RESEARCH AREA

Research Area

- RFIC : Transceiver, LNA, PA, PLL, Mixer, VGA, Phase-Shifter, *et al.*
- Frequency: From DC to 300GHz
- Process: CMOS (TSMC 28nm, others), III-V (Wolfspeed GaN, InGaAs etc)

Research Applications

- Mobile Wireless Communication
- High-speed Wireline Communication
- Vehicular Communication and Radar
- THz Communication

Assoc. Professor
Boon Chirn Chye
Program Director,
RF & MM-wave,
VIRTUS, NTU

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Web: http://www.ntu.edu.sg/home/eccboon

Research Funding in Recent 5 Years

Research Leadership in RF/MMW IC

Funding Source/ Project Title	Institute/University /Industry Partner	Role	Grant Period
Delta-NTU Corp. Lab: A Wireless Heterogeneous Network Transceiver Chipset for Content-Driven Transmission of Learning Media (SLE-RP3) Research Area (SLE)	Delta-Electronics	PI	1st July 2016 to 30th June 2021
MOE Tier 1: Monolithic Terahertz Passive Components in Advanced CMOS Technology: From Fundamental Understandings to Integrated Circuit Applications	MOE	PI	1st November 2016 to 31st October 2018
GlobalFoundries Singapore Pte. Ltd-NTU Joint R&D: Direct Integration of GaN Power Devices on CMOS Circuits for Demonstrate Power Management Solutions,	GlobalFoundries	PI	1st June 2016 to 31st December 2018
SMART-POC: An Integrated Platform Approach Towards Non-Invasive Continuous Blood Glucose Monitoring Addressing Clinical Need for Early Diagnosis and Improved Compliance	SMART-MIT	PI	1st July 2016 to 30th July 2017
Huawei Tech. Co. Ltd-NTU Joint R&D: 10GiFi research & development of ultra-wideband RF transceiver	Huawei	PI	15th July 2014 to 14th July 2018
Tier 2: High Thermal Resolution Ultra-Low Power Integrated Imager: Fund. Issues in CMOS	MOE	PI	July 2013 to June 2016
Electronic Circuit Design, Communications under SMART-IRG5: Low Energy Electronic Systems (MIT-NTU) (Multiple grants)	MIT	PI	1st April 2014 to 30th June 2021

Projecting Funding Since 2019

Project Title	Grant Type	Amount Approved	Project Start date
CMOS Terahertz Plasmonic Interconnect towards Tera-scale Coumputing	AcRF Tier2	788,736.00	28-Jan-2020
Transceiver Test and Development Applicable for V2X-System and mmW	RCA	125,000.00	22-Jan-2020
Transceiver Development Applicable for Hybrid “C-V2X-System +DSRC” V2X-System	IAF-PP(AME Domain)	2,889,900.00	01-Nov-2019
LEES III-V+CMOS Circuits & System towards Commerciallization	Singapore-MIT Alliance for research and Technology (SMART) Centre	364,800.00	01-July-2019

Main Projects in Recent 5 Years

2014 – 2018 (Carrier Aggregation RF Transceiver for Next Generation WiFi)

5-6GHz 3-Carrier Aggregation Transceiver, World First Demonstrated

HUAWEI

2016-2020 (Multi-Mode Transceiver for Smart Learning)

Sub-6GHz Transceiver:

Support 2.4G/5GHz WiFi, Bluetooth, ZigBee

2017- (LESS: CMOS+III-V)

5G NR and 802.11ax

Front-end :

CMOS + GaN

Wireless Power Transfer:

CMOS + GaN

SMART

Singapore-MIT Alliance for Research and Technology

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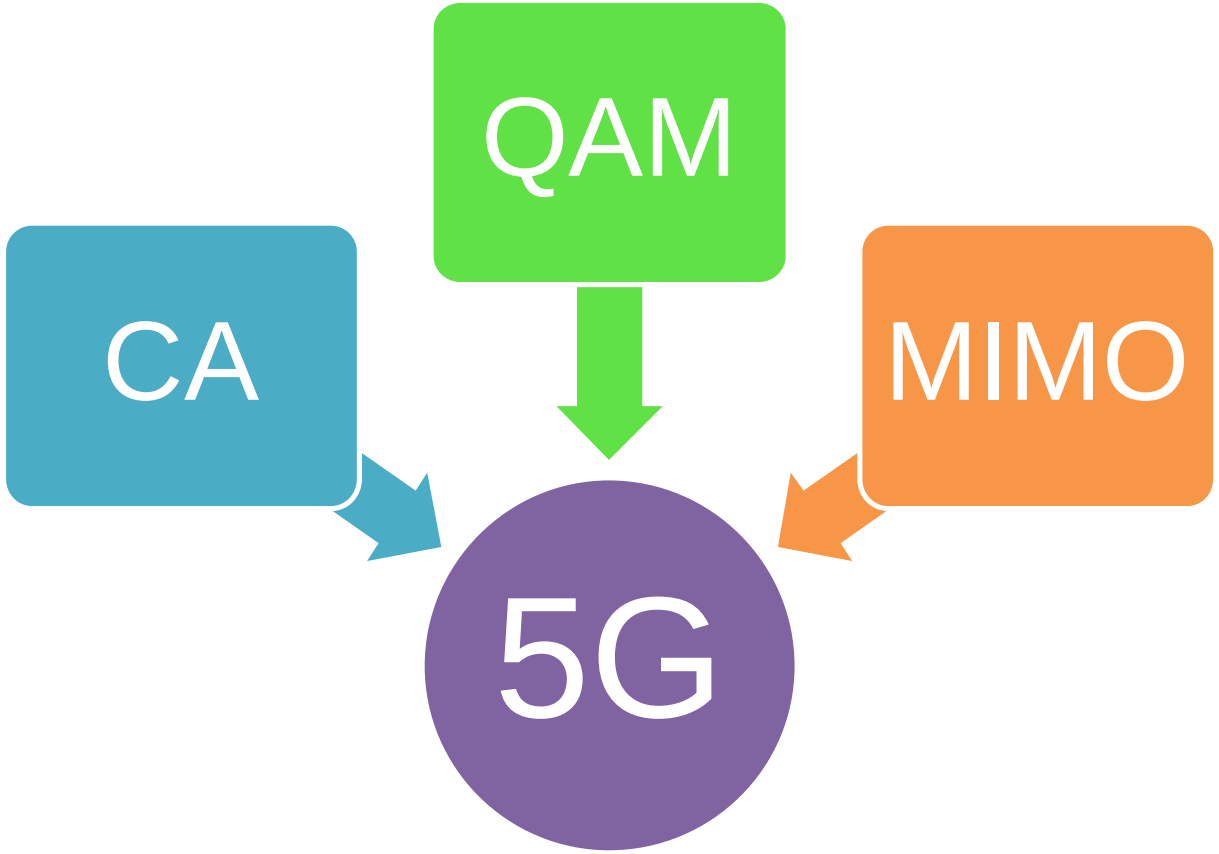
5G Key Enabling Technologies



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WiFi-6 vs 5G

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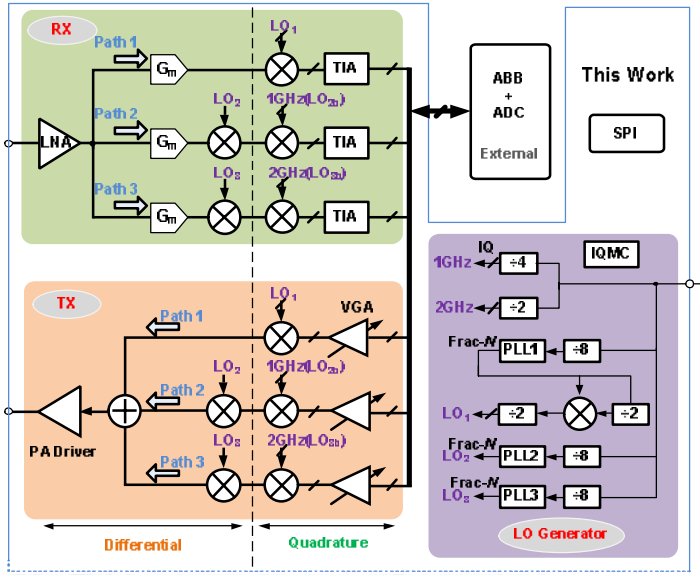
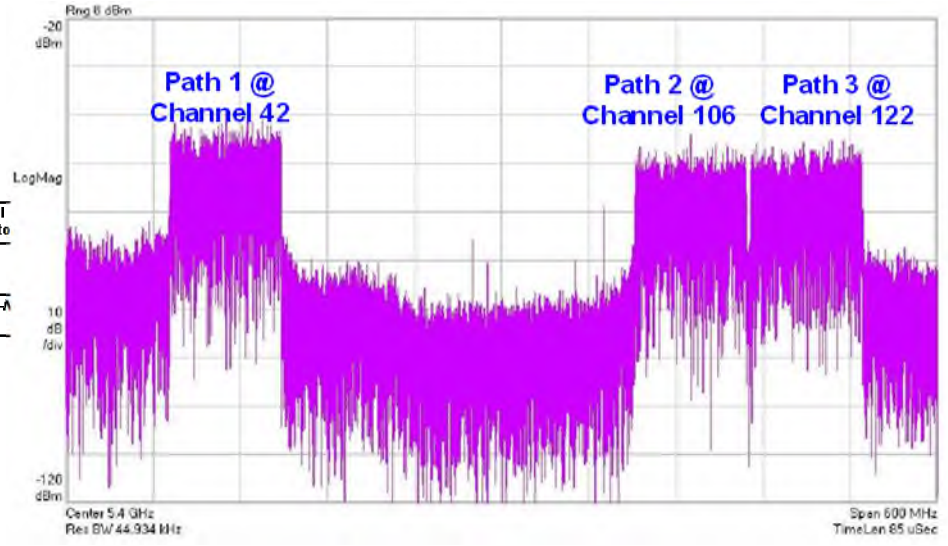
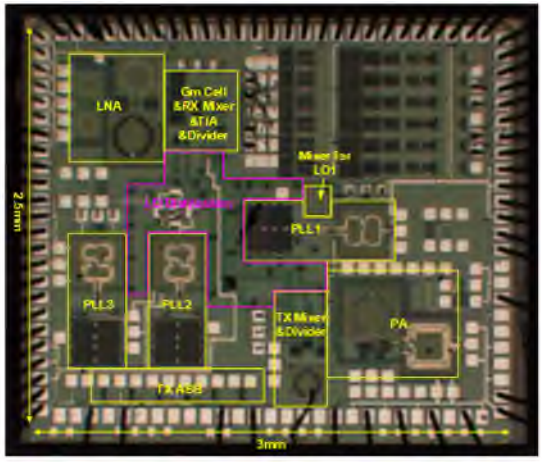
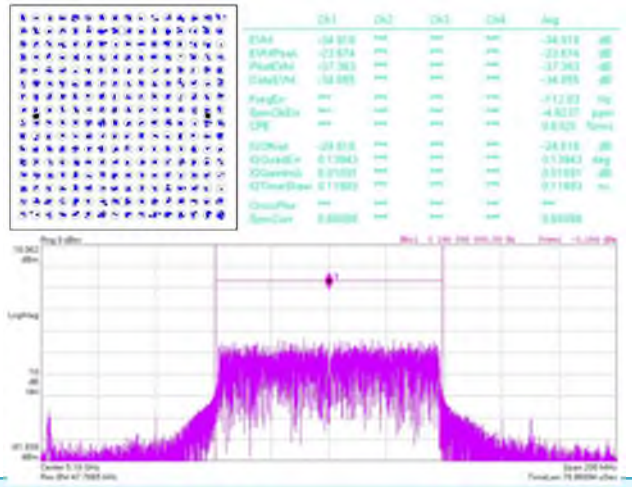
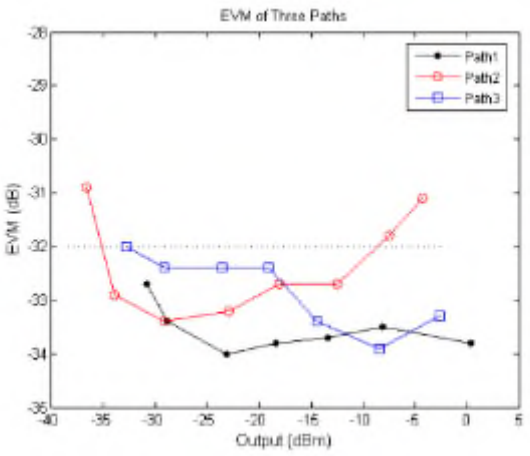
2 x 2 MIMO RFIC for Wireless Communication - 3-Carrier Aggregation Transceiver for WiFi-6





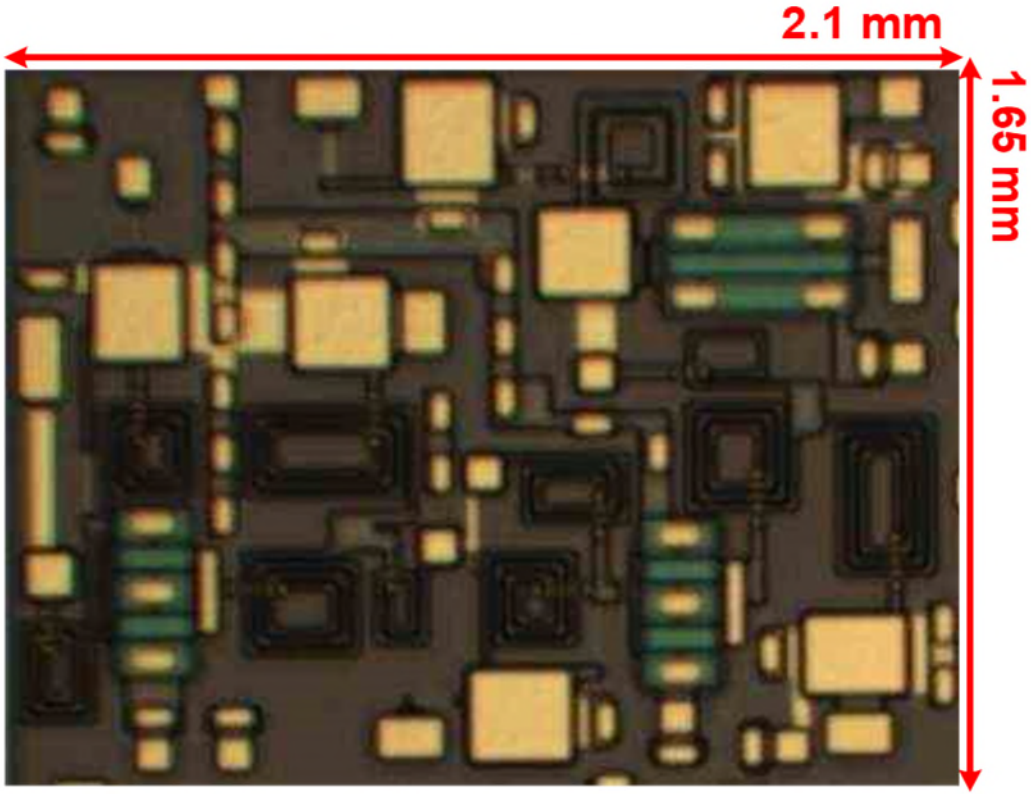






1. Proposed transmitter can mitigate cross-talk and VCO pulling
2. Proposed transmitter can support inter-band and intra-band carrier aggregation

Sub-6GHz 5G GaN PA:
2.4-6GHz (Fully Int. 2.1mm x 1.65mm)



GaN Die

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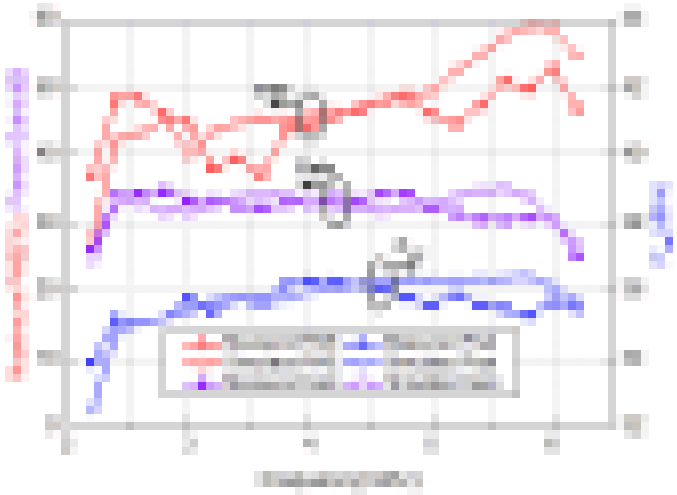
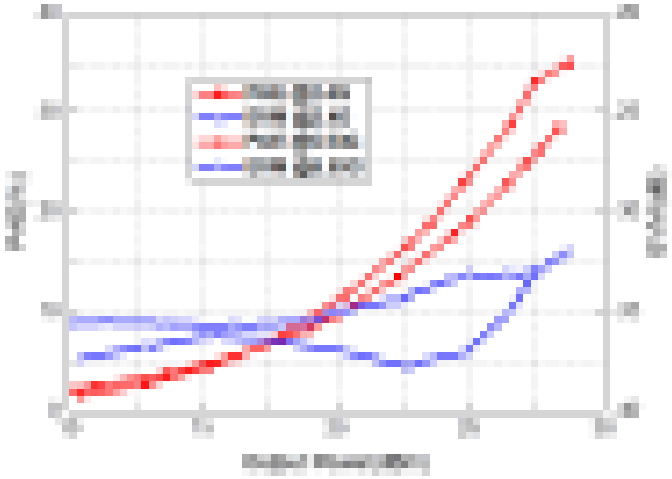
Sub-6GHz 5G GaN PA:
2.4-6GHz (Fully Int. 2.1mm x 1.65mm)

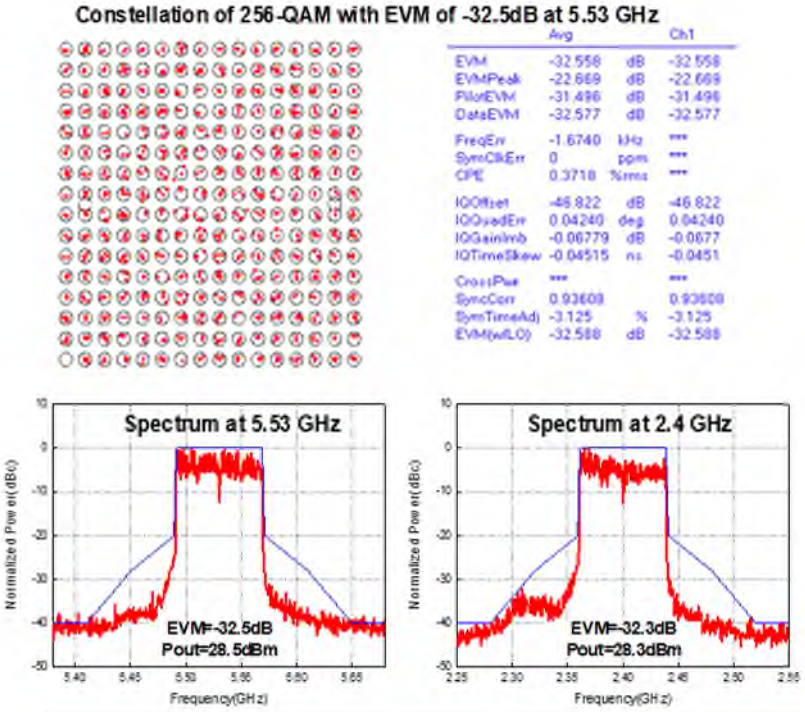
CW performance (**Broadband**)



PAE and EVM in different power level



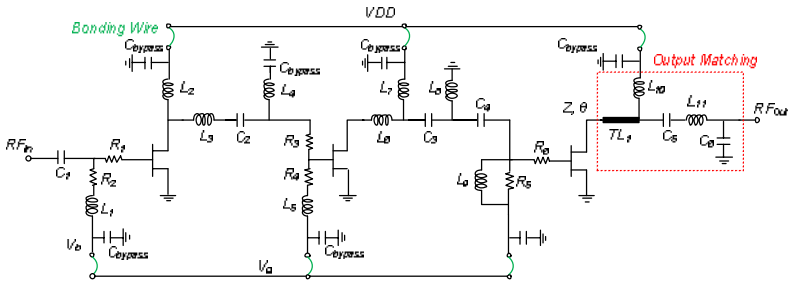
Measured EVM and spectrum using 80-MHz 256-QAM signal

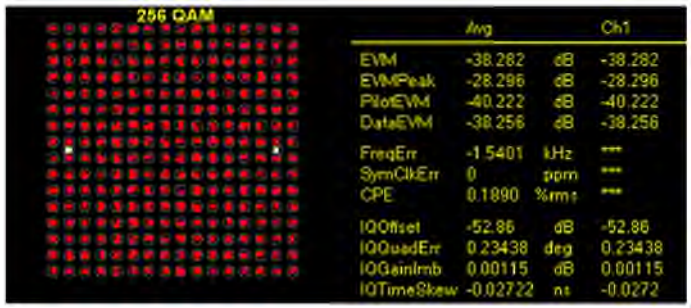


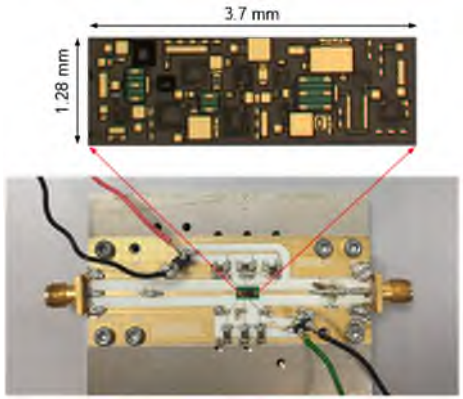
Measured CW performance:

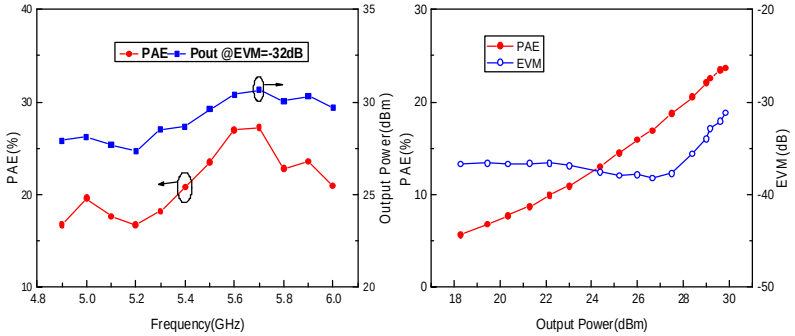
- **Frequency: 2.4GHz-6GHz**
- **Output power: 35.2-36.3dBm**
- **Efficiency: 38-53%**
- **Gain: 30.5-34.7dB**

RFIC for Wireless Communication
- Class-J GaN PA for WiFi-6 (ax)









	Proposed PA	SKY85402 (Skyworks)	RFFM8505 (RFMD)	RFPA5026 (Qorvo)
Frequency	4.9-5.9 GHz	5.1-5.8 GHz	4.9-5.85 GHz	4.9-5.9 GHz
Pout @-32dB EVM	23.7-26.3 dBm	22 dBm	19.5 dBm	25 dBm
Efficiency @ -32dB EVM	16.7-27.3%	11.4%	9.5%	9.4 %
Technology	GaN	SiGe	InGaP	InGaP

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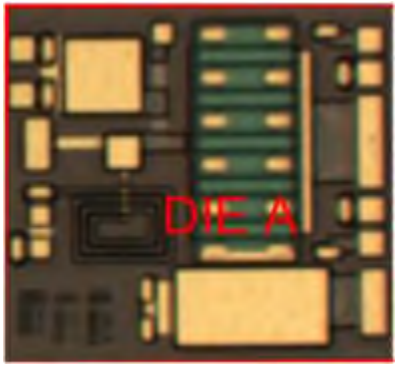
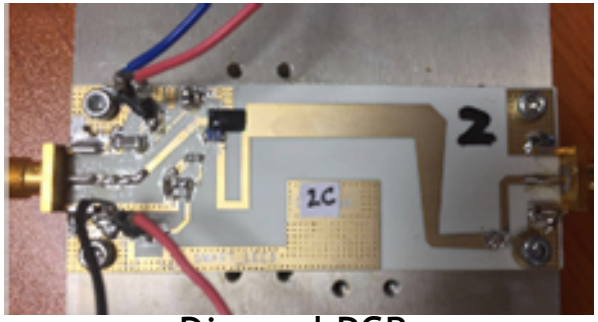
Performance comparison between the proposed PA and other commercial products

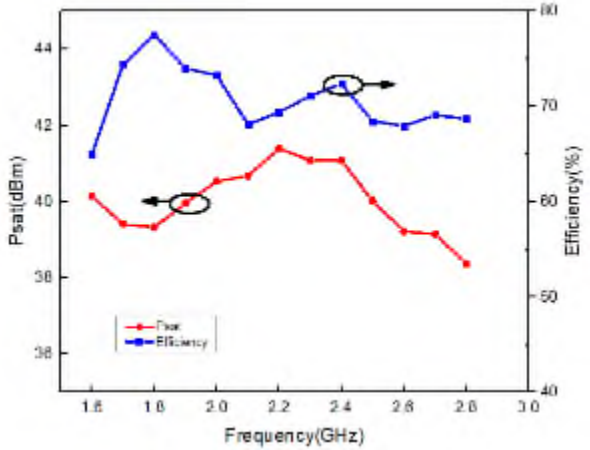
RFIC for Wireless Communication
- 1.6-2.7GHz GaN PA for LTE-Advanced



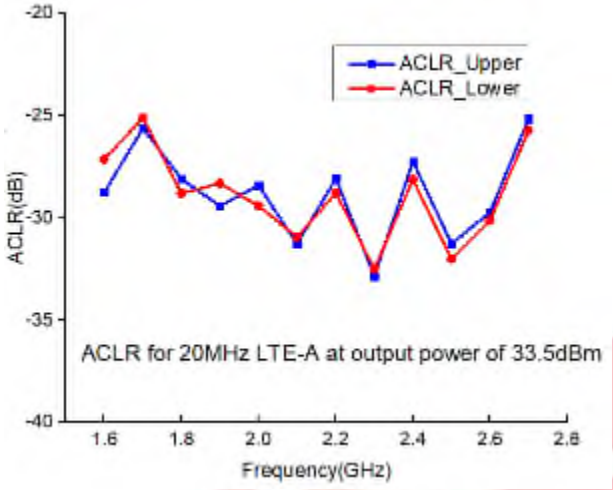


Die and PCB

Measured Psat and efficiency



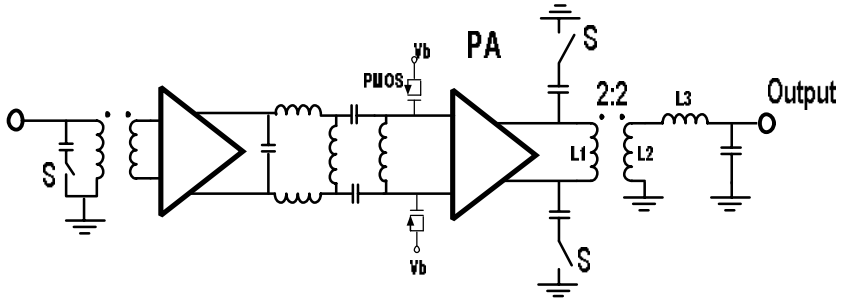
Measured ACLR for 20MHz LTE-A signal

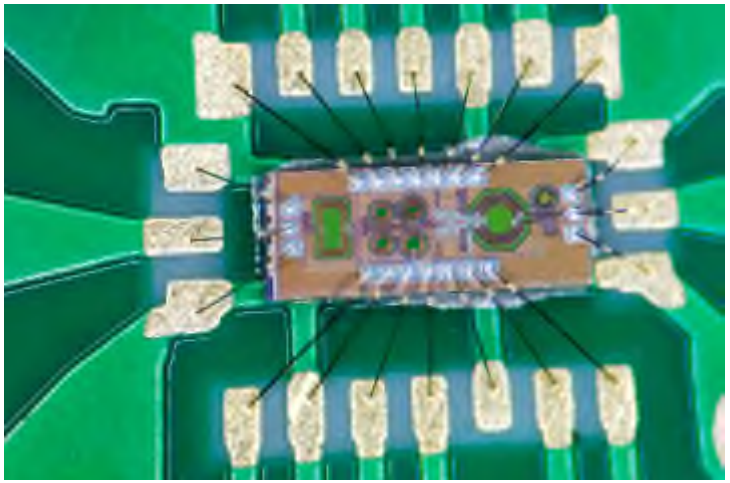


Measured performance:

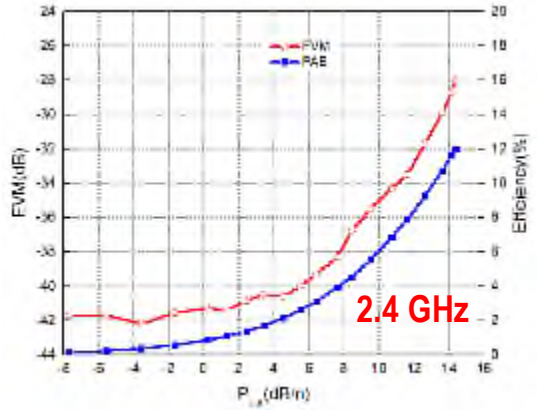
- **Frequency: 1.6GHz-2.7GHz**
- **Output power: 39.2-41.1dBm**
- **Efficiency: 63-77%**
- **Gain: 10-12.3dB (3.5mm^2)**

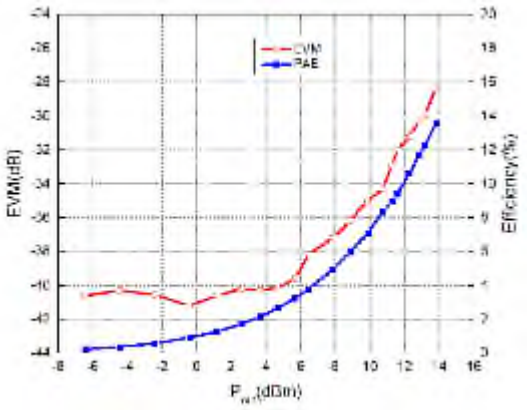
RFIC for Wireless Communication
- CMOS 2.4/4.9-5.9GHz Dual-band PA for Sub-6GHz CA



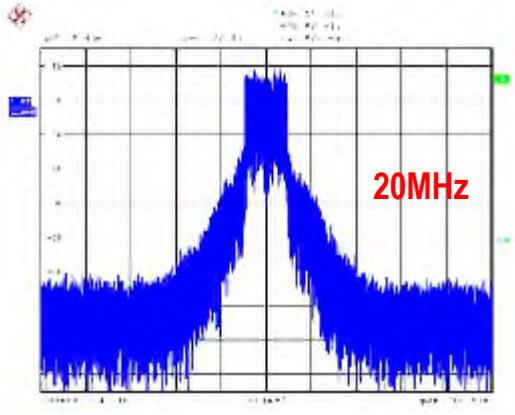


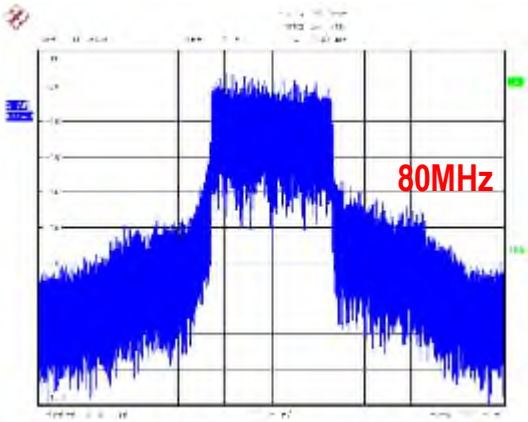
EVM and Efficiency for 80MHz, 256-QAM 802.11ax signal





EVM and Efficiency for 20MHz and 80MHz 802.11ax signal





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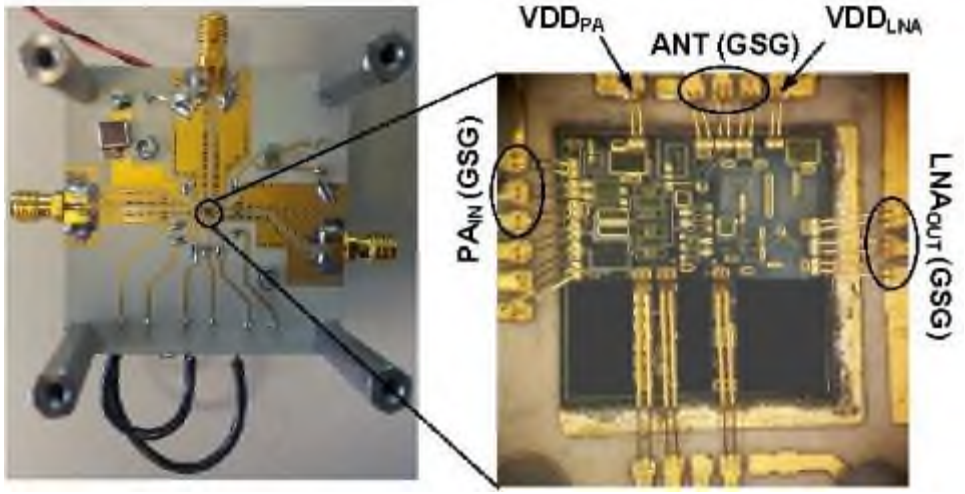
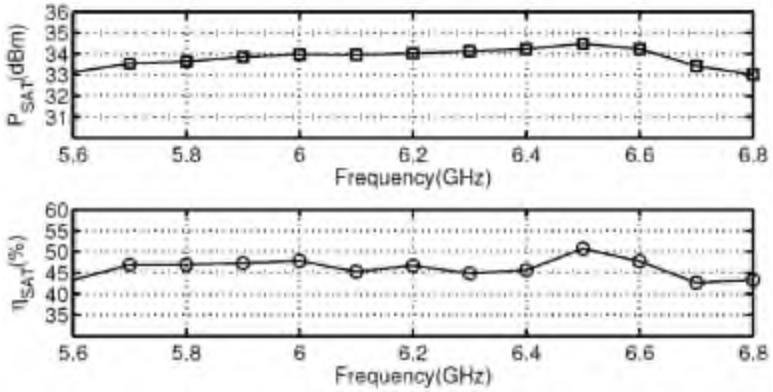
RFIC for Wireless Communication
- GaN RF front-end for 802.11p @ 5.9GHz DSRC



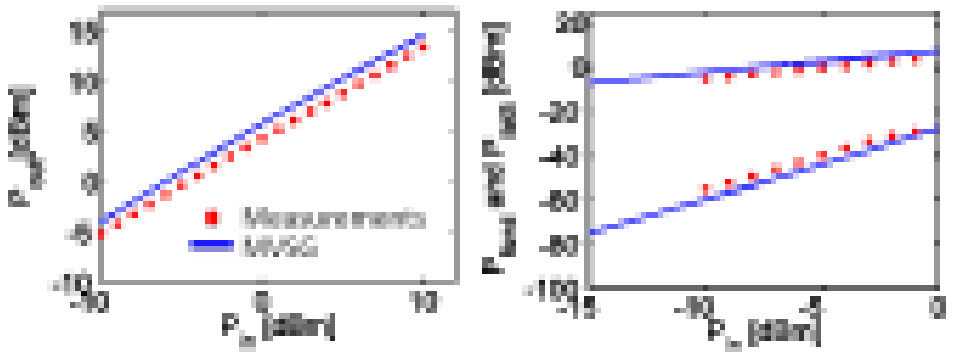
- Fully integrated & energy efficient RF
  - PA + LNA + ANT SW
  - 2mm x 1.2mm

Chip-on-Board

(No external matching)



Tx mode: 50% power efficiency @ 34dBm Psat



Rx mode: 22dBm OIP3

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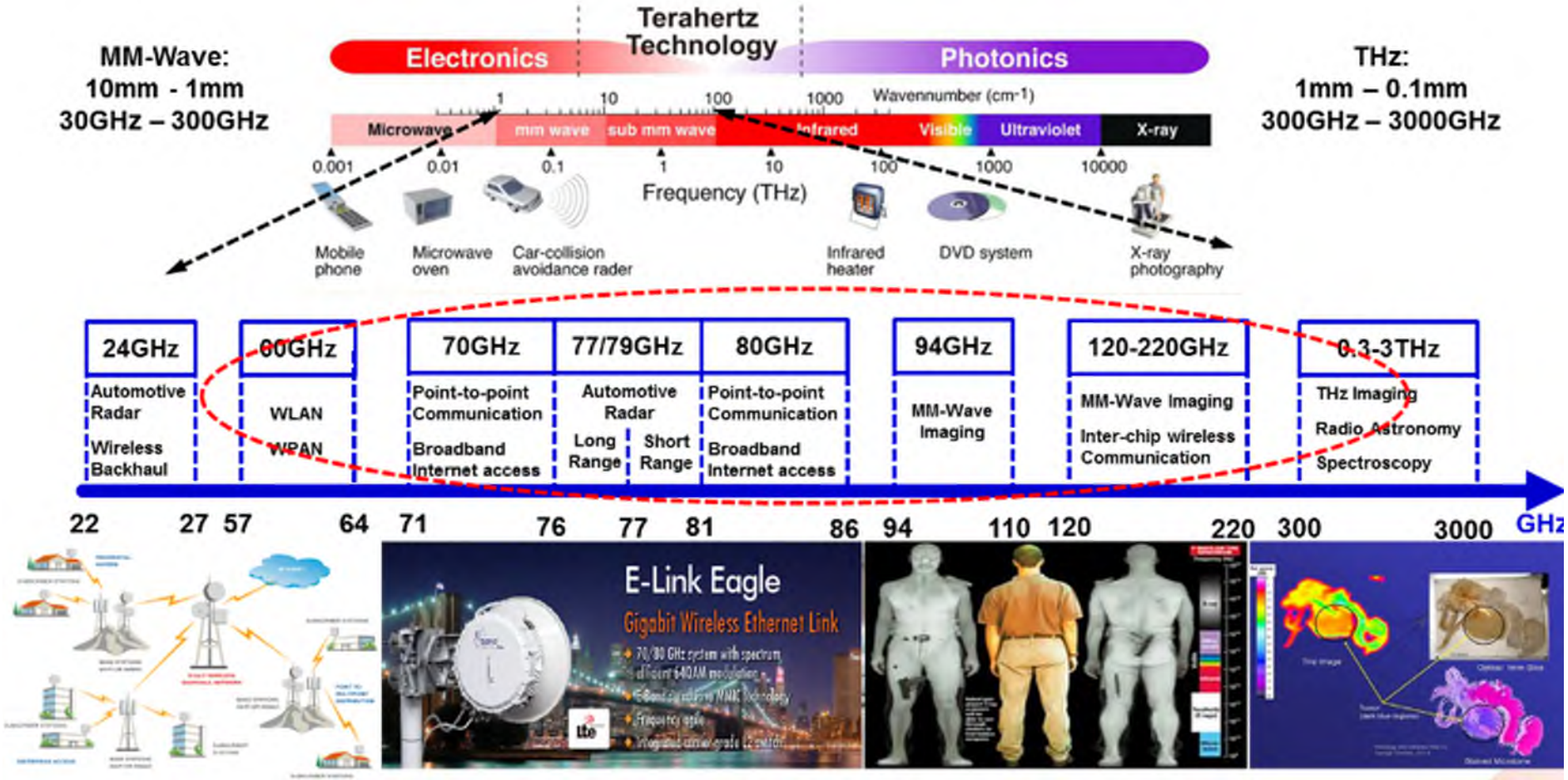
MM-Wave RFIC



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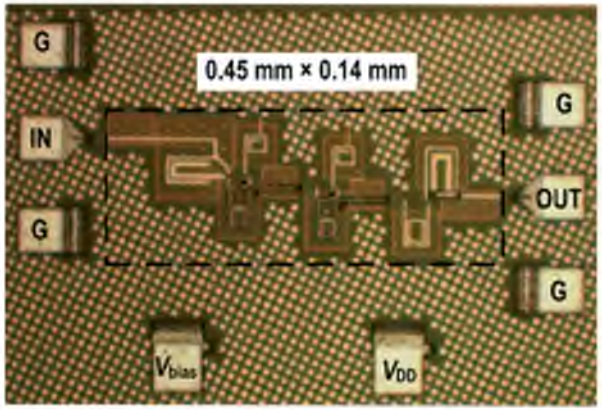
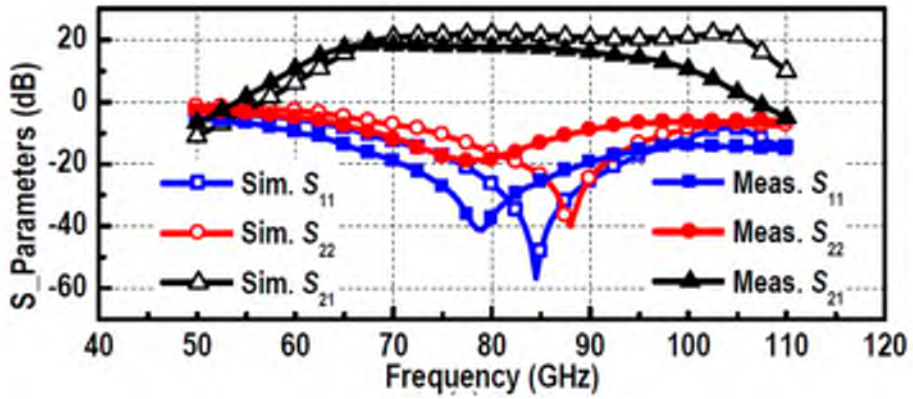
MM-Wave RFIC: Widest Bandwidth Highest BWER 100GHz LNA

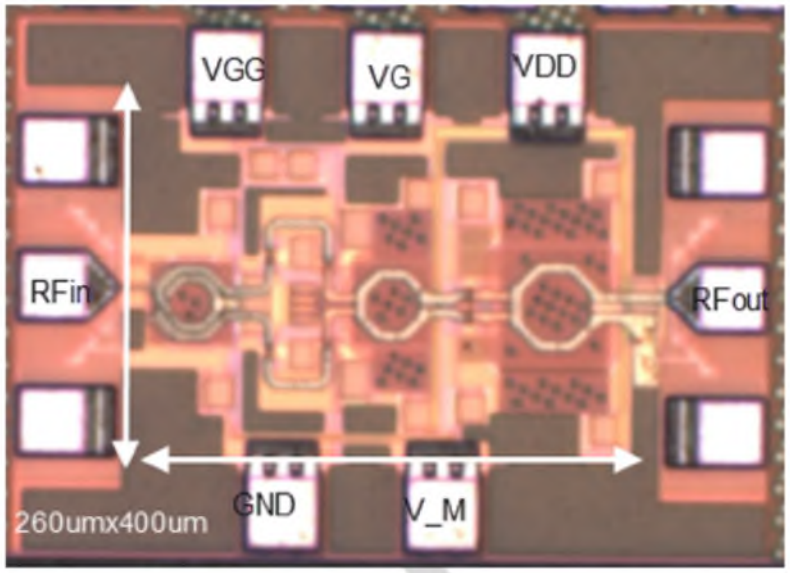


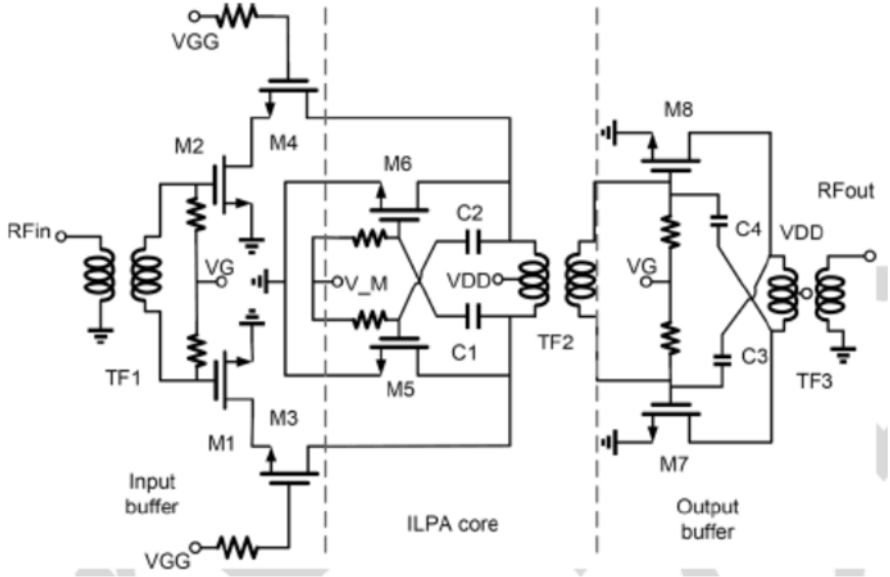


Overcoming Gain Flatness, Wideband Gain Trade-off for MMW Application.

	[4] TMTT 2012	[5] TMTT 2015	[6] ISSCC 2010	**This Work**
Technology	45nm SOI CMOS	28nm CMOS	65nm CMOS	**65nm CMOS**
Topology *	3-stage CS	2-stage Cas.	3-stage Cas.	**3-stage Cas.**
Power Gain [dB]	10.7@95GHz	13.8@66GHz	17.5@77GHz	**18.5@67GHz**
BW ** [GHz]	18	18	17 #	**30**
NF_{min} [dB]	6.0	4.0	7.4	**6.1**
P_{1dB} ## [dBm]	N/A	-12.5	-22.0	**-11.8**
P_{DC} [mW]	52	24	30	**27.4**
Size [mm²]	0.32	0.38	0.37	**0.24**
FoM † [GHz/mW]	0.40	2.43	0.95	**3.00**

MM-Wave RFIC: 50-59GHz High Gain Power Amplifier





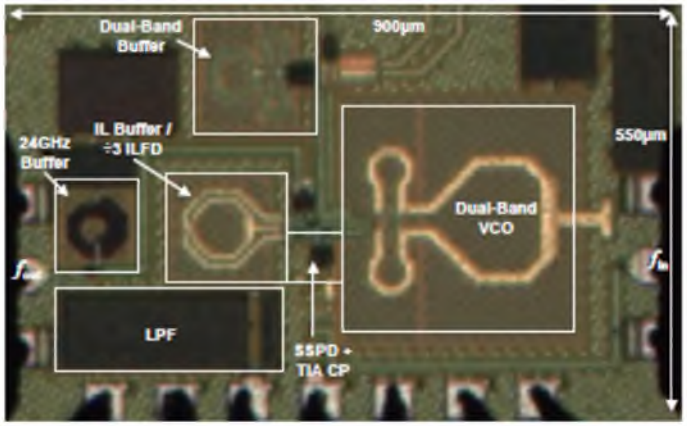
This work demonstrates an ILPA with largest injection locking bandwidth. The fabricated PA has achieved a injection locking range from 50 GHz to 59 GHz. Maximum output power of 11.39 dBm has been obtained while the highest PAE is 16.1 %. Moreover, the chip size is 260 µm x 400 µm excluding pads.

MM-WAVE CMOS HIGH EFFICIENCY PA

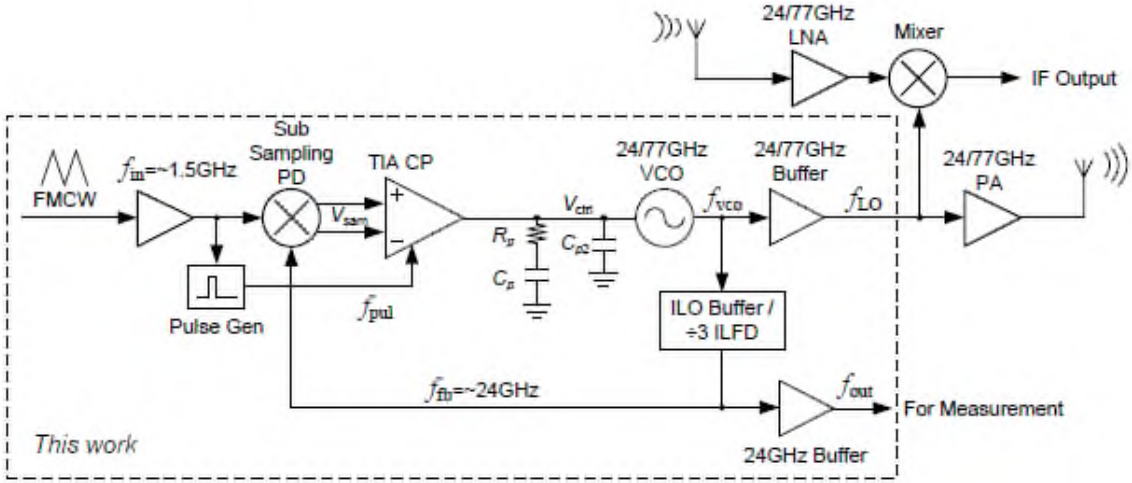
Technology	Topology	Freq(GHz)	Max Gain (dB)	Pmax(dBm)	PAE(%)	Area(mm2)
CMOS 65nm -This work	Buffered Input&Output	50-59	37.8	11.39	16.1	0.104
CMOS 65nm [3]	2 to 1 transformer	52.5-54.5	29	9.6	17.3	0.1
CMOS 65nm [1]	ZVS	57-65	5	-1.5	20*	NA

*Drain efficiency

MM-Wave RFIC: 24/77GHz Dual-Band vehicle FMCW Radar



←Best phase noise
← Best power efficiency



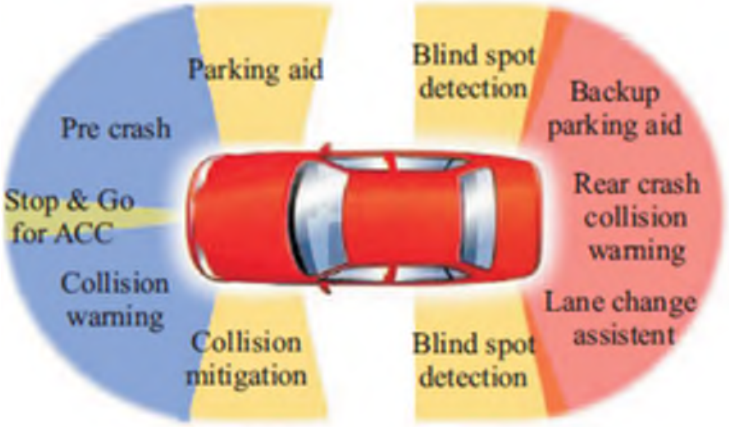


Fig. 1. Automotive radar applications

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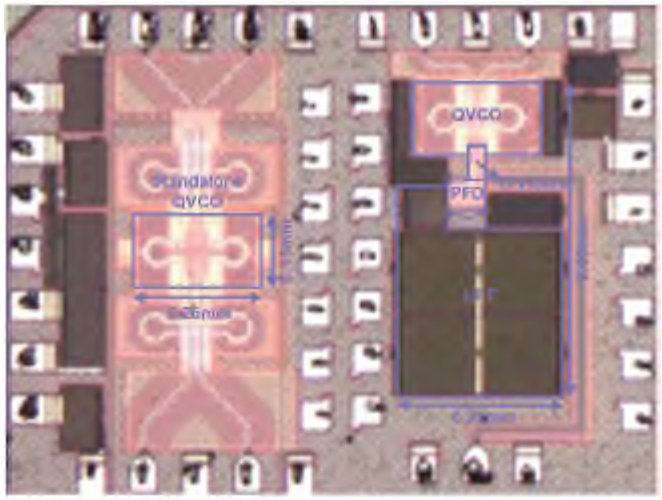
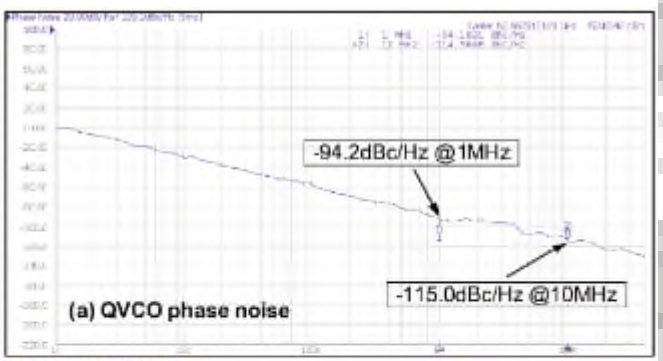
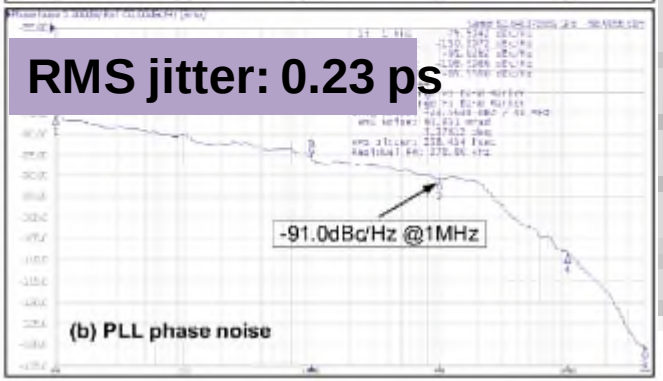
MM-Wave RFIC: 57.9-68.3GHz PLL

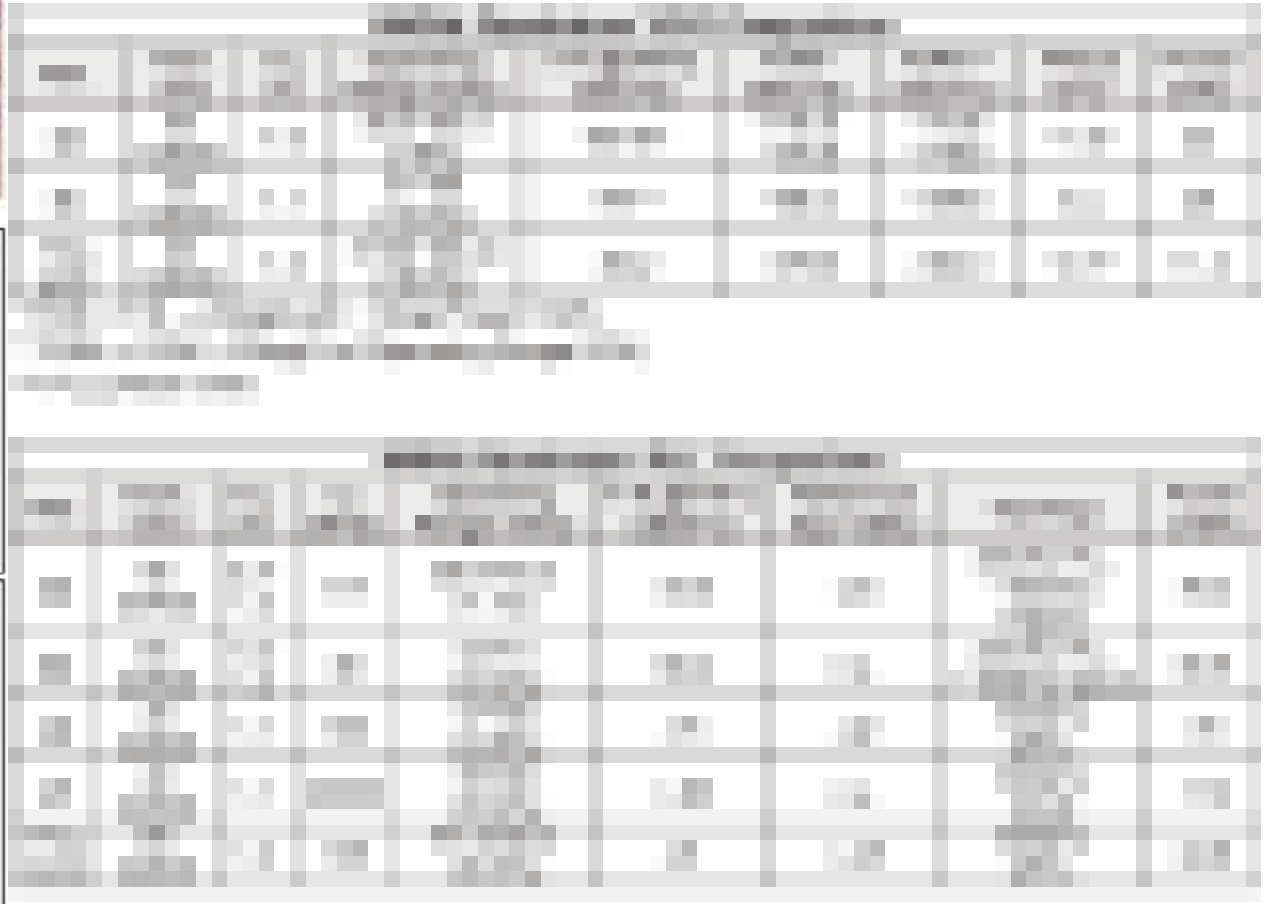


Yi Xiang, Boon Chirn Chye, et al. (ISSCC 2013)
Fast settling due to high reference freq., Ultra low phase noise (low jitter), energy efficiency.

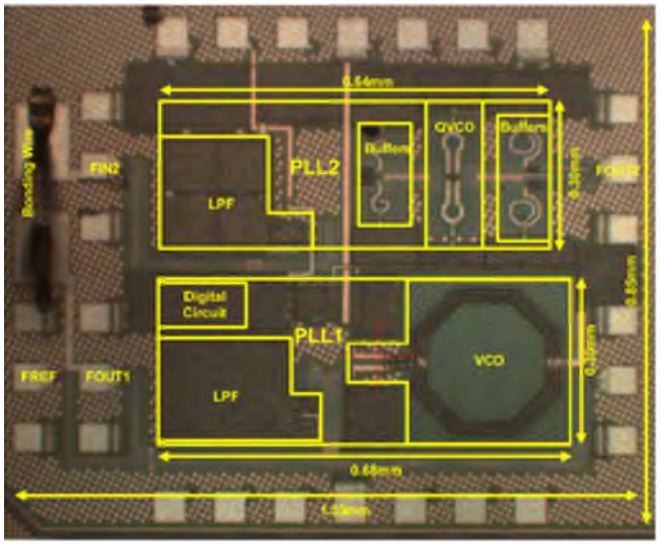




RMS jitter: 0.23 ps

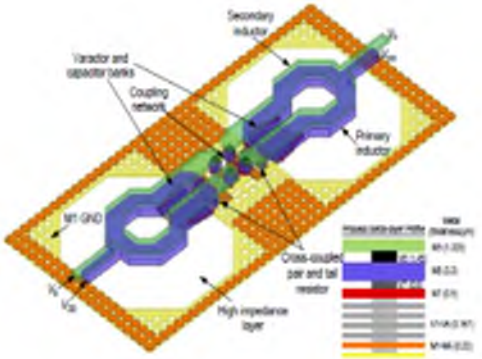


MM-Wave RFIC: World First 100GHz Fractional-N PLL in CMOS



Ultra-compact PLL
Overcoming frequency resolution, fast settling, signal purity trade-off.

Ref.	Tech. (nm)	Operating Range (GHz)	P.N.@1MHz /10MHz (dBc/Hz)	FOM[1]@1MHz /10MHz (dBc/Hz)	FOM$_T$[2]@1MHz /10MHz (dBc/Hz)	Output Phase	Power (mW)
[2]	65 CMOS	98~103.3 (5.2%)	-75[3] /-112.1	-164.49/ -181.59	-158.81 /-175.91	Differential	12~21
		91.7~95.5 (4.1%)	-80[3] /-118.8	-162.79/ -181.59	-155.04 /-173.84	Eight Phases	48~85
[3]	65 CMOS	100~110 (9.5%)	-92.83 /-100[3]	-175.9 /-163.1	-175.5 /-162.7	Quadrature	54
This work	**65 CMOS**	**93.24~105.02 (11.9%)**	**-93.80 /-112.67**	**-178.6 /-177.5**	**-180.2 /-179.0**	**Quadrature**	**30**



Ref.	Tech. (nm)	f_{ref} (MHz)	Operating Range (GHz)	P.N.@1MHz /10MHz (dBc/Hz)	Reference Spur (dBc)	Resolution (MHz)	Output Phase	Architecture	Power (mW)
[4]	65 CMOS	371.5 ~377.0	95.1~96.5 (1.5%)	-76 /-93[3]	-51.8	f_{REF}	Differential	Integer-*N*	43.7
[5]	65 CMOS	185.7 ~211.9	96.8~108.5 (11.4%)	-88 /-105[3]	-40	f_{REF}	Differential	Integer-*N* + Push-Push	14.1
[6]	65 CMOS	402.6 ~408.5	103.058~104.58 (1.5%)	-80.41 /-101.08	-63.8	f_{REF}	Differential	Integer-*N*	63
This work	**65 CMOS**	**100**	**93.4~104.8 (11.5%)**	**-86.07 -86.07[4] /-108.75 -103.53[4]**	**-44.69**	**0.000036f_{REF}[4]**	**Quadrature**	**Frac-*N* + Sub-Sampling**	**57**

[1] FOM = P.N. – 20log(f_0/Δf) + 10log(Power/1mW).
[2] FOM$_T$ = FOM – 20log(% of Operating Range/10%).
[3] Estimated from figures.
[4] PLL is in fractional-*N* mode.

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MM-Wave RFIC: 160GHz 3.7mW Output Power Signal Source

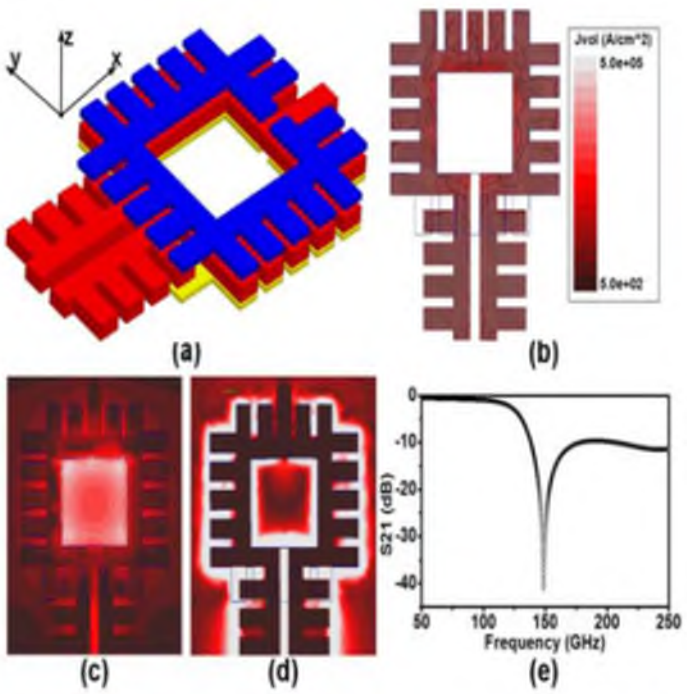


Fig. 3 (a) The proposed surface-wave resonator, the simulated (b) surface current distribution, (c) magnetic field distribution, (d) *E*-field distribution, and (e) S_{21} of surface-wave resonator.

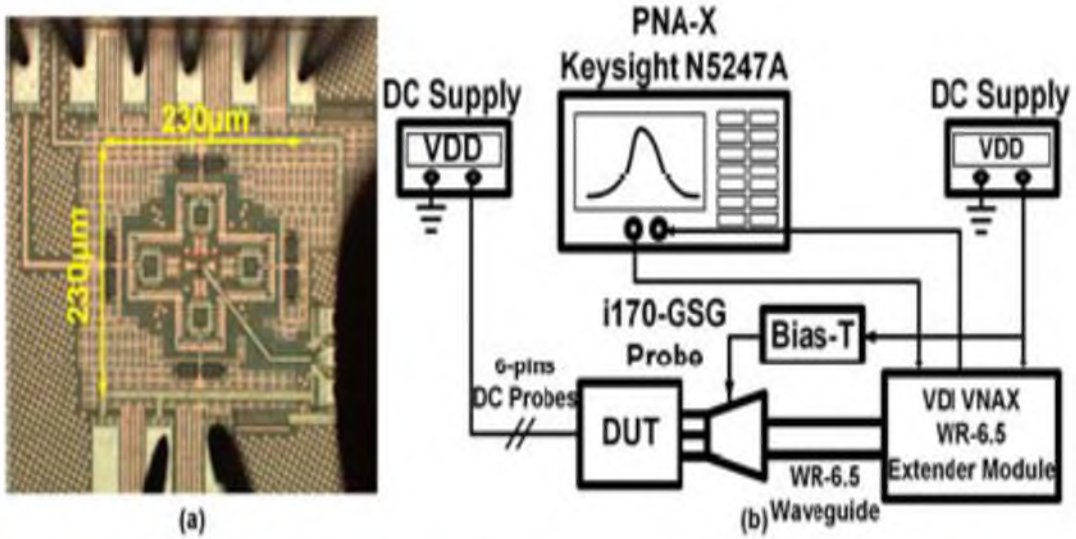
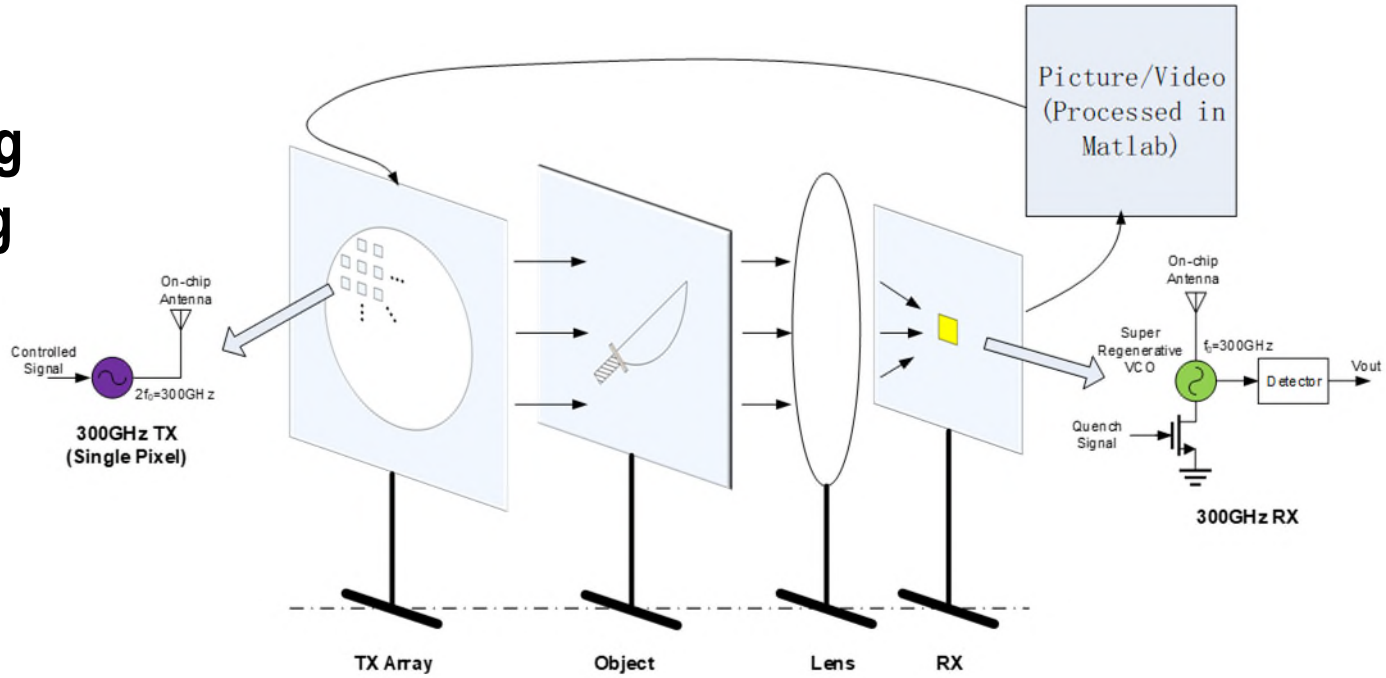


Fig. 5 (a) Die photo, and (b) the 110-170 GHz measurement setup

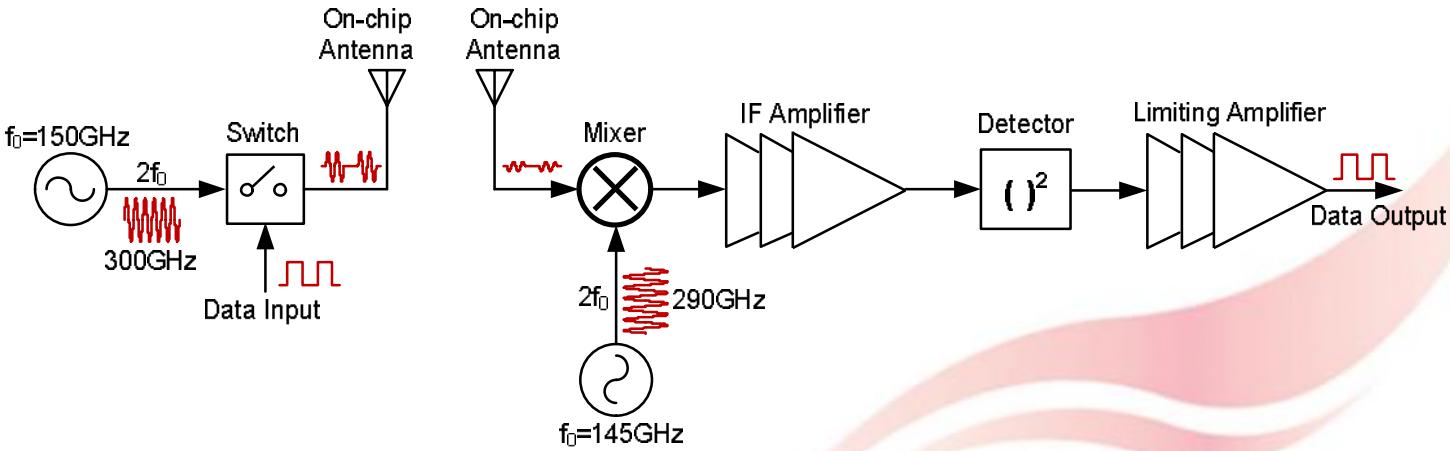
A 4-way surface-wave signal source is designed in 65nm CMOS at 160 GHz.
Low loss as signal source for sub-THz communication.
Measurement results 3.7 mW output power
5.5% DC-RF efficiency, 6.3% FTR and -105 dBc/Hz phase noise at 10 MHz offset, leading state-of-the-art FOM of -171 dBc/Hz and FOMT of -172.7 dBc/Hz in literature.

THz RFIC: 300GHz Power Source and Imaging Sensor

300 GHz Imaging Video Streaming



THz Transceiver 9Gbps Communication



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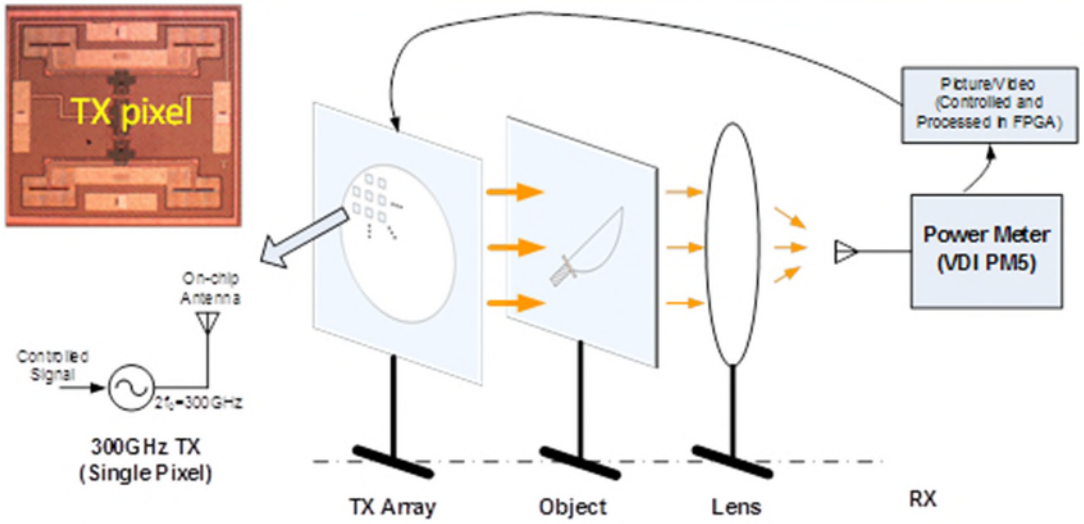
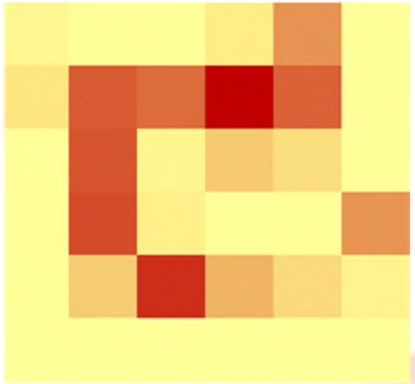
THz RFIC: 300GHz Power Source and Imaging Sensor



Metal letter "C" is inside a black non-transparent plastic bag.



(a) Visible image

(b) mmW image

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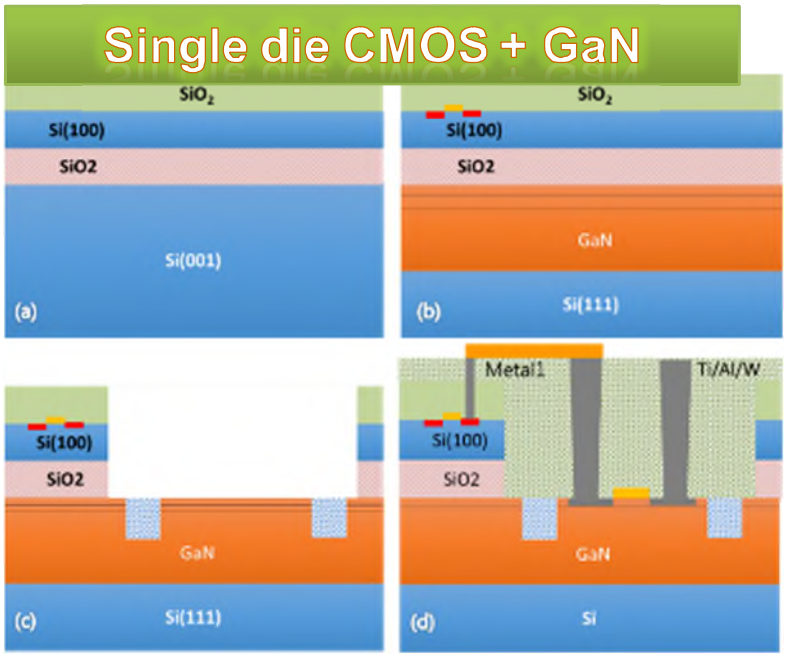
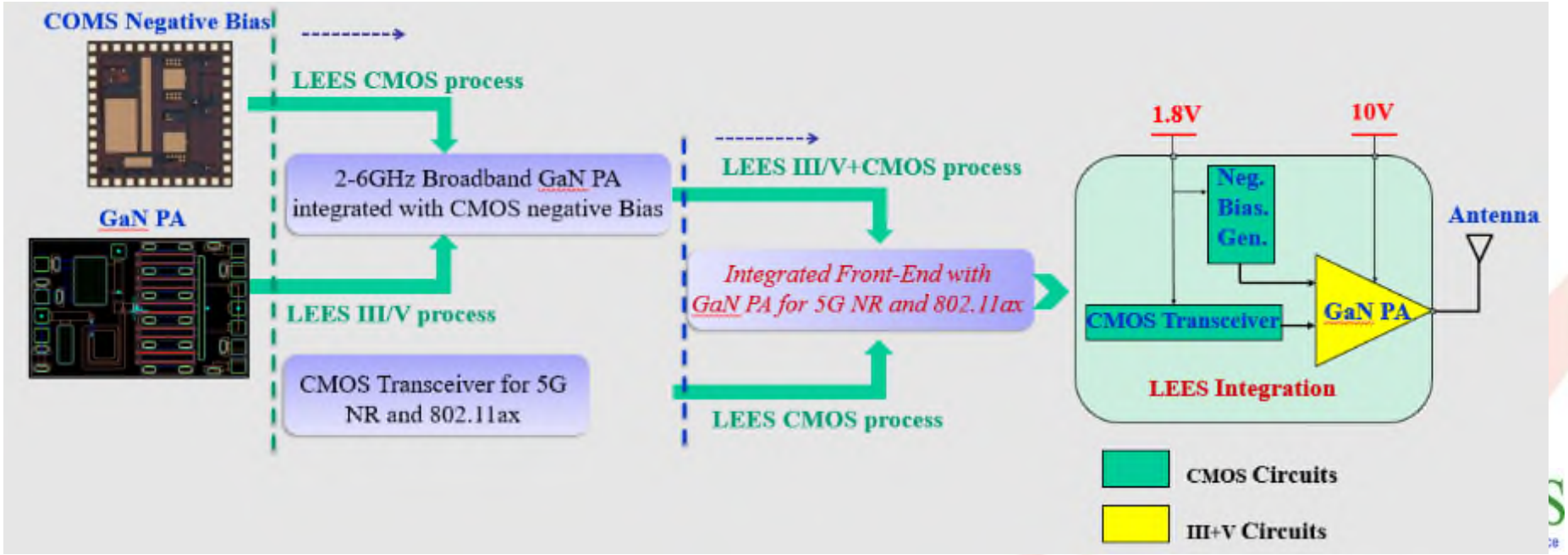
Current Work: CMOS + GaN Integrated in a Single Chip



Research Direction:

- 5-6GHz CMOS transceiver for 802.11ax WLAN
- Sub-6GHz CMOS transceiver for **5G NR**
- 2-6GHz Broadband GaN Power Amplifier
- Integrated CMOS transceiver and GaN Power Amplifier in a single chip



Thank you for your time and effort to understand our work.

Web: http://www.ntu.edu.sg/home/eccboon for full list of patents/publications/books

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