Signal Chain Integrity

Optimizing the Performance of the RF Signal Chain

Central Apps Webinar Series

Larry Prestia

ANALOG DEVICES
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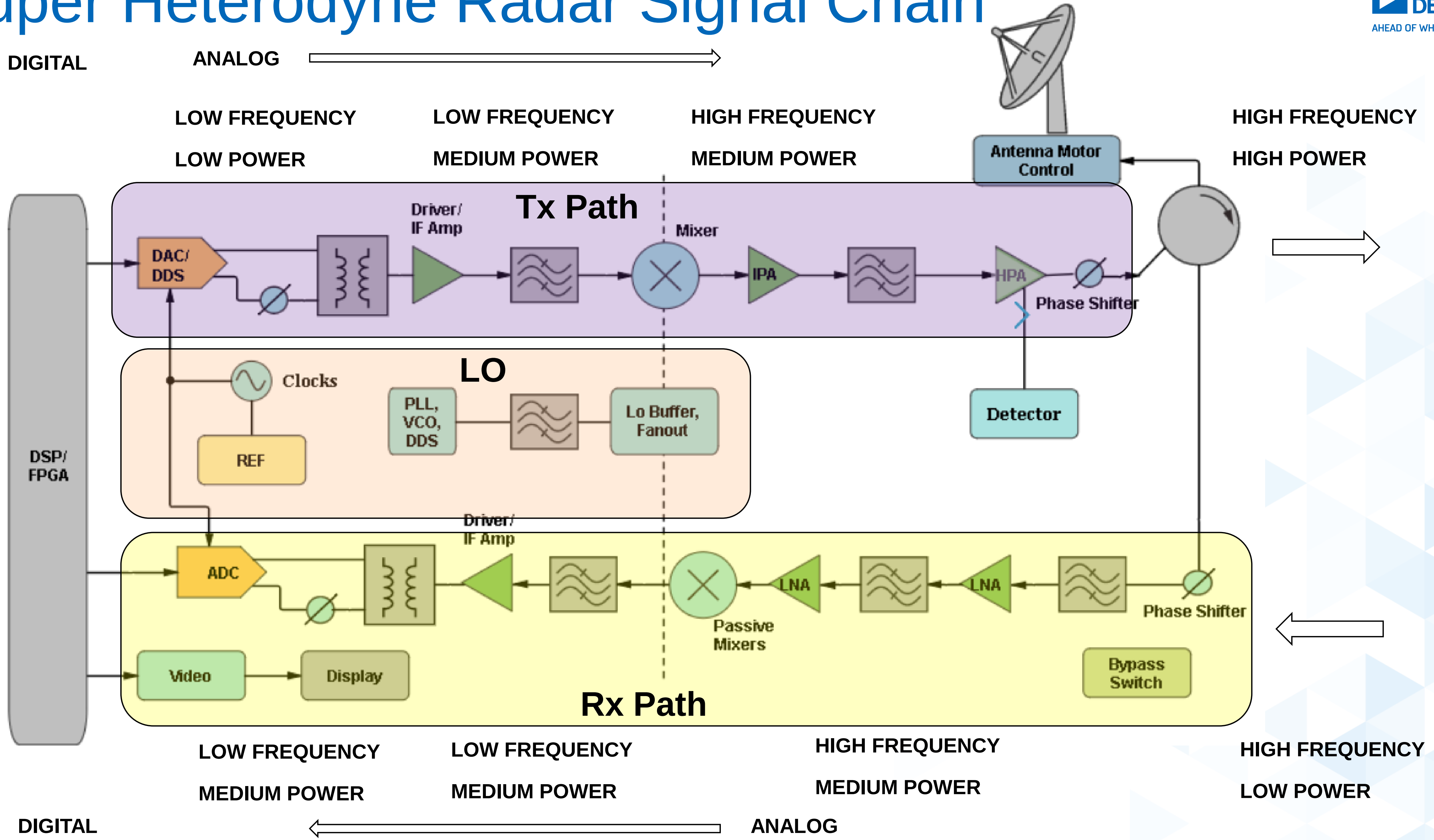
Agenda

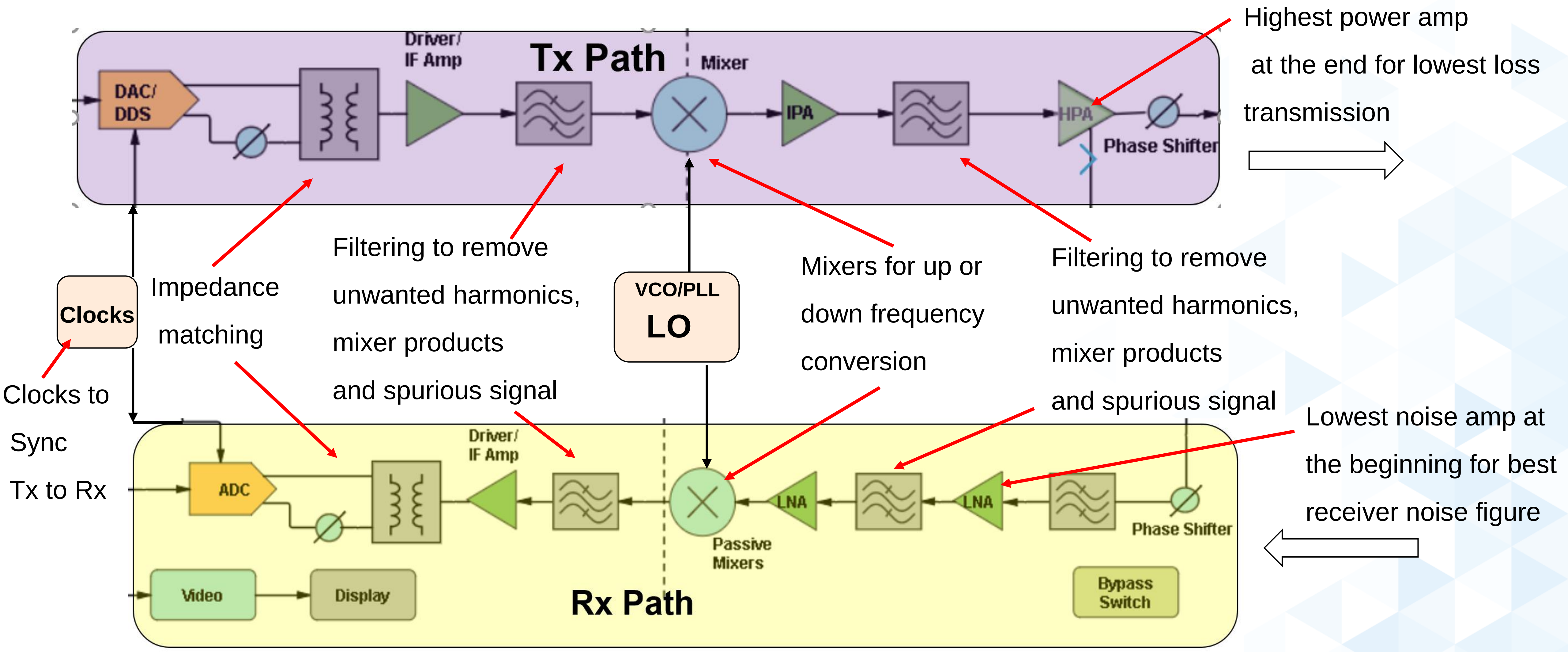
- RF Signal Chains
  - Radar and communications signal chains
  - Design goals
- Technology Consideration
  - GaAs vs. SOI switch
  - GaAs vs. GaN power amplifier
- Level of Integration
  - Integration advantages
- Component Matching
  - Mismatch power loss
  - Interstage matching
- PCB Layout Technology
  - Shielding and isolation
  - Layout guidelines
- Dynamic Range
  - RF performance improvements
- Improving the Signal Chain Performance
- Tools

RF Signal Chain

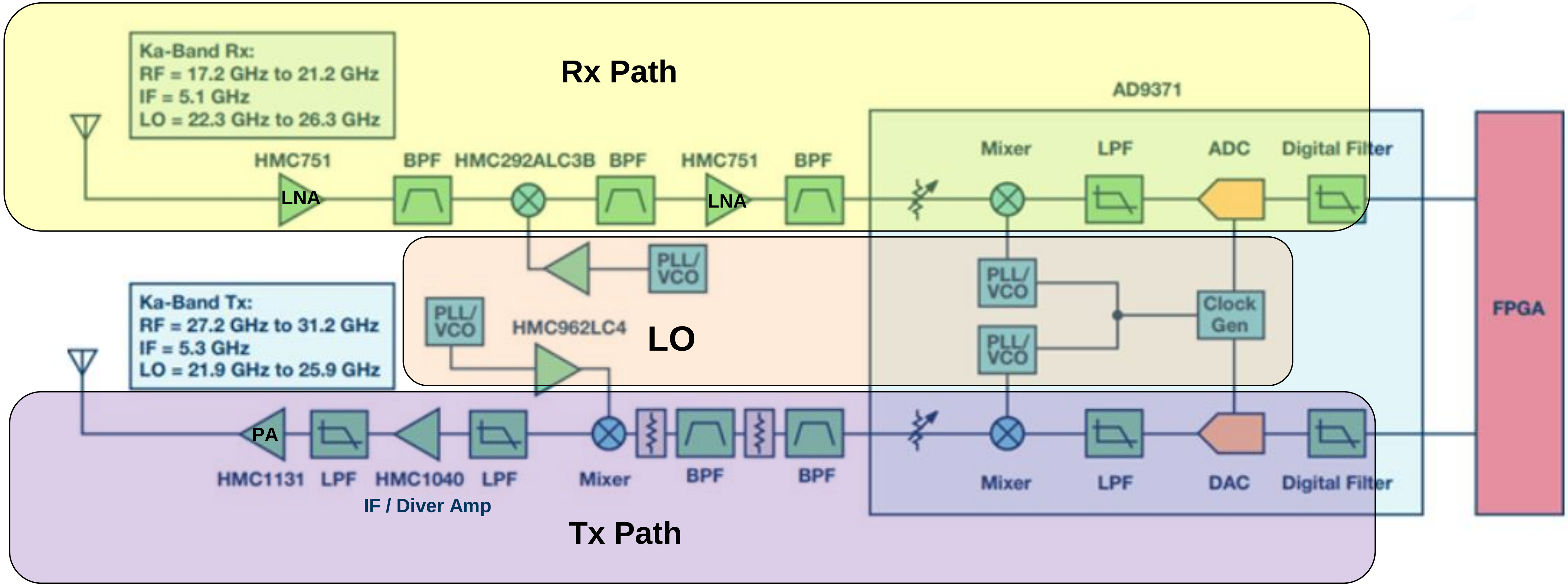
Super Heterodyne Radar Signal Chain



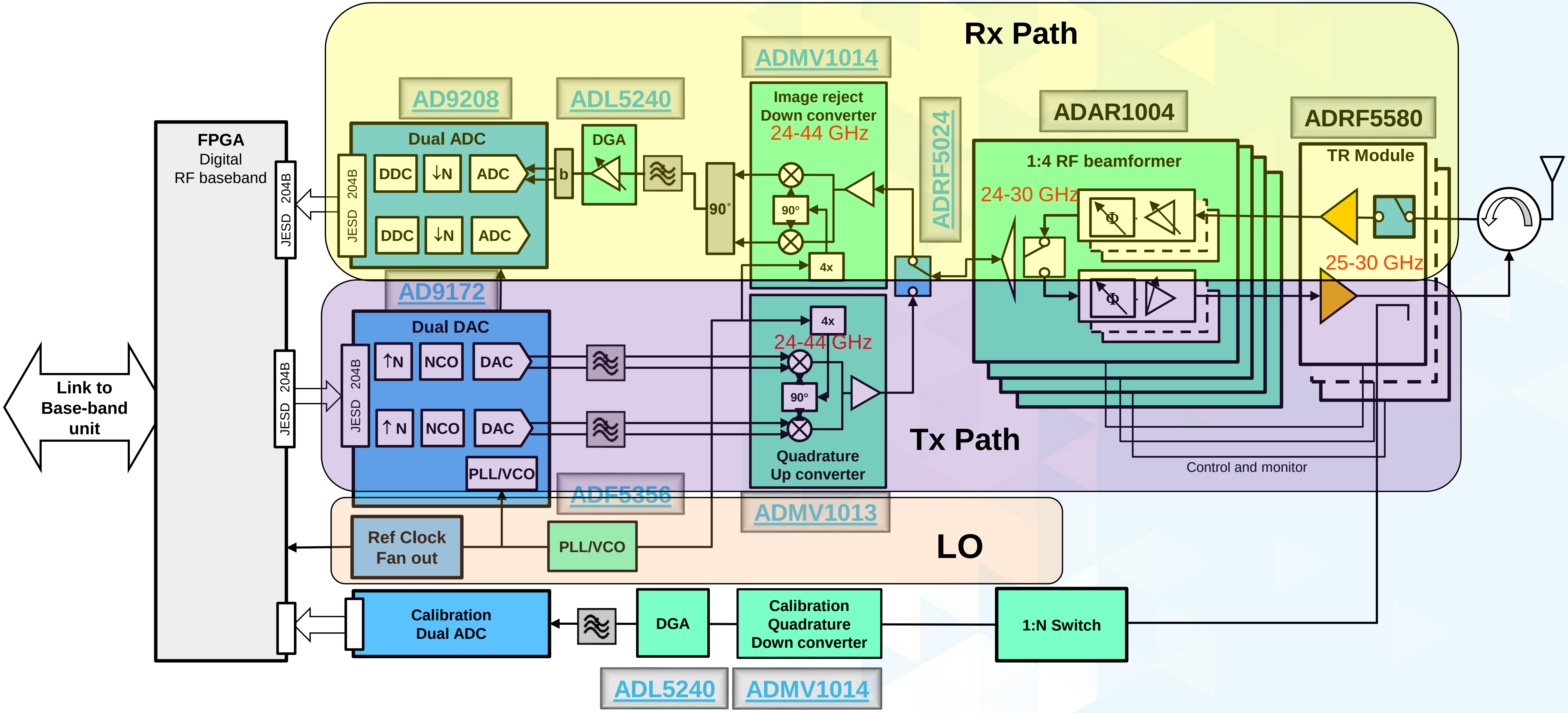
RF Signal Chain Lineup



SATCOM Signal Chain



5G Signal Chain (24 GHz – 30 GHz)



Design and Optimization Goals

- Smallest Size / Weight
- Lowest Cost
- Best RF Performance for the Application
- Lowest Power Consumption
- Ease of Use

Process Technology Considerations

Gallium Arsenide(GaAs)? Gallium Nitride (GaN)? Silicon (Si)? Silicon Germanium(SiGe)? Silicon on Insulator (SOI)?

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We consider the best technology to use by…

- Foundry Availability
- Frequency / Speed
- Power level required for the application
- Noise and linearity considerations
- Amount of integration capability
- Cost vs. throughput

GaAs? GaN? Si? SiGe? SOI? – Application Specific

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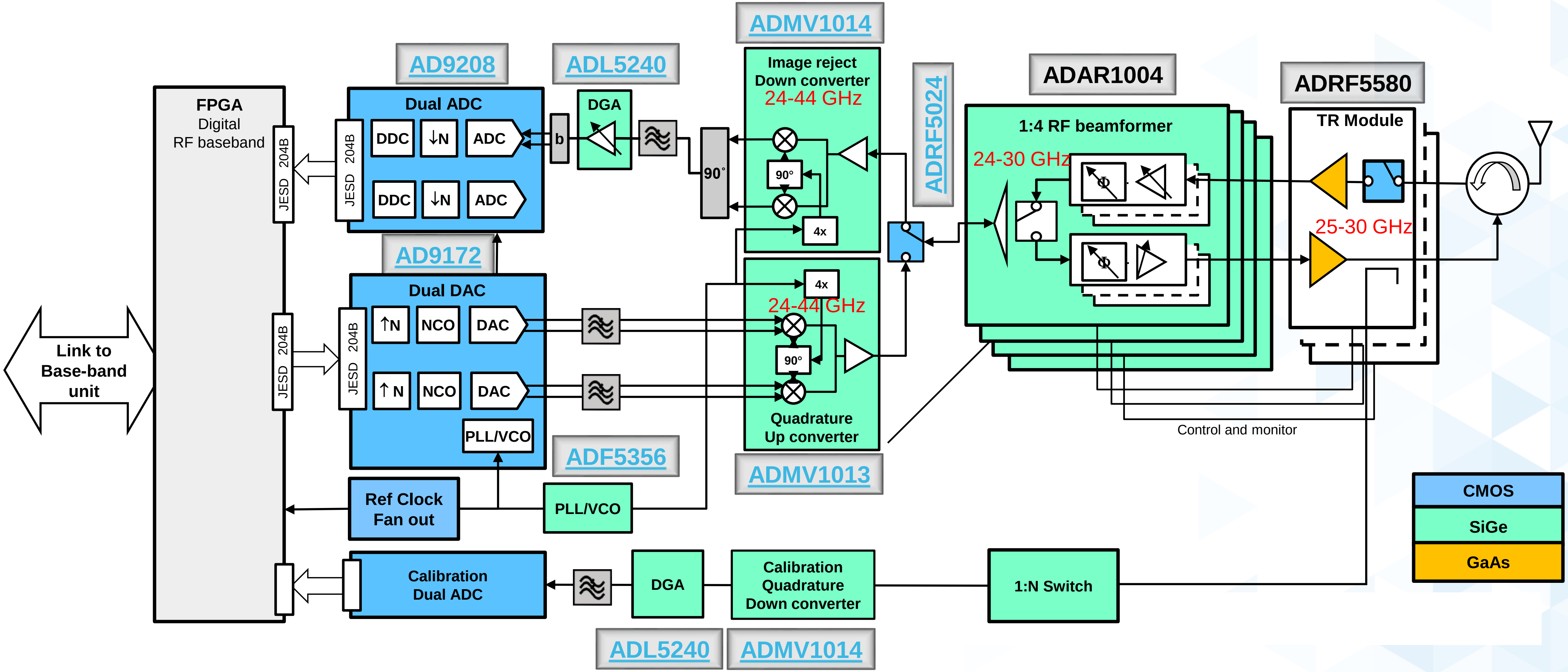
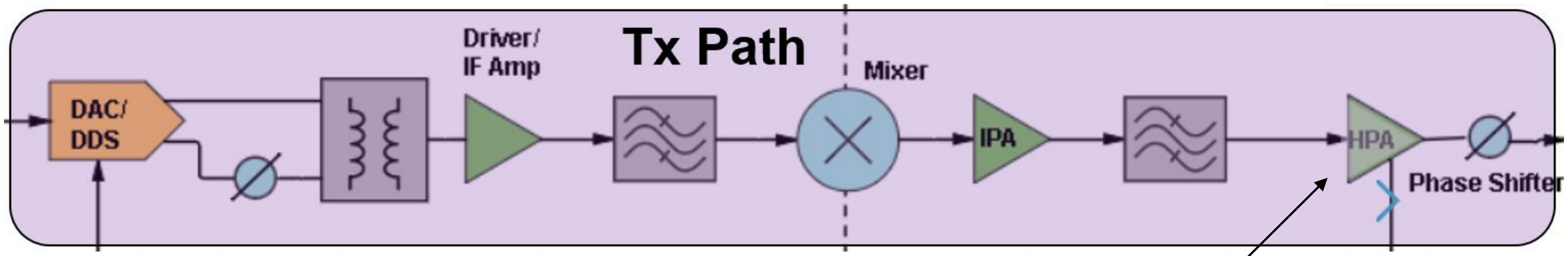
RF Fabrication Technology	Foundry Availability	Frequency	Power	Linearity	Cost	Integration
Silicon	High	Low	Low	Medium	Low	High
Silicon Germanium	Low	Low to High	Medium	High	High	High
Silicon on Insulator	High	Low to High	Medium	High	Low	High
GaAs	Medium	High	Medium	Low	Low	Low
GaN	Low	High	High	Low	High	Low

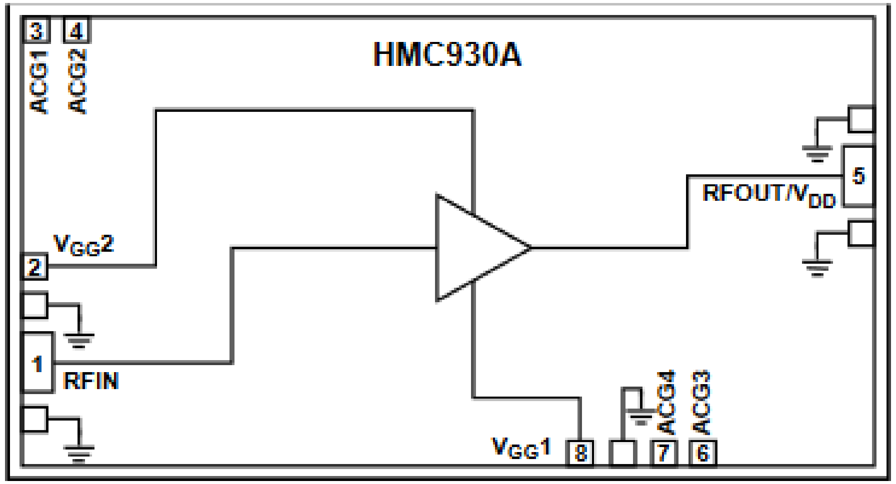
GaAs? GaN? Si? SiGe? SOI? – Mixed Technologies



Power Amplifier GaAs vs. GaN – Application Specific Example



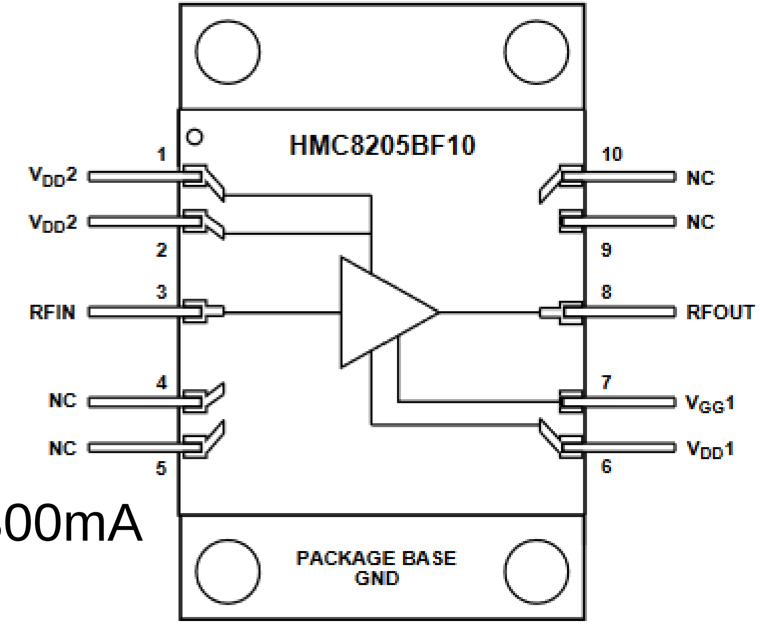
**GaAs, pHEMT, MMIC,
0.25 W Power Amplifier, DC to 40 GHz**



10V @ 175mA

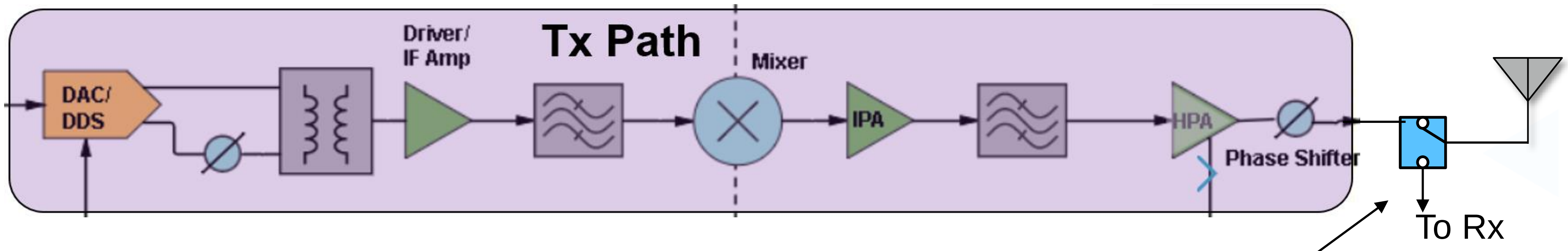
OR

**0.3 GHz to 6 GHz, 35 W, GaN
Power Amplifier**



50V @ 1300mA

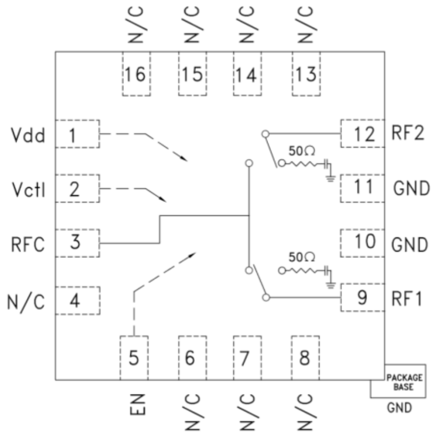
T/R Switch GaAs vs SOI – Technology Advancement



GaAs

HIGH ISOLATION SPDT NON-REFLECTIVE SWITCH, DC - 6 GHz

HMC849

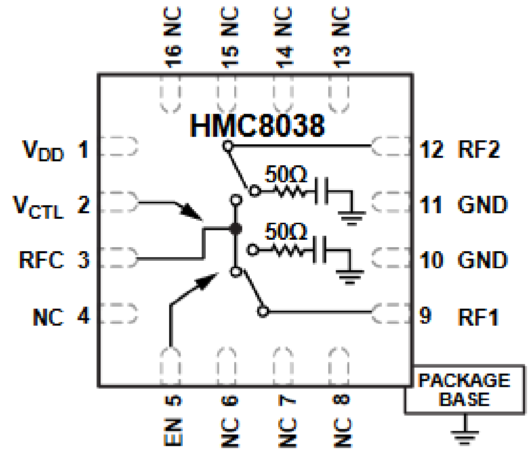


IP3 = 52 dBm

Input P1dB = 33 dBm

SOI

High Isolation, Silicon SPDT, Nonreflective Switch, 0.1 GHz to 6.0 GHz



IP3 = 60 dBm

Input P1dB = 36 dBm

Level of Integration

Level of Integrations

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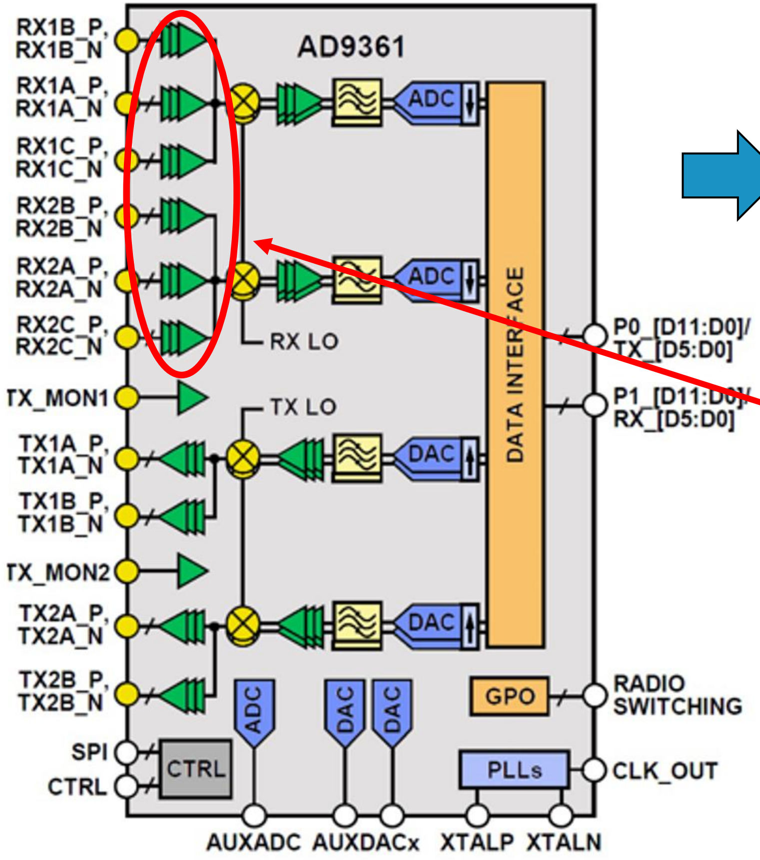
- Chip level
- Module Level
- System Level

Chip level Integration – Application Specific Example

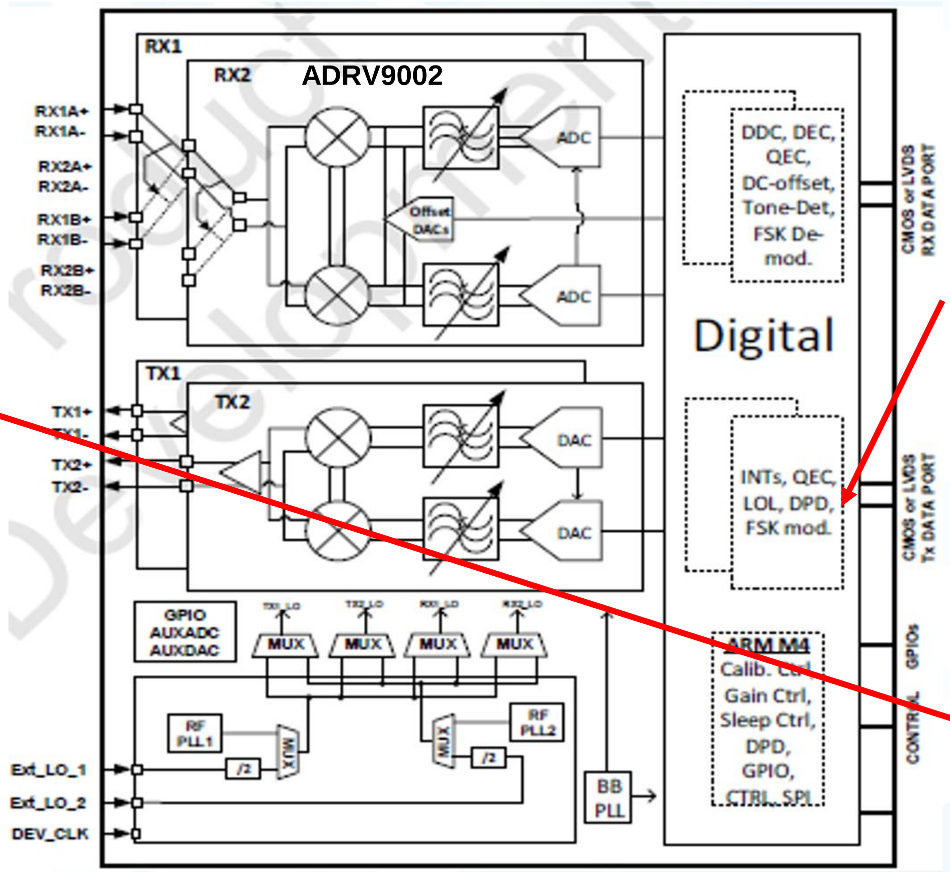
Fixed Cell Site

CATALINA – AD9361



Mobile Cell Site

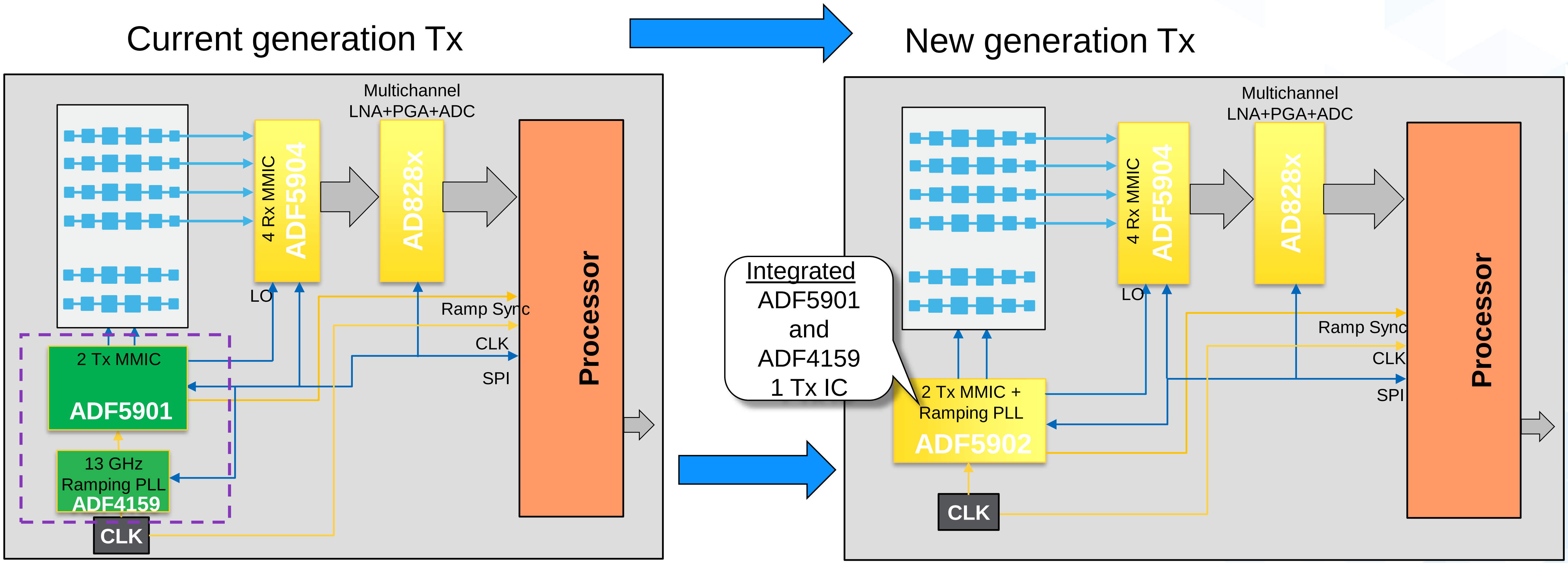
NAVASSA – ADRV9002



Added digital predistortion to improve dynamic range

Remove LNAs to increase agility and flexibility

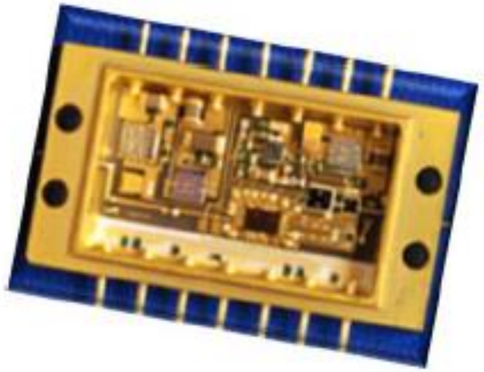
Chip Level Integration - 24 GHz Radar System
ADF5901 and ADF4159 into ADF5902



Module Level Integration – High Reliability Products

<u>Integrated Die & Passives</u>

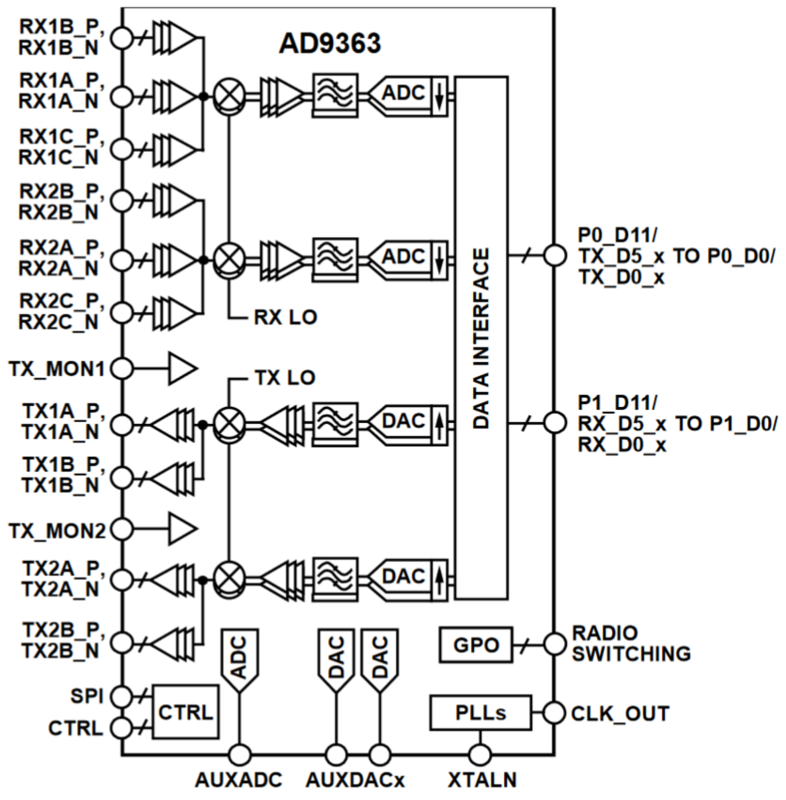
- Amplifier
- VCO
- Diodes
- Prescaler
- Synthesizer
- Voltage Regulators
- Op Amp

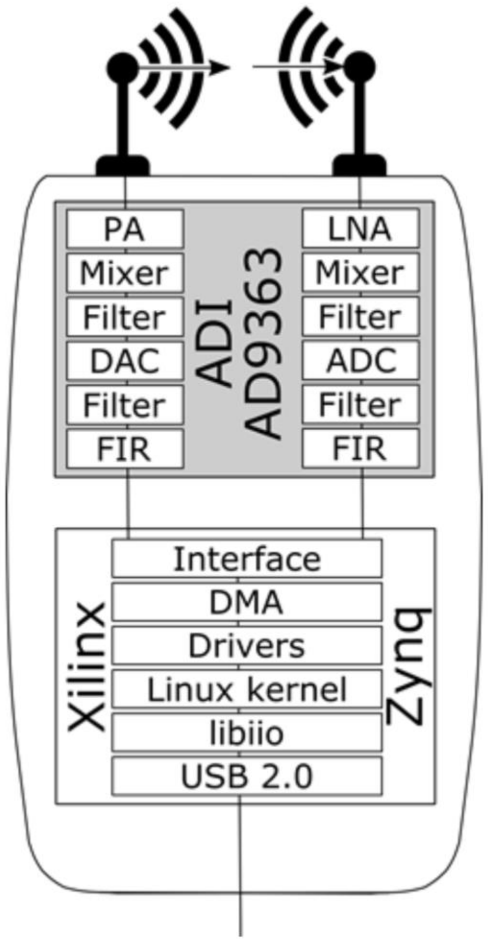


<u>Features</u>

- Octave Bandwidth
- Commercial & Hi Rel version
- Contains MMIC that are only available within ADI in die form

System Level Integration
ADALM-PLUTO – Fully integrated SDR with software

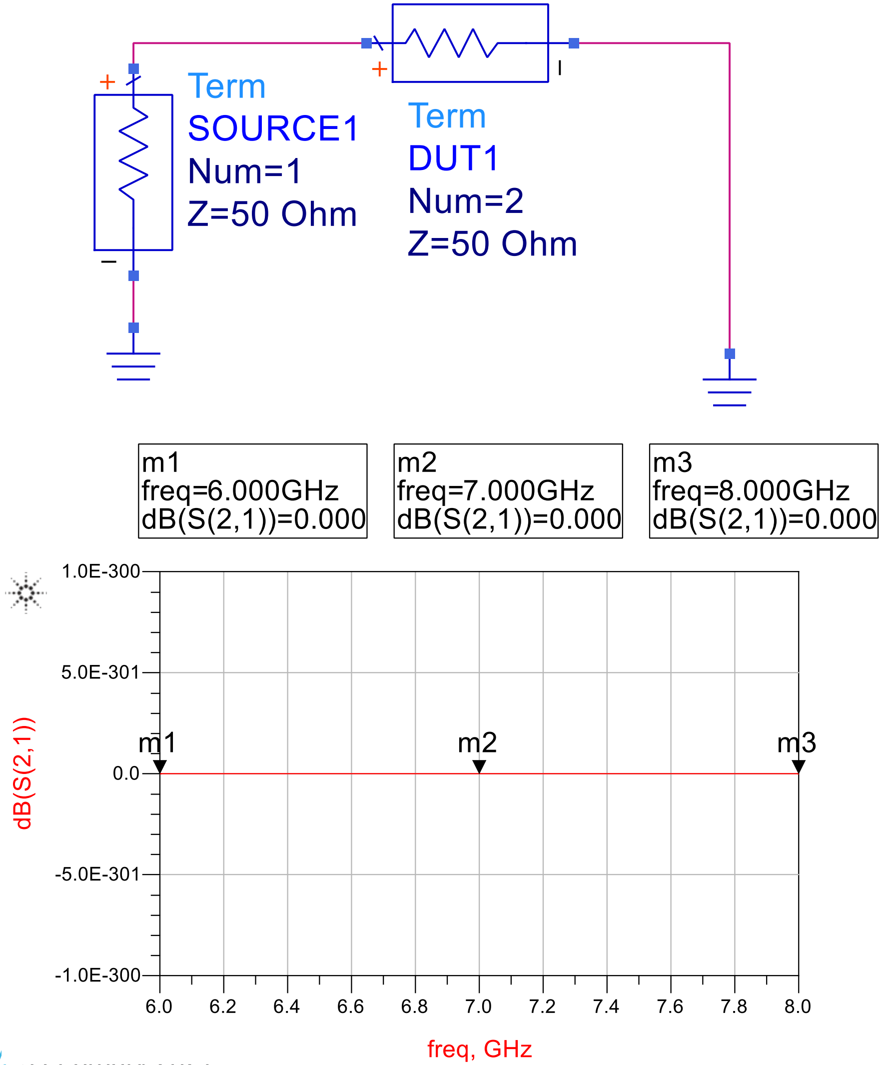


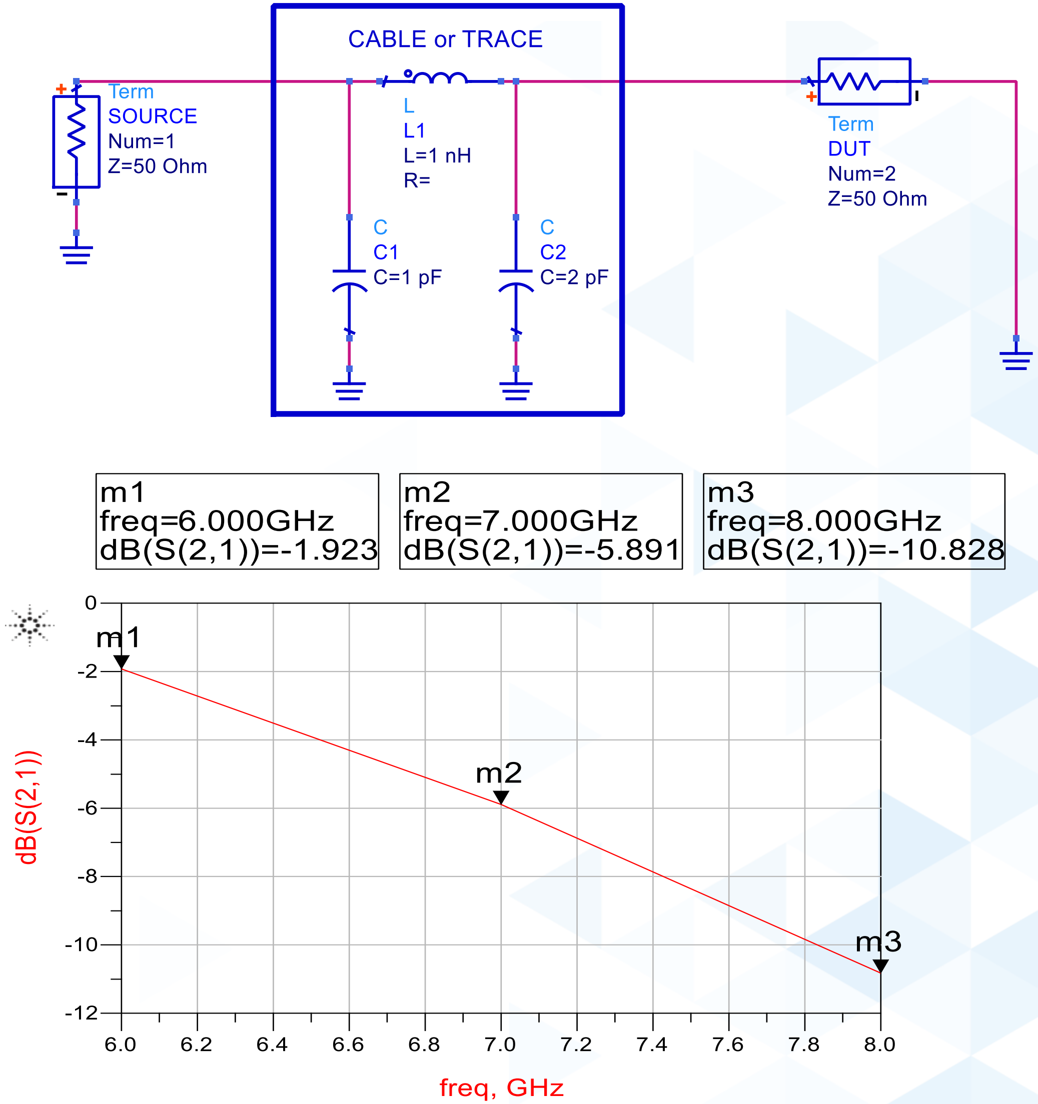


Component Matching

Component Matching

- When 2 impedances are different and connected, reflections can occur causing power loss.



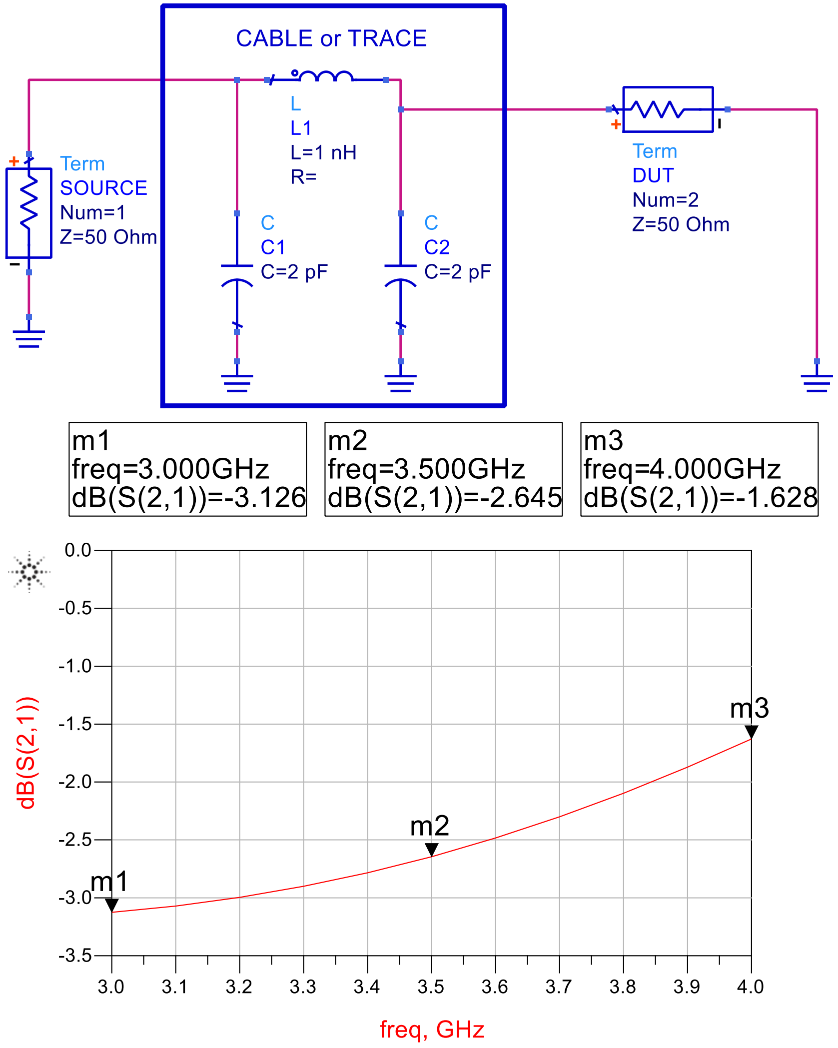


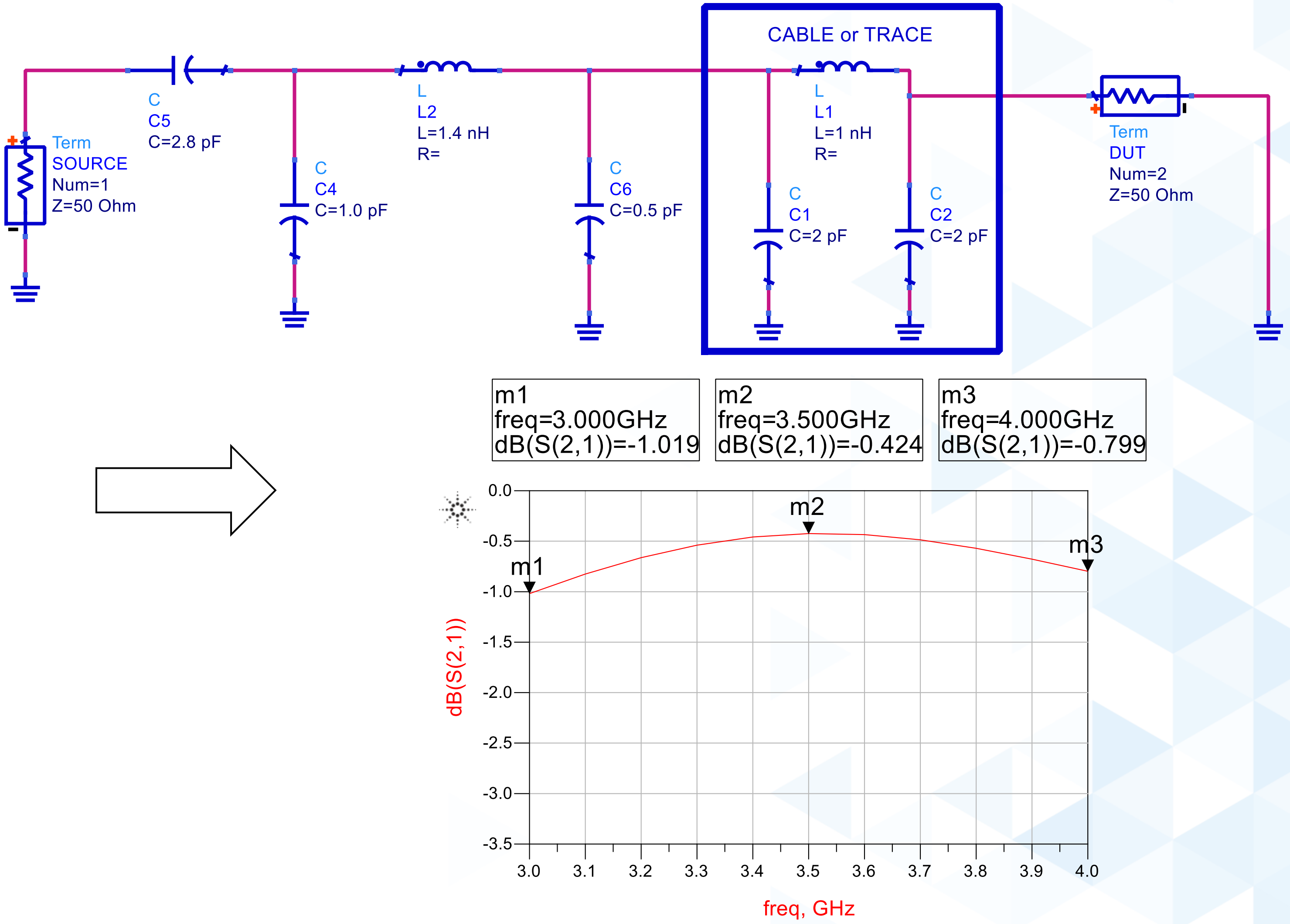
Component Matching – Power Loss

Source Impedance (ohms)	Load impedance (ohms)	Reflected Power (%)	Through Power (%)
50	1000	81.86	18.14
50	50.00	0.00	100.00
50	33.33	4.00	96.00
50	25.00	11.11	88.89
50	20.00	18.36	81.64
50	16.66	25.00	75.00
50	11.30	36.00	64.00
50	10.00	44.45	55.55
50	5.00	66.95	33.05

Component Matching

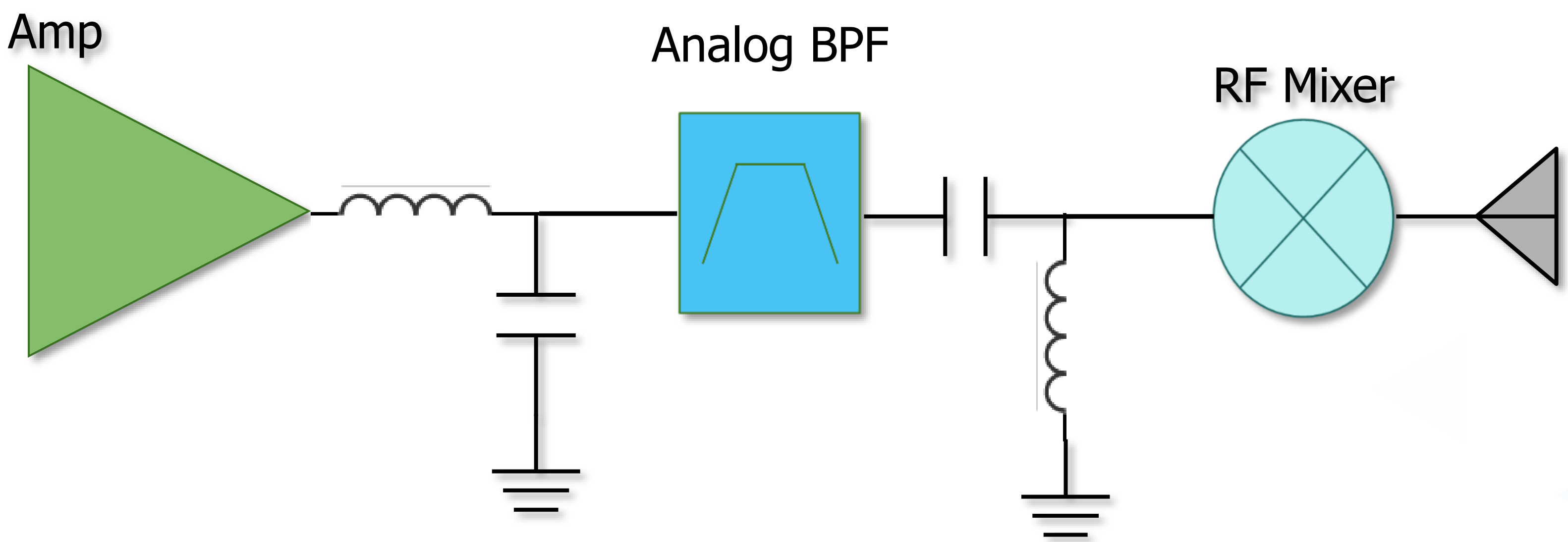
- Proper impedance matching by components or transmission line design can reduce or eliminate reflections.





Inter-Stage Component Matching

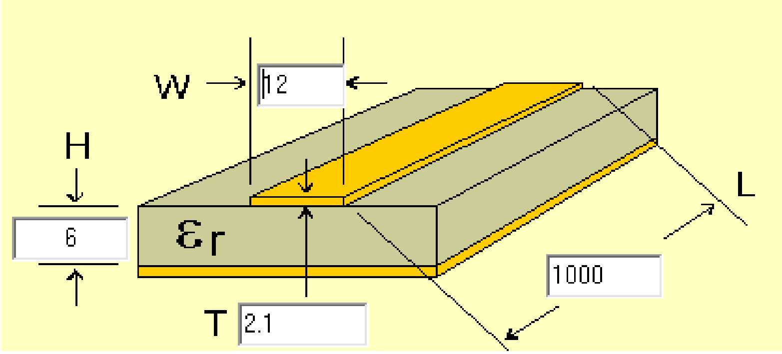
- Inter-Stage matching can be very challenging. Very often it is difficult to determine the magnitude of loss due to integrated interstage matching.



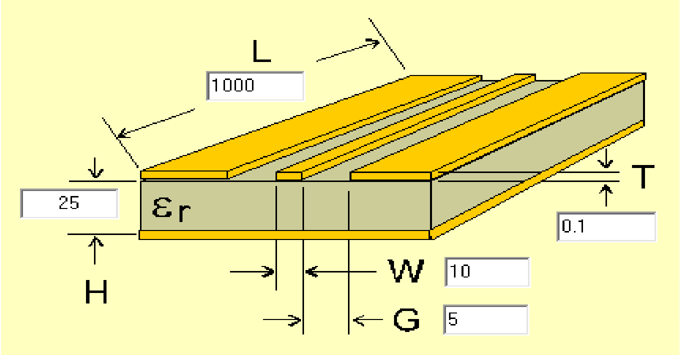
PCB Layout Technology

Printed Circuit Board - Technology

Microstrip – Lowest loss at high frequencies

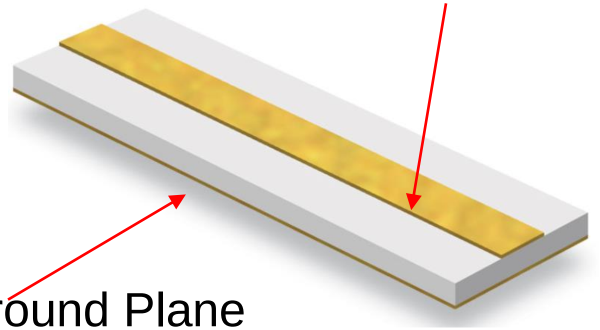


Coplanar – Best isolation



No vias used as no top-level ground exist.

50-ohm transmission line

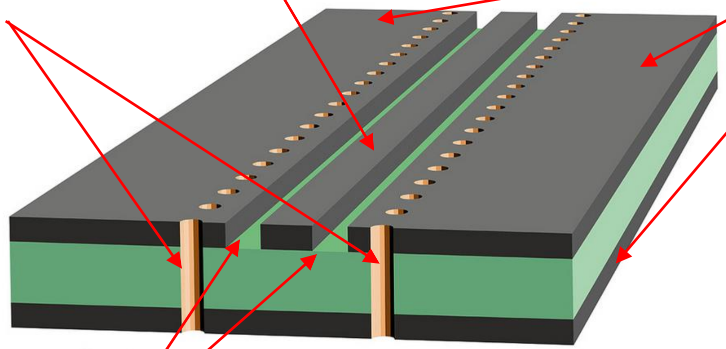


Ground Plane

50-ohm transmission line

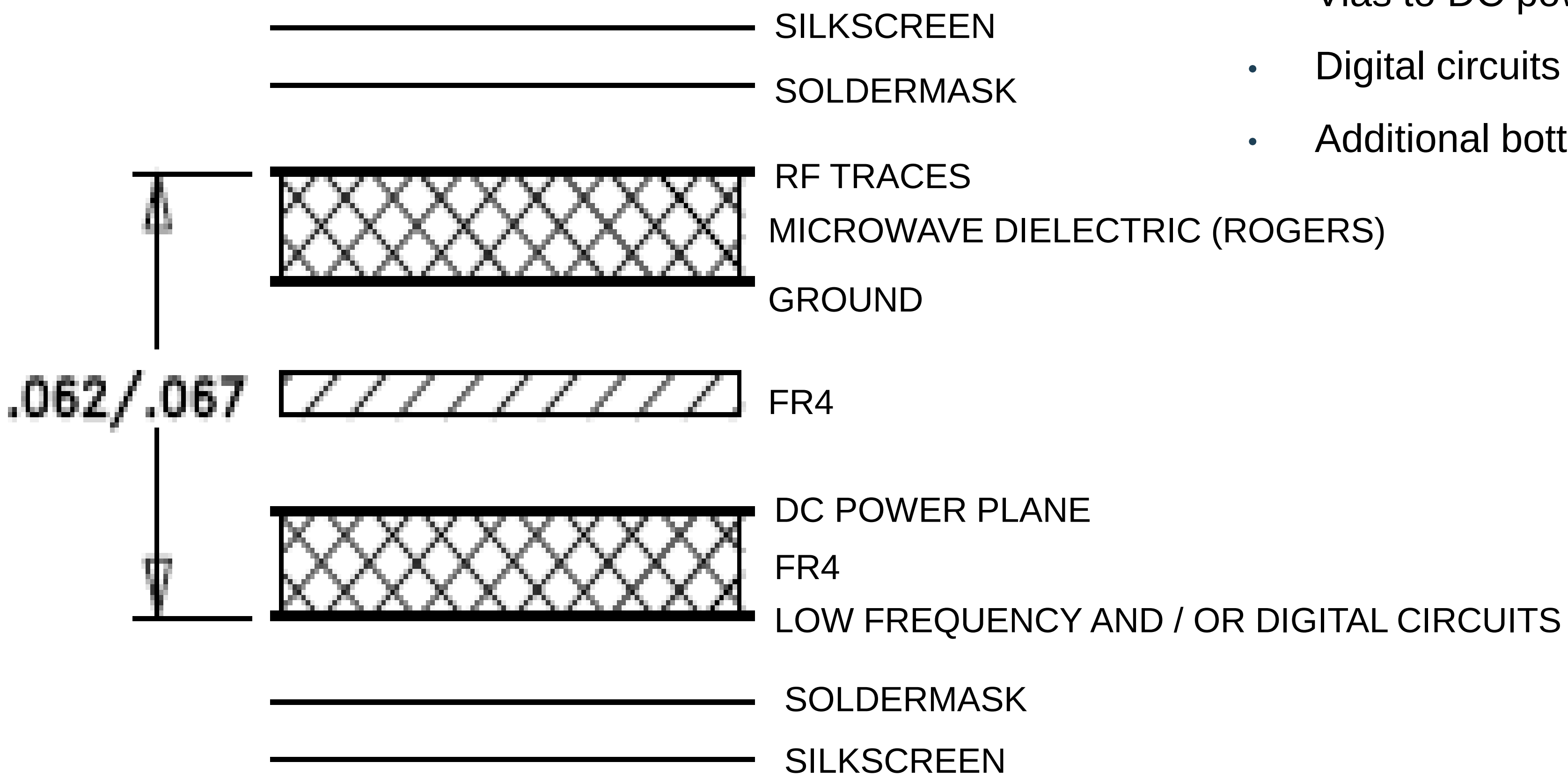
Copper plated via fences connects top ground planes to bottom ground plane

Ground



Gap - No copper

RF Printed Circuit Board Stack up – 4 Metal Layer Example

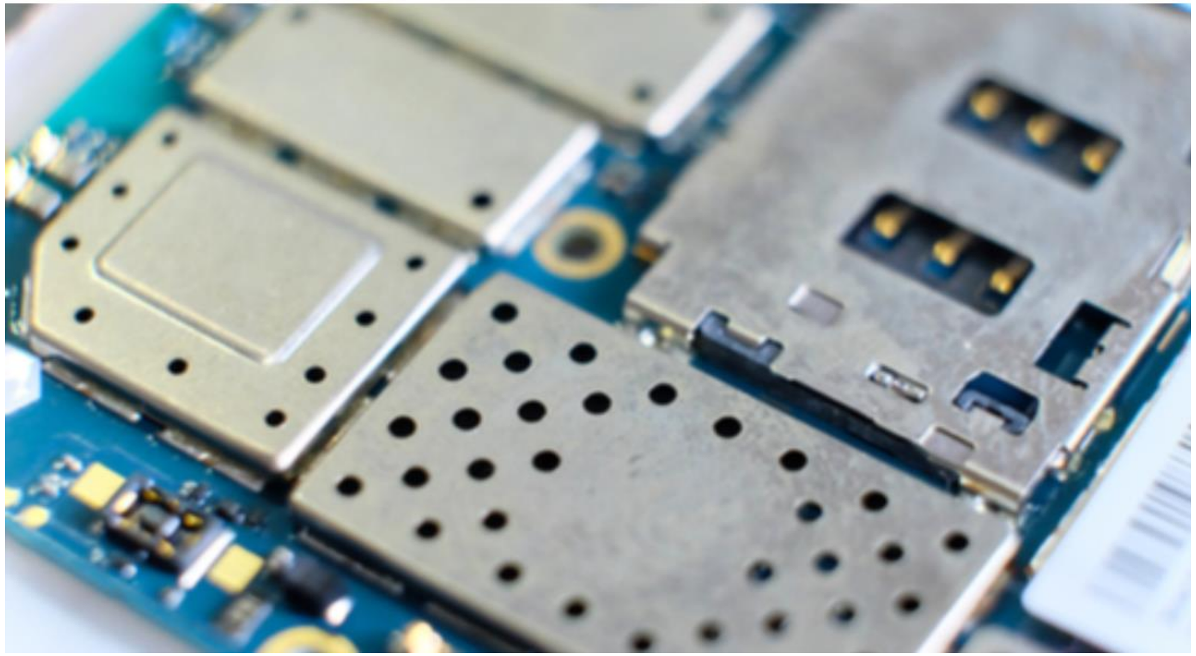


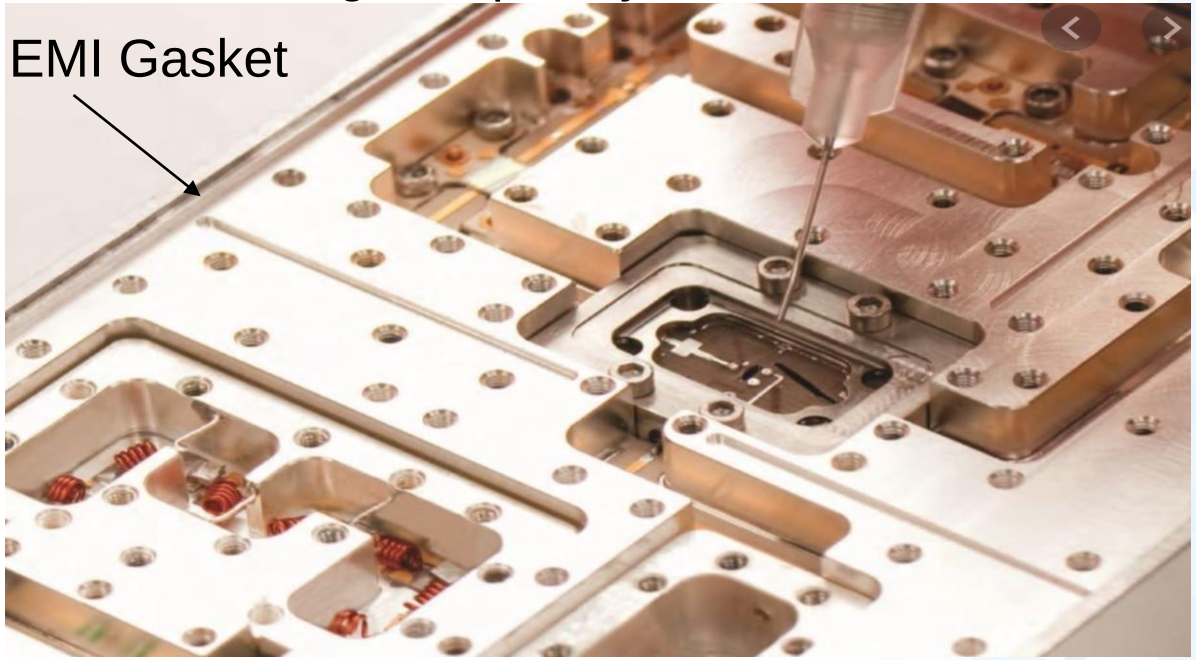
- Internal ground layer(s) isolate RF circuits
- DC power planes instead of DC traces on RF layer
- Vias to DC power plane used to power RF components
- Digital circuits isolated from RF circuits
- Additional bottom layers for ground and RF can be added

RF Printed Circuit Board – Shielding and Isolation

Metal shielding placed over components and traces

Machined module housings isolating sensitive high frequency circuits





- RF shieldings and metal housings separates transmit and receive signals
- EMI gaskets prevents outside signals from interfering
- RF shielding isolates RF signals from DC power and digital / clock signals

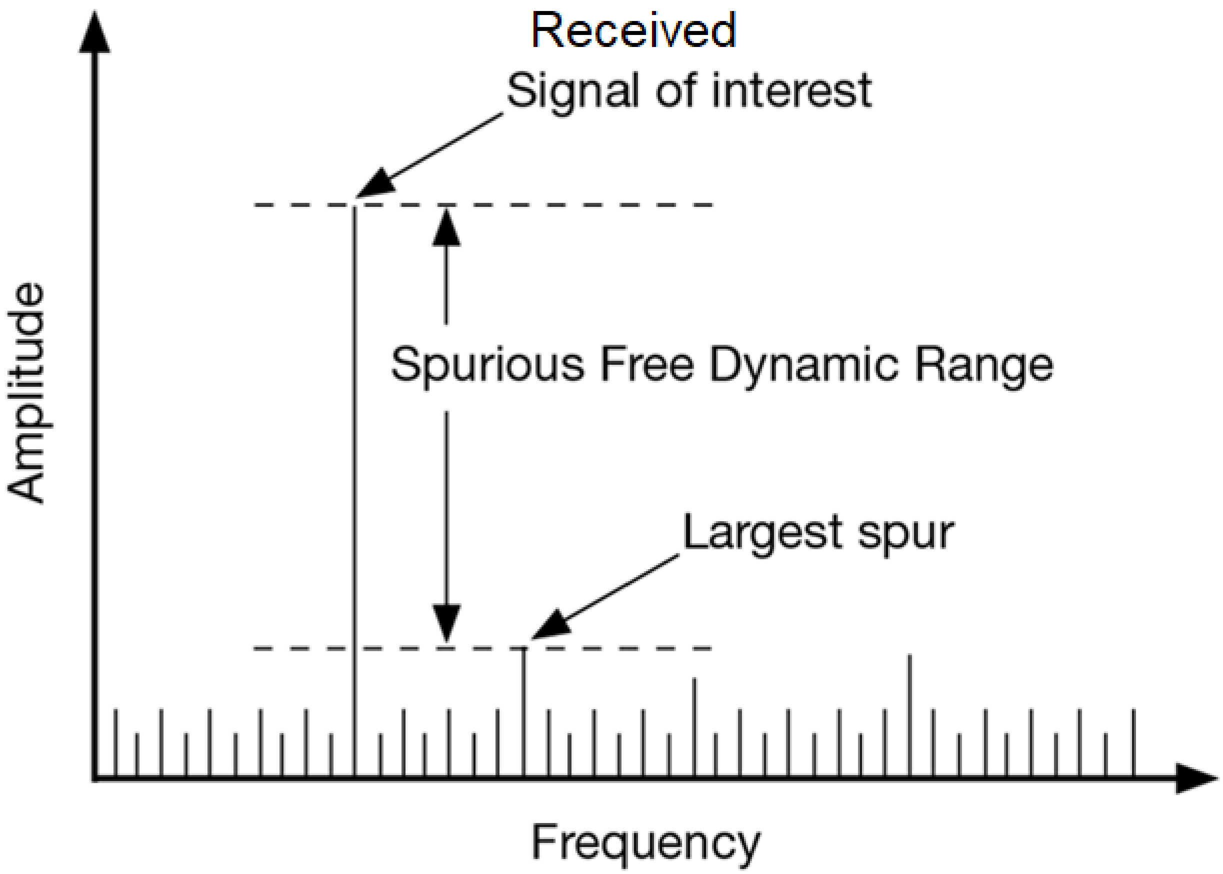
Printed Circuit Board Signal Integrity Guidelines

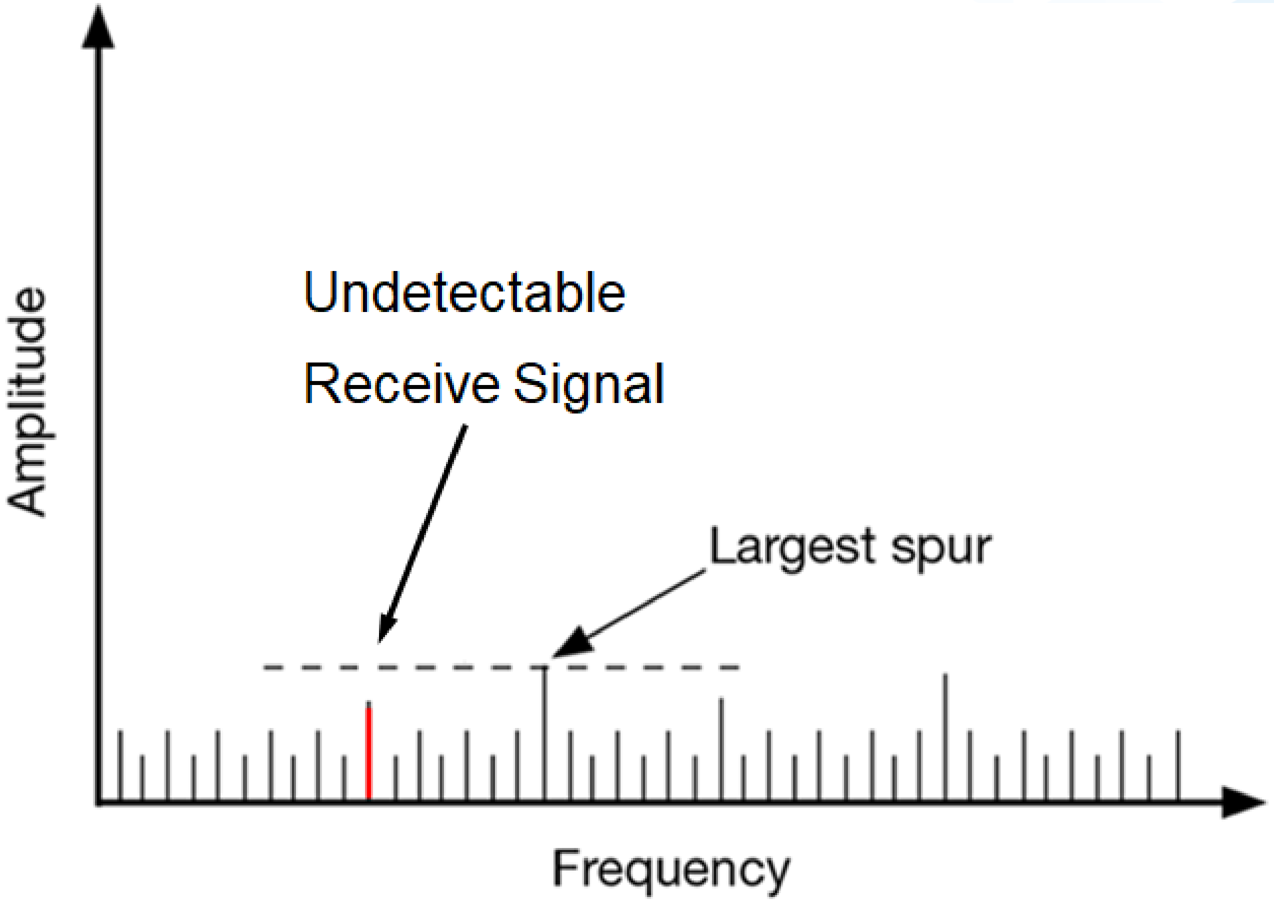
- No sharp 90-degree corners on RF traces. Only use these under specific conditions after EM modeling (ie. stubs, filters, DC taps, etc)
- Always keep an RF ground plane directly under the RF signal layer
- Use coplanar technology when RF isolation is critical. Use microstrip when losses are critical.
- When isolation is required between 2 RF signals on the same layer, it is best to have them perpendicular to each other
- When isolation is required between 2 parallel RF signals, provide at least 4 trace width spacings from trace edge to trace edge.
- Use lots of ground vias. Use at least 2 rows of offset ground vias on each side of coplanar traces whenever possible.
- To isolate RF components (ie, TX to RX), shielding is always the best option.

Dynamic Range

Dynamic Range – What is it?

Dynamic range is the measurement of a receiver's ability to process a range of input powers from the antenna. If the signal is too weak, it can't be picked out from the noise.





Dynamic Range – Optimization

- Improve linearity
- Lower noise level
- Reduce spurious signals
- Minimize transmit and receive path losses

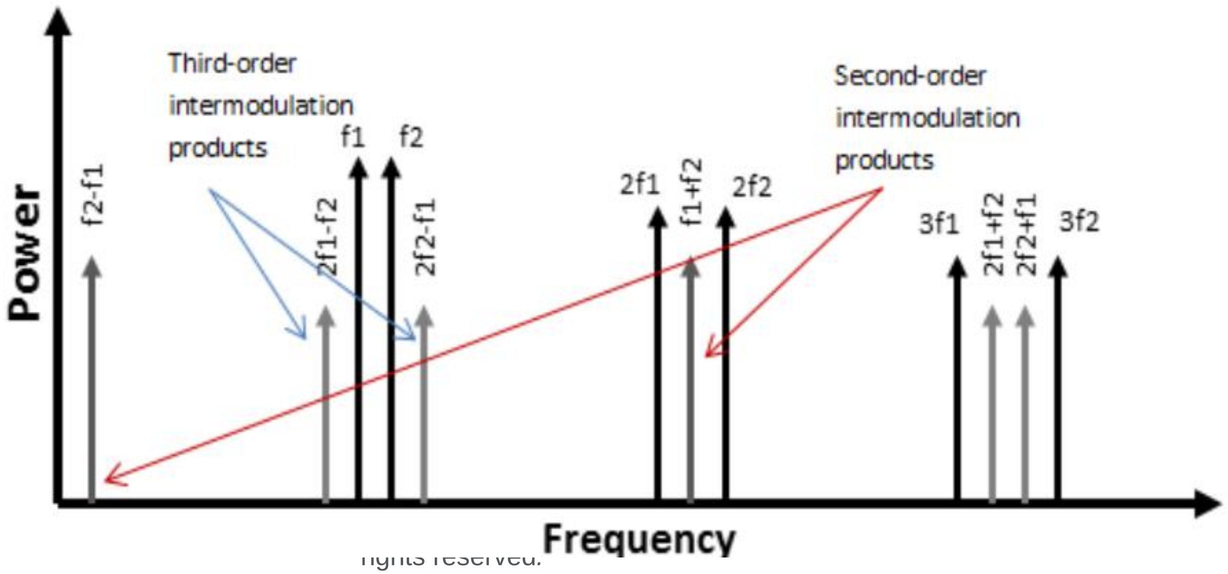
Dynamic Range – Linearity

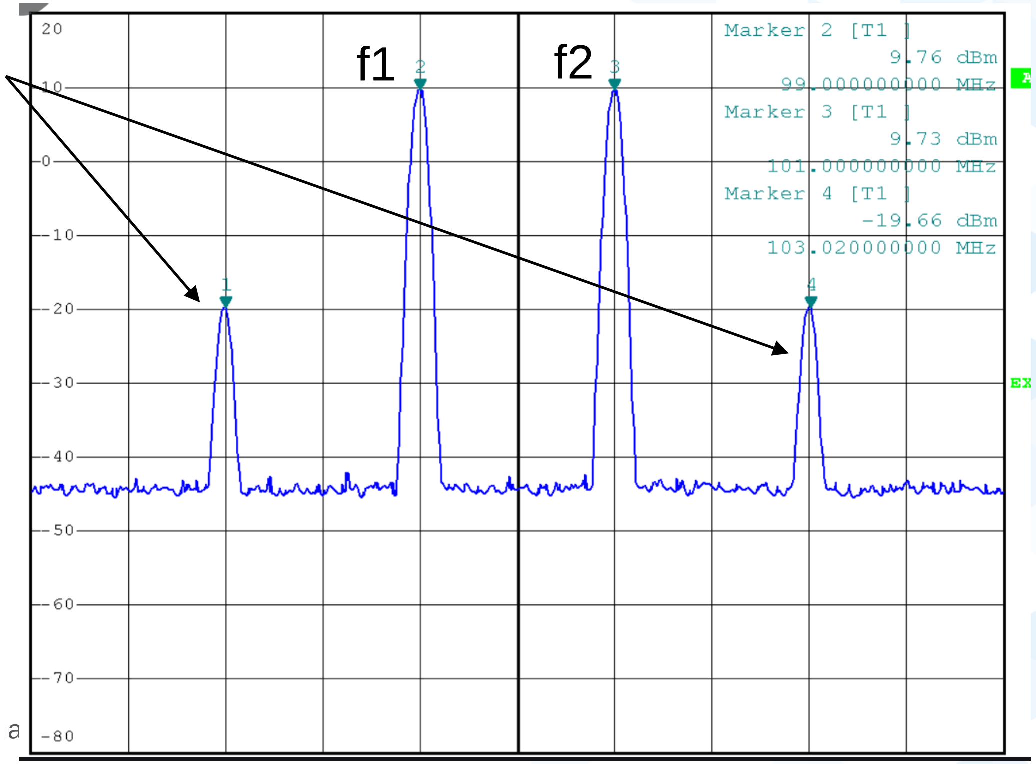
2nd or 3rd Order Intercept Points (IP2 or IP3), also known as linearity measurements, measures spurious related signals created when multiple tones are presented to a device or a receive signal chain. These spurious products, also known as intermodulation distortion products (IMD), are often within a desired receiver's bandwidth reducing dynamic range. Greater distance between transmitted signal and IMD signals, better the IP2 / IP3 !!

Third-order

Intermodulation

Products (IMD)



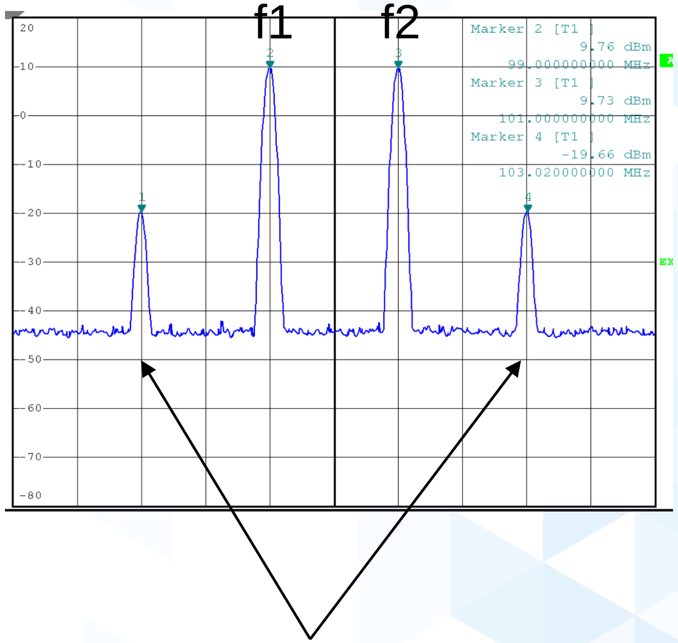


Dynamic Range – Linearity

Output 3rd order intercept (OIP3) =
(f1(dBm) – lower 3rd intermod product (dBm))/2 + f1(dBm) &
(f2(dBm) – upper 3rd intermod product (dBm))/2 + f2(dBm)

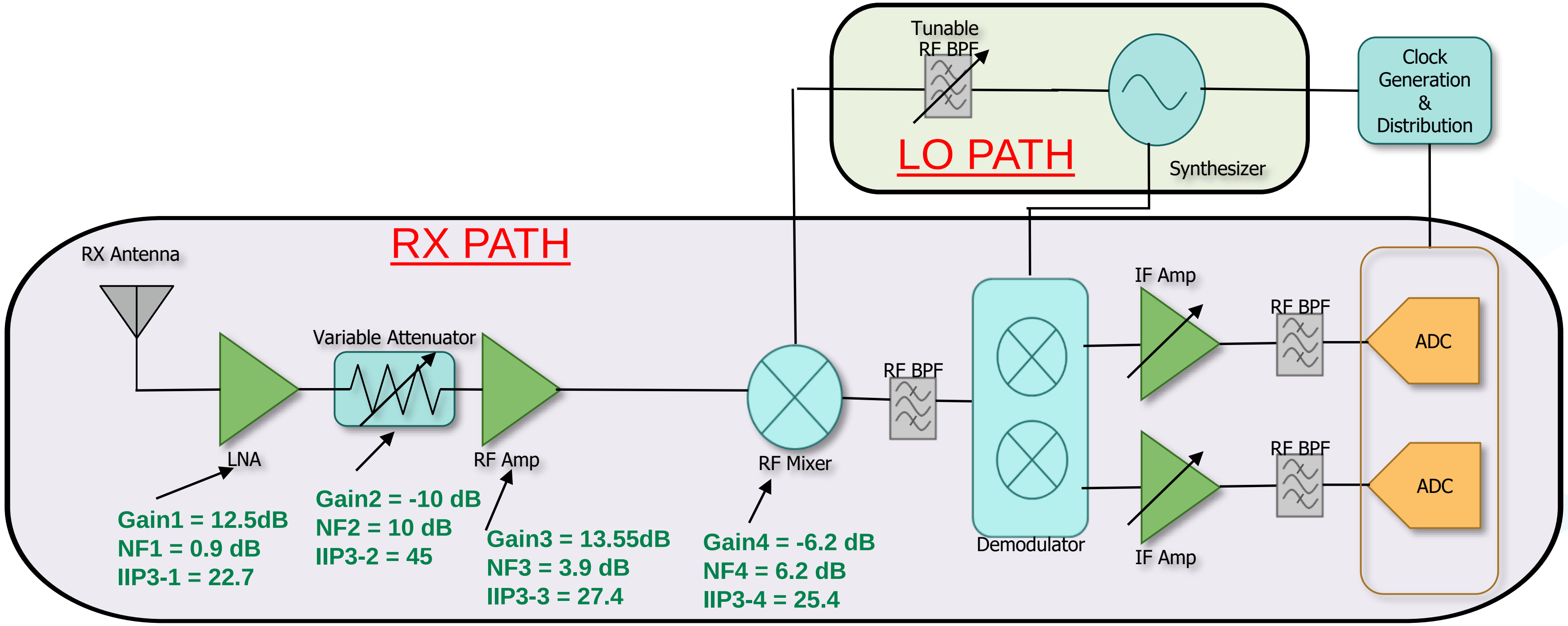
Example… f1(output power) = 20 dBm, lower 3rd intermod = 4 dBm
OIP3 = ((20 – 4)/2)) + 20
OIP3 = 28 dBm

For Input 3rd order intercept (IIP3) =
(f1(dBm) – lower 3rd intermod product (dBm))/2 + input power(dBm) &
(f2(dBm) – upper 3rd intermod product (dBm))/2 + input power(dBm)



Third-order
Intermodulation
Products (IMD)

Dynamic Range – Cascaded Intermodulation

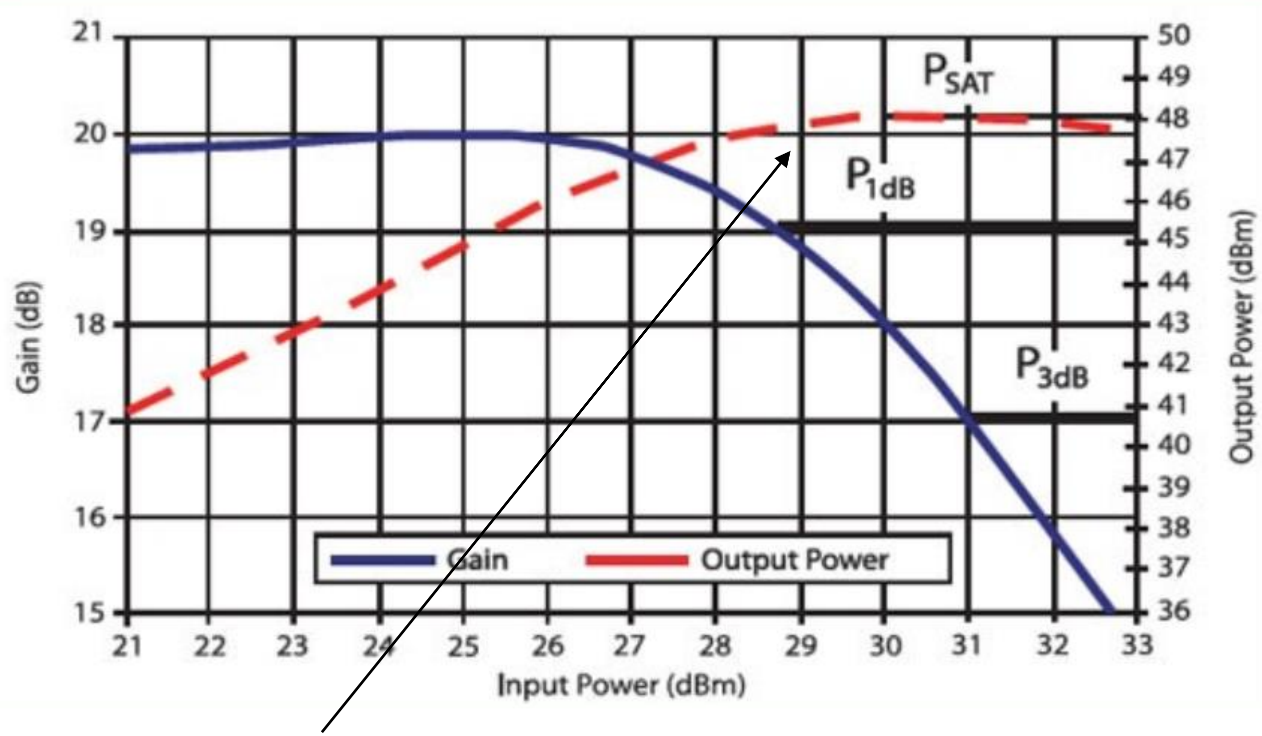


Total Input IP3 (mW) = 1 / (1/(IIP3(1)*G2*G3*G4)) + (1/(IIP3(2)*G3*G4))+ (1/(IIP3(3) *G4))+ (1/(IIP3(4))

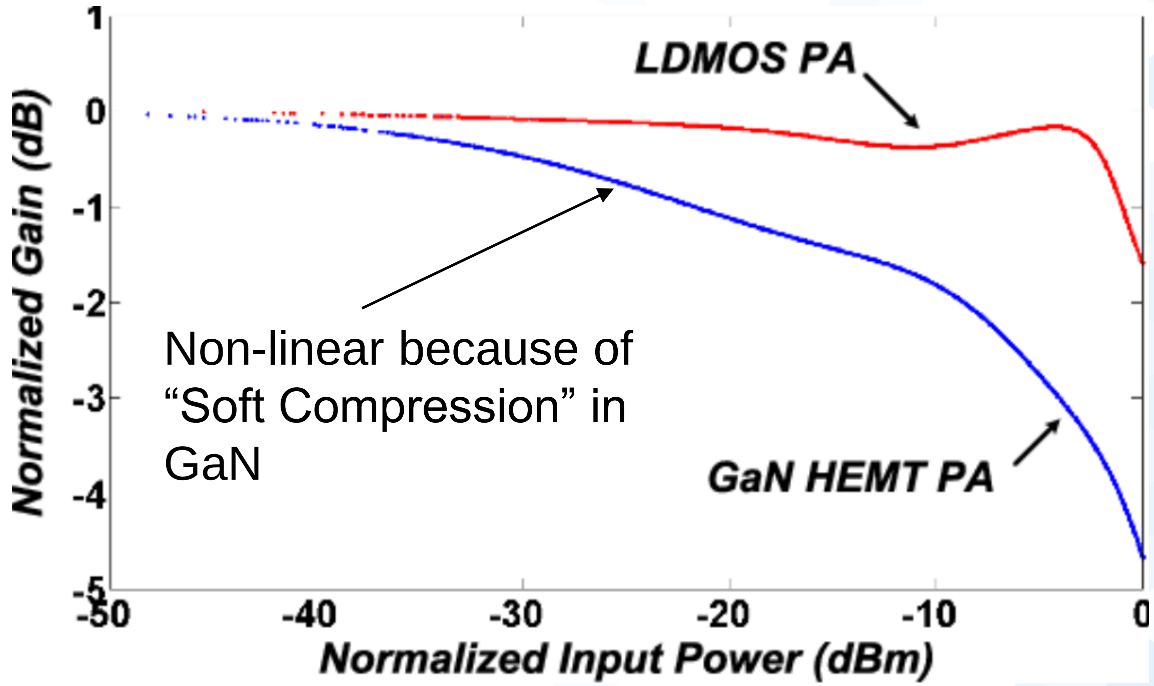
Input IP3(dBm) = 10 log (IIP3 in mW)

Dynamic Range – Power Handling and Compression

1dB compression (P1dB) helps determine how much usable power the part can deliver.
It can also tell us the linear and non-linear input / output power levels in the signal chain



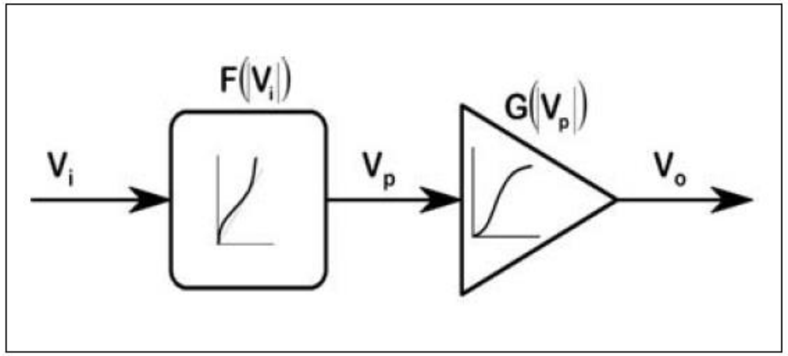
Non-linear region

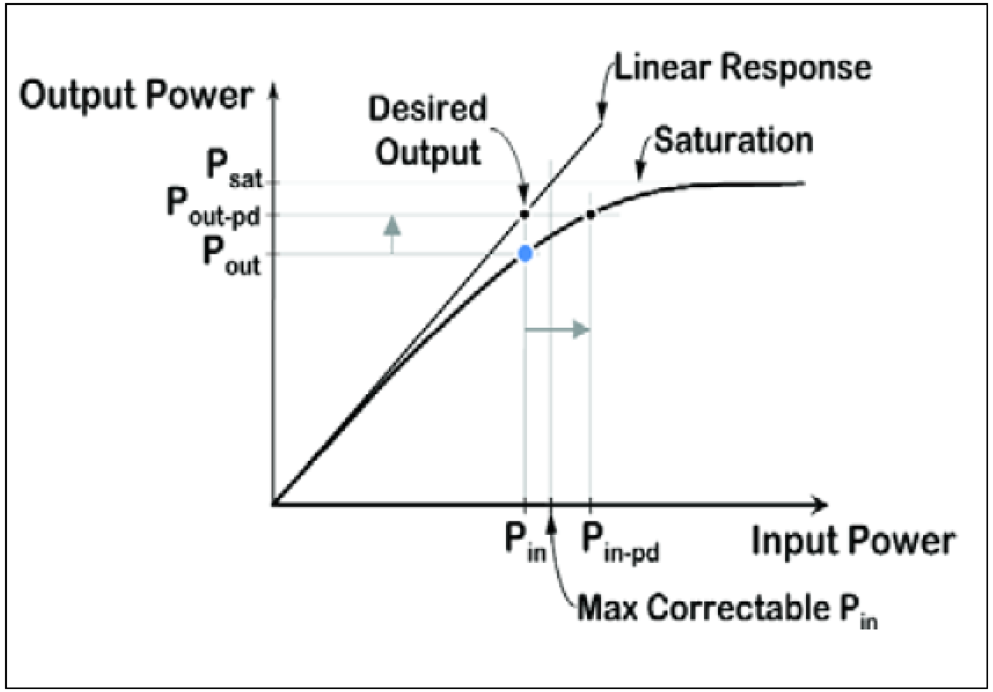


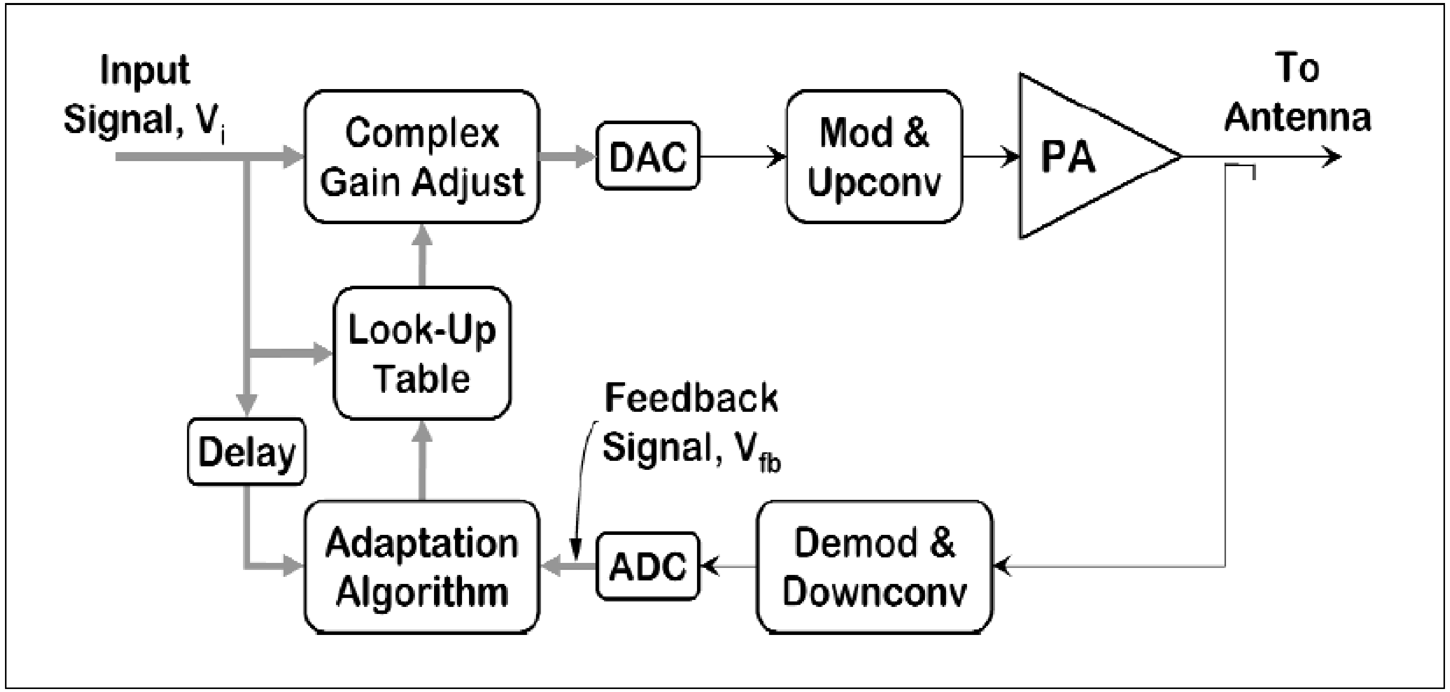
Non-linear because of "Soft Compression" in GaN

Dynamic Range – Linearity – Digital Pre-Distortion (DPD)

Phase and gain adjustments of the power amplifier's non-linear region are fed back and corrected in the baseband



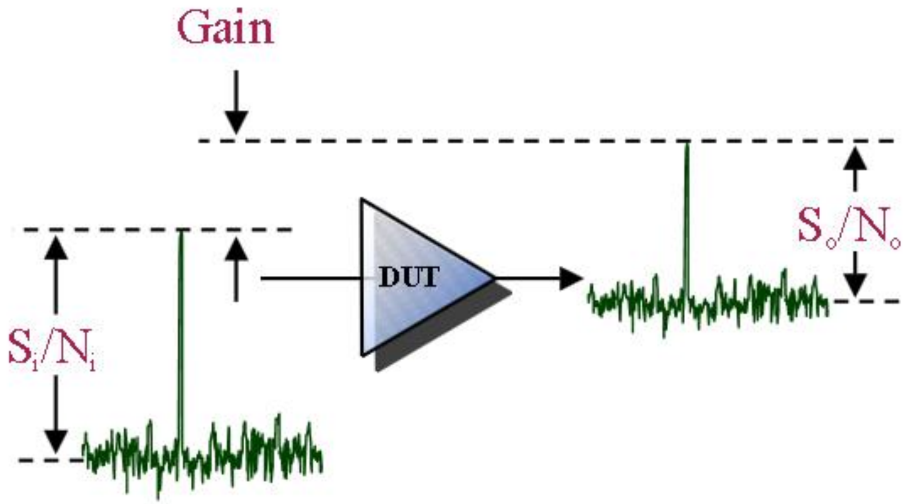


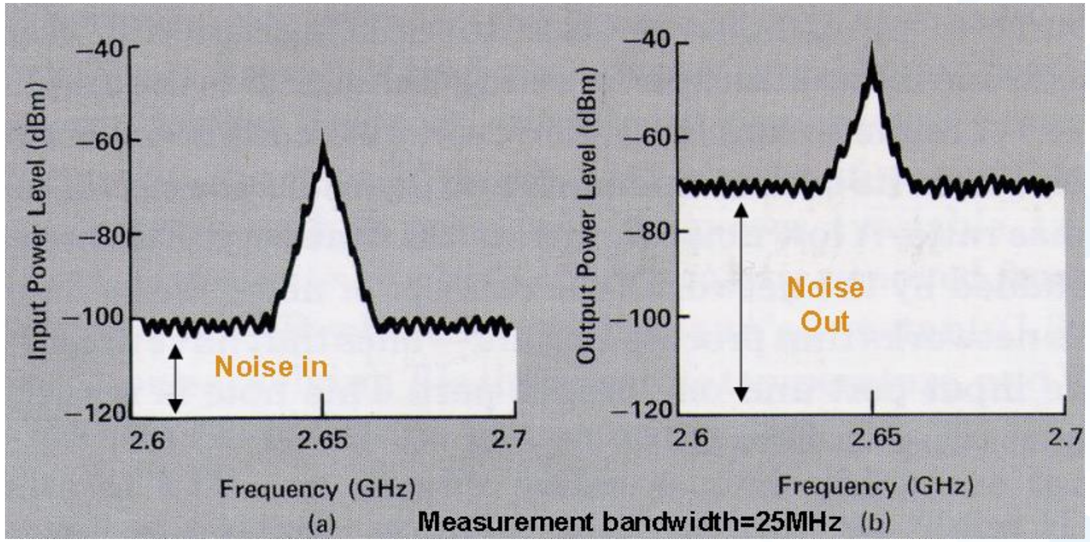


Dynamic Range – Noise

$$\text{Noise Factor} = F = \frac{\left(\dfrac{S}{N}\right)_{in}}{\left(\dfrac{S}{N}\right)_{out}}$$

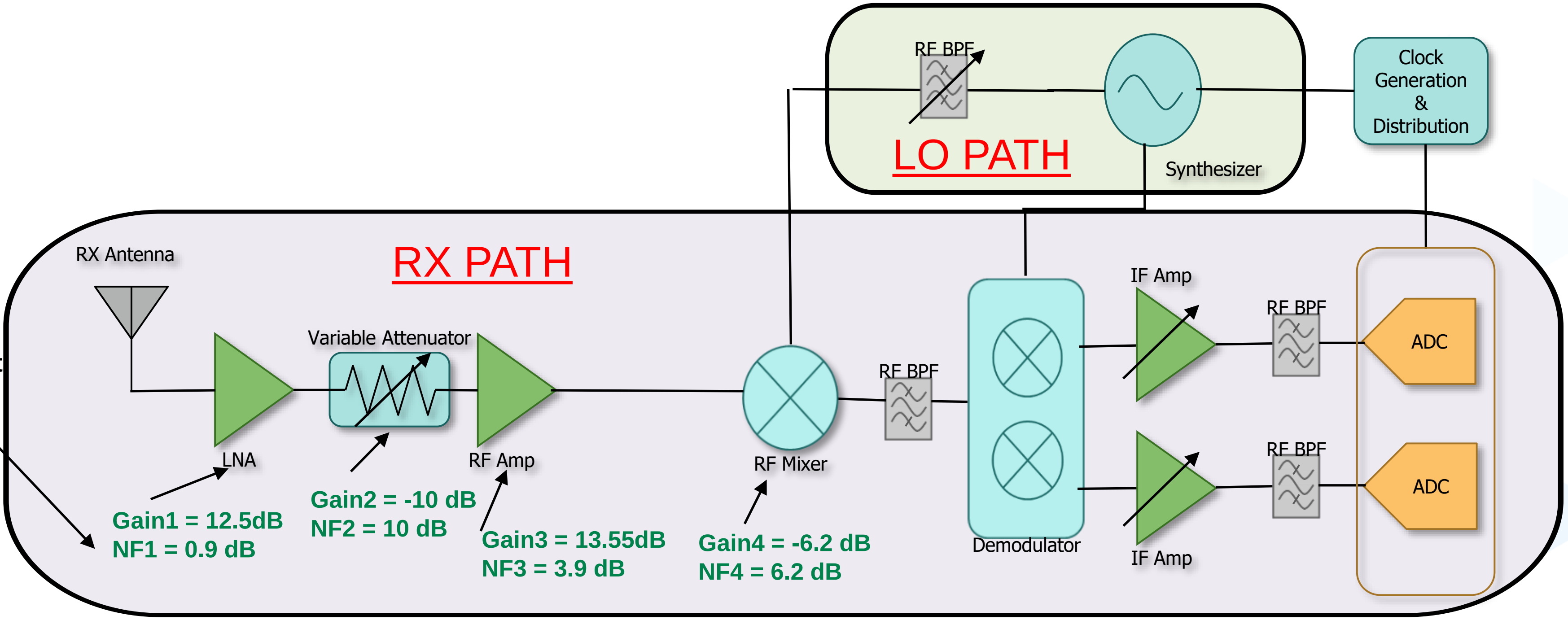
$$\text{Noise Figure} = 10\log(F)$$





Dynamic Range – Cascaded Noise

Note :
1st stage is 1st order effect

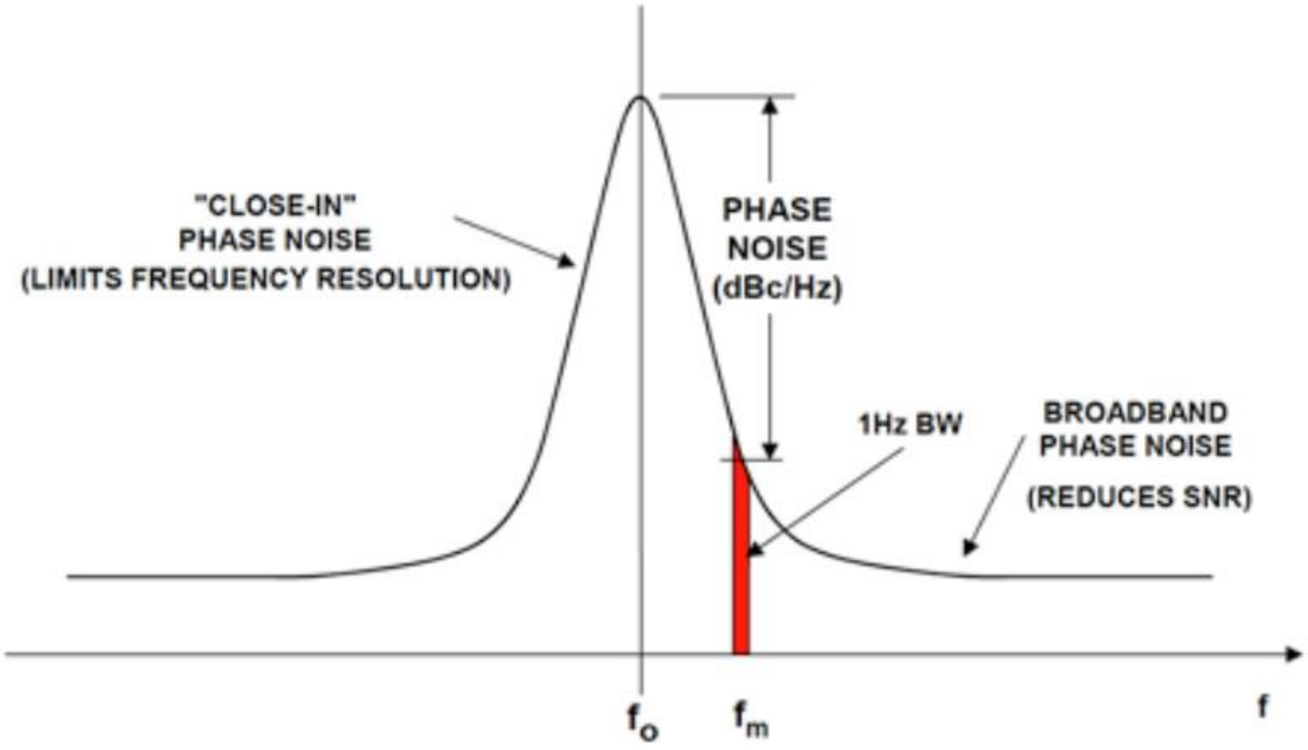


Total Noise Factor (NF in milliwatts) = NF1 + (NF2-1)/G1 + (NF3-1)/G1*G2 + (NF4-1)/G1*G2*G3…

Noise Figure (dB) = 10 log (NF)

Dynamic Range – Phase Noise

- Phase noise – Generated from a VCO or synthesizer which is close in frequency to the source



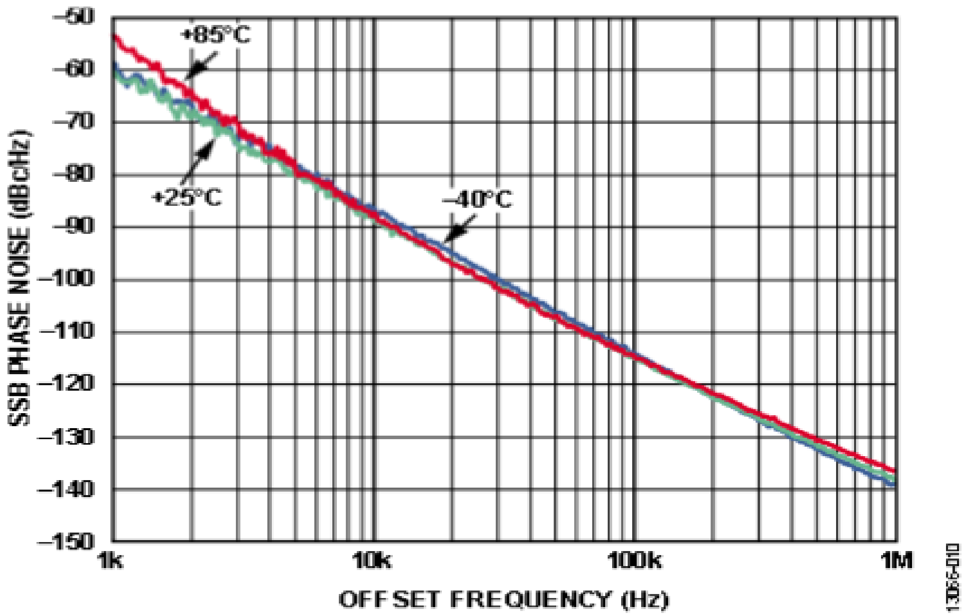
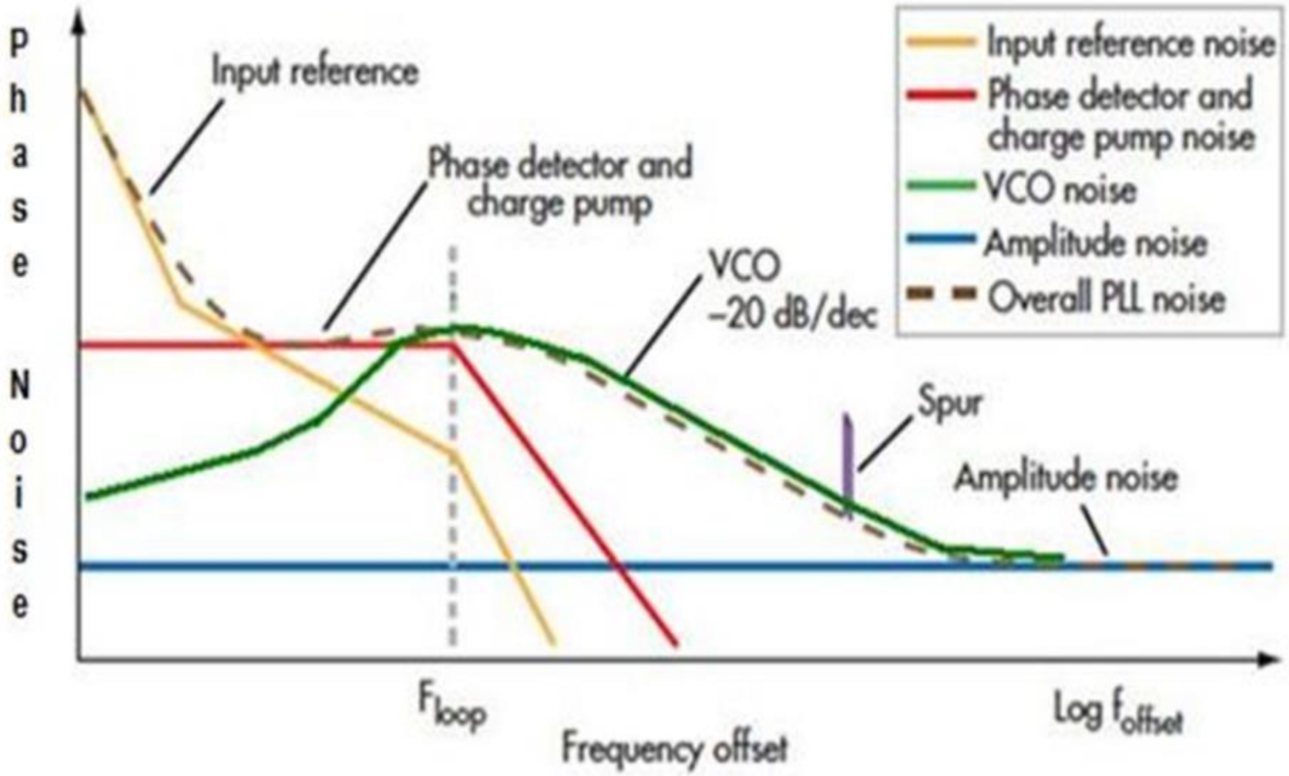
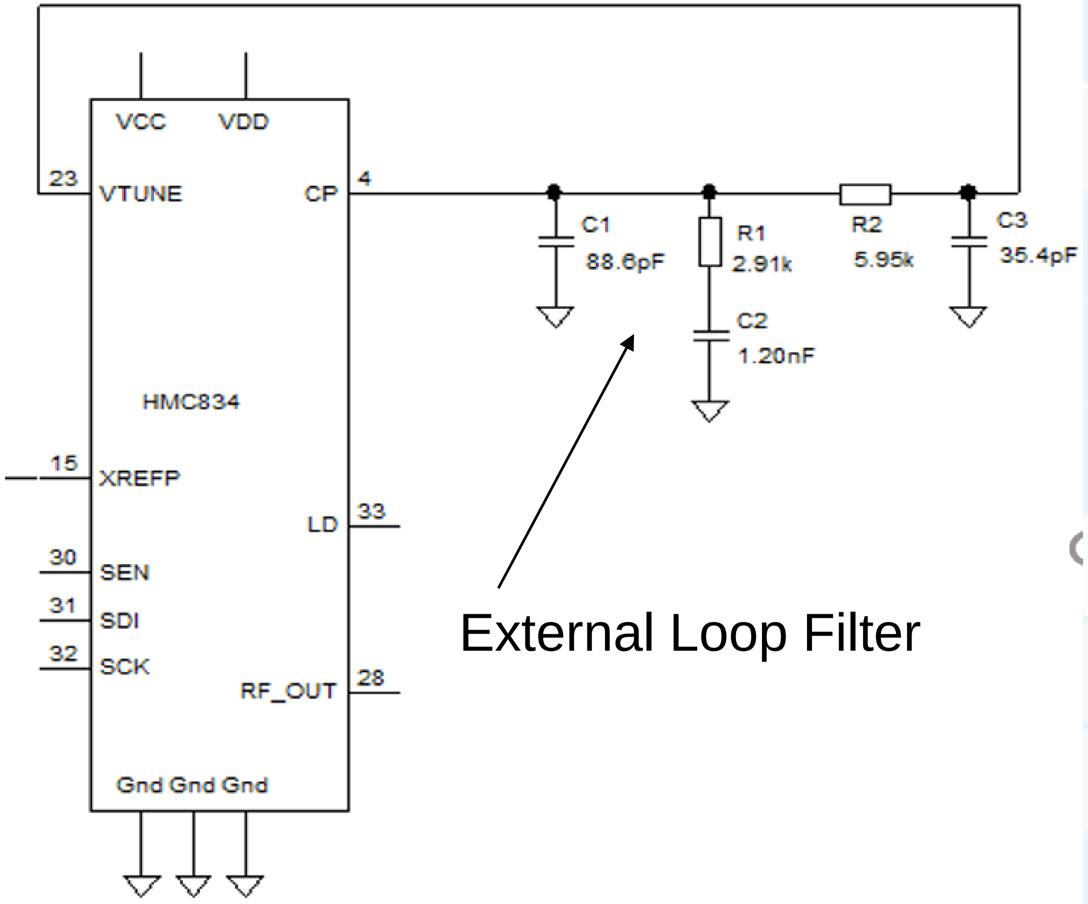


Figure 15. SSB Phase Noise vs. Offset Frequency at VTUNE = 5 V

Dynamic Range – Synthesizer Phase Noise

- Synthesizer phase noise is a compilation of several components of the synthesizer such as the input reference, phase detector, charge pump and phase lock loop.



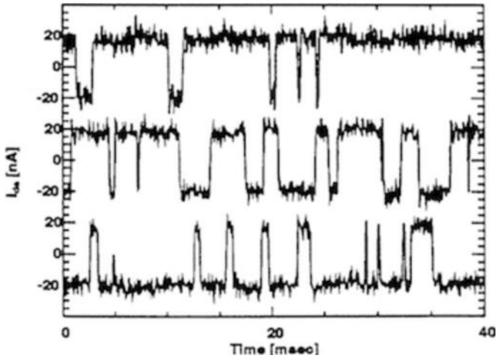


External Loop Filter

Dynamic Range – Other Noise Types

- Thermal (Johnson-Nyquist) noise – Broadband frequency noise created by all components and varies with temperature

- Popcorn (Burst) noise - Caused by defects in semiconductors with trapping and releasing charges



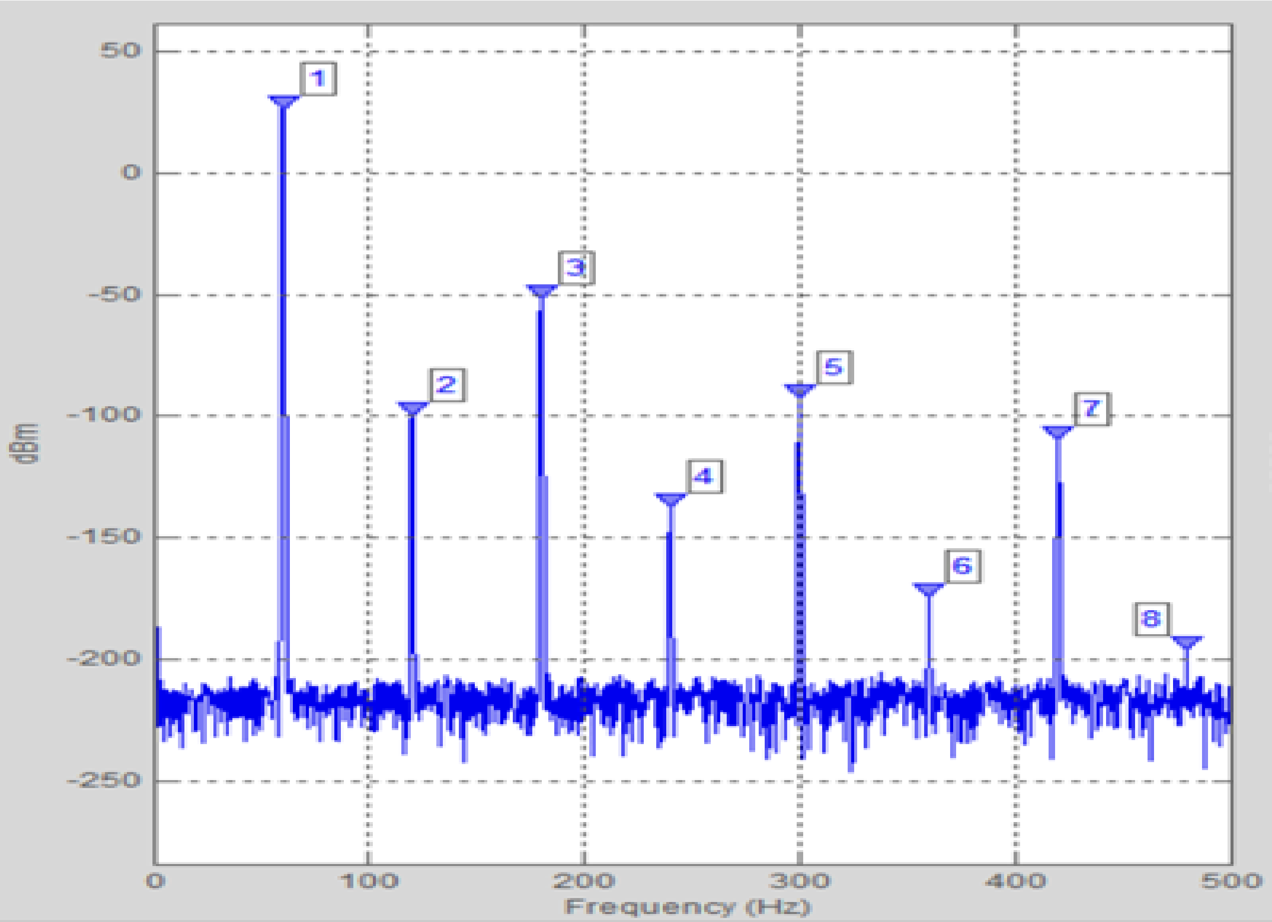
- Shot noise – Broadband frequency noise in all electronic devices and varies with current

- 1/f (Flicker) noise – Very low (Hz or sub Hz) noise and decreases as frequency increases

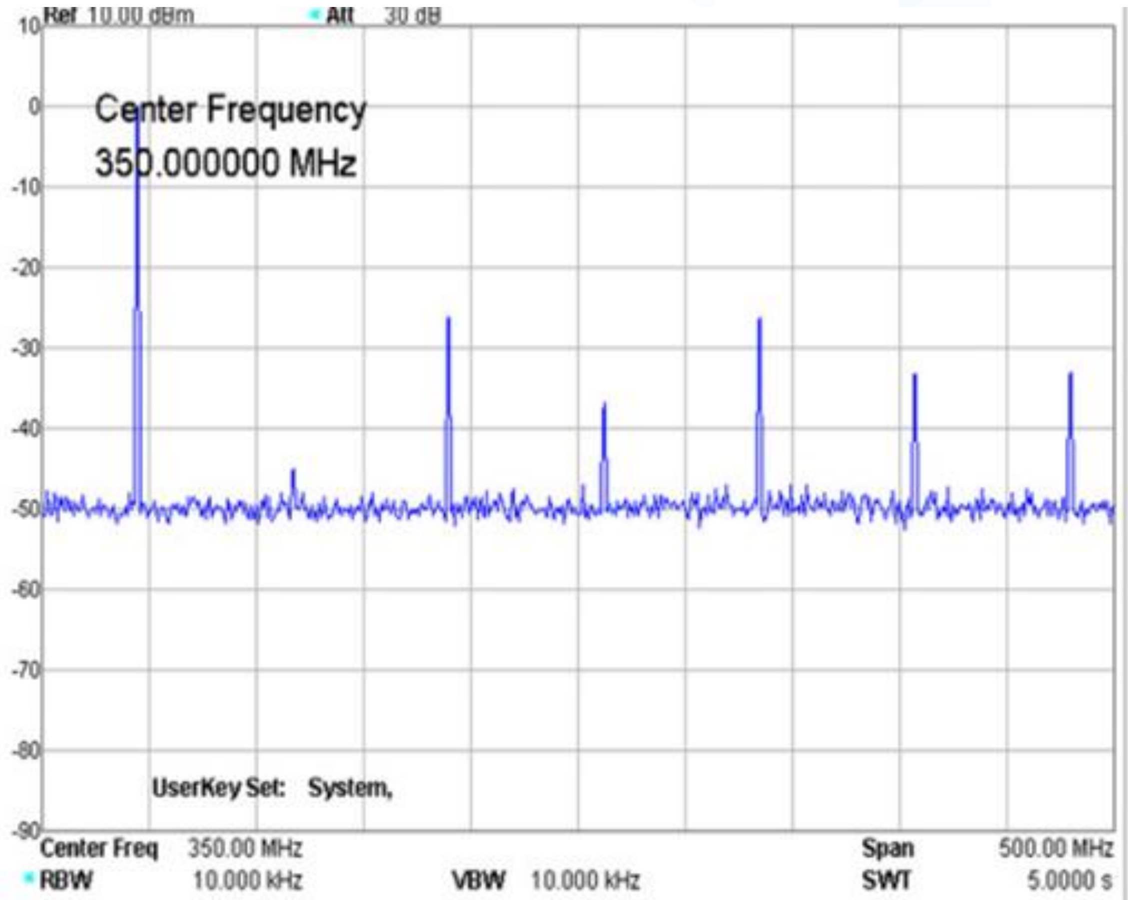
- Quantization Noise - Leftover energy created by the converters after conversion.

Dynamic Range – Spurious Signals

- Harmonic and non-harmonic spurious signals are found in every signal chain
- Non-harmonic spurious signals can come from within or outside the signal chain.



Harmonics

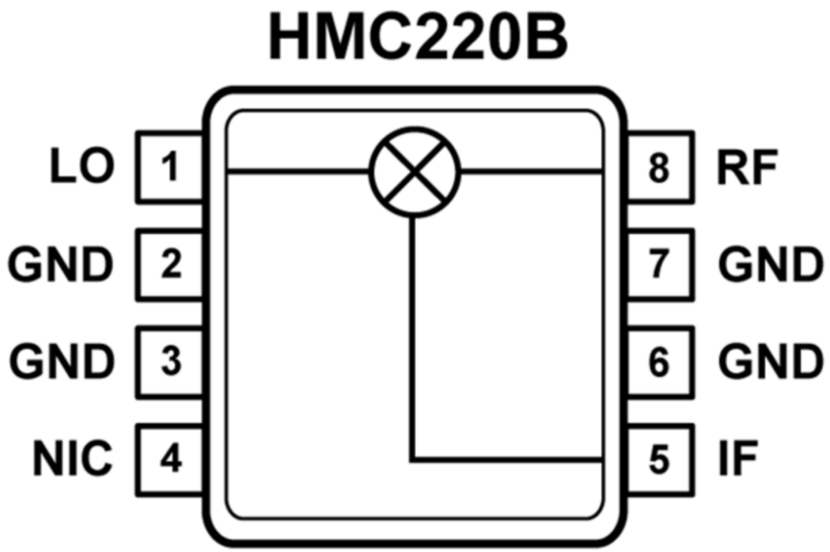


Spurious Signals

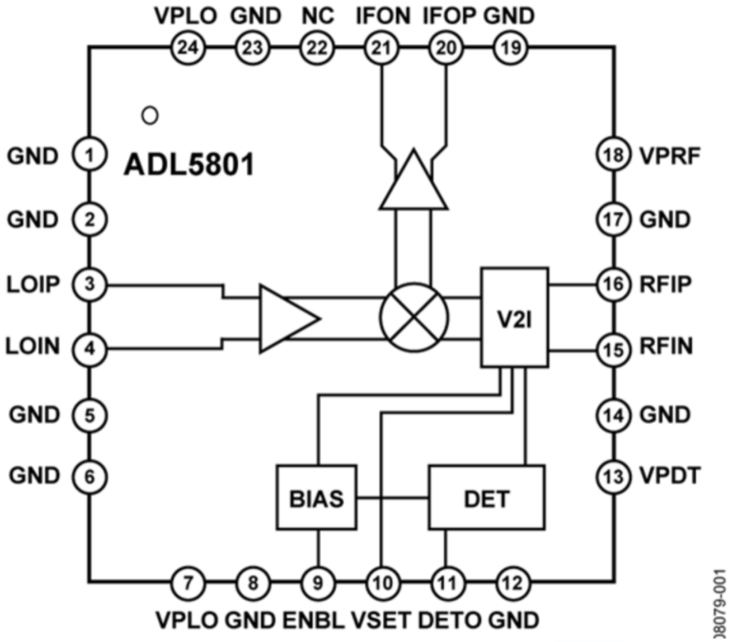
Dynamic Range – Mixers

- Mixers can come in various types, passive, active, IQ and others.

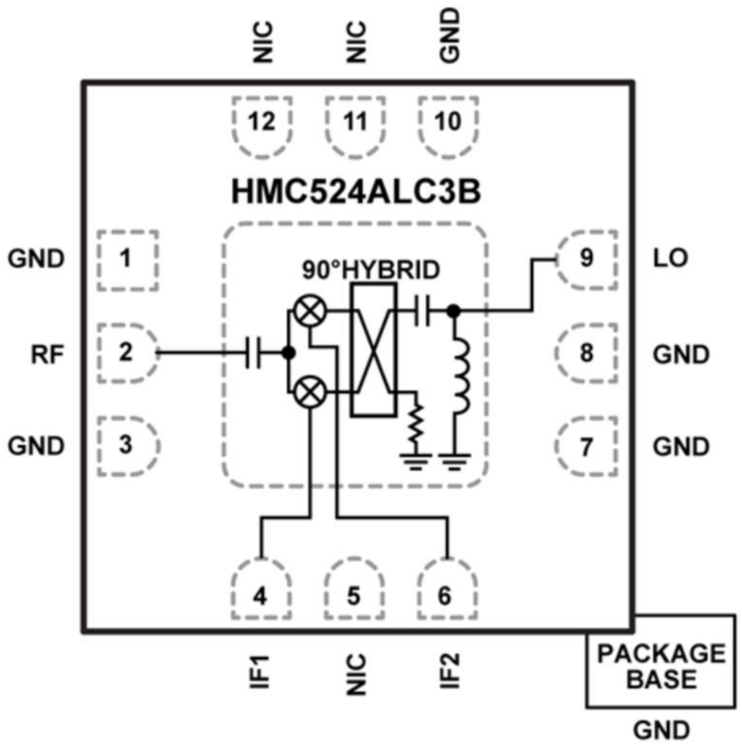
Passive



Active

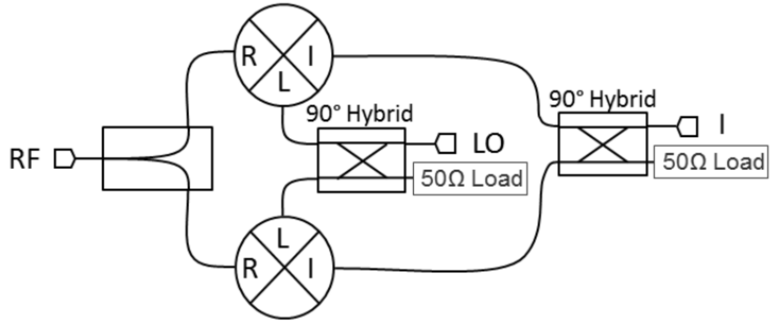


IQ



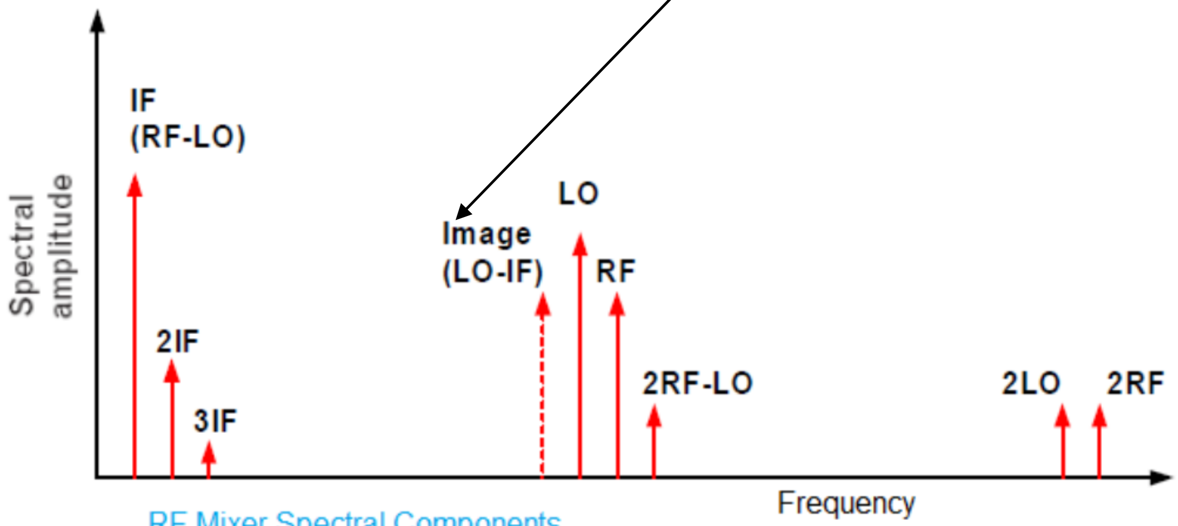
Dynamic Range – IQ Mixers – Image Rejection

- IQ Mixers, also known as image reject or single sideband mixers can help dynamic range by cancelling the image using phase cancellation



IR/SSB Mixer

Image reduced or cancelled by phasing

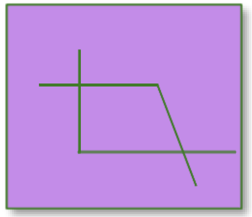


RF Mixer Spectral Components

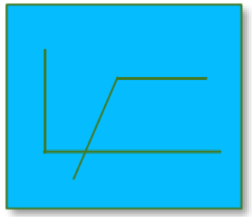
Dynamic Range – Spurious Signals - Filters

- 4 basic types of filters can be used. Some may be tunable
- Often filters cannot help with close-in signals such as IMD tones, images or in-band receiver spurious

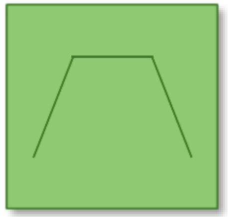
Low Pass Filter



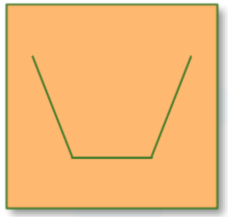
High Pass Filter



Band Pass Filter



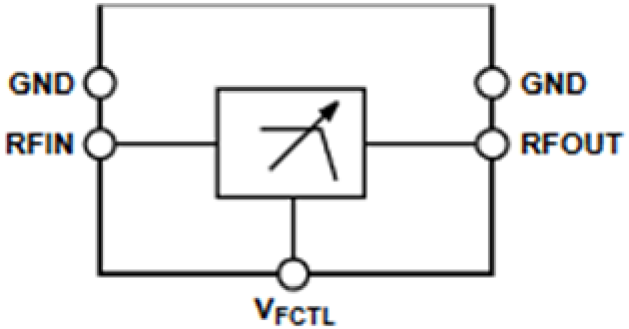
Band Stop Filter



Dynamic Range – Spurious Signals - Filters

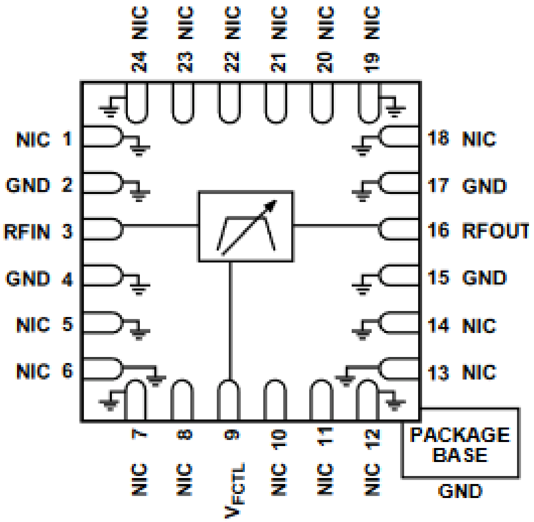
3.95 GHz to 6.9 GHz,
Tunable Low-Pass Filter

HMC882A



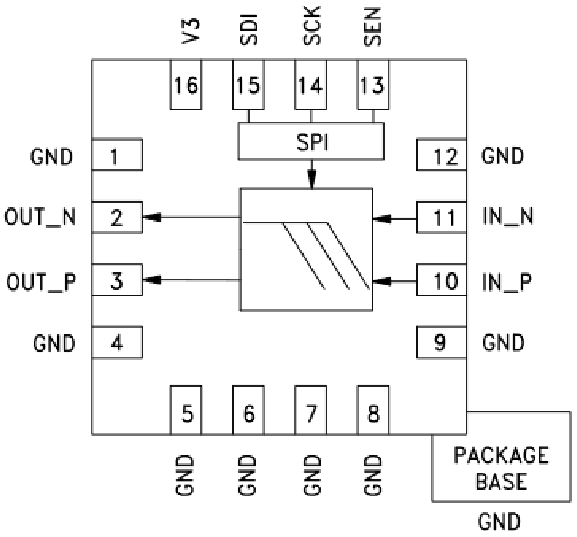
11 GHz to 20 GHz,
Tunable Band-Pass Filter

ADMV8420



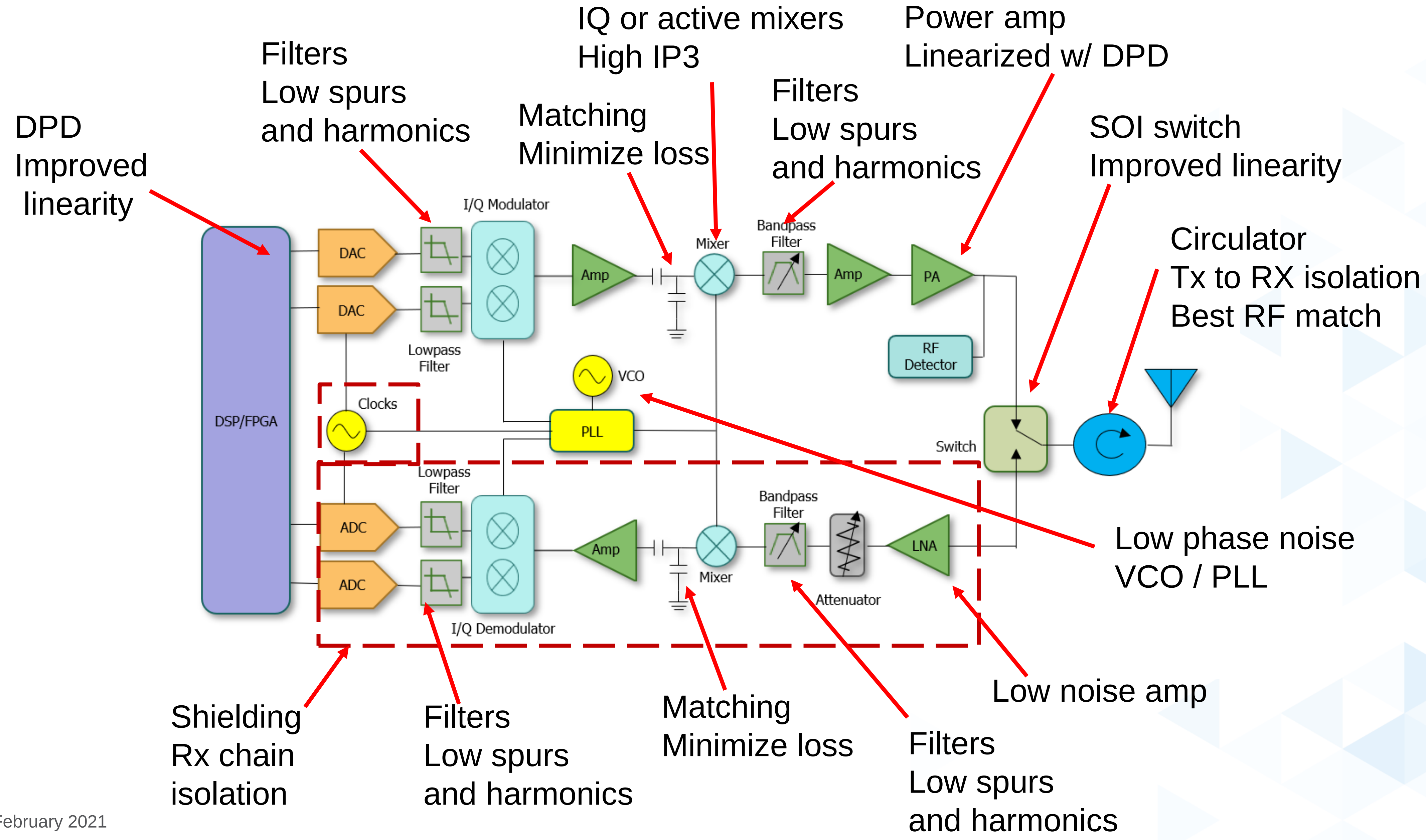
Programmable Harmonic
Low Pass Filter

HMC1044LP3E



Improving the RF Signal Chain

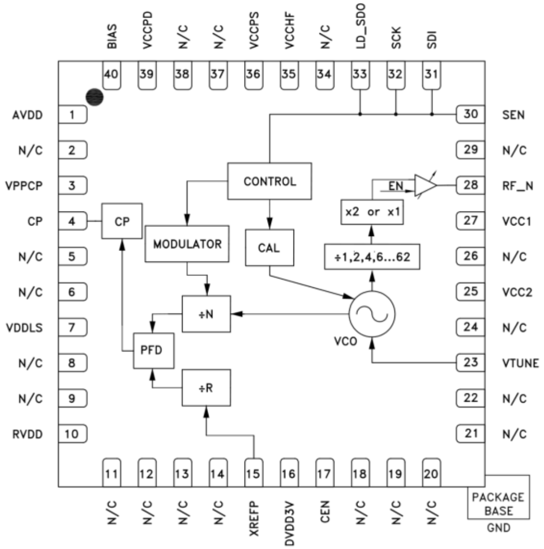
Optimizing the Signal Chain – In Review



Tools

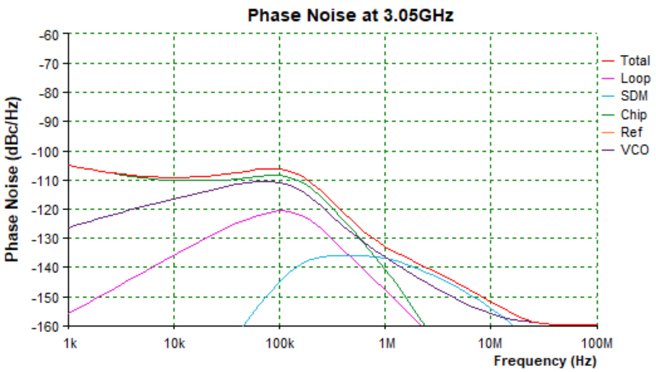
Tools - ADISimPLL

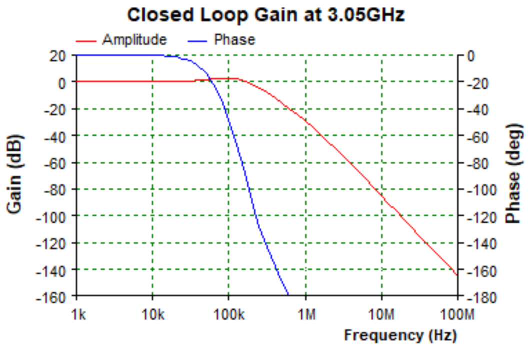
HMC834

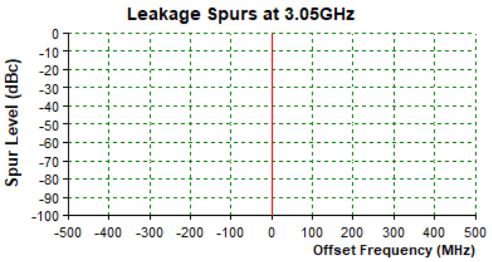


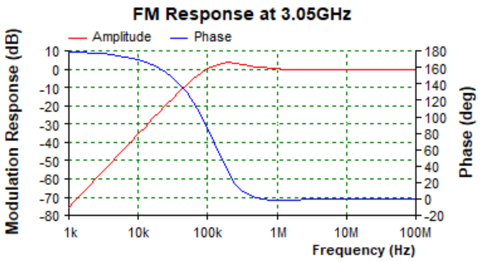
Synthesizer simulated

RF performance



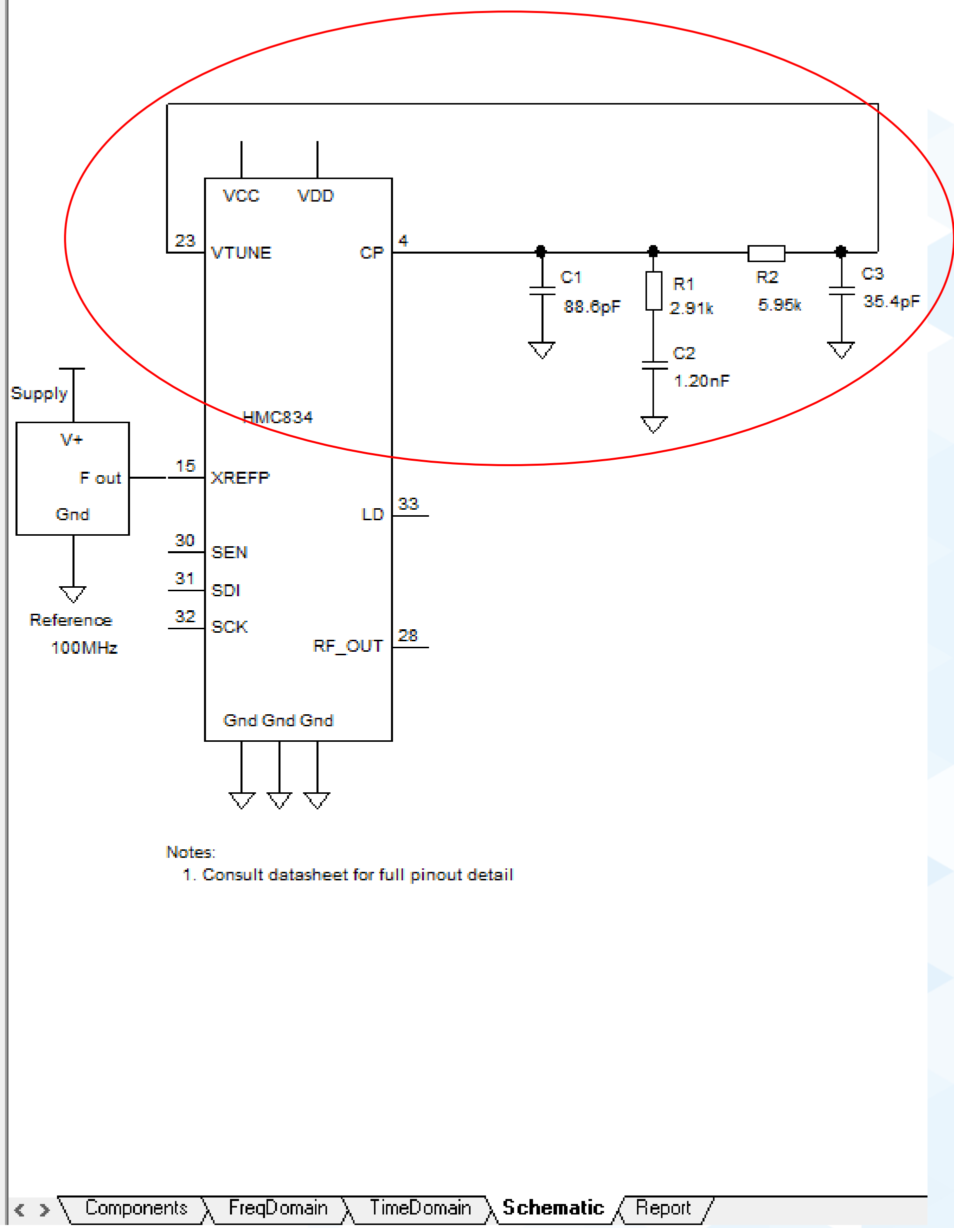






System	
Min Freq	3.00GHz
Max Freq	3.10GHz
Channel Spc.	2.980 Hz
PD Freq.	50.0MHz
Modulus	2^24
Design Freq	3.04959GHz
Reference	custom
Frequency	100MHz
Phase Noise	None
VCO	HMC834
Tuning Law	Multiband
Input Cap.	5.00pF
Divider N	1
Phase Noise	Table
Chip	HMC834
Mode	Normal
Main Divider	
Ref Divider	
Phase Detector	Charge Pump
Lock Detect	None
Speedup Mode	None
Loop Filter	CPP_3C
Specify:	Phase Margin
Loop Bandwidth	127kHz
Phase Margin	45.0 deg
Zero Loc.	45.3kHz
Pole Loc.	356kHz
Last Pole	1.27MHz
C1	88.6pF
R1	2.91k
C2	1.20nF
R2	5.95k
C3	35.4pF
Lock Detect	None
FreqDomain	
Min Freq	1.00kHz
Max Freq	100MHz
Pts per Decade	10

Loop filter design



Tools - ADISimRF

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

Signal Chain Analysis

ANALOG DEVICES
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+	-

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Transmit	DAC	VGA	Mixer (Tx)	Driver Amp	GaN PA	SPDT T/R
Toggle Tx/Rx	AD9162V2	ADRF6520VGA1	AD8342	ADL5320-3V	HMC8205BF10	HMC646LP2-Rx
Output Freq (MHz)	500	500	2000	2000	2000	2000
Zin (Ohms)	100	100	50	50	50	50
Zout (Ohms)	100	100	50	50	50	50
Power Gain (dB)	-12.57	-12	4.65799949645996	12.6	25.94	-1.3
Voltage Gain (dB)	-12.6	-12	4.7	12.6	25.9	-1.3
OIP3 (dBm)	17.6	36	20.7	31.4	47.7	32.7
OP1dB (dBm)	25	12.5	10.5	22.8	42.1	17.7
Pout (dBm)	-12.6	-24.6	-20.4	-7.8	18.1	16.8
Pout Backoff (dB)	37.6	37.1	30.9	30.6	24	0.9
Peak Backoff (dB)	37.6	37.1	30.9	30.6	24	0.9
Noise Figure (dB)	23.2	39	13.8	3.6	6	1.3
Voltage (V)	3.3	3.3	5	3.3	50	0
Current (mA)	697	140	98	44	1300	0

Input

Number of Stages	6	
Input Power	0	dBm
Analysis Bandwidth	1	MHz
PEP-to-RMS Ratio	0	dB
P1dB Backoff Warning	10	dB
Peak Backoff Warning	1	dB

Analysis

Output Power (rms)	16.82	dBm
Output Voltage (rms)	1.55	Vrms
Output Voltage (pp)	4.38	Vpp
OP1dB	17.67	dBm
IP1dB	1.9	dBm
Power Gain	16.82	dB
Voltage Gain	13.81	dB

Noise Figure	51.77	dB
Output NSD	-105.4	dBm/Hz
Output NSD	1.2	uV/rtHz
Output Noise Floor	-45.4	dBm
SNR	62.2	dB

OIP3	32.34	dBm
IIP3	15.5	dBm
IMD3 ((Pout-3dB) per tone))	-37	dBc
SFDR	51.7	dB
ACLR (est.)	-51	dB
Pwr Consumption	68.4	W

Tools – Keysight ADS / Momentum

ANALOG DEVICES
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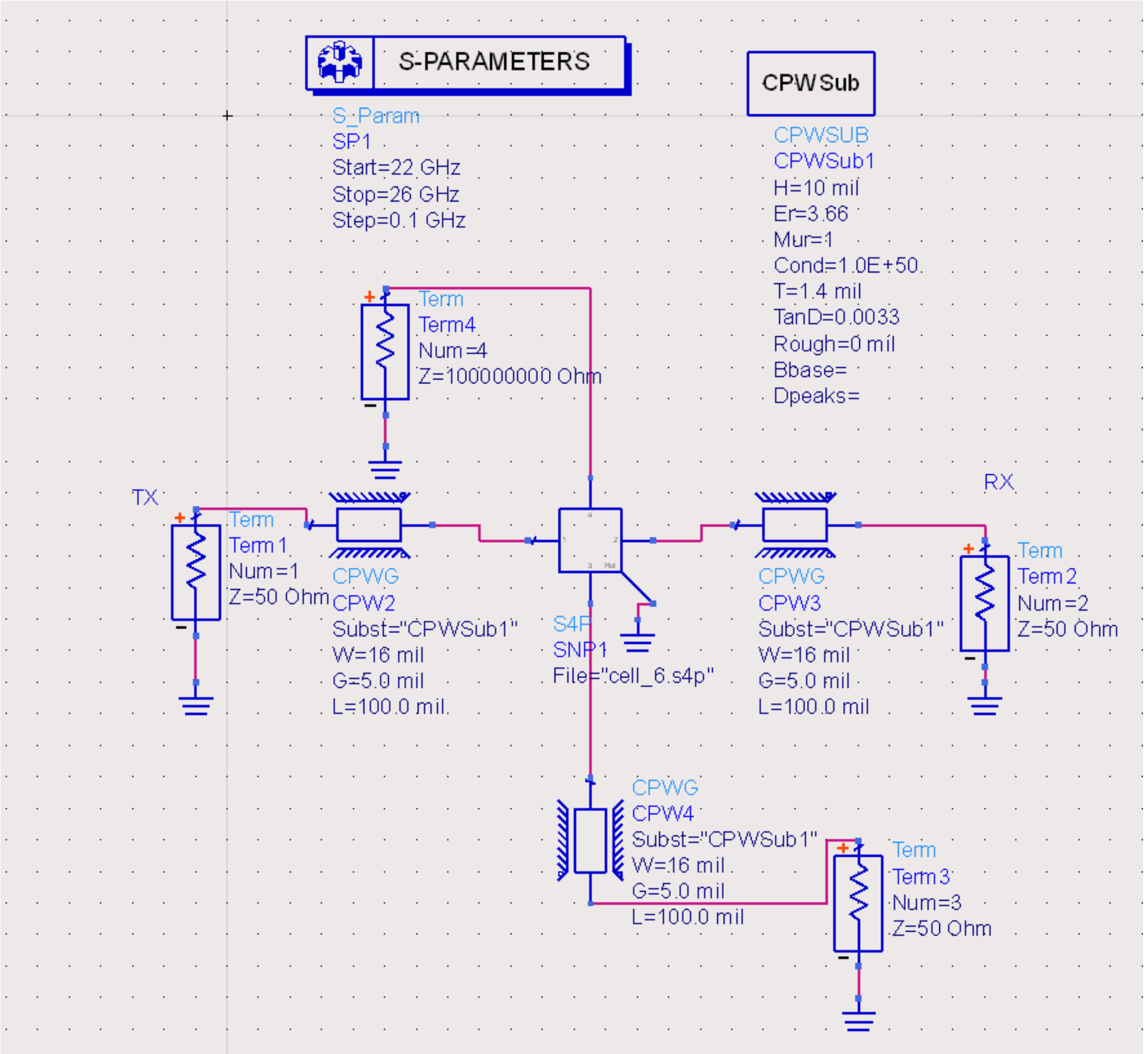
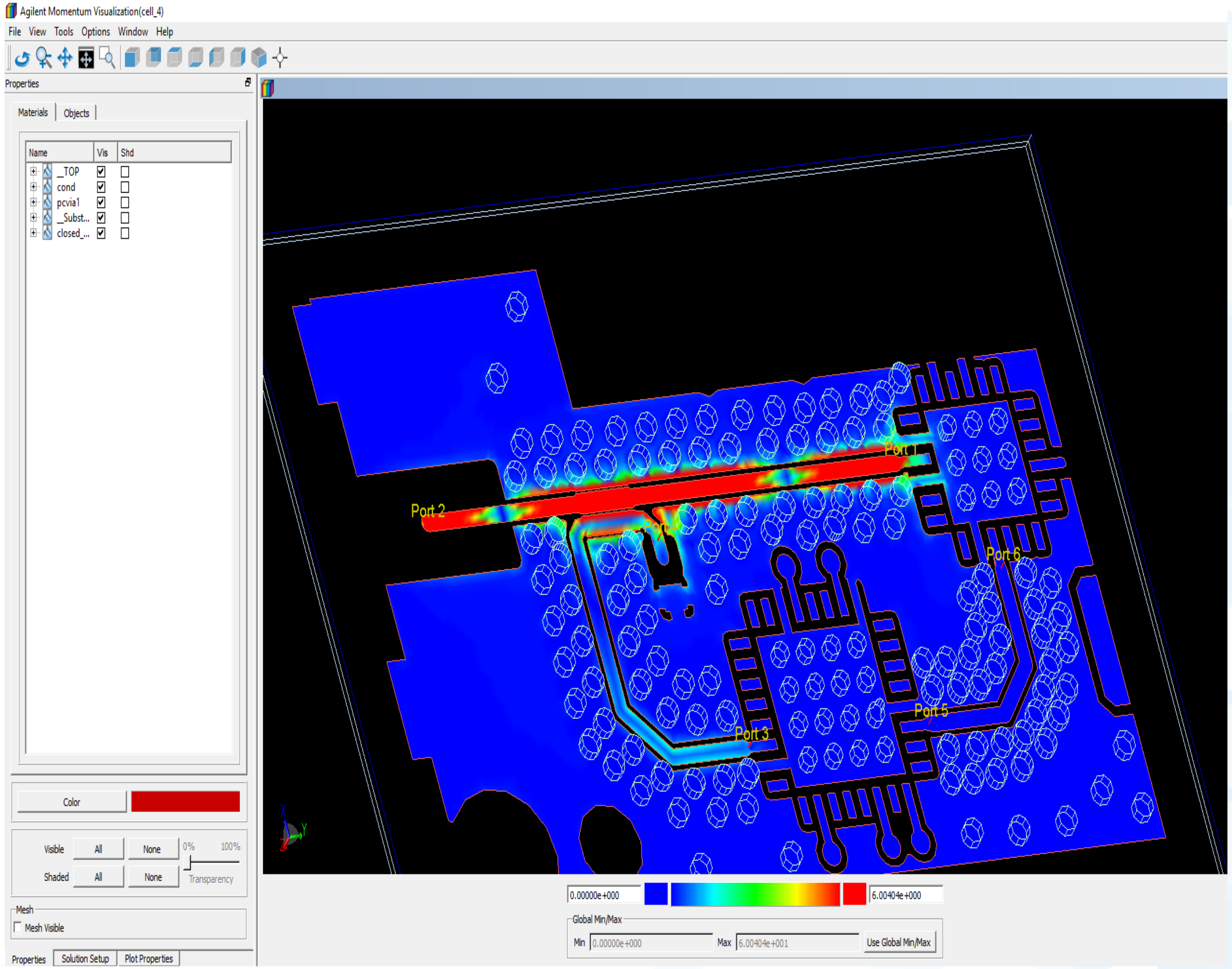
Linear Analysis

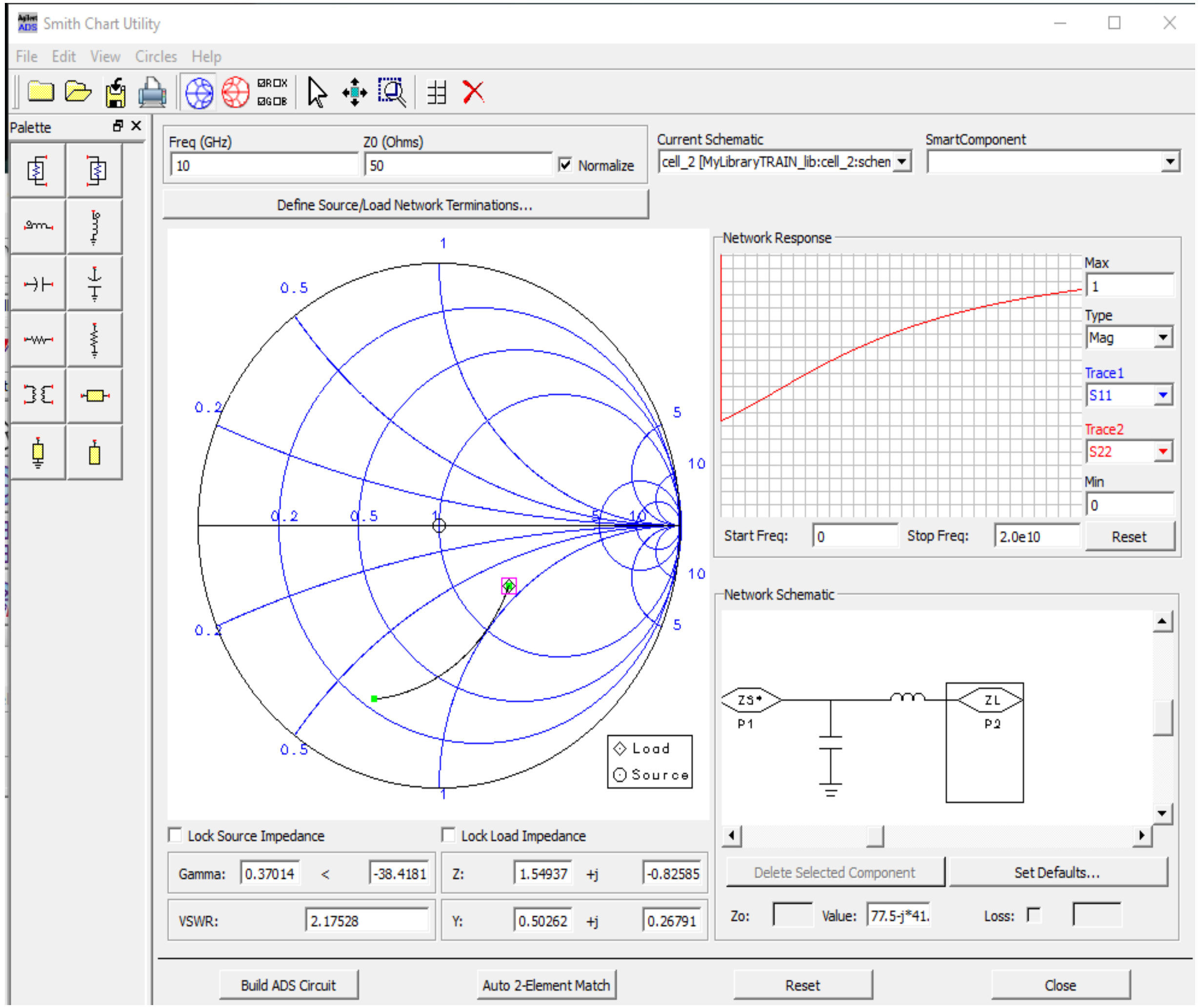


Electromagnetic Simulation

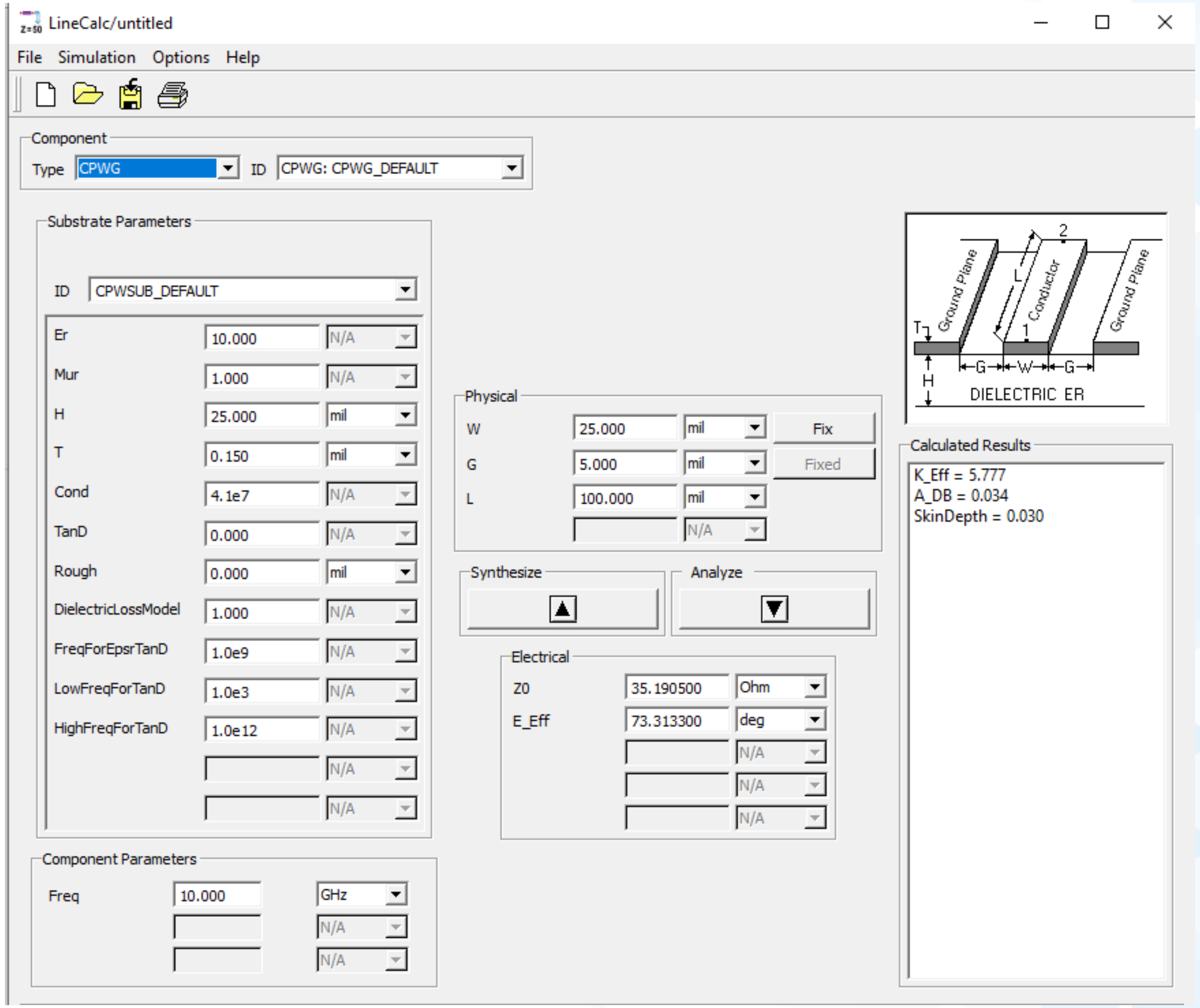


Tools – Keysight ADS / Momentum

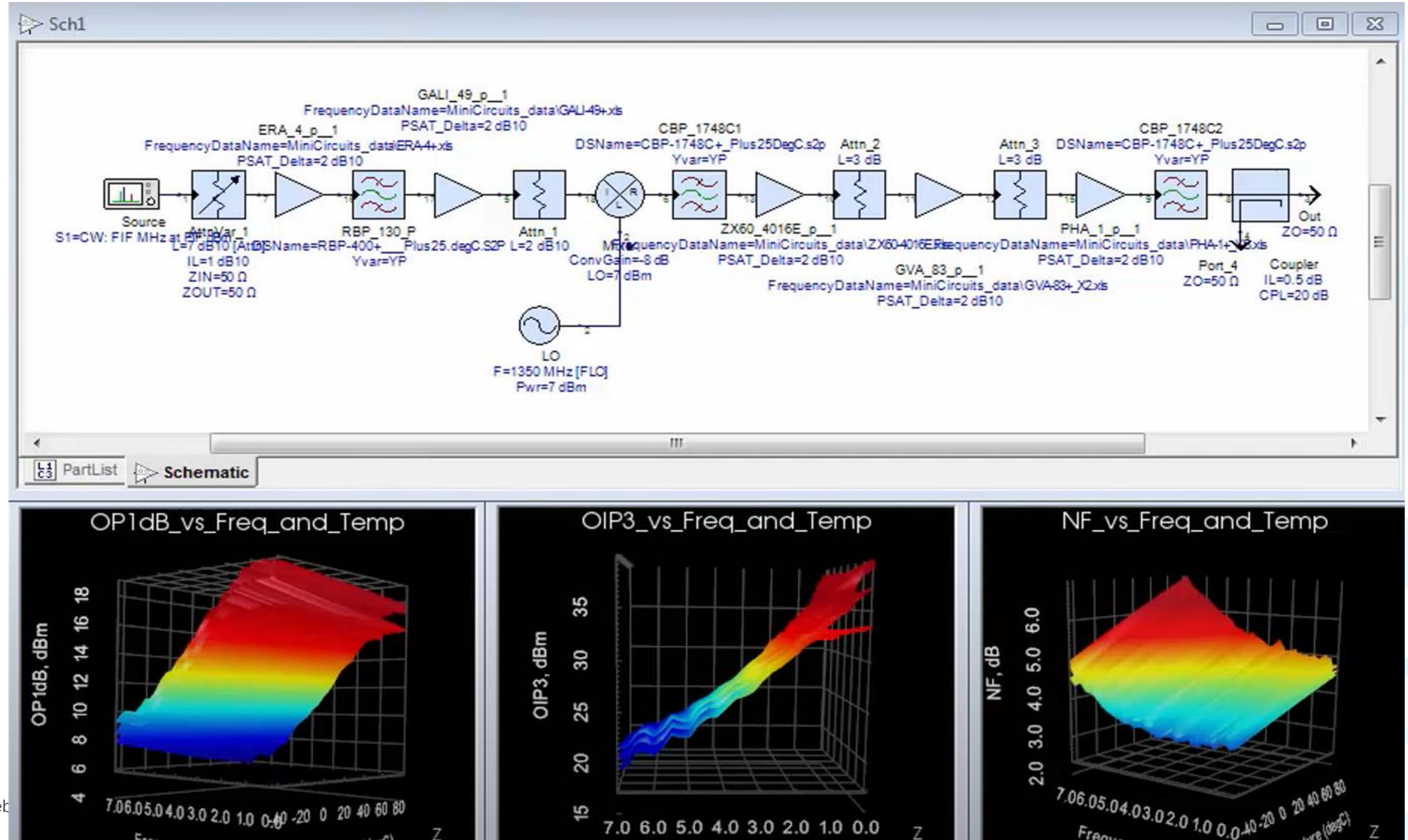
Smith Chart Utility



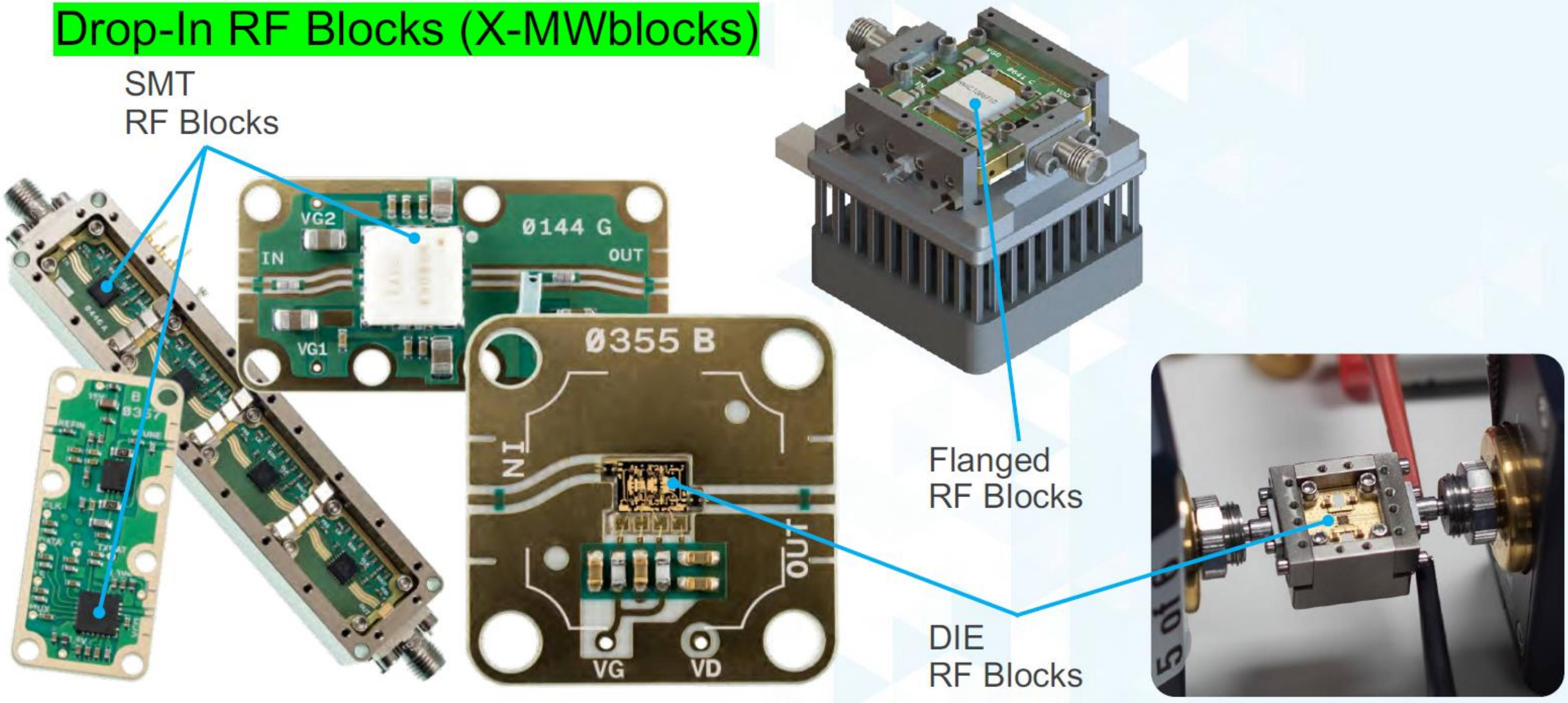
Line Calc



Tools – Keysight Genesys



Tools – X-Microwave



Questions ?

Thank You !!

ADI Central Applications – 1-800-262-5643

Email – cic.americas@analog.com

References

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By Kelly Mekechuk, Wan-Jong Kim, Shawn P. Stapleton, Simon Fraser University

Jong Heon Kim, Kwangwoon University

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3. SOI process information – WaferPro - https://waferpro.com/what-are-soi-wafers-or-silicon-on-insulator-wafers/

4. “**The Effect of Via Spacing on the Signal Integrity Performance of PCB with Slotted Ground**”

By Soonyong Lee, Wonbum Seo, and Jaehoon Choi at Hanyang University

5. “**Applying shielding and ferrite materials**”

By Alex Snijder of Wurth Electronics

References (cont.)

Arrow Related Webinars –

Title: Designing Power Solutions for RF Signal Chain Applications

https://event.on24.com/eventRegistration/EventLobbyServlet?target=reg20.jsp&partnerref=ARROW&eventid=2390134&sessionid=1&key=DC41DD047B402583E3458DCDD1E63AEB&regTag=&sourcepage=register

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