	-80dBm (estimate)
BS RX and UE TX Antenna Gains:	
BS Max Antenna element gain	6dBi
BS RX Max antenna array (64) gain	24dB
Total BS Avg Array Gain over +/-30°	28dB (2dB degradation)
UE TX Max Antenna Element Gain	6dBi
UE TX Max Antenna Array (8) Gain	9dB
Total UE S Avg Array Gain over +/- 90°	10dB (5dB degradation)
Total average Antenna Gains	38dB
Propagation Attenuations	
Estimated Basic Pathloss	133dB (250m distance)
Fading/other margins	6dB
Rain Attenuation	3.75dB (15dB/Km)
Total Propagation attenuations	142.75dB
Total UE TX to each ant elemt: RX BS sensty – BS & UE Ant G + Prop Attn	+24.75dBm
UE average TX EIRP	+34.75dBm
Power req to each UE TX antenna elemt (Total UE TX power -9dB)	+15.75dBm
TX losses between PA and Antenna elemt (TX RF Fltr, SW, other losses)	3dB
Required PA Output Power	+18.75dBm
Peak PA Output Power (Assumed PA backoff of 6dB)	+24.75dBm

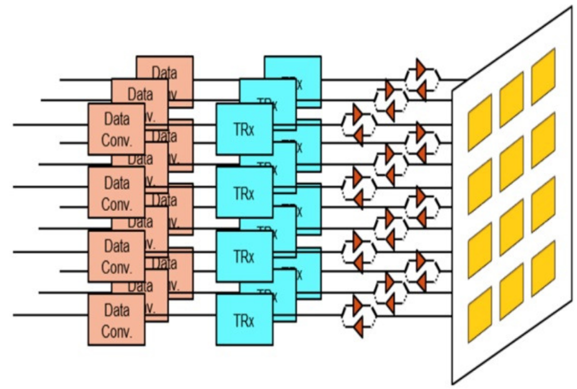
UE Architectures

Beamforming/Module Architectures

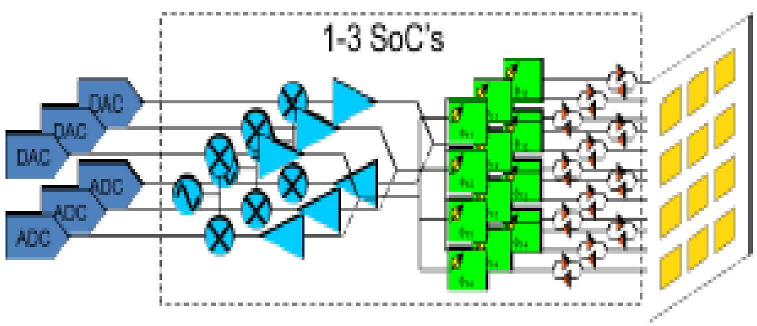
mmWave operation is unattractive.. but Beamforming provides a solution



Analogue Beamforming Array



Digital Beamforming Array

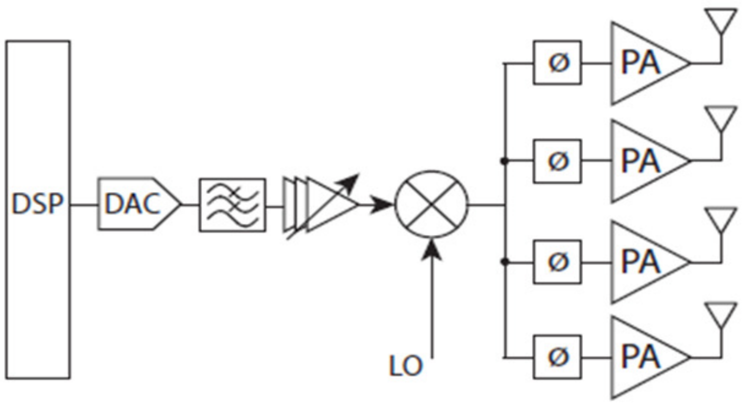


Hybrid Beamforming Array

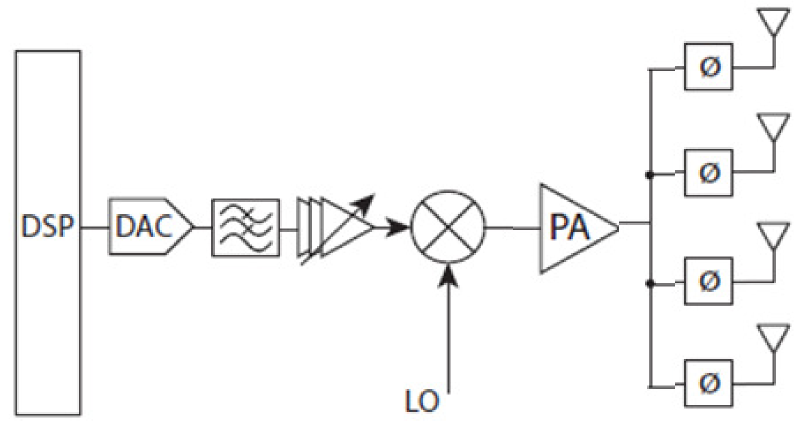
~100m+ cell sizes possible with 1-10GBit/sec data-rates

IMS2016 Ampleon, EU Flex5Gware project

Possible mmW Analogue Array Architectures (showing TX path)



Individual PAs for each antenna element



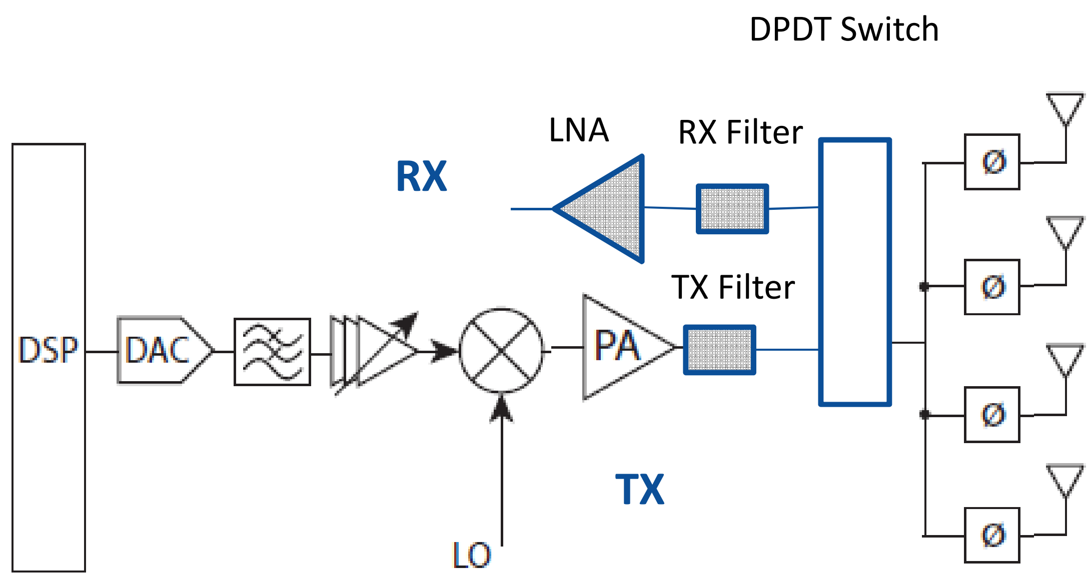
One Power Amplifier (PA)

UP Link Budget (UE Power):

- BS receiver sensitivity: -80 dBm;
- BS and UE array size: 64 (8x8) and 8 (4x2)
- UE Peak PA output Power: ~ 25 dBm (average power 19dBm =6dB back-off assumed)

* This is an example power level based on assumptions including antenna gain, coverage (250 m) etc.

TX/RX Chain Approach



Analogue Array 1 PA Architecture Including TX and RX Filters and LNA

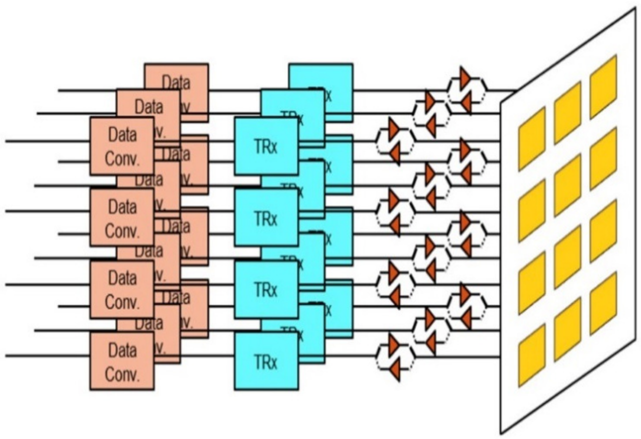
Architecture	DC Power Consumption - best CMOS/SOI PA 6dB back-off, η =16%	DC Power Consumption - best published PA 6dB back-off, η =22%	Power Consumption – Eff. enhanced PA, η = 32%	Lowest heat dissipation (DC-RF power)
Multiple TX/RX	3.7W	2.7W		2.1W
TX/RX (2.5dB post PA IL to PS and related aspects)	5.3W	3.8W	2.6W	1.8W

TX/RX Approach viable with efficiency enhanced single PA and low loss PS (<2dB)

Front-End Critical Components :

For performance, size and power consumption

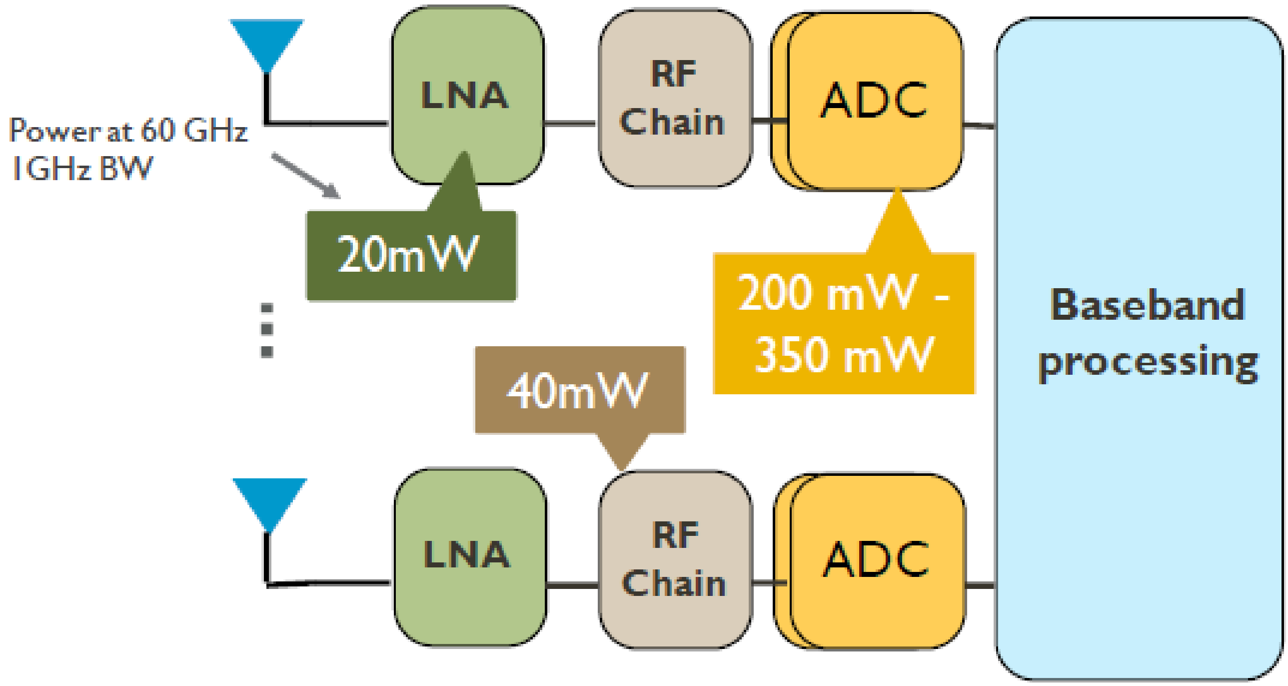
- ADC/DAC
- Up/Down Converters
- Antenna Array and related technologies
- Filters
- Phase Shifters
- LNA
- Switch
- Power Amplifier



eetindia

mmW Integration Challenges and Techniques

The Implementation Challenge



For a receiver with 4 antennas, the power consumed by this front end at mmWave would be 2W !!!

Power consumed by a 2.4 GHz, 20 MHz BW front end would be 120 mW

High Power Consumption for mmW

* R. Heath, N. Gonzalez-Prelcic, S. Rangan, A. Sayeed, W. Roh "Overview of signal processing techniques for millimeter wave MIMO systems", under review IEEE JSTSP 2015

The Thermal and Electromagnetic Challenge

Areas for Cooling and for Array

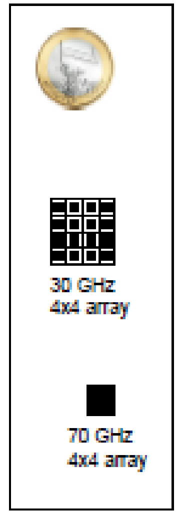
30 GHz	Total diss. [W]	Cooling Area [mm²]	Array Size [mm²]
Analog BF	3	1200	400
Digital BF	4.5	1800	400

45 GHz	Total diss. [W]	Cooling Area [mm²]	Array Size [mm²]
Analog BF	4	1600	178
Digital BF	5.5	2200	178

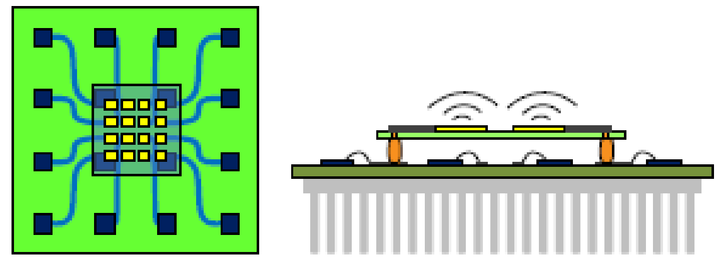
73 GHz	Total diss. [W]	Cooling Area [mm²]	Array Size [mm²]
Analog BF	11.5	4600	68
Digital BF	13	5200	68

- Dissipation estimated for a 4×4 antenna array with 20 dBm peak P_{OUT} per antenna
- Cooling capacity is 1 W per 4 cm² to enable passive cooling

Jos et al IMS2016 Ampleon, EU Flex5Gware project

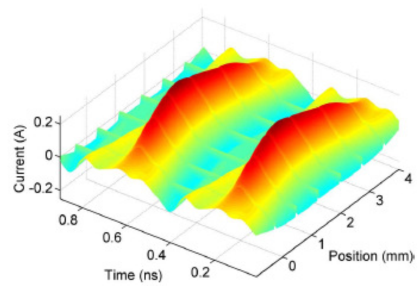


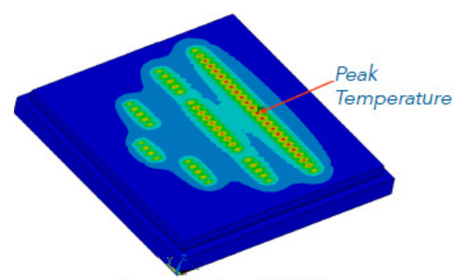
Dense Array and Passive Cooling



Dense Array: Antennas spaced ½λ apart

Cooling area >3x module size: thermal problem!

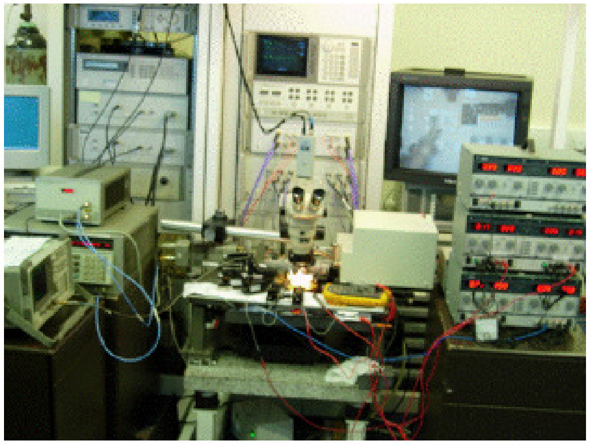




Thermal simulation, measurement & design required

The Extreme Measurement Challenge

- mmWave: Wavelength small –big measurement uncertainties can easily result from physical distances and practical calibration constraints
- 5G RF bandwidths will exceed 1GHz: all commercial equipment solutions struggling to accommodate this requirement
- Modulation constellations very complex in order to provide the ultra-high data-rates. Measurement of constellation errors extremely challenging

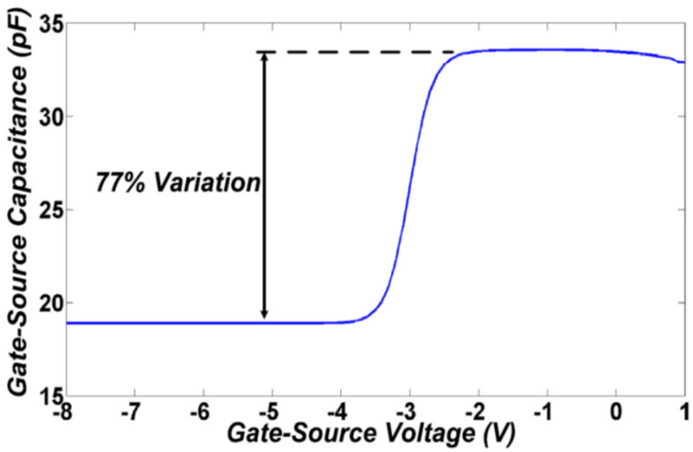


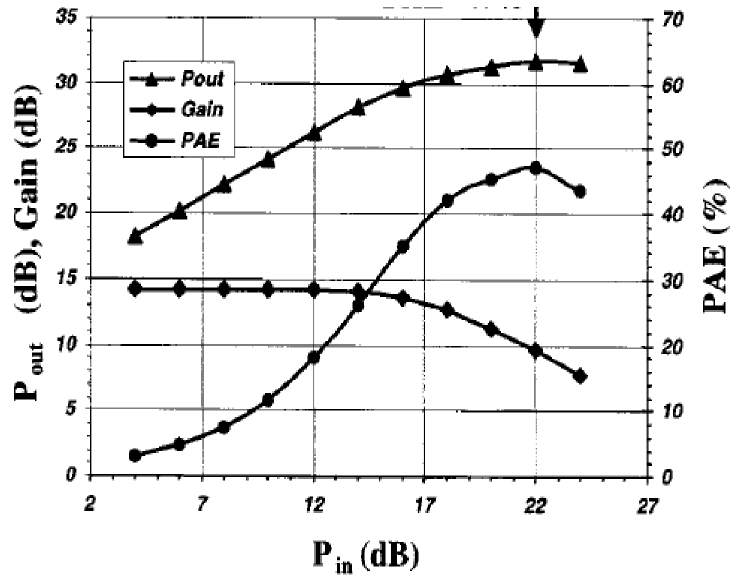
Many requirements beyond current commercial equipment capabilities and calibration techniques crucial

Challenges of Wideband PA

- Difficulties are to simultaneously achieve high P1dB power across a wideband bandwidth, and high efficiency and linearity for high PAPR.
- Inherent slow-compression (for GaN), yet achieving high P1dB power
- Class of operation and thermal loads
- Memory/ hysteresis effect and modulation recovery
- Efficiently dissipating the ultra-high heat flux generated at micro-scale gate fingers - electrical and mechanical consideration for interfacing and heat spreading/packaging materials

Typical G-S Capacitance & P1dB Power



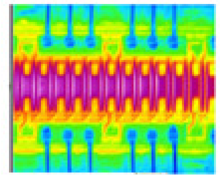


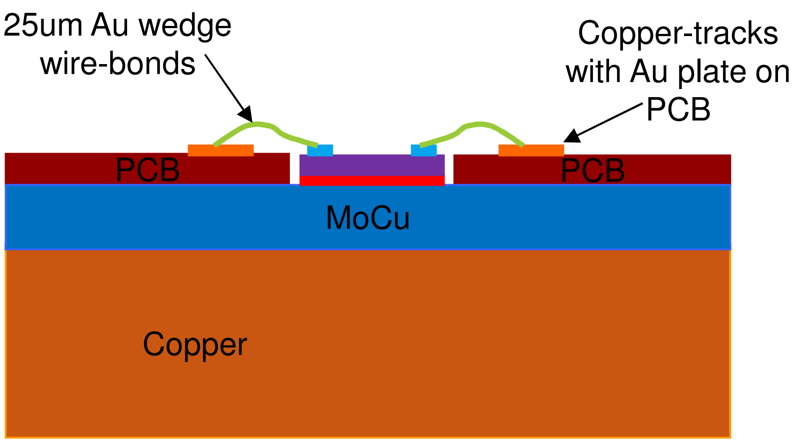
Power Performance of AlGaN/GaN PHEMT

- Slow gain-compression (for GaN)
- P1dB far away from Psat
- PAE maximum closed to Psat
- P1dB power vaguely reflects GaN's power capability

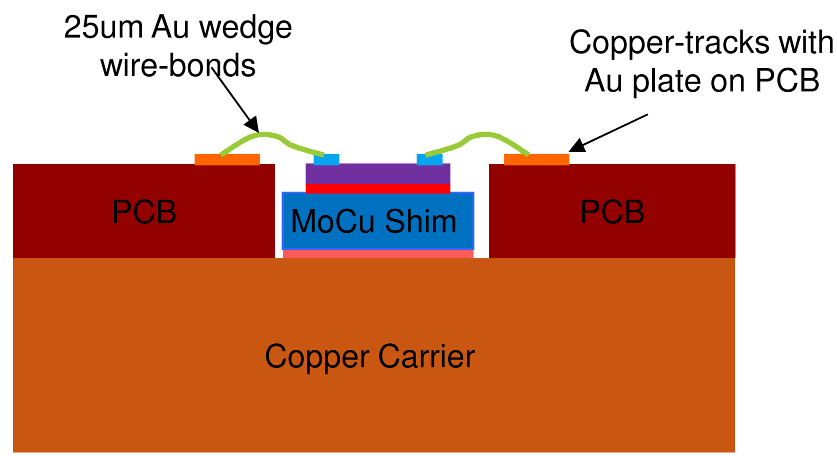
K. K. Samanta, "Packaging of Wideband High Power GaN Amplifiers", IEEE IMS2015, Phoenix, May 2015.

Die-Based GaN PA Integration





MoCu Carrier



MoCu Shim Under the Device

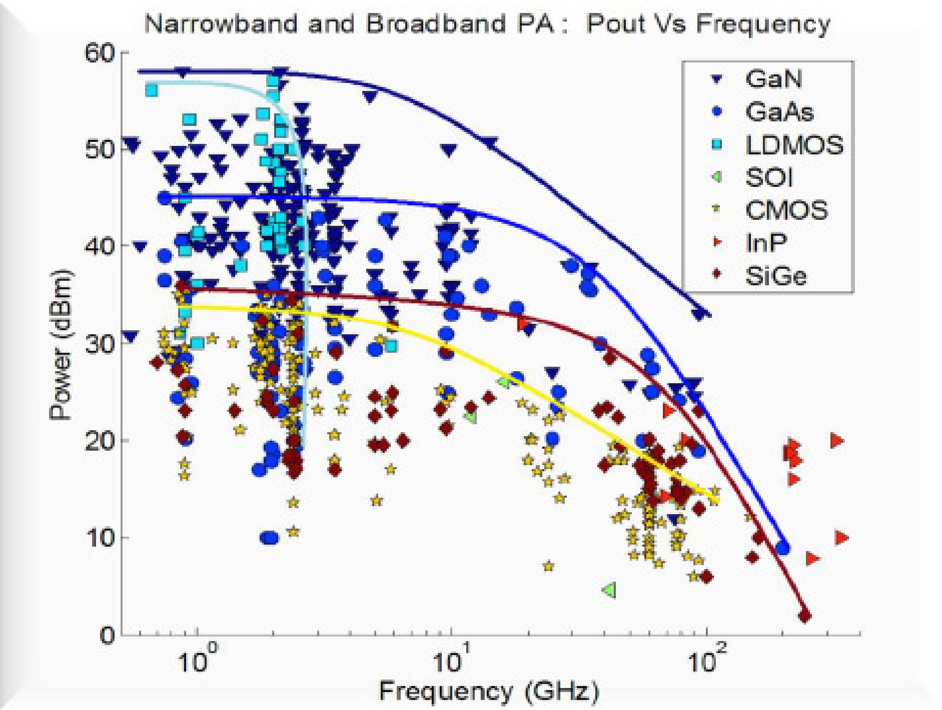
- Parasitic reduced
- Better high freq performance

- Additional Parasitic is introduced (including inductance)
- High freq response is affected- oscillation

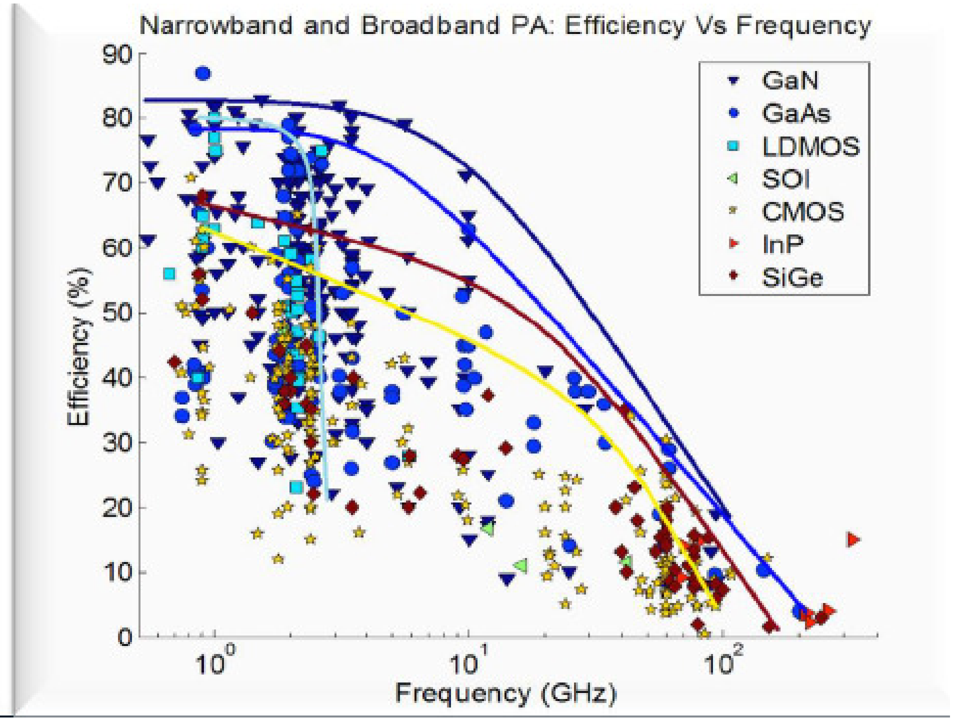
K. K. Samanta, "Wideband PA and Packaging: Part-2 ", IEEE Microwave Magazine, Nov, 2016.

Techniques for Addressing the Mobile Device Power Consumption/Efficiency

The Importance of PA Device Technology Choices



Pout Vs Frequency

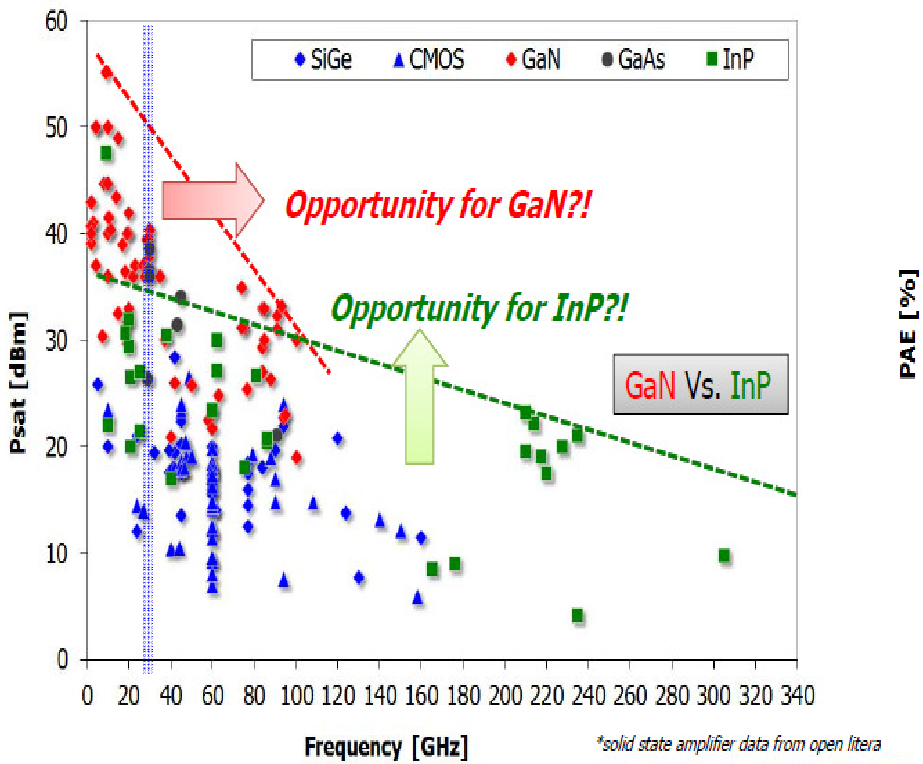


Efficiency Vs Frequency

Skyworks,2016 IMS WSB

The Importance of Device Technology Choices

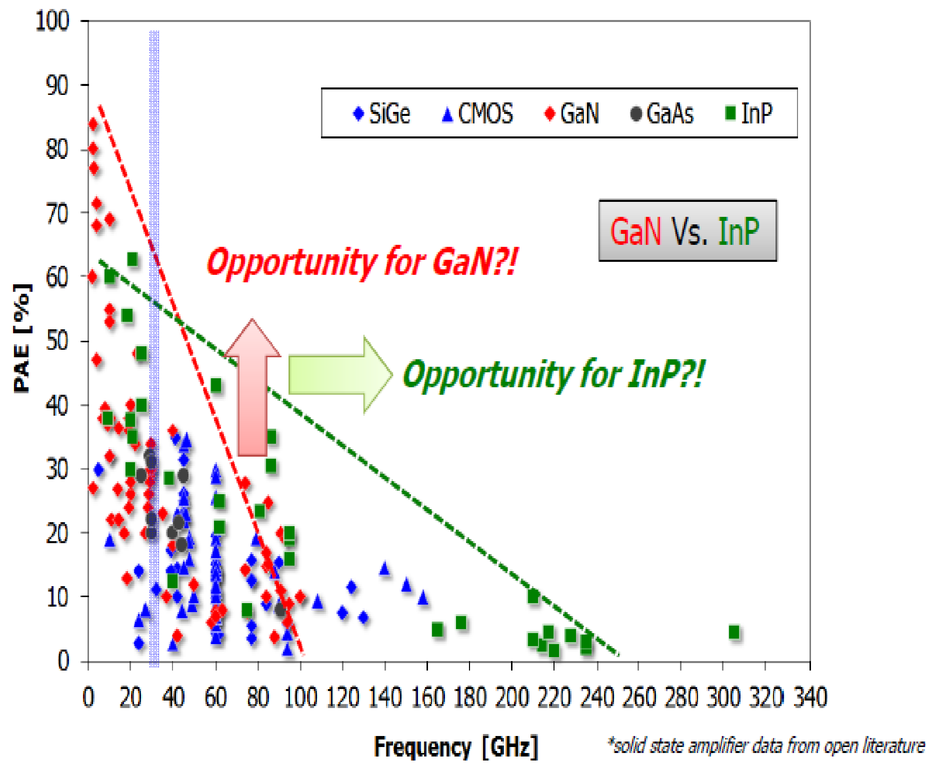
28GHz



Psat Vs Frequency

28GHz

Daniel S. Green, DARPA, 2015 IMS

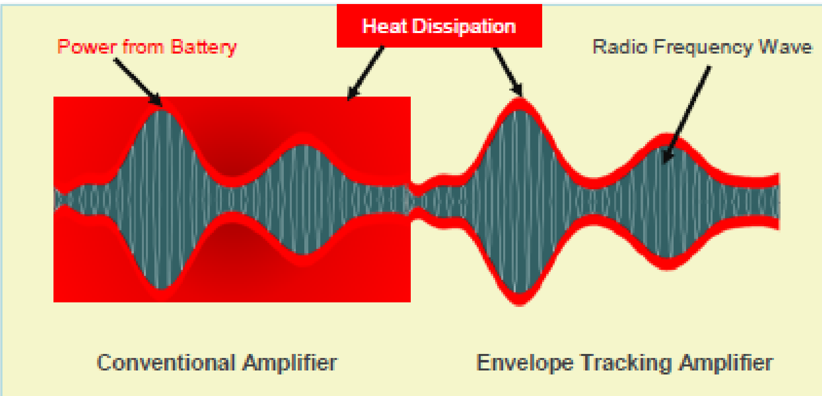


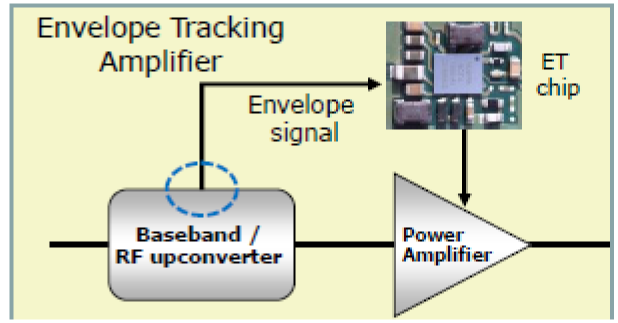
PAE Vs Frequency

PA Candidate Approaches:

- ET (Envelope Tracking), EER.
- Doherty
- LINC/Chireix (outphasing)
- Use of above with/without DPD (Digital Pre-distortion) or APD (Analogue Pre-distortion)
- Class S?

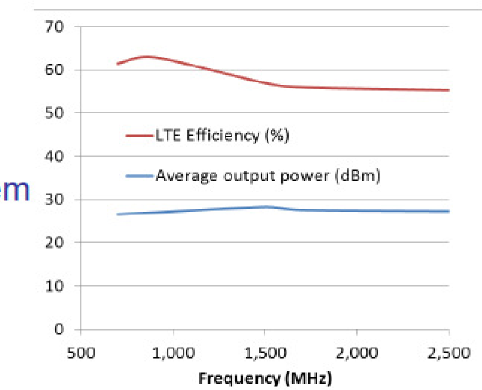
Envelope Tracking: Used for 4G But More Challenging for 5G





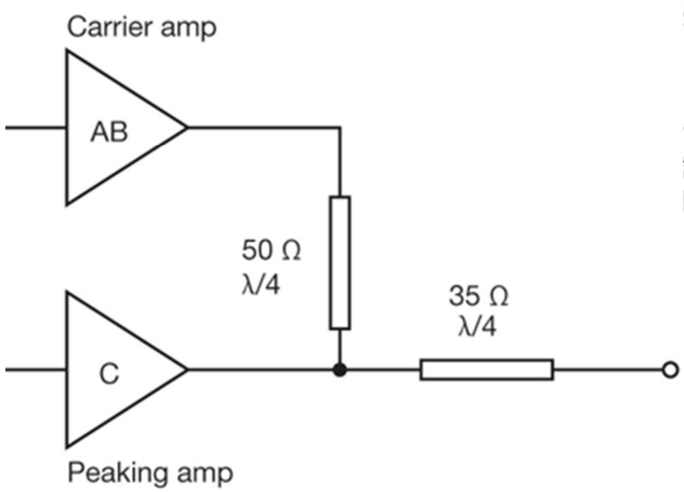
One PA to rule them all?

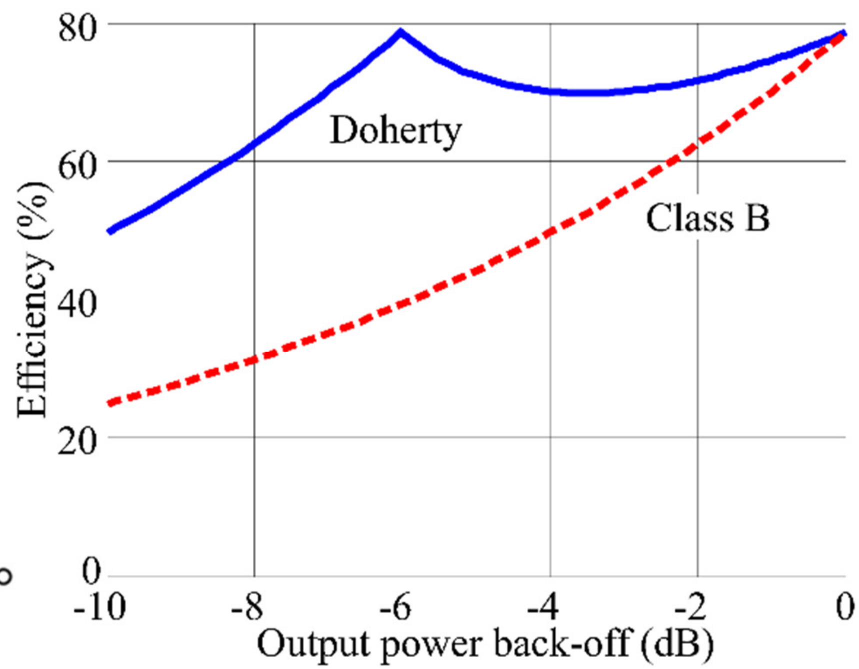
- Sony Semiconductor prototype GaAs JPHEMT broadband output stage
- Measured using Nujira ETPA characterization system
- >55% final stage efficiency with LTE waveform from 700 MHz to 2500 MHz
  - 25RB QPSK
  - >-36 dBc ACLR
  - 27-28 dBm average Pout



- ➢ **Supply modulation techniques such as ET become increasingly difficult beyond 20MHz**
- ➢ **May be practically limited to 50-100MHz in terms of any efficiency improvement**

Doherty: Proven But Size & Complexity Overhead

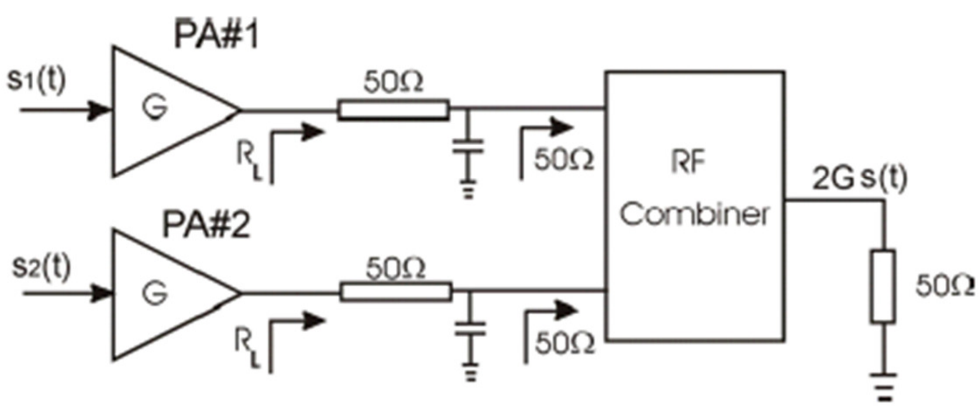


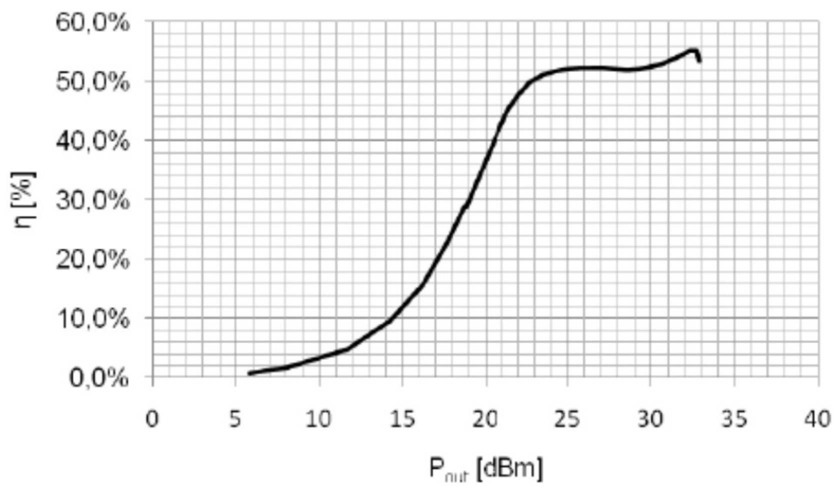


General Architecture of the Doherty Power Amplifier and Efficiency/output Power Characteristic

[mwrf.com, Saffian & Dunn] [Vittorio Camarchia , Marco Pirola and Roberto Quaglia, Sept 2014]

Out Phasing PA: Also Size & Complexity Overheads

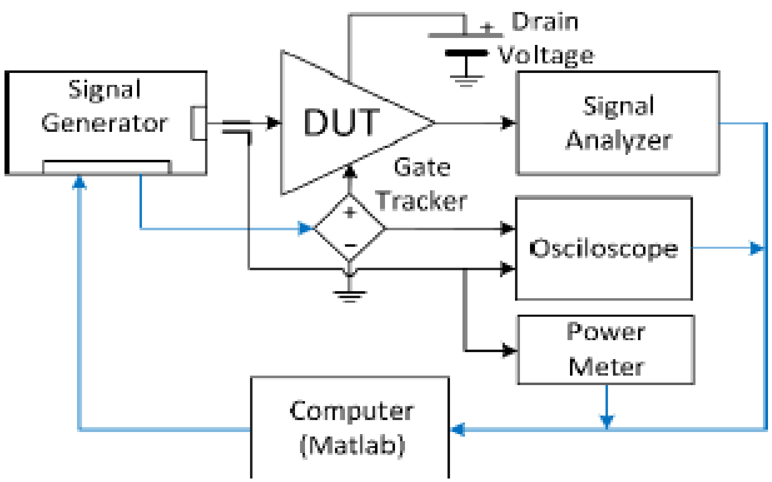


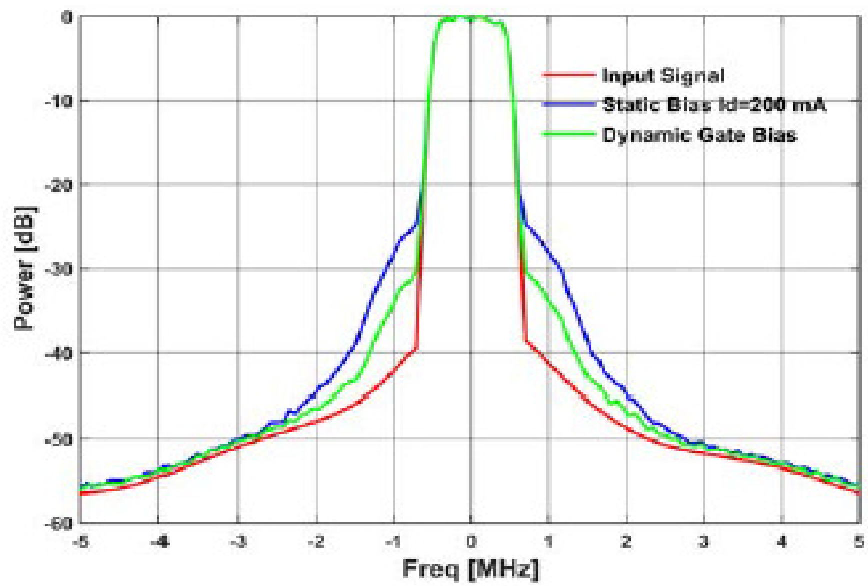


Chireix/Outphasing PA and Efficiency/Output Power Characteristic

[Napieralska et al][schie et al]

Adaptive Bias Control





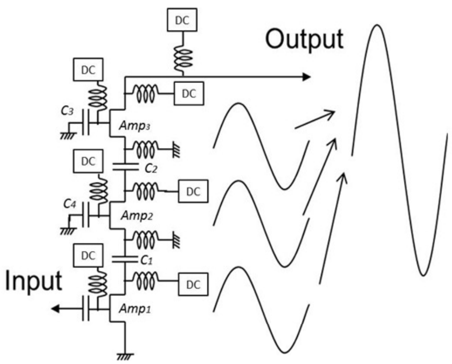
Adaptive Gate Bias Control: **1.7-2.7dB higher output power with 1.3-8.5% higher efficiency achieved**

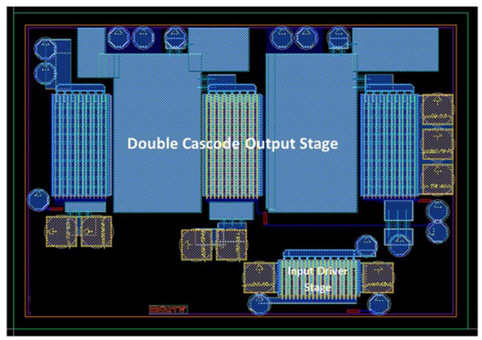
[Gecan, IMS2106]

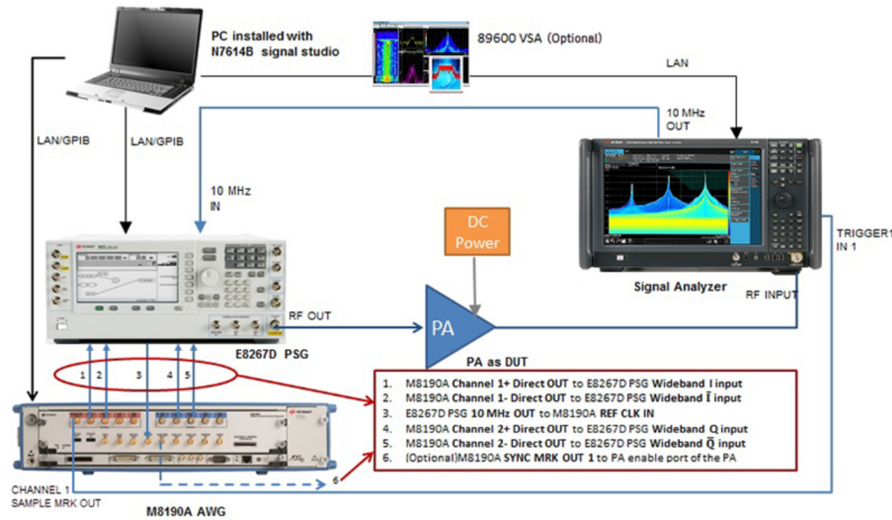
DPD Likely to Continue to Play Important Role

Channel BW >100-300MHz gets more challenging even for test equipment

Good 4G Results with DPD







SIMULATION RESULTS OF DIGITAL PRE-DISTORTION APPLIED TO THE PA ARCHITECTURE

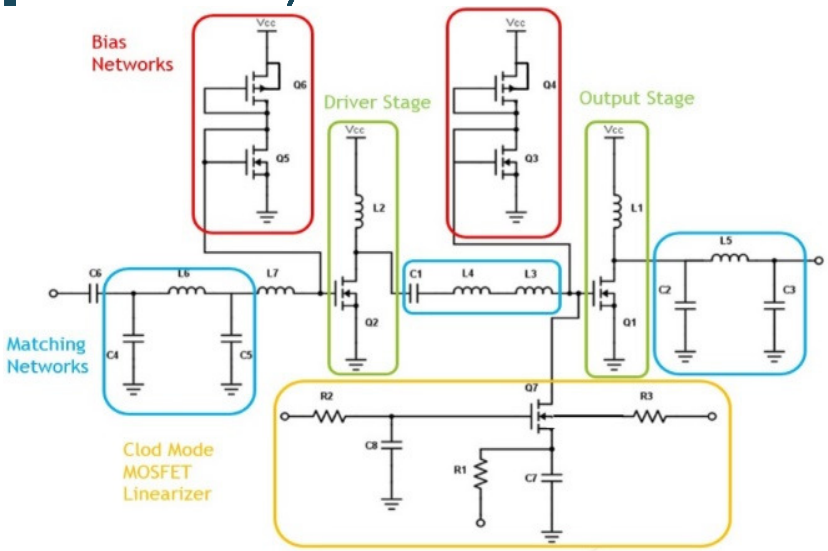
Configuration Carrier frequency 1.8GHz Vds=3.5V	ACLR (dBc)		Average output power (dBm)	Average Drain efficiency (%)
	Lower	Upper		
20 MHz LTE memory-less DPD	36.6	37.3	24.5	30.4
20 MHz LTE without DPD	36.1	41.4	21.2	20.2

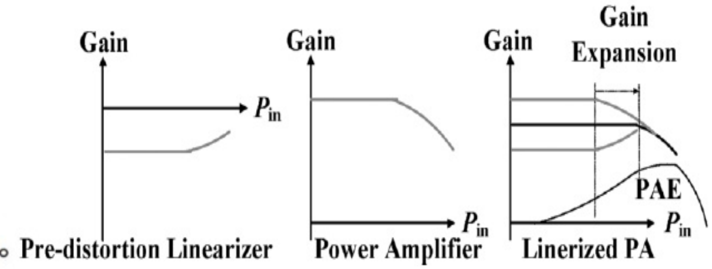
AUS, Sony, Bristol IEEE 2016

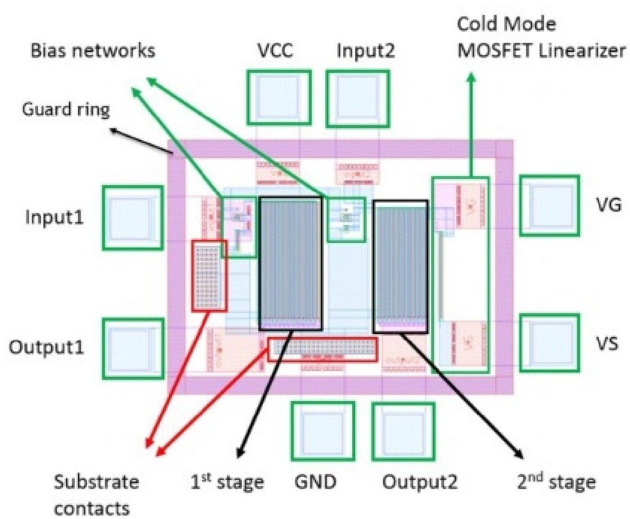
Over-sampling ~3-5 x BW

http://www.keysight.com/main/measurement solution

Despite Limitations of an Analogue Approach, APD Shows Good Promise







28GHz CMOS PA: Seyed Mohammad Kashfi; Supervisor: L. Albasha

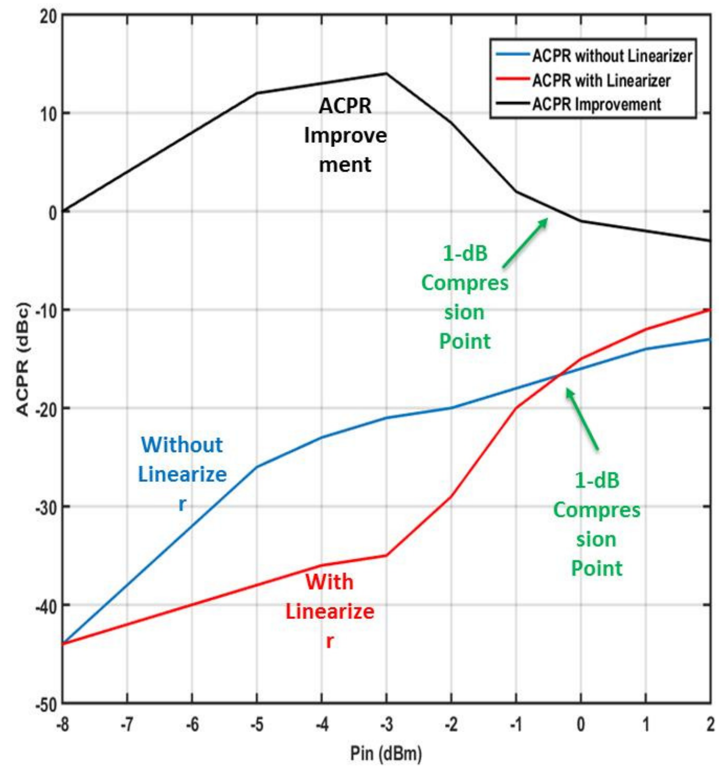
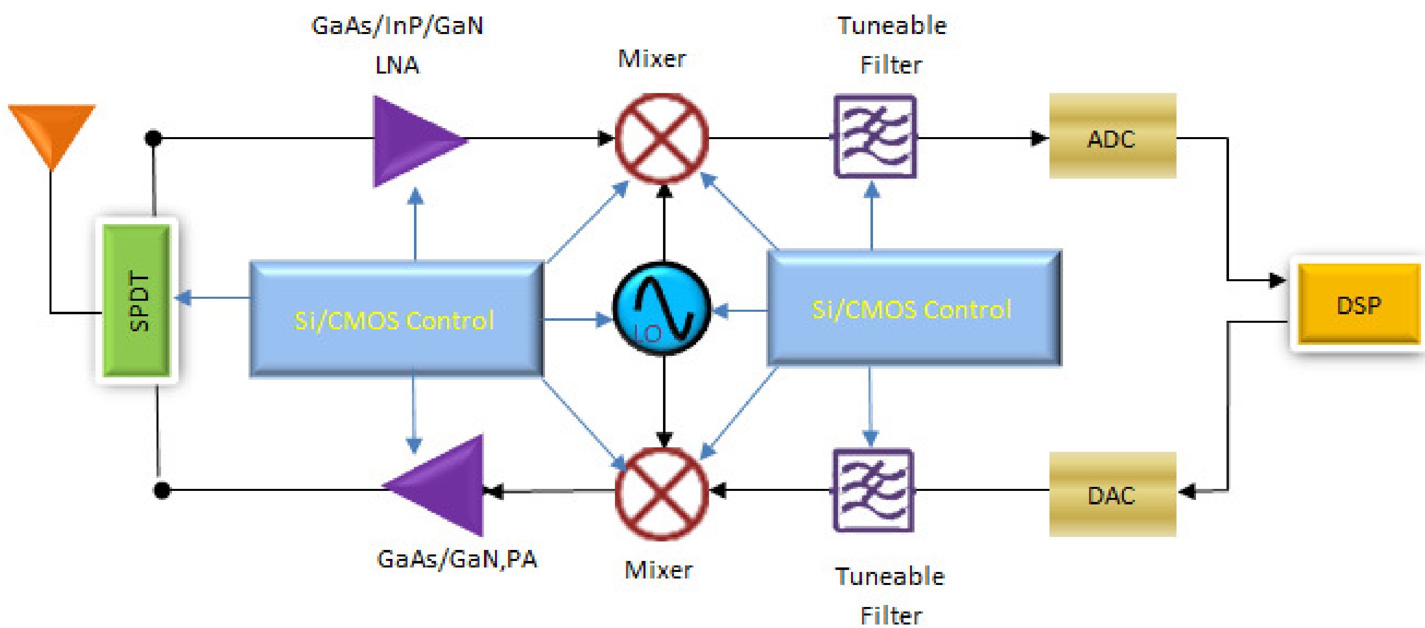


Figure 53. ACPR Comparison

A Typical Transceiver: Integration of III-V CS and Si Devices



Provides Benefits from Both
- high frequency performance of CS
- complex digital/control functionality and cost benefit of Si

K. K. Samanta, IEEE Microwave Magazine, vol. 18, no. 2, 2017

Challenges – Interdisciplinary

❖Multilayer fabrication with fine geometry and accurate alignment

❖Metallization with smooth and well-defined surface and near vertical edge

❖Compatible coefficient of thermal expansion (CTE)

❖Novel material- better electrical, microwave and thermal properties at a low cost

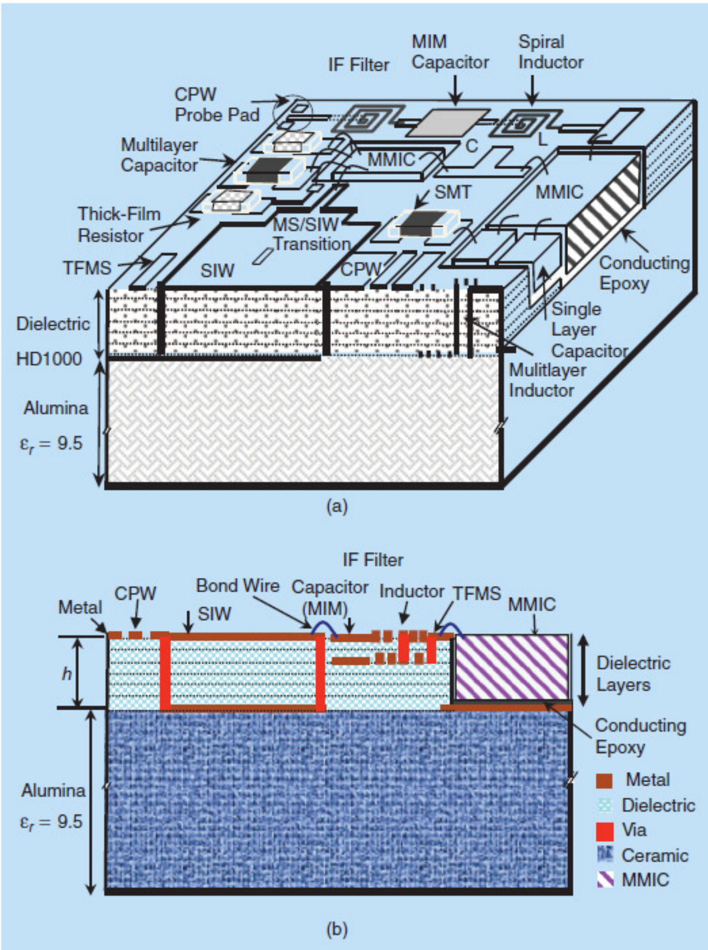
❖Precise IC/SMT mounting pedestal or pocket formation

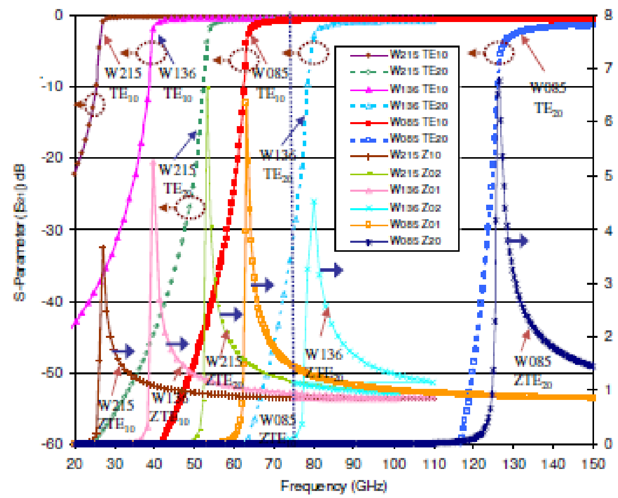
❖Novel circuit design and thermal managements techniques

❖Multiphysics analysis/modelling : SC with metal and dielectric; mechanical, thermal, optical, in addition to electrical and microwave/mmW

❖Co-simulation of package, circuit and device (SC) – including circuit, EM and thermal analysis.

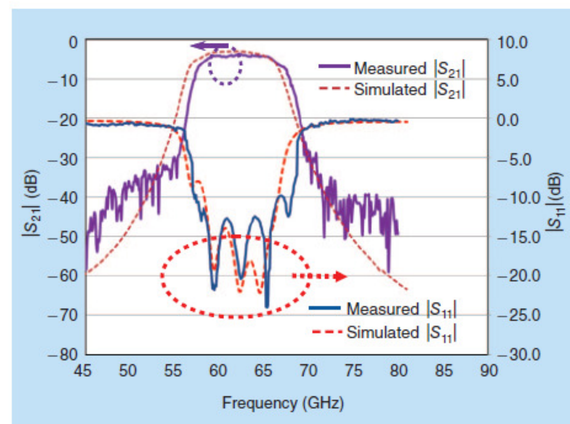
mmWave Highly Integrated Module : High Accuracy Multiphysics Design Essential





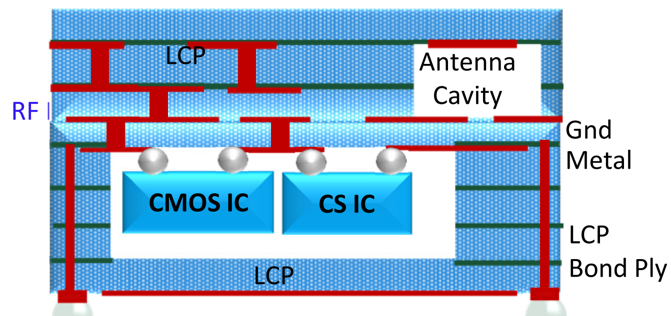
Attenuation (frequency of operation) and normalised impedance for fundamental (TE_{10}) and first order mode (TE_{20}) of substrate integrated waveguides:

Cavity width (a) of 2.15 mm, 3.16 mm and 0.85 mm, Dielectric heights (h) of 60 µm

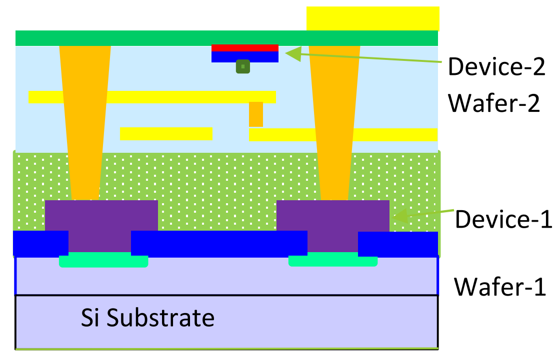


K. K. Samanta ,.. "Multilayer … SoP Comp.. mmW and Beyond" IEEE Mw Magazine, Jan 2016

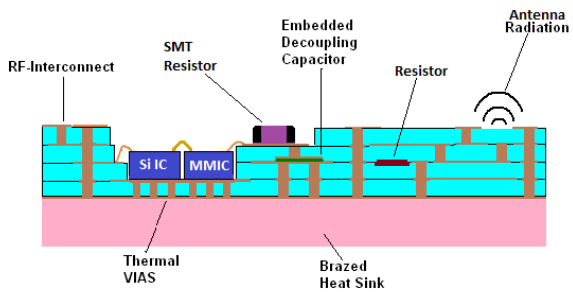
Solutions: Advanced Multilayer/3D Multichip and Heterogeneous Integration



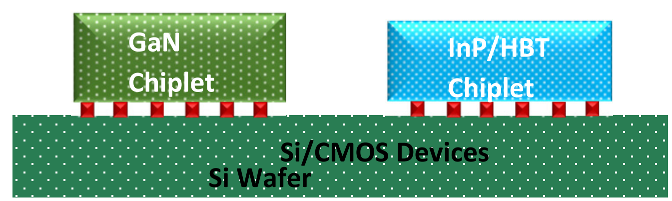
(a) Organic/Laminate



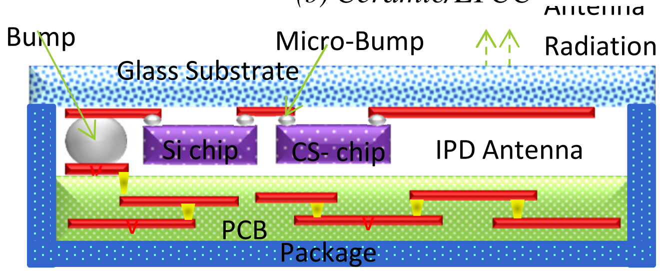
(d) Wafer-Bonding



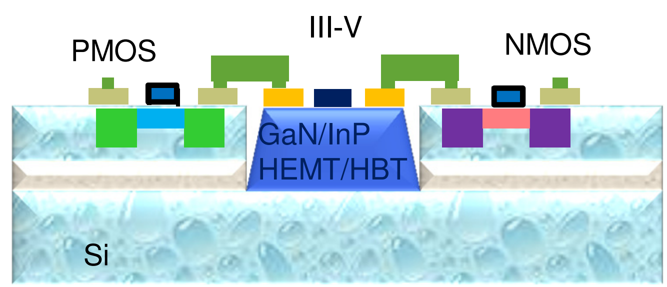
(b) Ceramic/LTCC



(e) Chiplets



(c) IPD (Si/Glass)



(f) Monolithic

K. K. Samanta, IEEE Microwave Magazine, vol. 18, no. 2, 2017.

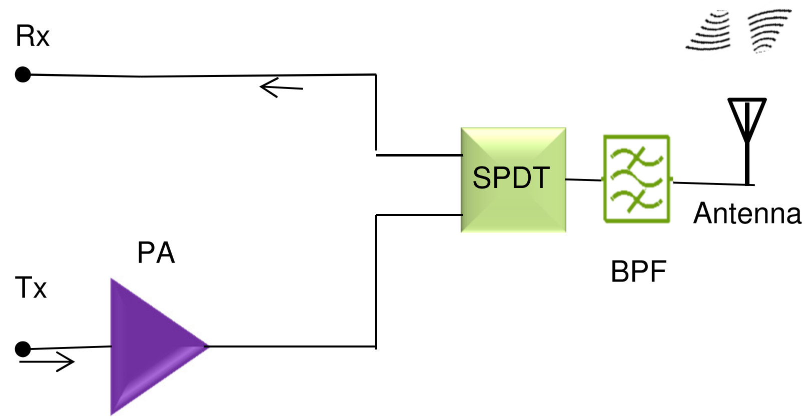
Relative Advantage and Disadvantage of Multilayer Integration Techniques

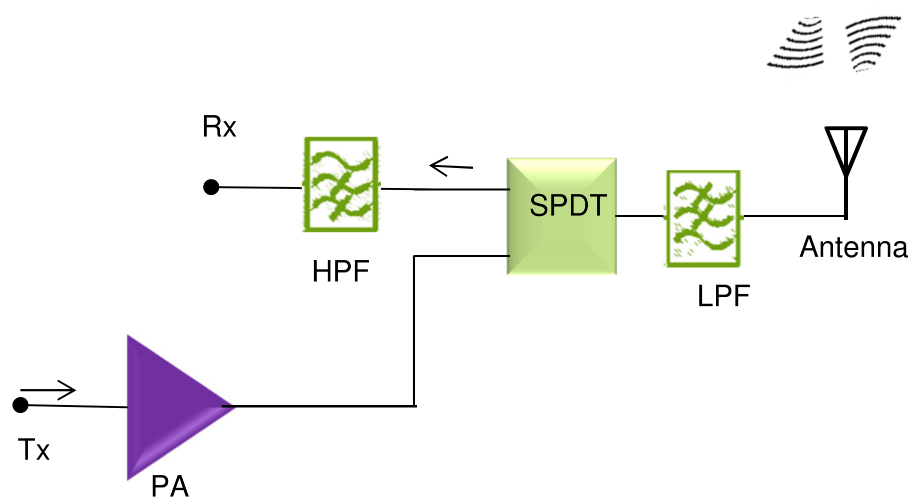
MCM/SOP Technology	Advantages	Disadvantages
Laminates: PCB/Organic material/LCP (MCM-L)	• Low cost and established infrastructure • Easy to repair/re-work • Low ε_r – for antennas • Parallel Processing • Availability of new low loss organic/LCP	• High moisture sensitivity • Low wiring density • High CTE • CTE mismatch with die Low TC • Difficult to integrate passives
Ceramic (LTCC) (MCM-C)	• Good RF, mechanical and thermal • Easy integration of passives • Real 3D integration/packaging capability • A range of layer properties • Radiation hardness, hermetic packaging • CTE matches with semiconductor • High resolution and trench via - PI-TF process	• Shrinkage of substrate (zero-shrinkage process) • High dielectric constant • More expansive than laminates • Longer lead time than laminates • Difficult fine conductor or trench-filled metal-wall
IPD (MCM-D)	• High geometric resolution and wiring density • Low dielectric constant • Easy integration of passives	• Expensive process • Limited number of layers • Difficult to repair or rework

K. K. Samanta, IEEE Microwave Magazine, vol. 18, no. 2, 2017.

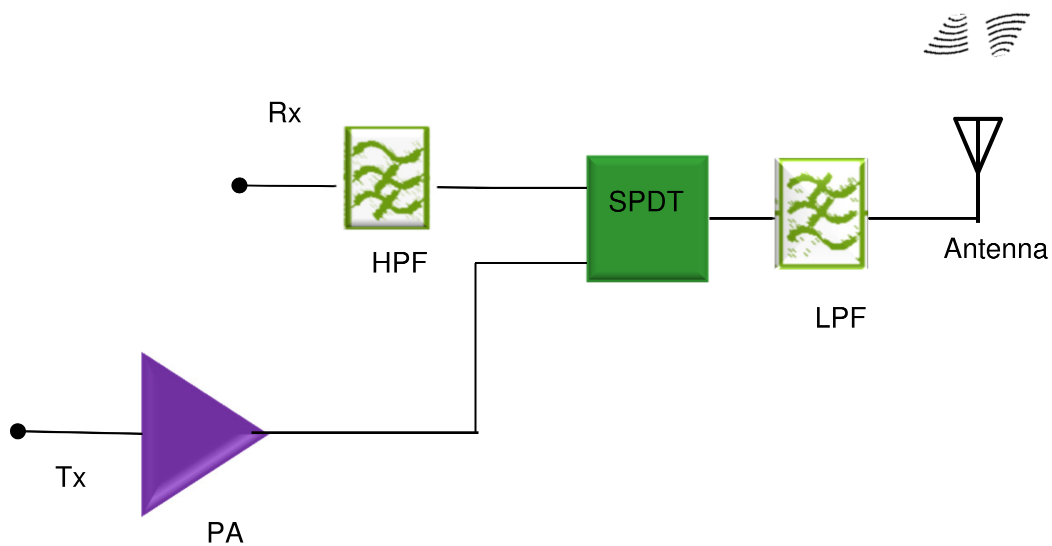
Prototype 28 GHZ Front-End Module (FEMV1) With Single PA

Possible Front-End Architectures with Filters





Basic Block Diagram of a Front-End Module (FEMV1)



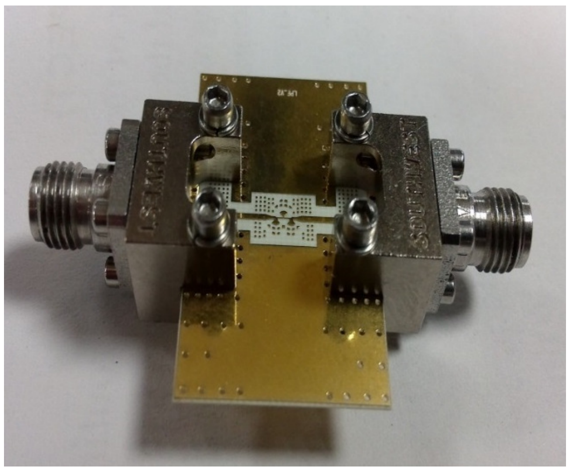
Block Diagram of FEMV1

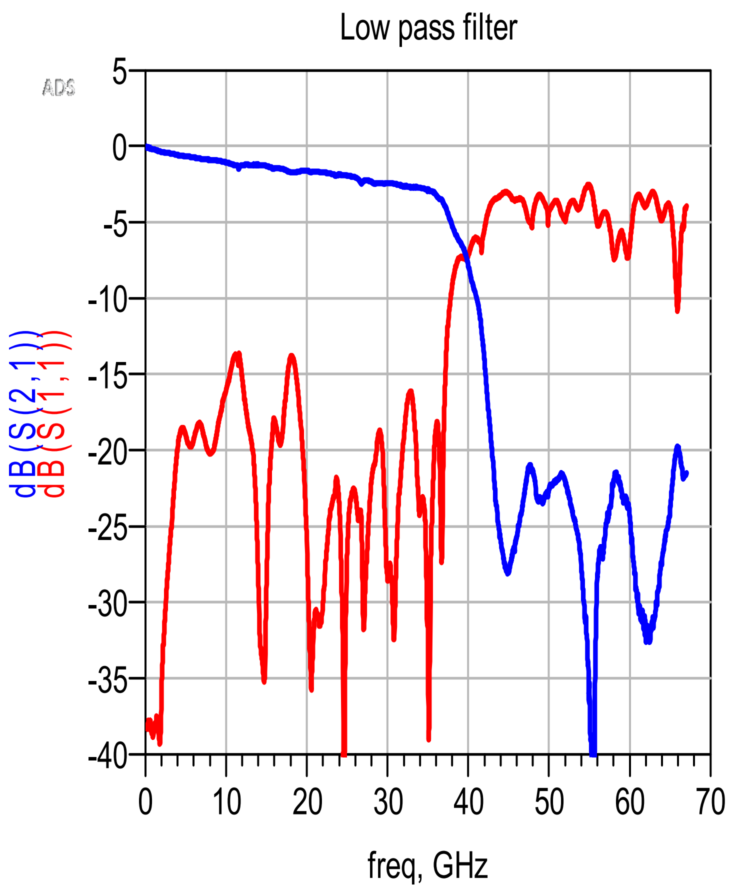
Laminate/PCB	RO4350B
Dielectric Const	3.66
TanD	0.0037
CTE (ppm/°C)	+40
TC (W/m.K)	0.69
Min thickness (um)	101

Filters Requirements and Constrains

- Specification of a filter is governed by the system specs and achievable specs of converts; harmonics from PA and antenna module.
- Basic Requirements:
  - Rejection of harmonics and spurious in Tx channel
  - Rejection of out of band unwanted signals in Rx channel : around 60 GHz (WLAN/WiFi) and <10 GHz (Cellular/WiFi)
- Difficulties:
  - High dielectric, ohmic and radiation losses at mmW
  - Maintaining low IL loss of a filter across a wideband: meeting NF for Rx and o/p power for Tx

Low pass filter : Photograph and Measured Response

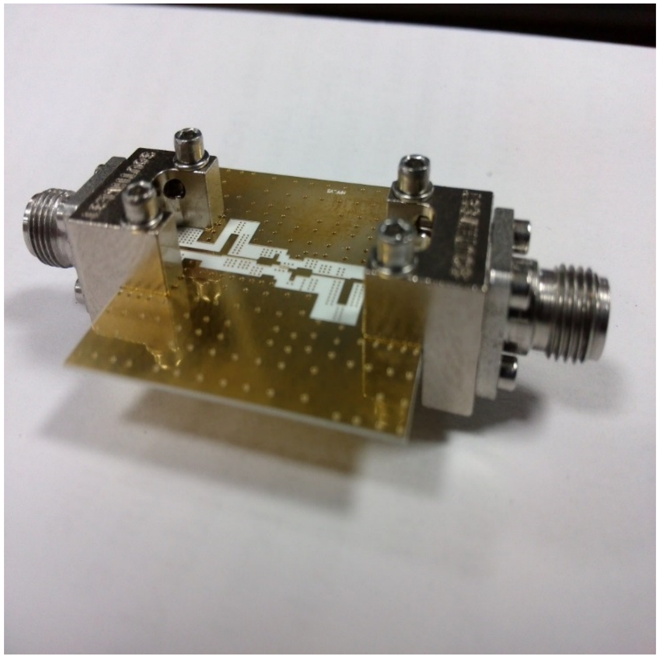


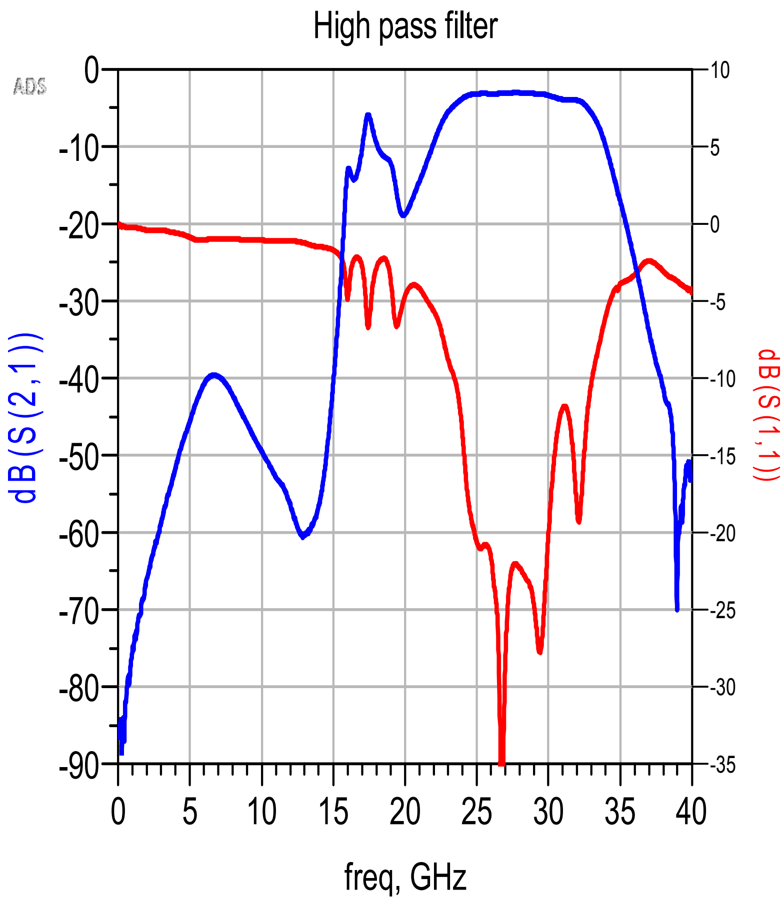


Test Results:
Adapter loss = 0.2 dB + I/O Connector + line loss : ~ 1.1 dB

Filter Loss:
< 1dB@28GHz

Band/High Pass Filter : Photograph and Measured Response

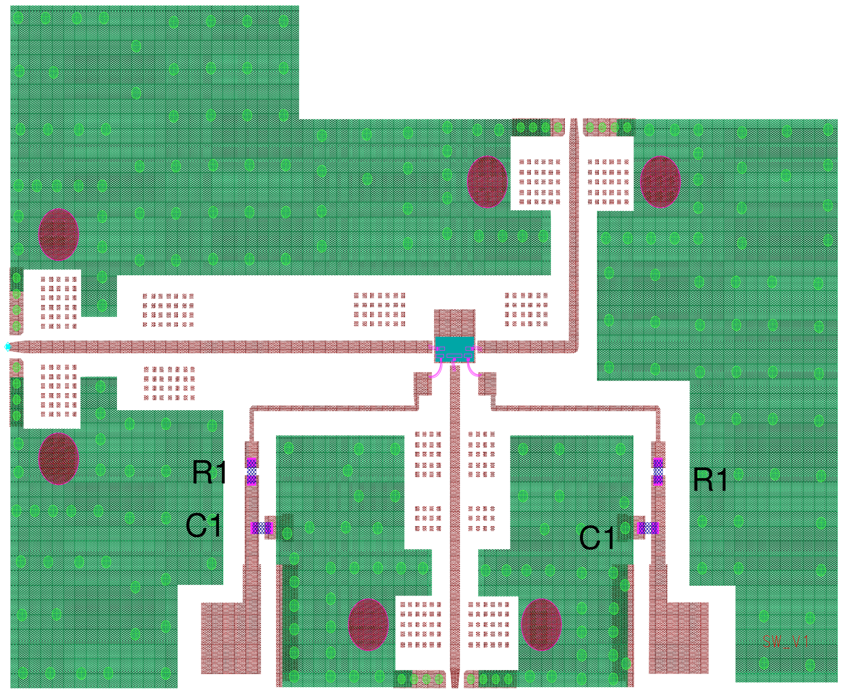


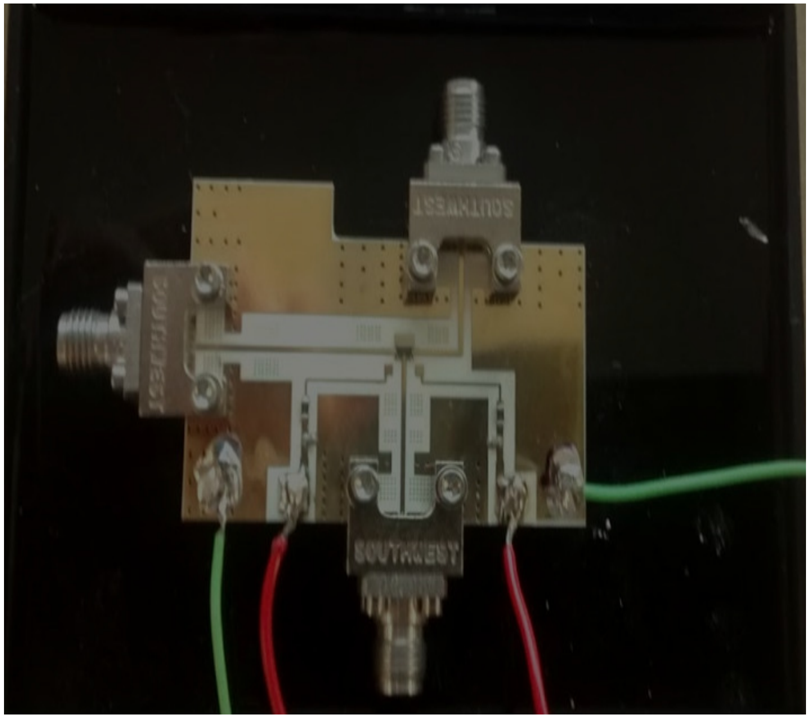


Test Results:
Adapter + I/O Connector + line loss: ~ 1.3 dB

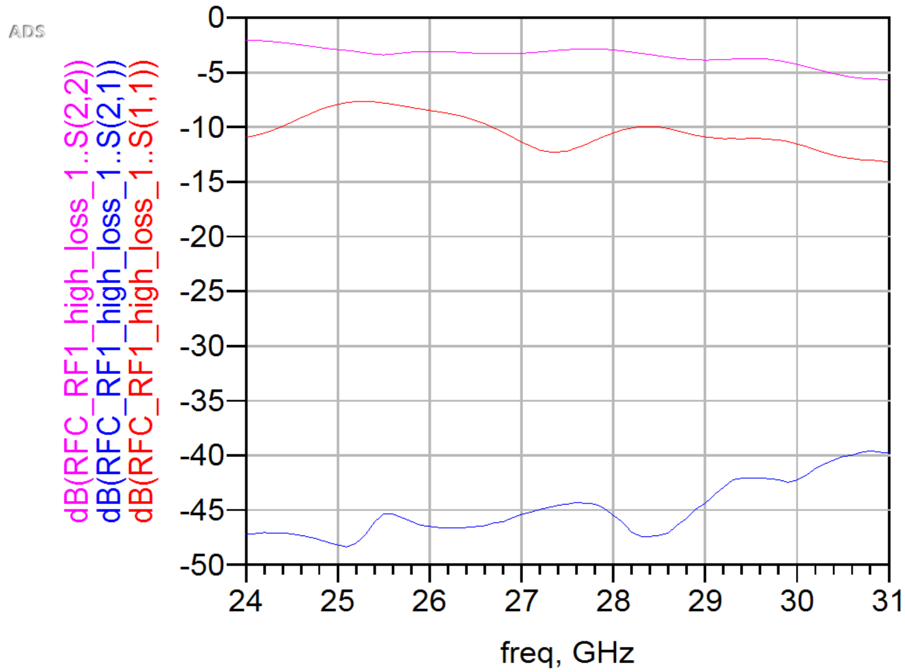
Filter Loss:
< 2 dB@28GHz

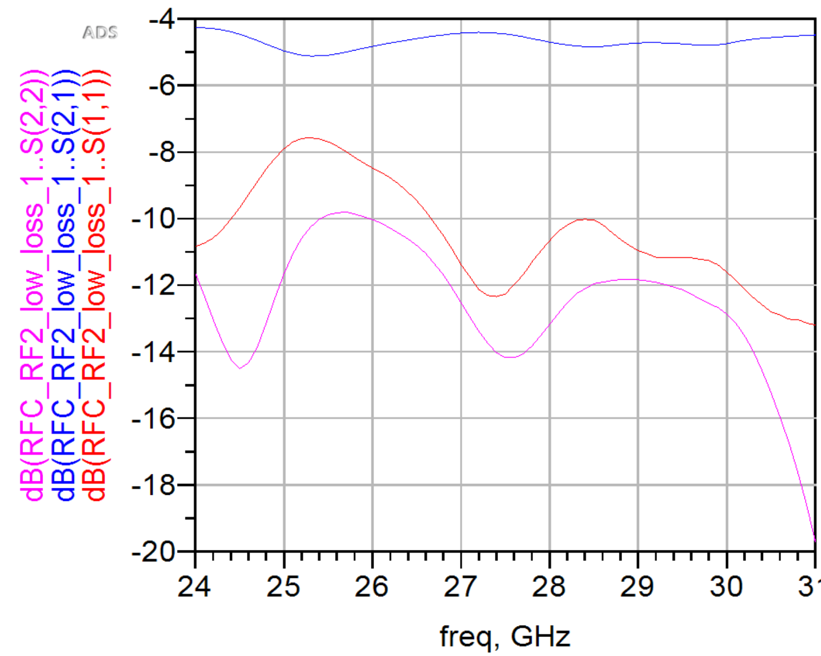
Photograph and Layout of SPDT SW





SPDT Switch: Measured S-Parameters RFc to RF1 high loss & RFc to RF2 low loss

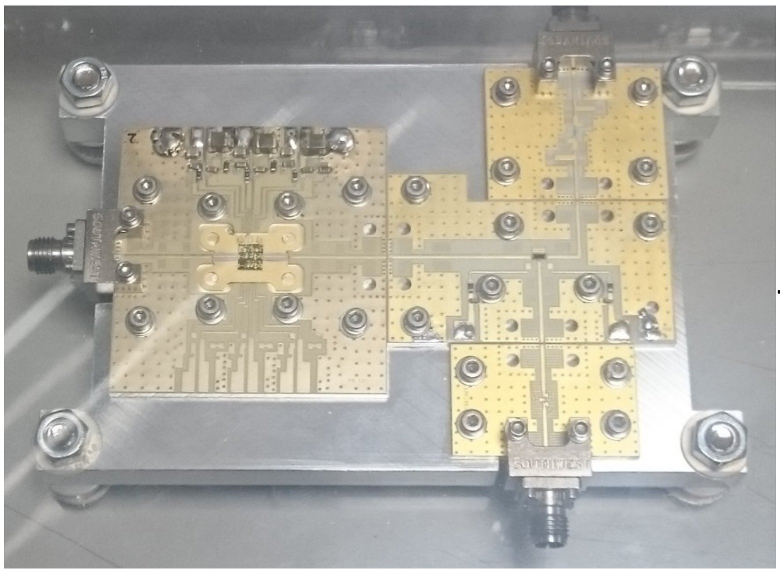




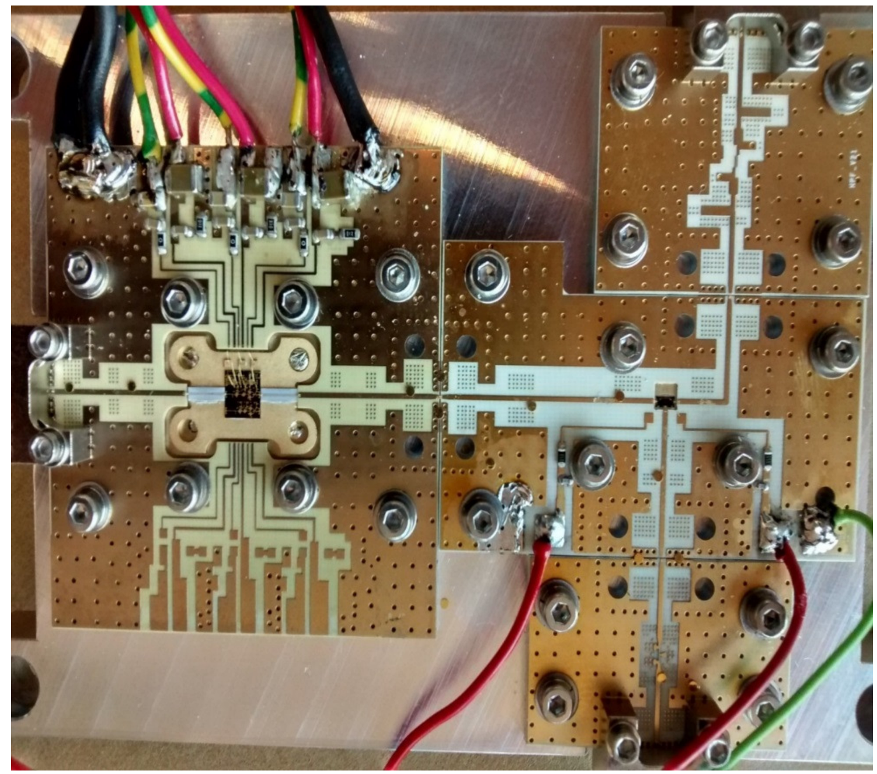
Includes line losses for modular approach

Photograph of 28 GHz Front-End Module (with Modular Approach)

RX port

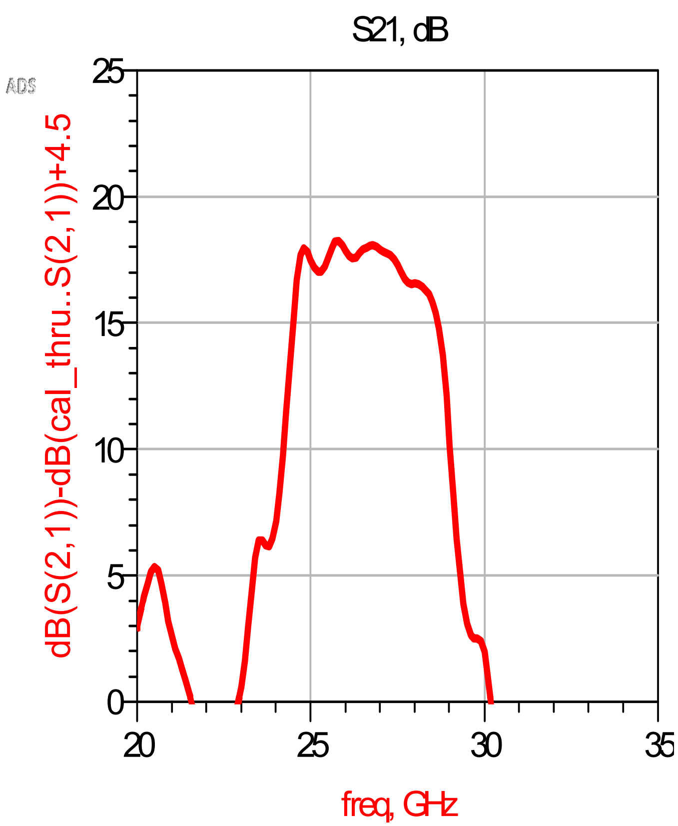


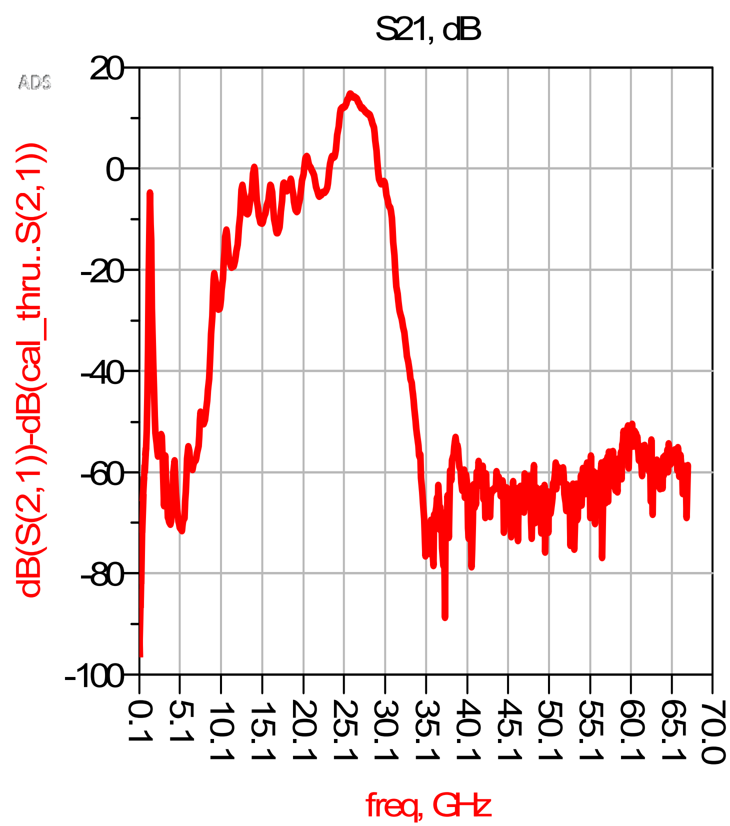
TX port



Antenna port

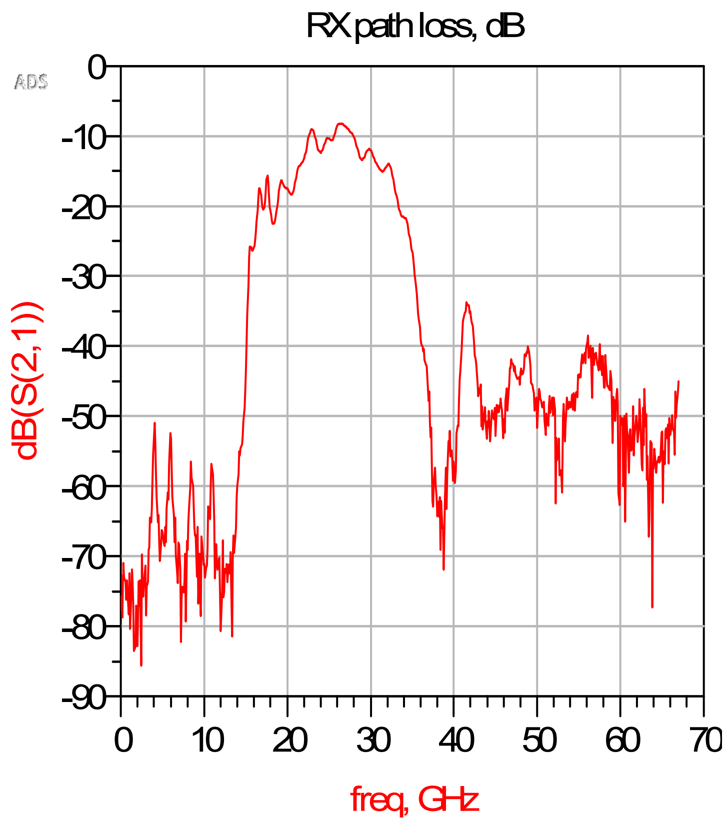
Measured TX Gain/IL: 20 to 35 GHz & 0.1 to 67 GHz

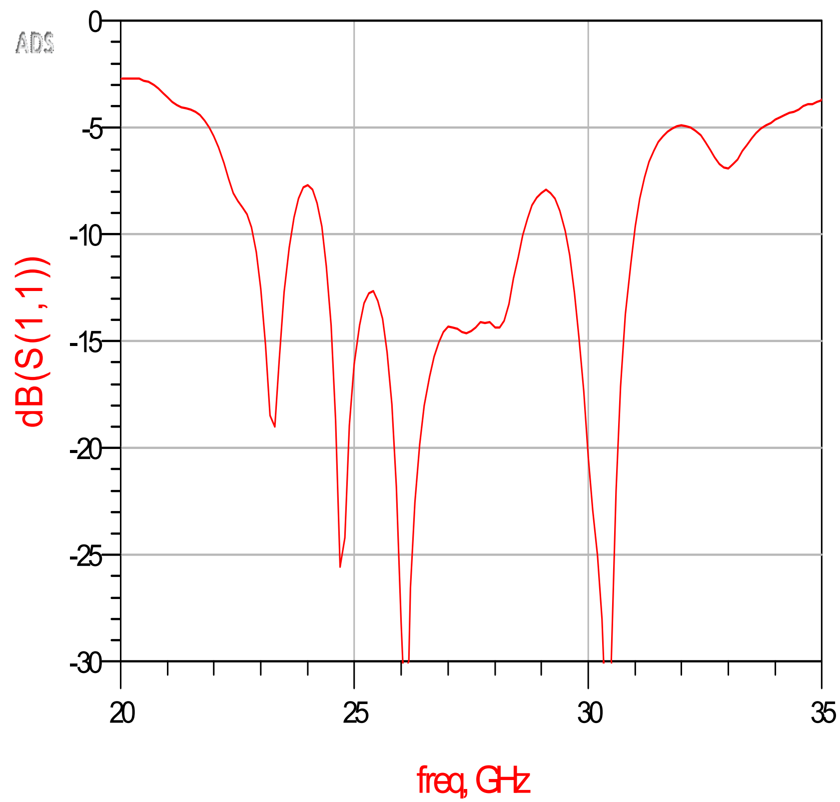




Includes line losses for modular approach

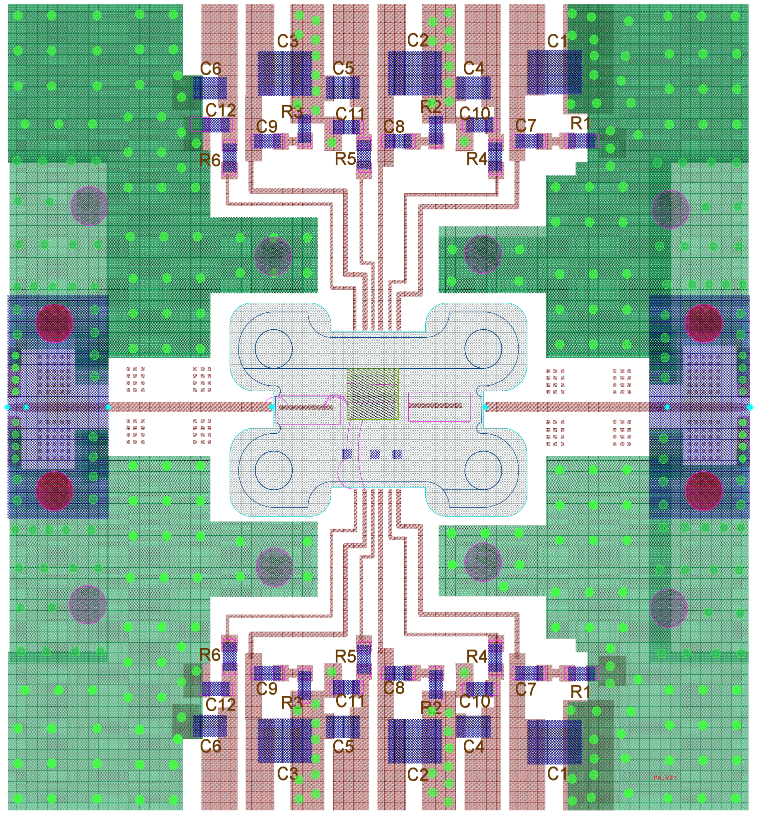
RX insertion loss, 0.1 to 67 GHz & Return loss



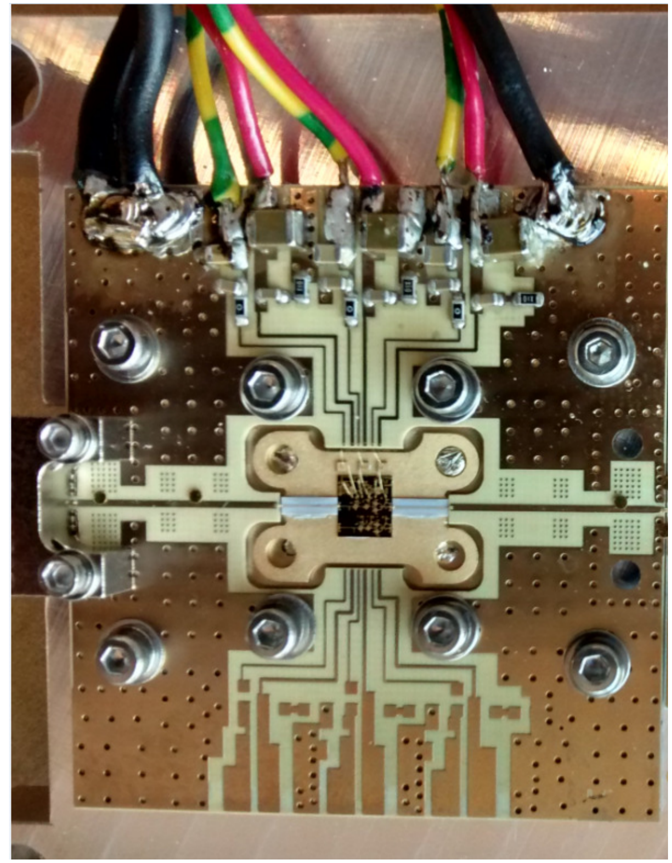


Includes line losses for modular approach

Layout and Photograph of PA

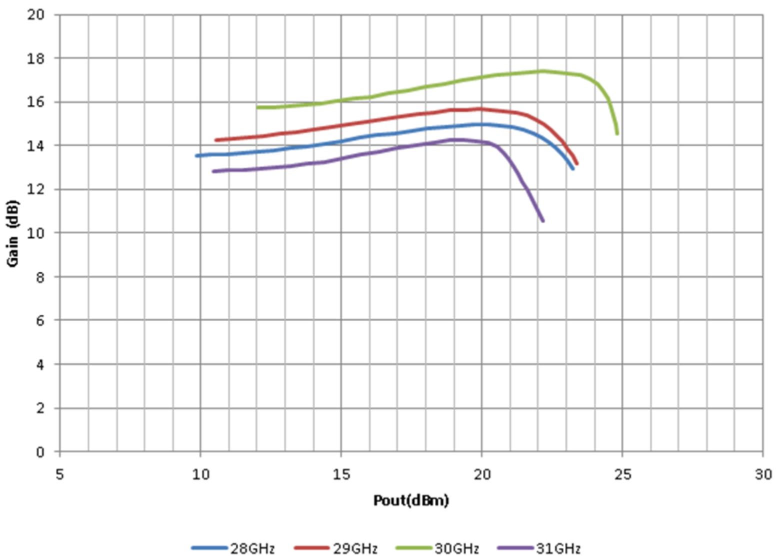


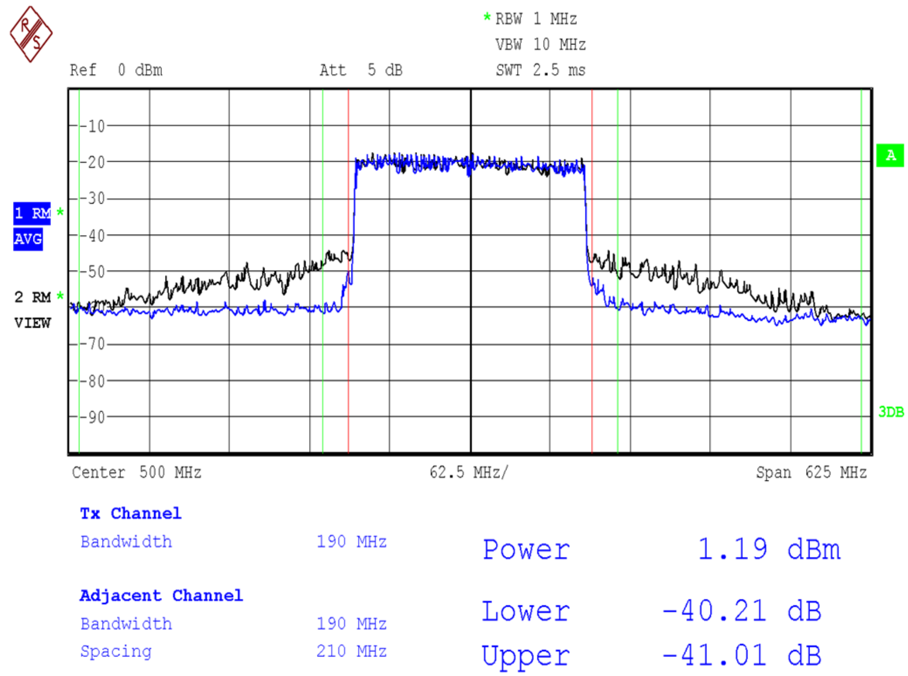
Layout of PA



Photograph of PA

Measured Performance of PA





Measured Performance of PA

Performance of PA with Wideband DPD

Conclusions

- 5G vision for Applications and Use Cases Taking Shape
- 5G mmWave Link Budget & Possible Architectures
- A Lot of Scope for R&D Activities Relating to Front-End Implementation: novel PA topology, low loss PS and SW, efficient and low cost integration technique, compact size yet effective thermal management, innovative multiphysics analysis and modelling
- PA Techniques for Addressing Power Consumption/Efficiency
- Measured Performance for the First Prototype FEM with Modular Approach and Single PA

THANK You