Reconfigurable RF CMOS Circuits for Cognitive Radios

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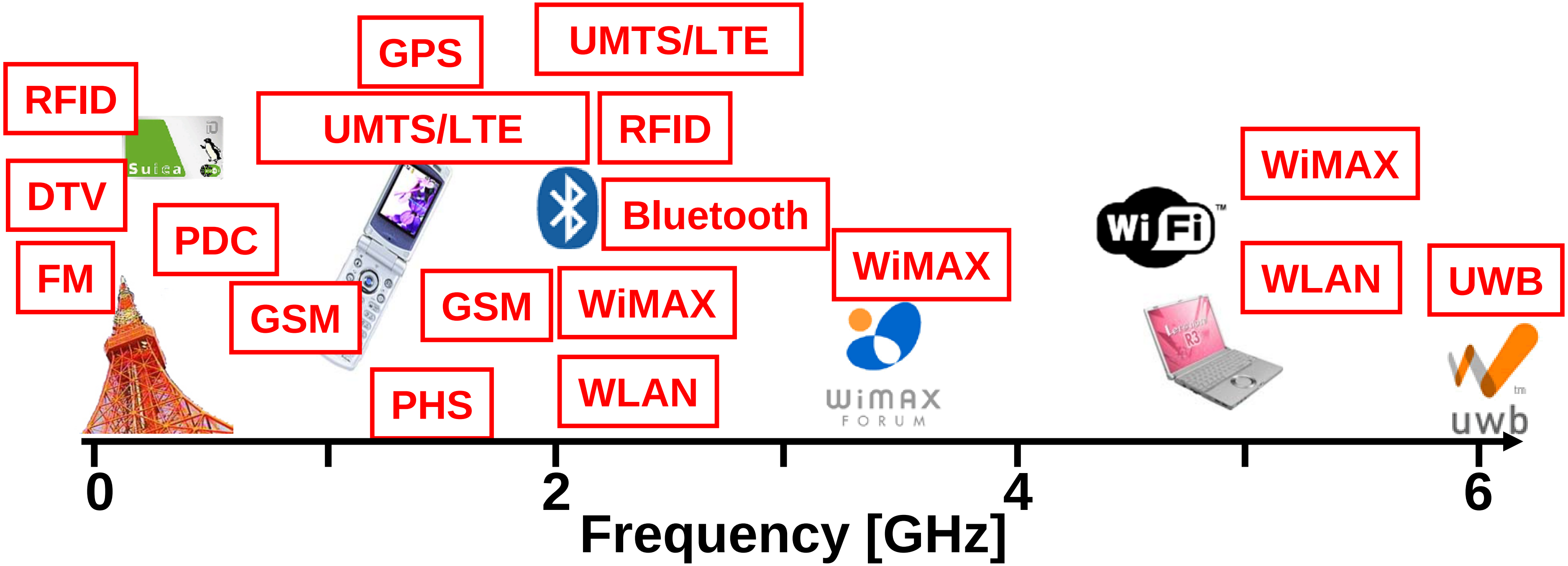
Outline

- **Roadmap for multi-standard RFIC**
- **Rx requirements**
  - **Linearity & NF**
- **LO requirements**
  - **Q and V_{DD}**
  - **Frequency tuning range**
  - **Multiband VCO results**
- **Tx requirements**
  - **Tunable PA results**
- **Conclusion**

Motivation



<u>**Demand for a multi-standard RFIC**</u>

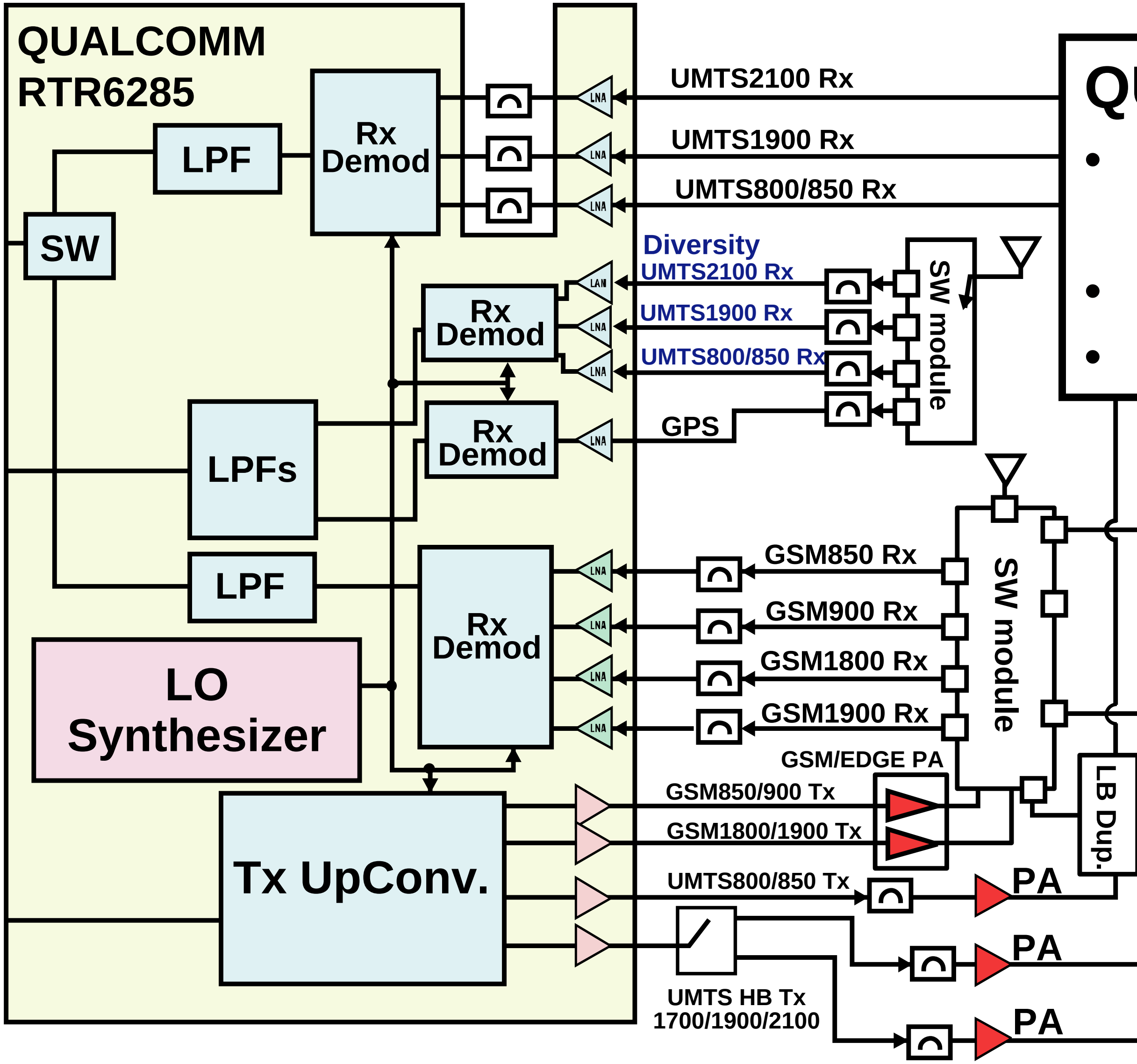
- **Frequency range from 400MHz to 6GHz**
- **Smaller footprint**
- **Smaller number of components with competitive sensitivity and Pdc**

Multi-standard radio roadmap

		Present			Future
		individual approach	near-band combined	one-chip limited reconfiguration	one-chip full reconfiguration
Rx	LNA*	NF <2.2dB (2.5dB total)	NF <2.2dB (2.5dB total)	400MHz-6GHz NF <2dB	400MHz-6GHz NF <2dB
	Mixer	IIP3 >-5dBm	IIP3 >0dBm w/o SAW filter	IIP3 >0dBm w/o SAW filter	IIP3 >0dBm with tunable BPF/BRF
		IIP2 >40dBm	IIP2 >60dBm	IIP2 >70dBm	IIP2 >70dBm
Tx	PA	Off-chip PAs	Reduced off-chip PAs, Reduced off-chip matching	On-chip single-band PAs	On-chip multi-standard PA
				Off-chip multi-standard PAs	Off-chip multi-standard PA
LO	VCO	GSM	GSM	-185dBc/Hz(FoM) no spurs, GSM	-190dBc/Hz(FoM) no spurs, GSM
		Multiple PLLs	Reduced multiple PLLs	400MHz-6GHz with 1 inductor	400MHz-6GHz with 1 inductor

*Lower NF/sensitivity is required for some commercial applications.

The present multi-standard RFIC



QUALCOMM RTR6285

- UMTS 9 bands with diversity
- GSM/EDGE 4 bands
- GPS 1 band

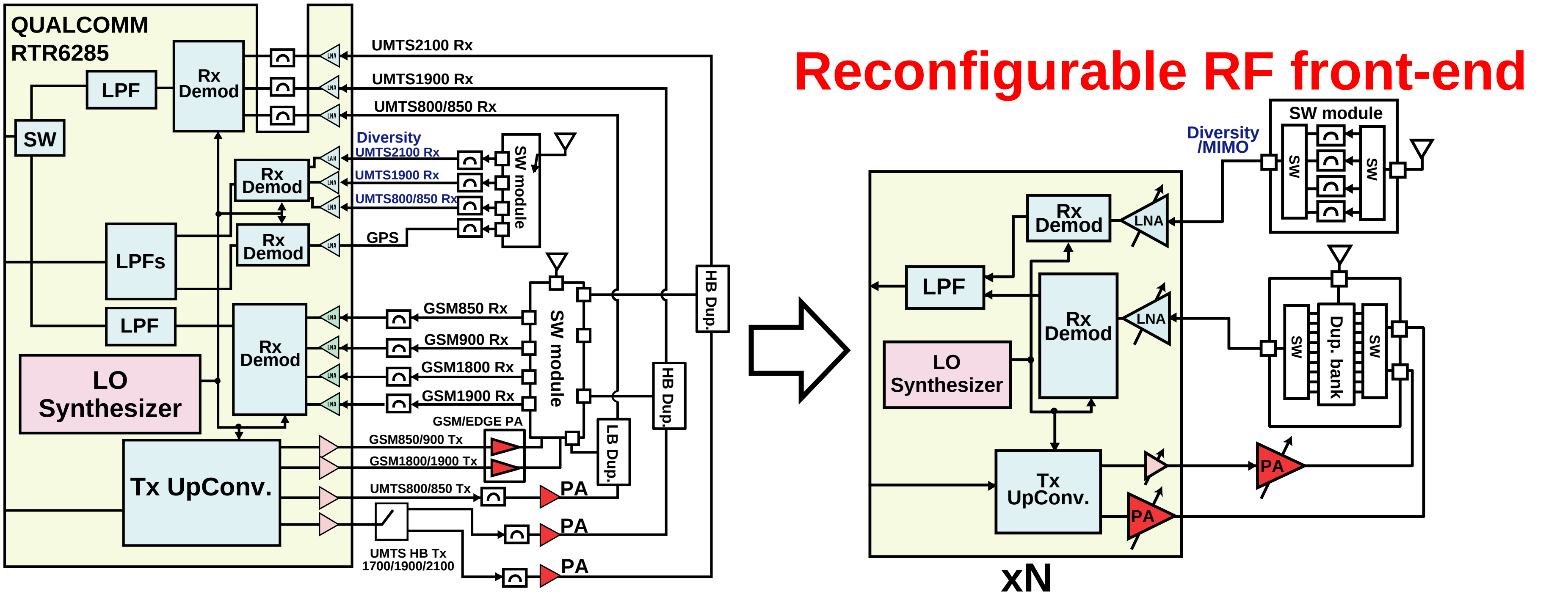
from datasheet

The near-future multi-standard RFIC

- Smaller number of IO pins and external components
  - A single-ended input is better.
- HB Rx(1.8-2.1GHz) should be combined without SAW filters.

  NF<2.2dB, IIP3 >-2.5dBm, IIP2 >70dBm
- GSM bands should also be combined.
- Handling of UMTS/LTE bands 7 and 11
- Must keep the same sensitivity with smaller area and smaller power consumption

One-chip Reconfigurable RFIC



- All cellular, WLAN/WPAN, and broadcast services should be covered.
- On-chip tunable Tx/Rx filters optimized for some particular bands
- On/off-chip tunable/switchable multi-standard PA
- External switchable duplexers are utilized for each FDD standard.

One-chip full Reconfigurable RFIC

- **Equally designed for every bands**
- **Just advancement of NF and linearity improvement with tunable on-chip filters for possible interferers**
- **On/off-chip tunable/switchable multi-standard PA**
- **without special optimization for particular bands**
- **Possibly, external switchable duplexer/SW are still required.**
- **Seamless TDD/FDD reconfiguration**
- **Reconfigurablity is required for RF/ABB**
- **Much smaller frequency step**
- **Cognition time (RF assisted)**

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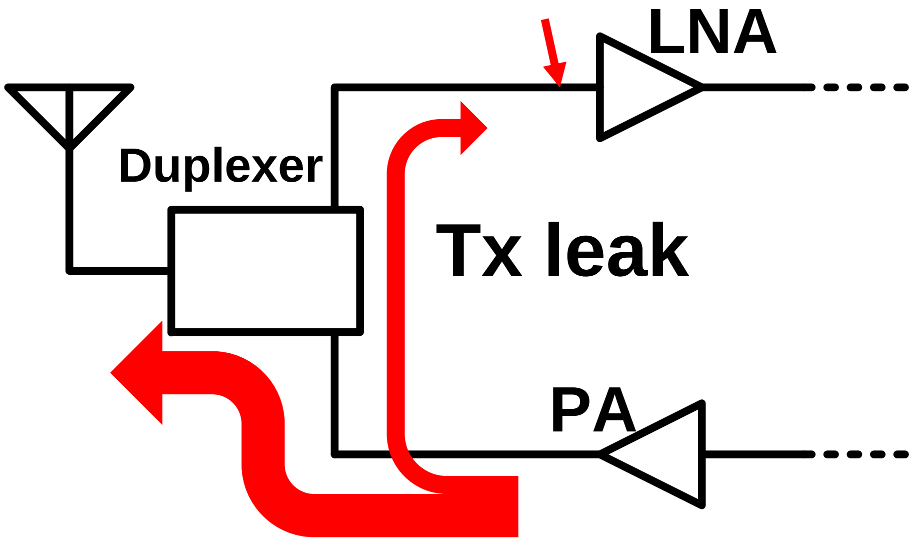
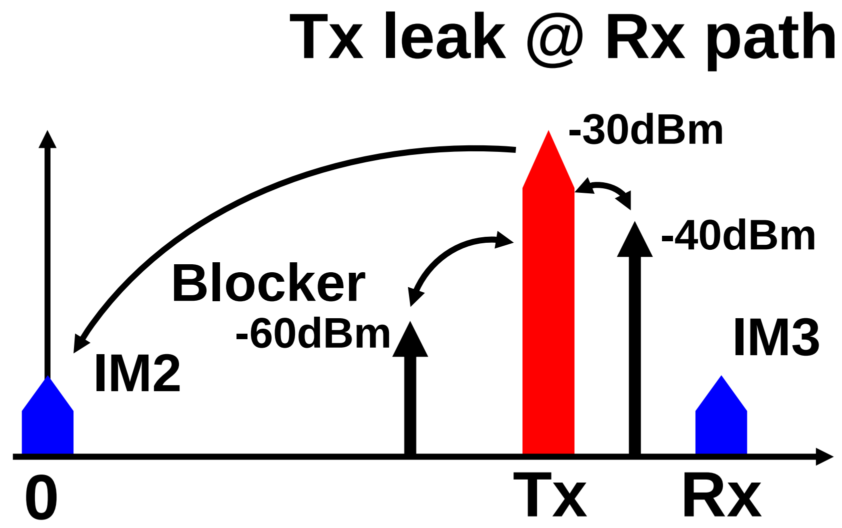
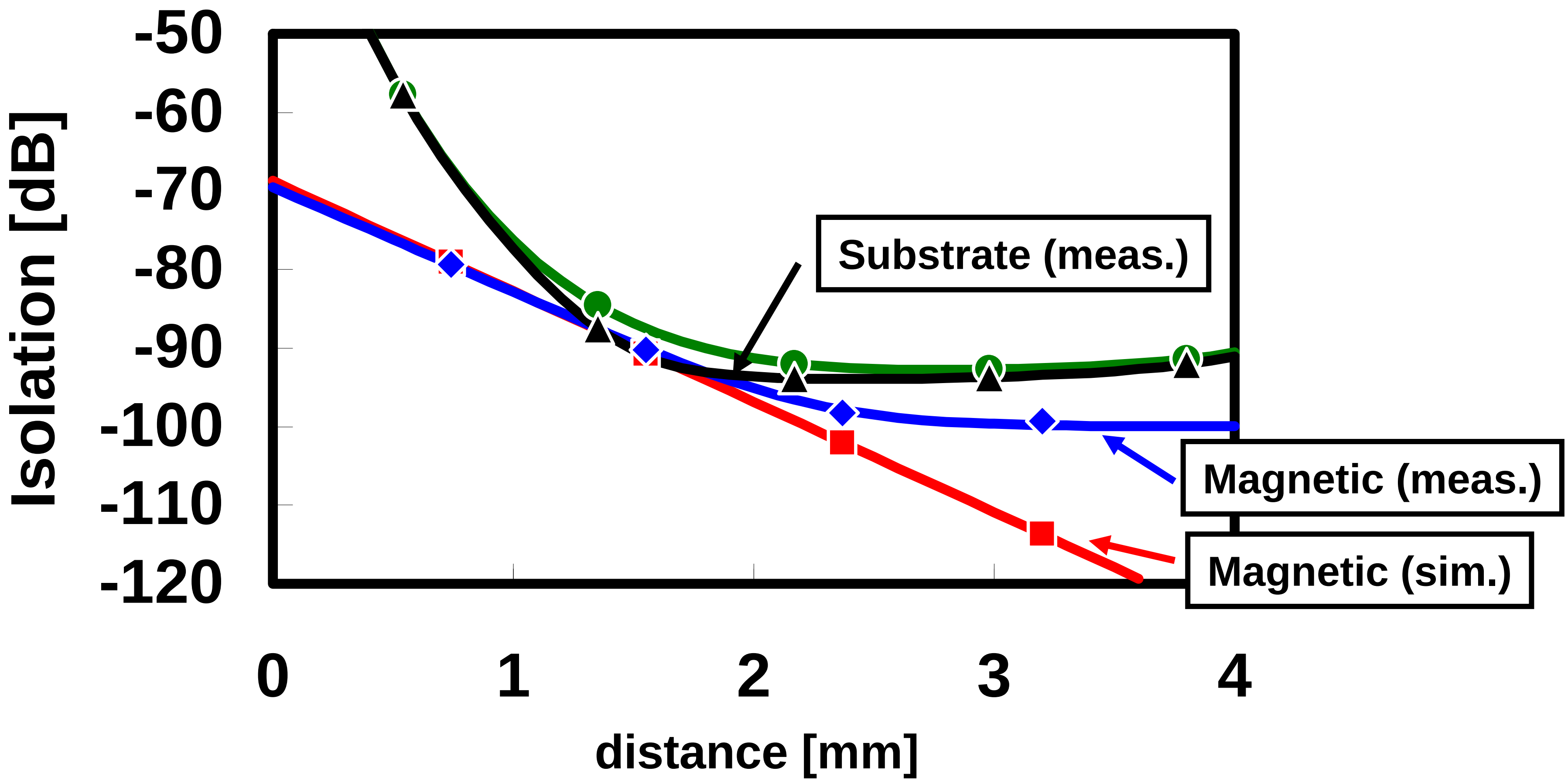
Rx requirements





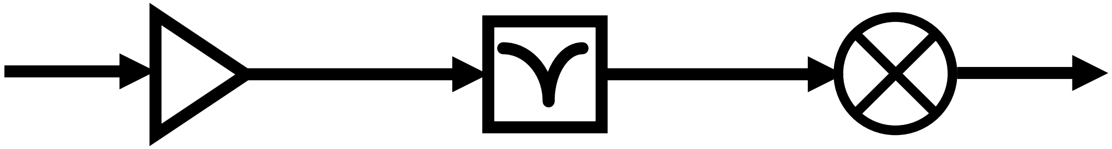
- Linearity is very important for FDD systems like UMTS.
- Tx signal leaks into Rx path, and it becomes a very large interferer.
- Linearity is also very important, especially for concurrent operation of multiple on-chip transceivers.

On-Chip PA-to-LNA isolation



Must consider isolation between on-chip RF blocks for concurrent operation of multiple front-ends

Requirements for SAW-less UMTS Rx



PG=15dB
NF=2.2dB
IIP3=0dBm

-20dB@Tx

PG=10dB
NF=6dB
IIP3=6.1dBm
IIP2=30dBm

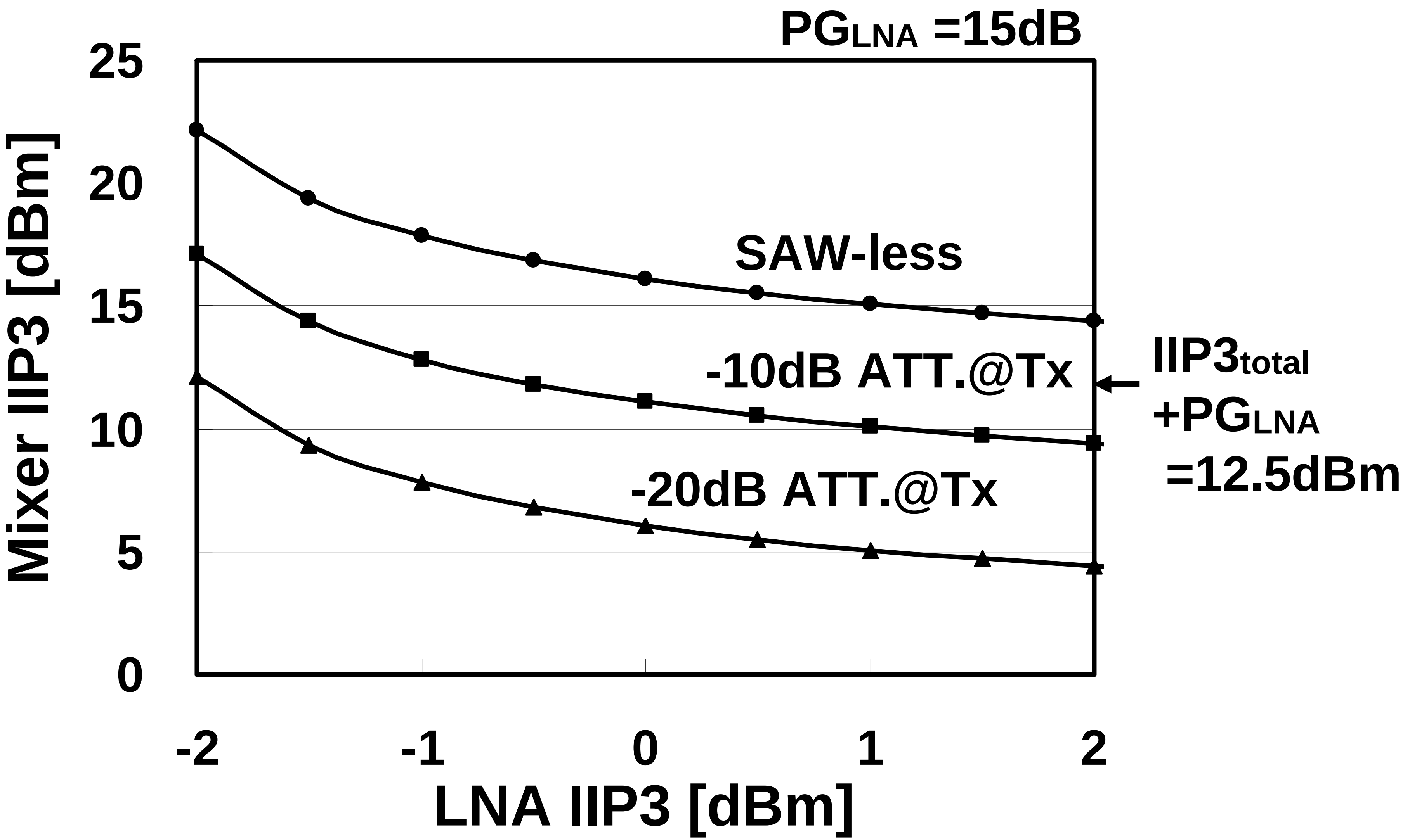
PG=15dB
NF=2.2dB
IIP3=0dBm
for out-of-band

PG=10dB
NF=6dB
IIP3=16.1dBm
IIP2=70dBm
for out-of-band

for both cases
REFSENS=-110dBm
PG=25dB
IIP3=-2.5dBm
IIP2=70dBm
NF=2.5dB (3dB total)
Dup.loss=3dB
with
P_{Tx}=-30dBm
P_{CW_inter}=-40dBm
P_{CW_out}=-60dBm

from Panasonic

Required IIP3 for SAW-less mixer



IIP3 of -2.5dBm is required for the entire Rx chain.

Requirements for multi-standard Rx

Some kind of reconfiguration is required.

On-chip tunable filter is indispensable.

Rx

- **Band width 400MHz-6GHz**
  - **GSM/UMTS/LTE, GPS, WLAN, BT, DTV/FM, etc**
- **Rx NF <2.5dB for Cellular, IIP3 >-2.5dBm for UMTS**
- **Rx NF <2dB for GPS**

LNA

- **IIP3 >0dBm**
- **NF <2.2dB**
- **PG = 15dB**

Mixer (with LNA of PG=15dB, NF=2.2dB, IIP3=0dBm)

- **NF <6dB**
- **IIP3 >16.1dBm without inter-stage filter**
- **IIP2 >70dBm without inter-stage filter**

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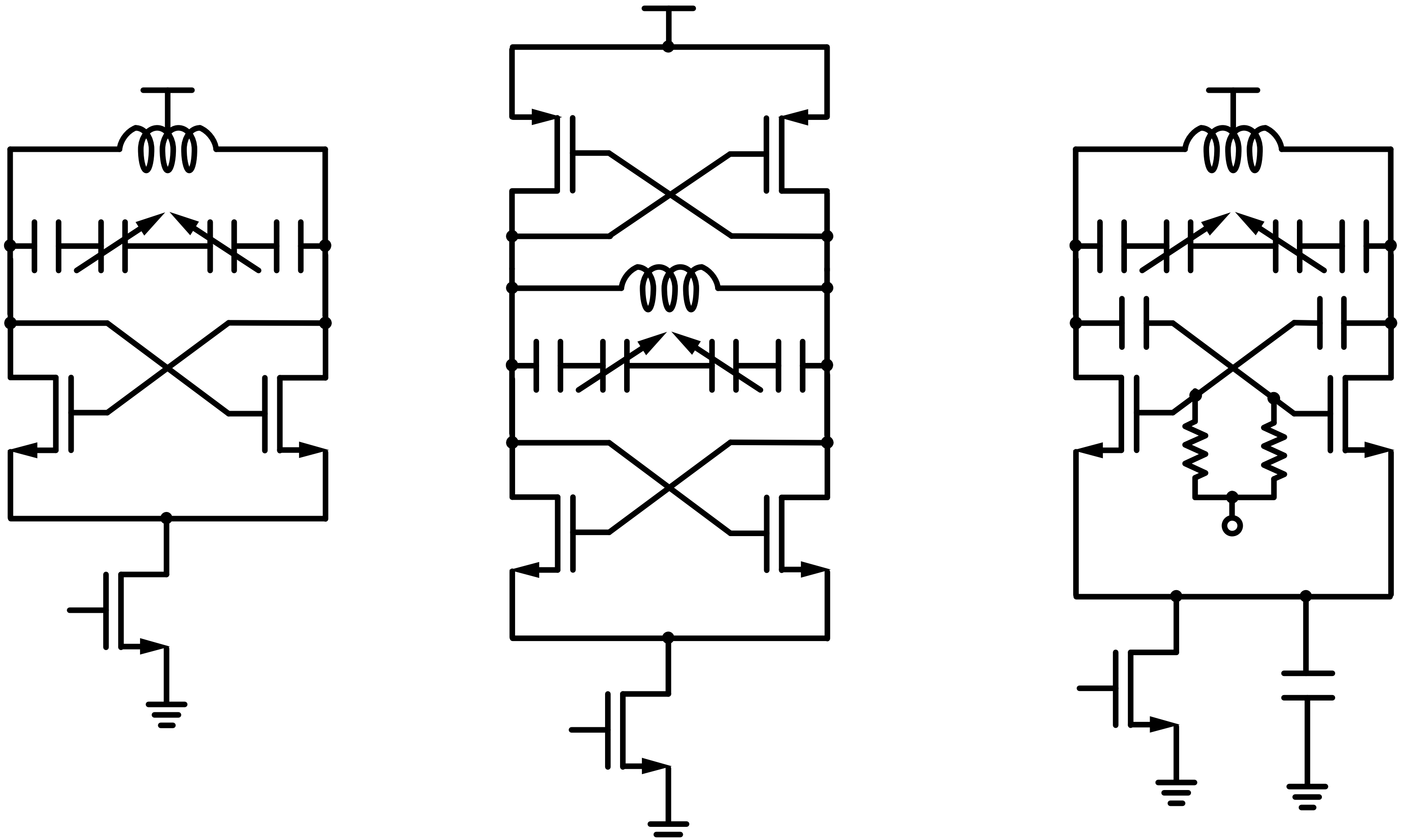
LO requirements

- **10MHz-10GHz continuous tuning**
- **Low phase noise**
  - **GSM850/900 -162dBc/Hz@20MHz-offset**
  - **Q of on-chip inductor < 15**
  - **Supply voltage <1.5V**
- **No spurs**
- **Quadrature outputs with less I/Q mismatch**
- **Low power consumption**
- **Small layout area**
  - **smaller number of on-chip inductors**

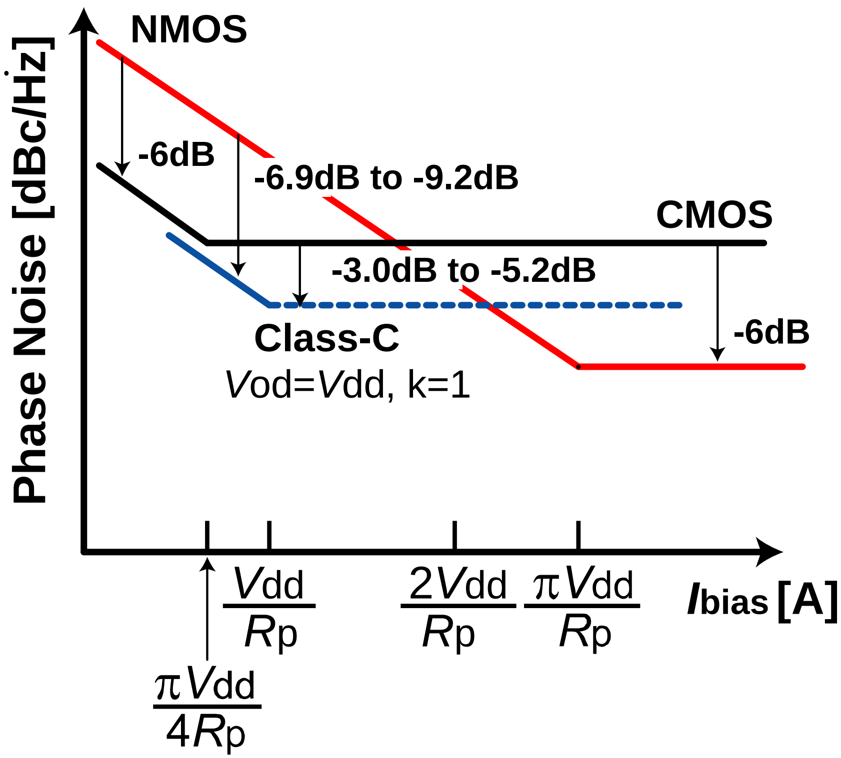
VCO topologies

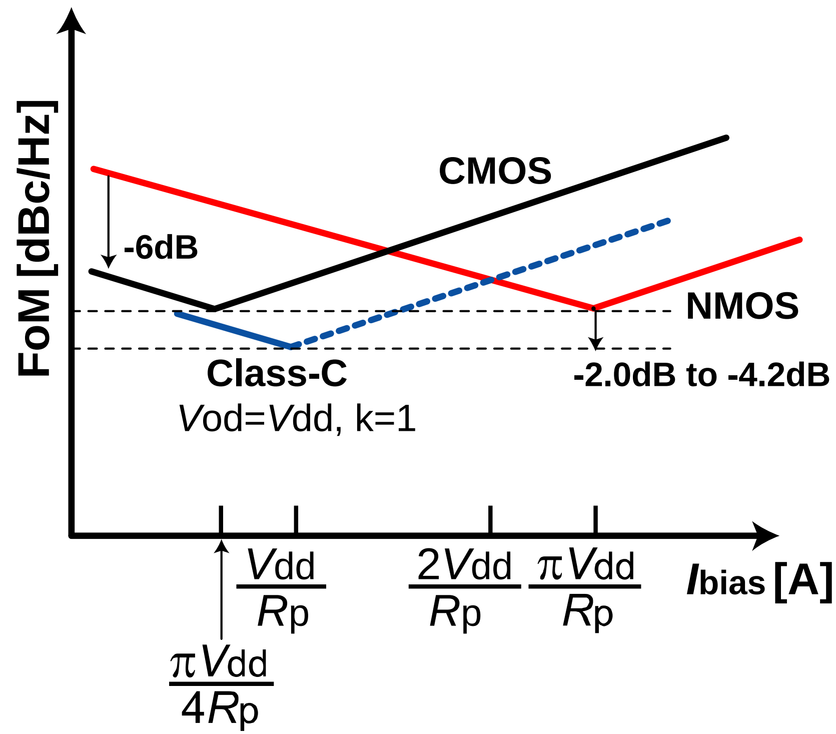


(1) NMOS VCO (2) CMOS VCO (3) Class-C VCO*

***A. Mazzanti and P. Andreani, JSSC 2008**

Theoretical limit of phase noise



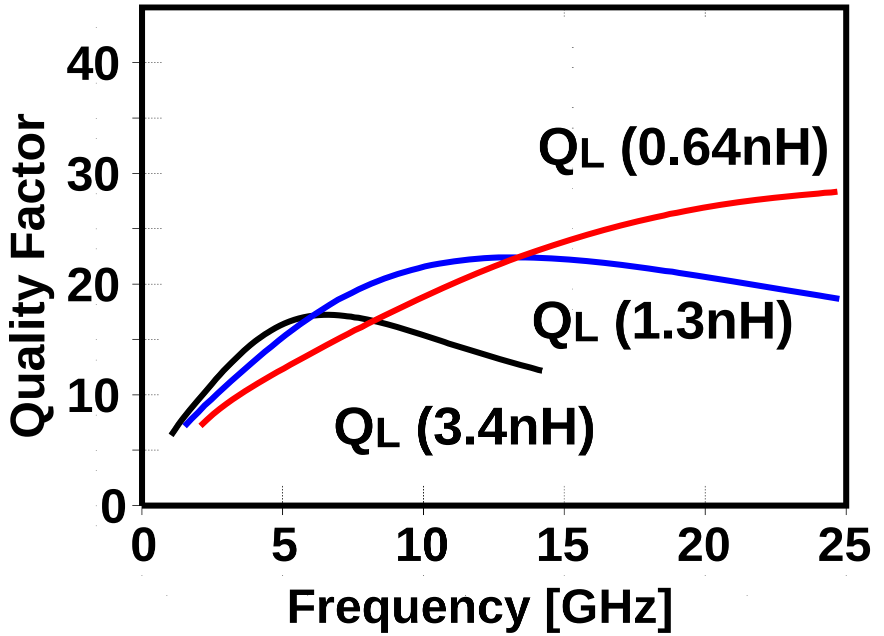


NMOS VCO can realize the lowest phase noise theoretically.

$$PN = 10\log_{10}\left(\frac{\omega^3}{\Delta\omega^2}\frac{L}{Q}\frac{k_B T(1+\gamma_n)}{4V_{DD}{}^2}\right)$$

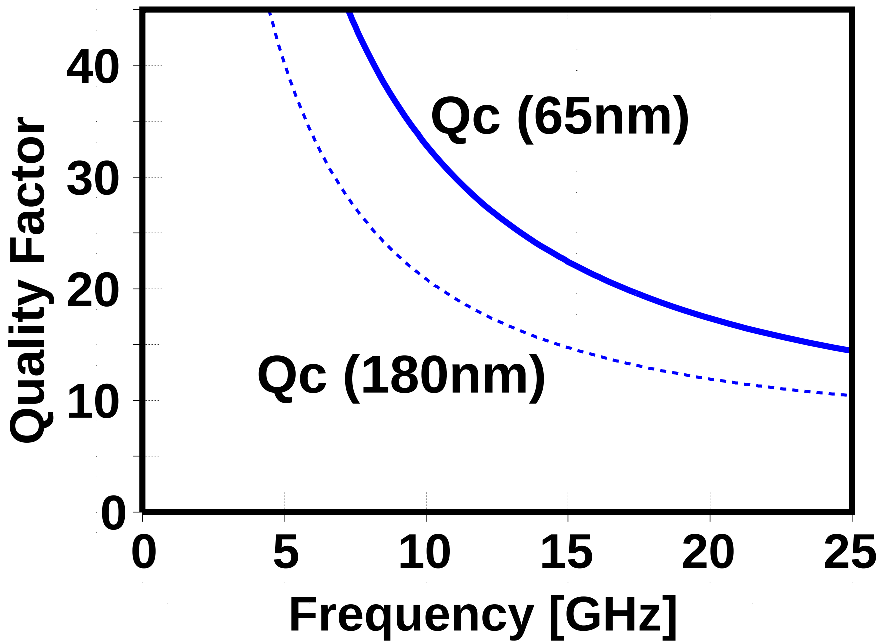
Limited Q-factor

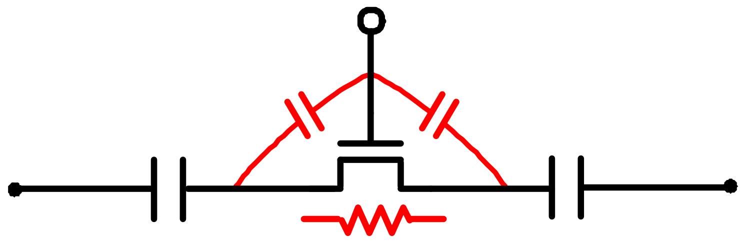
Inductor



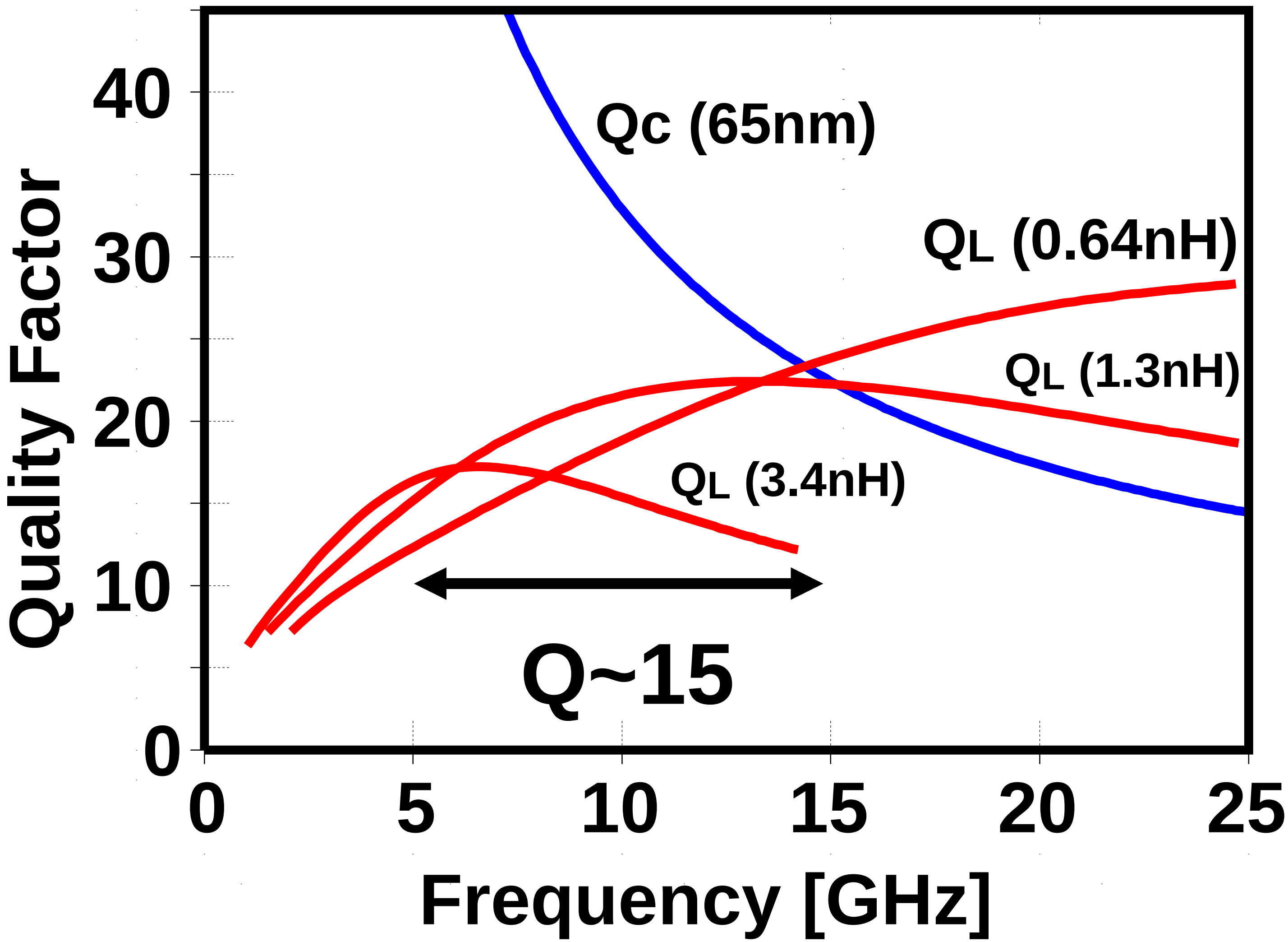
$$Q_L = \frac{\omega}{2}\left|\frac{1}{Z}\frac{\partial Z}{\partial \omega}\right|_{\omega=\omega_0}$$

Switched cap.





Q-factor of LC tank



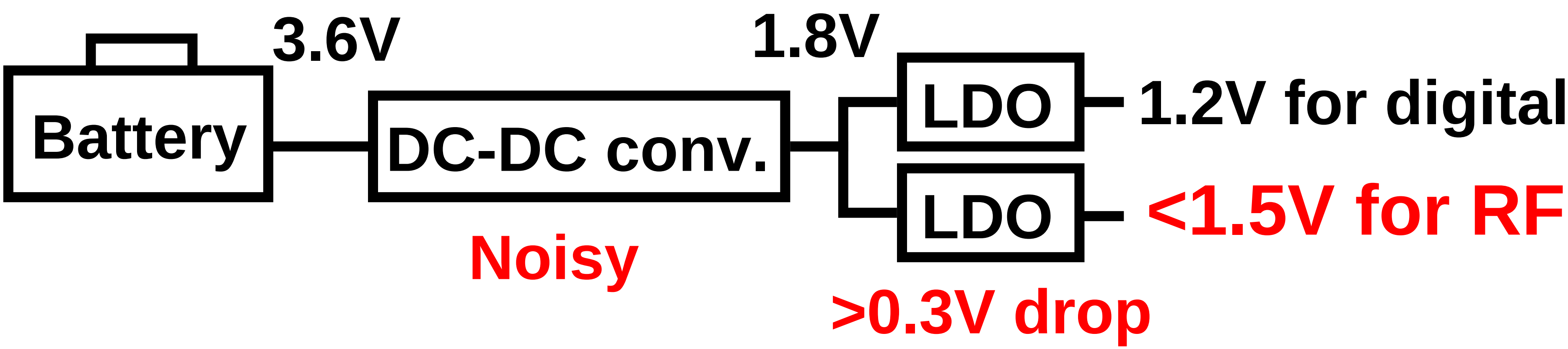
5GHz-to-15GHz is better to obtain a high-Q LC resonator.

Supply voltage issues

- **VCO Phase Noise**
- **LNA Linearity, PA Pout**

$$PN = 10\log_{10}\left(\frac{\omega^3}{\Delta\omega^2}\frac{L}{Q}\frac{k_B T(1+\gamma_n)}{4V_{DD}^2}\right)$$

Power supply for a mobile RFIC



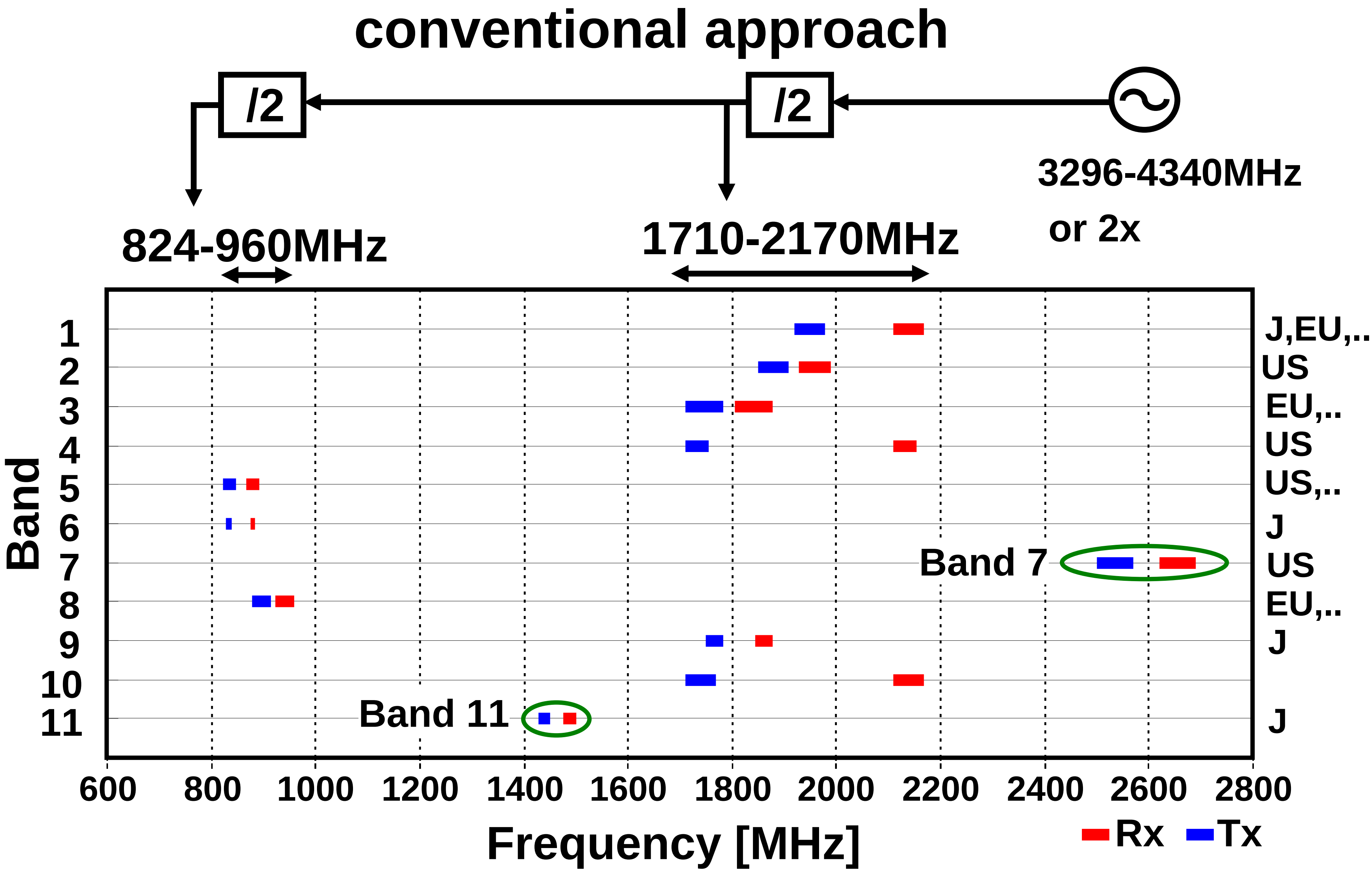
Required supply voltage for GSM

GSM900 Tx LO: -165dBc/Hz@20MHz-offset

Q_{tank}	V_{DD} [V]	Ideal PN [dBc/Hz] +5dB @0.9GHz	Required I_{bias} [mA]	P_{dc} [mW]
Q=9 (L=3.4nH) @3.6GHz	1.2	-162	7.8	14.1+α
	1.5	-164	7.8	14.1+α
Q=12 (L=1.3nH) @7.2GHz	1.2	-164	5.8	10.5+α
	1.5	-166	5.8	10.5+α
Q=30 (ext.) (L=1.3nH) @7.2GHz	1.2	-168	1.5	2.7+α
	1.5	-170	1.5	2.7+α

VCO cannot reach with low digital V_{DD}.

LO generation for GSM/UMTS/LTE



Requirements for multi-standard LO

- Satisfy all existing/possible wireless standards
- 10MHz-6GHz continuous tuning with 1 inductor
- Fine tuning and fast settling for cognitive radios
- Low phase noise (GSM850/900)
- No spurs for wideband RF signal
- Quadrature outputs with less I/Q mismatch
- Low power consumption <10mW

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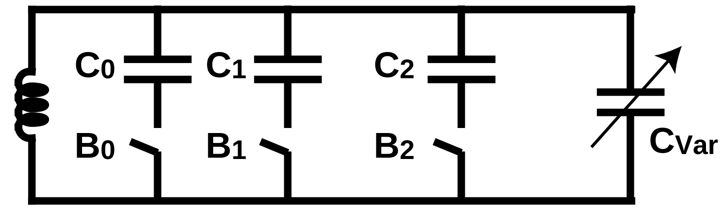
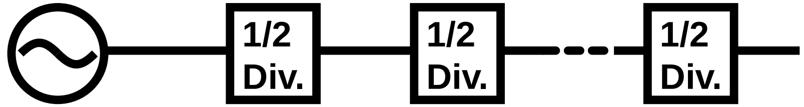
Previous work for multi-band VCO

- **Switched-Capacitor Resonator**



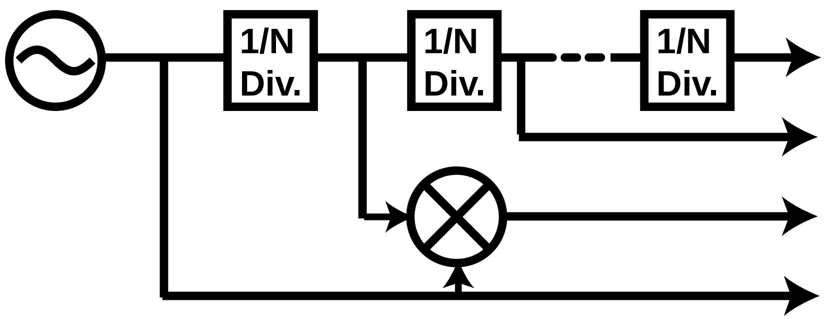
  + Reduced K_{VCO}
  - Q_L is degraded at edge of tuning range
  - Limited C_{max}/C_{min} (parasitic capacitance limited)

- **1/2 Divider**



  + Continuous wide tuning range
  - Wide tuning range requirement for VCO
  - Poor phase noise

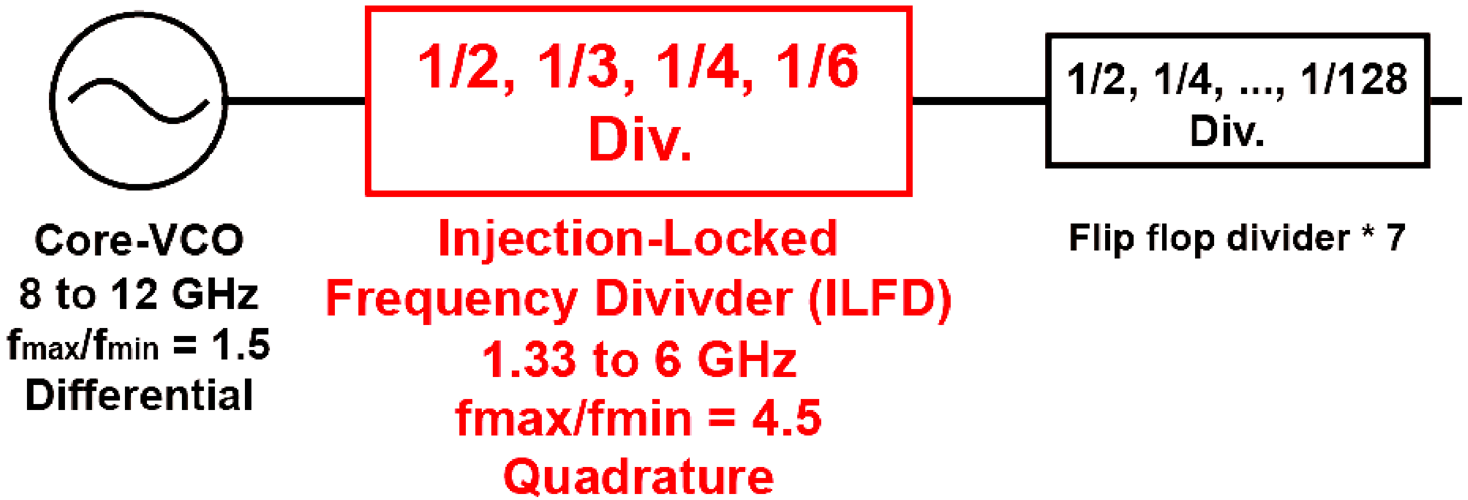
- **Dividers, Mixers**



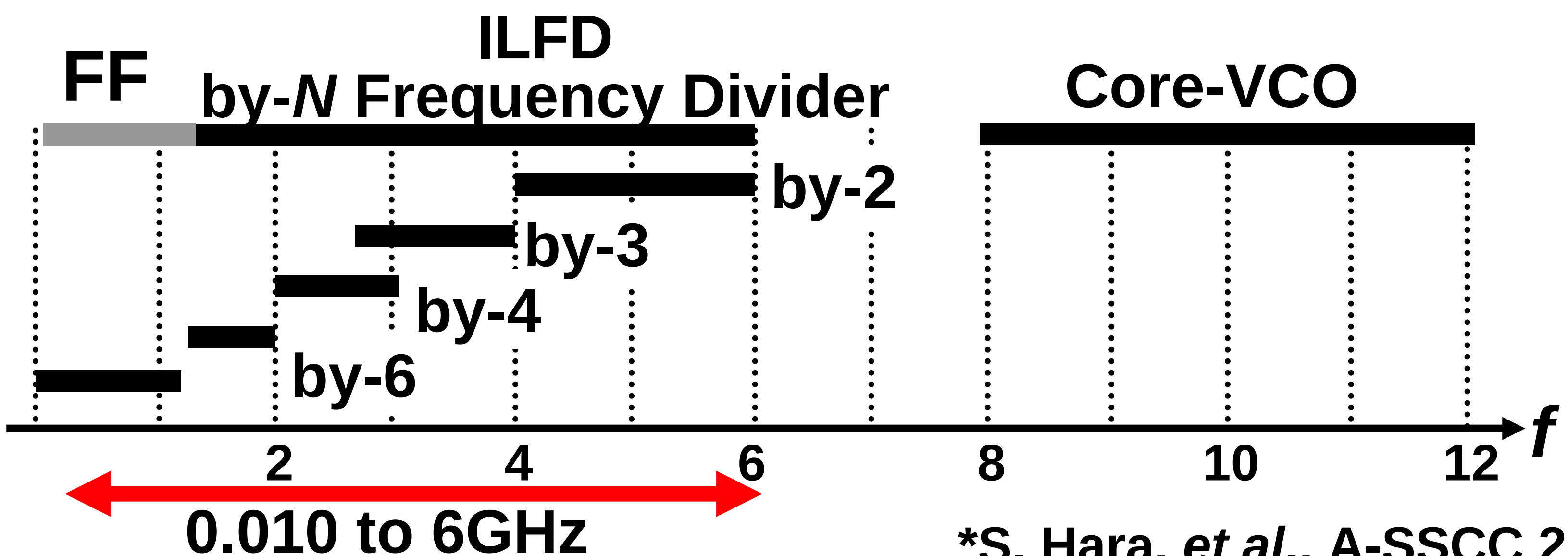
  + Small area
  - Large power consumption
  - Spurious tones

*Z. Safarian, *et al., CICC*, Sep. 2008.

Proposed wideband VCO

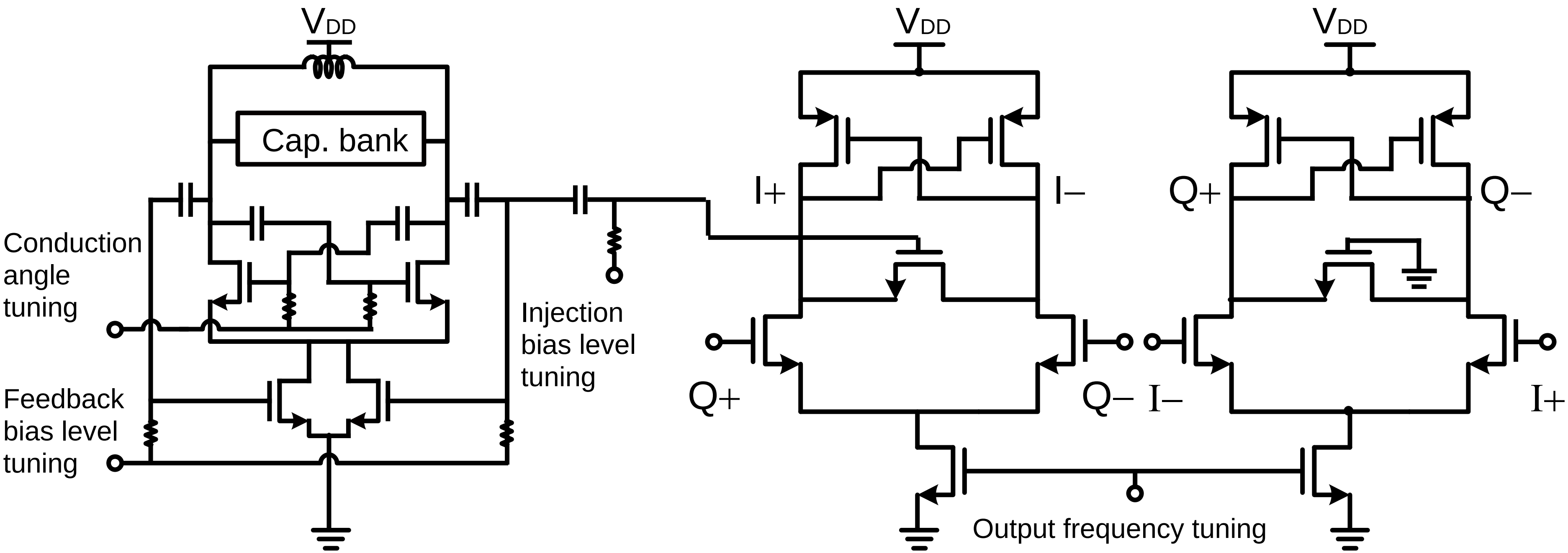


Narrow required tuning range, No spur, Quadrature output



*S. Hara, *et al*., A-SSCC 2009

Circuit schematics

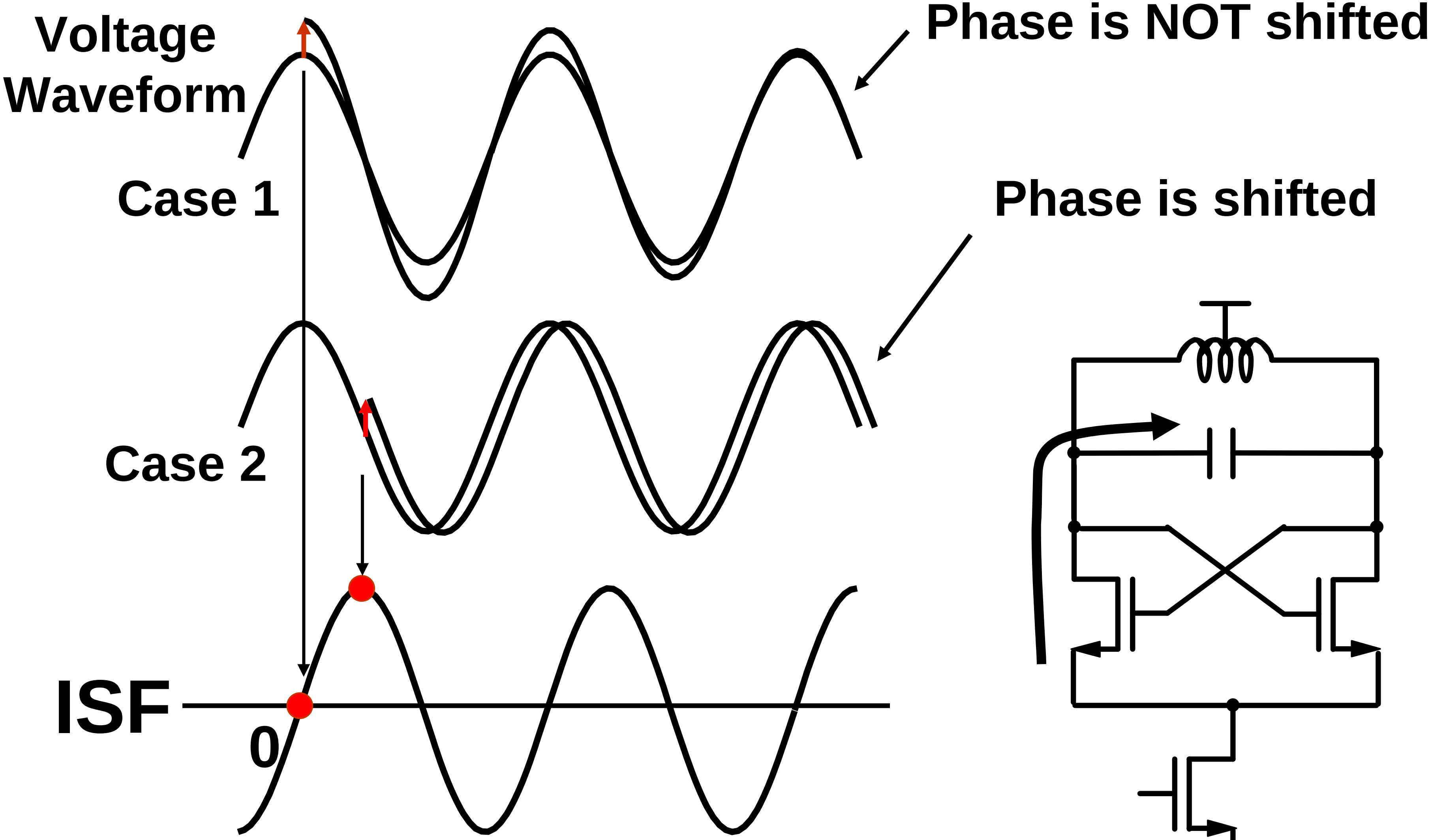


Core VCO

Injection locked frequency divider

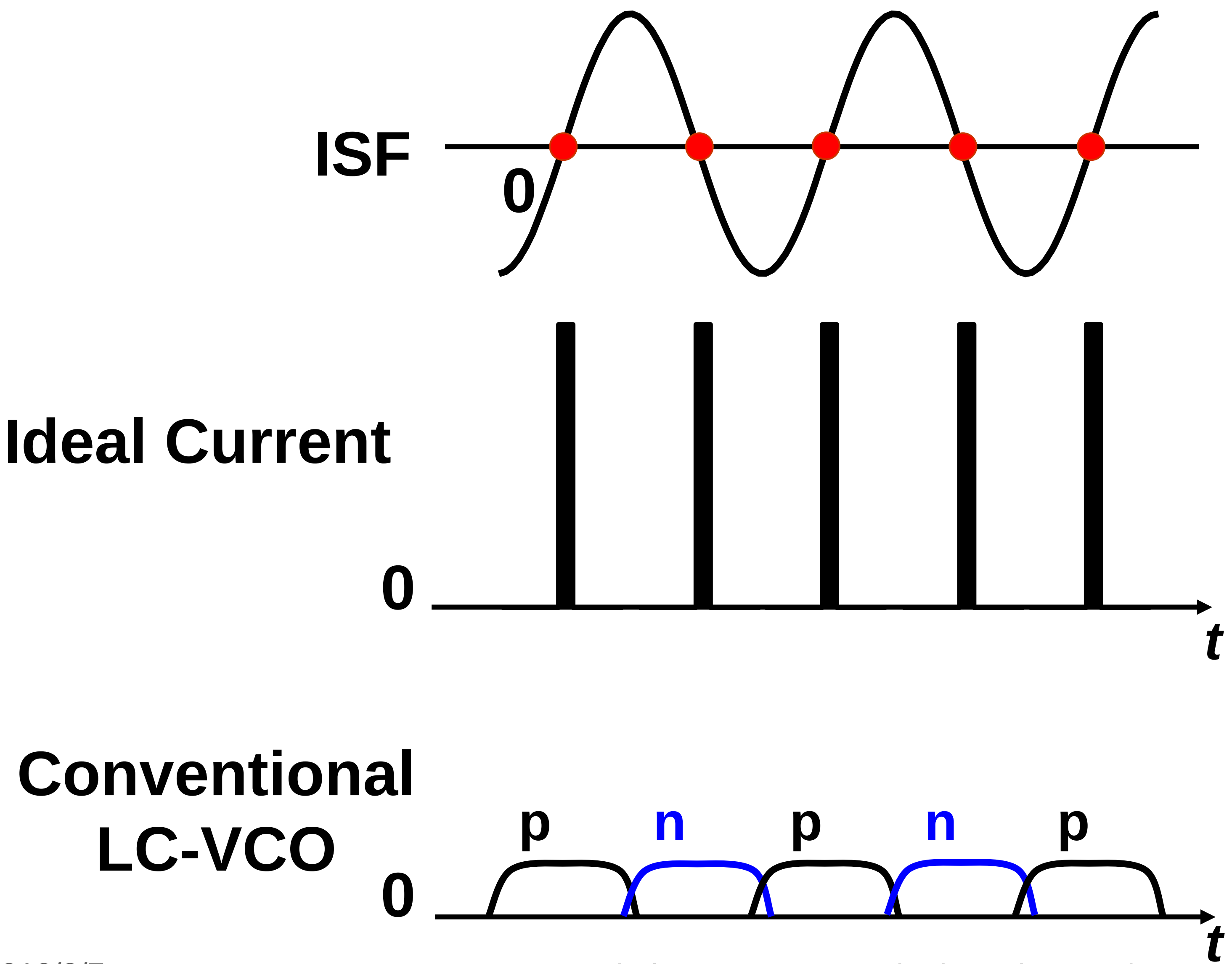
- **ILFD generates 1.33 to 6.0 GHz output.**
- **Lower frequency (under 1.33GHz) can be obtained by using FF dividers.**

Impulse Sensitivity Function (ISF*)

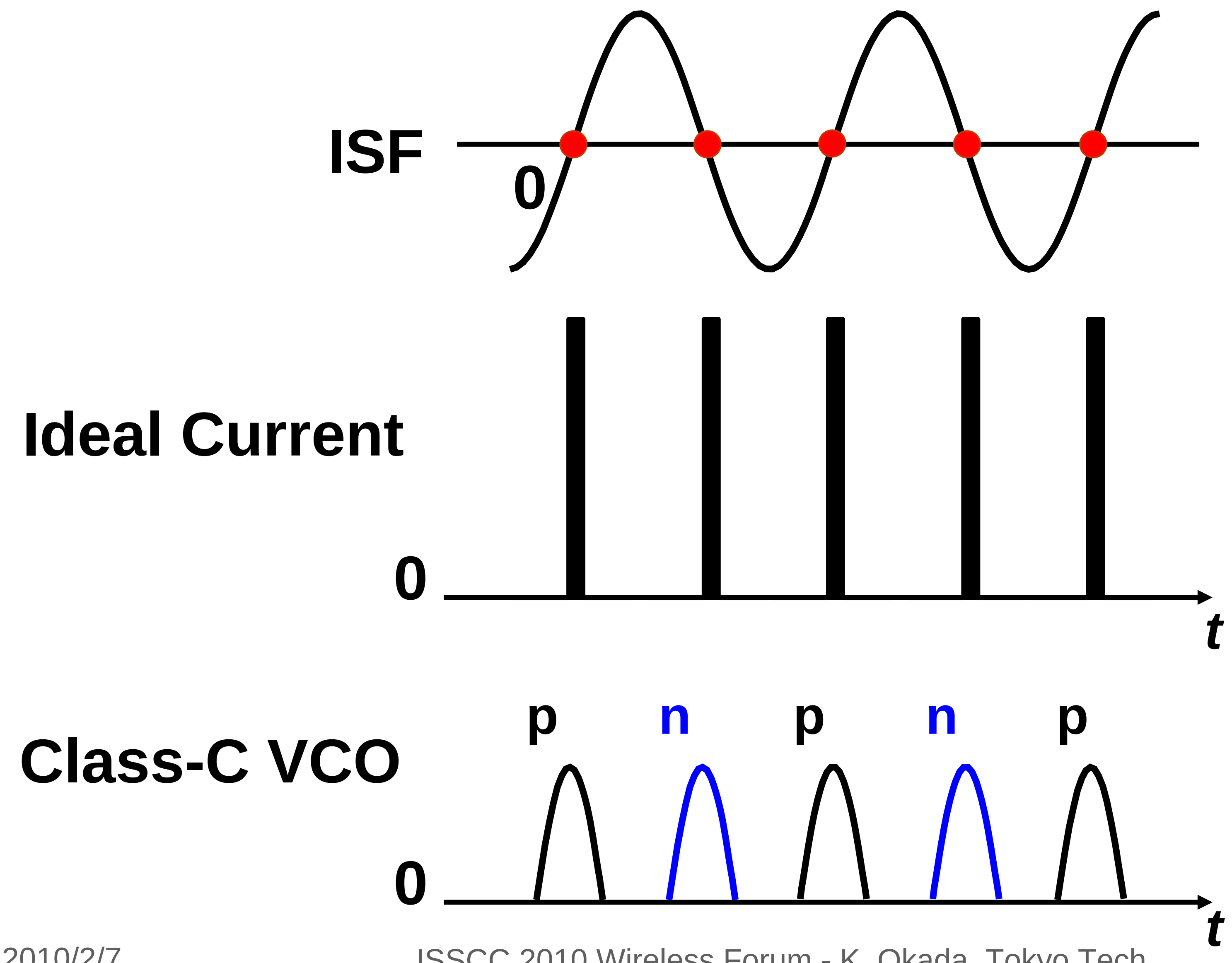


*A.Hajimiri, and T.Lee, JSSC 1998

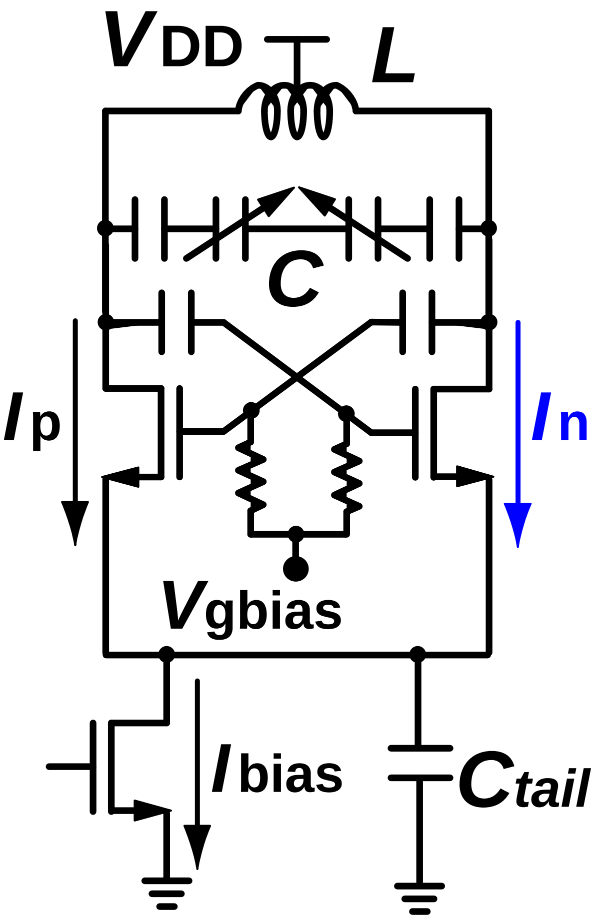
Ideal Current Conduction

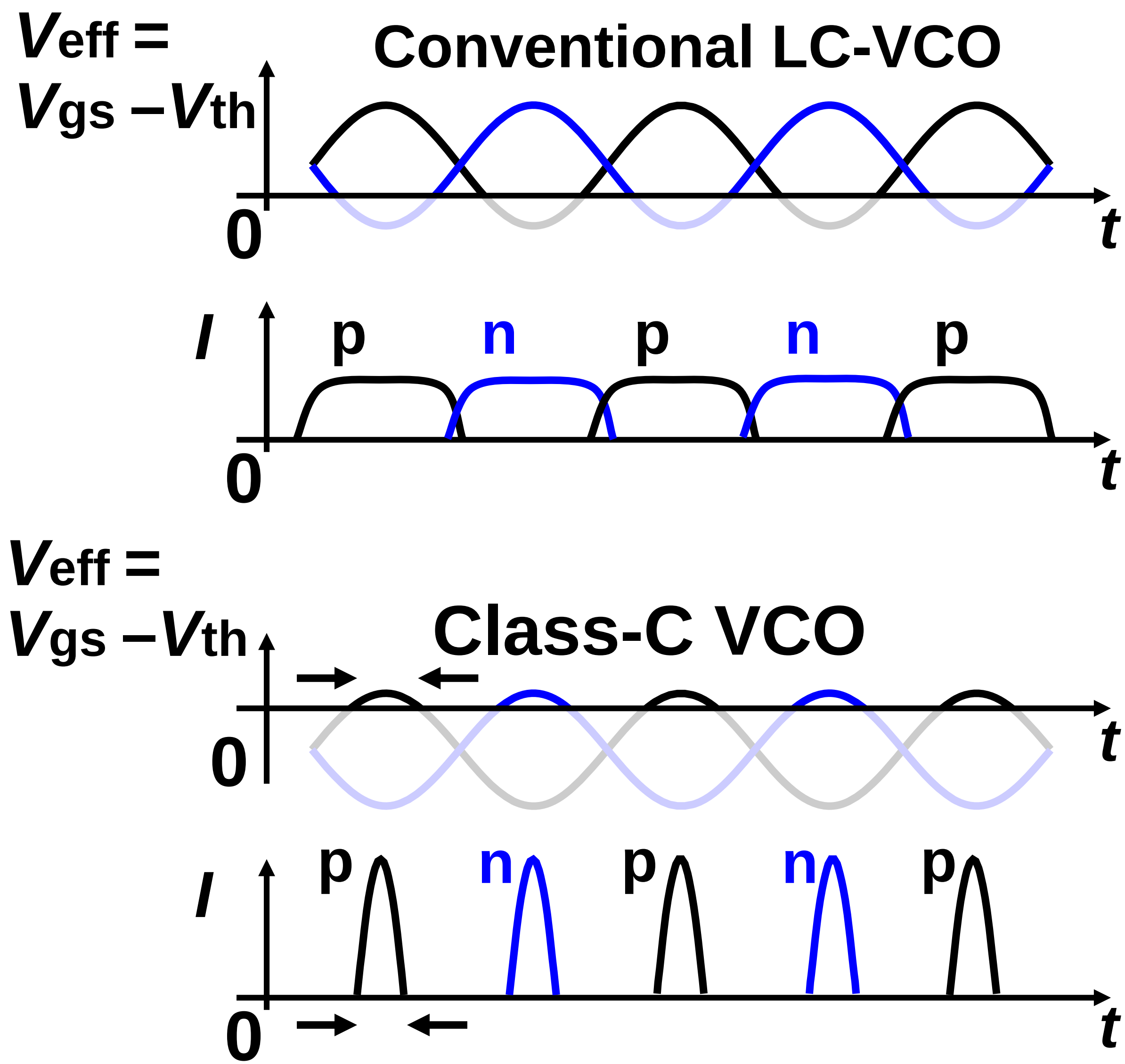


Current conduction of class-C VCOs



Class-C VCO





*A. Mazzanti, *et al*., JSSC 2008

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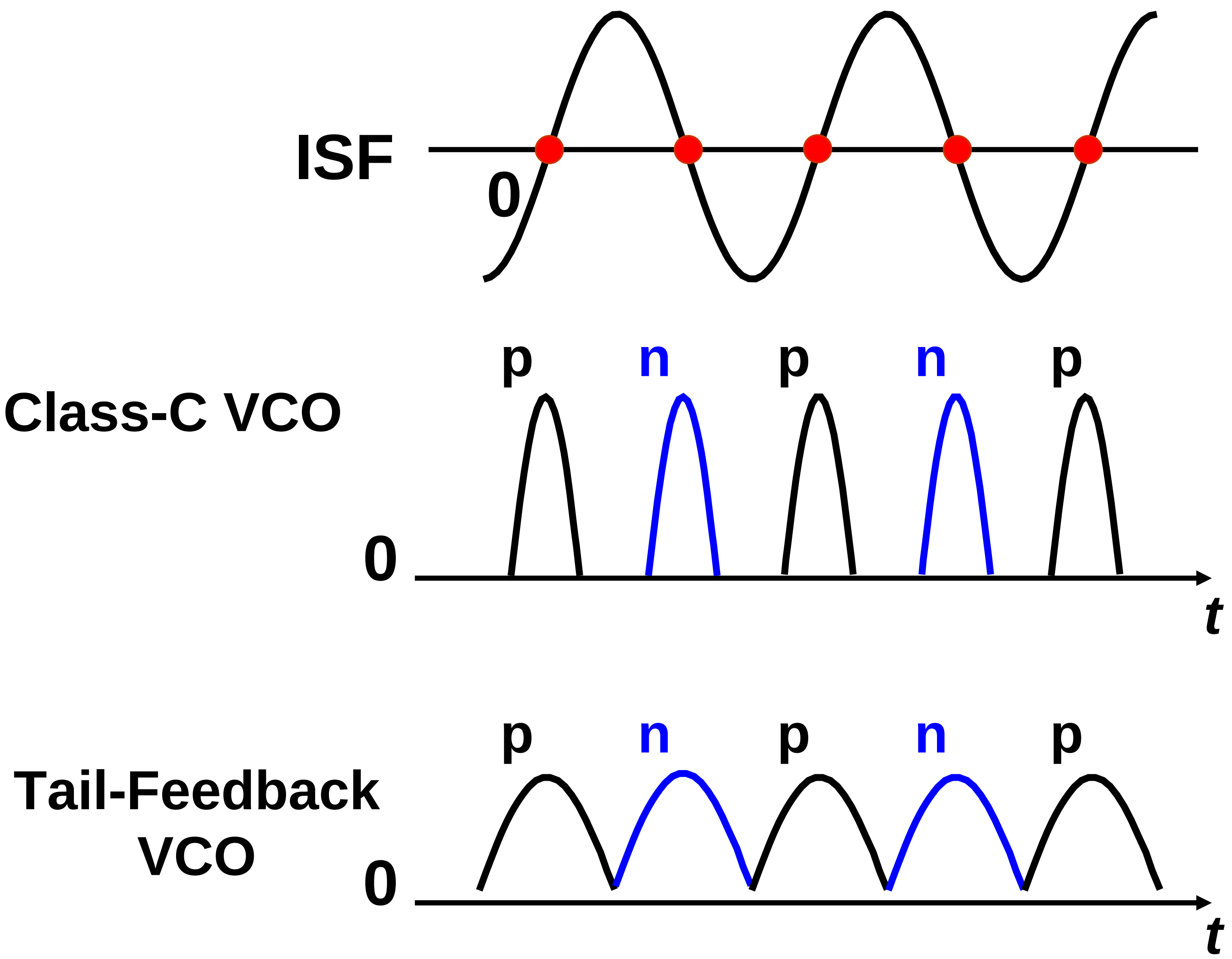
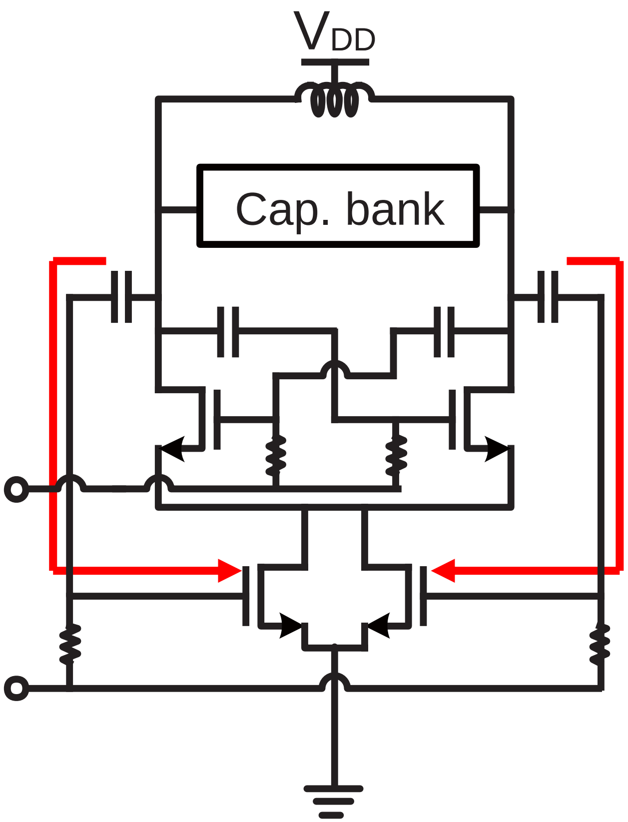
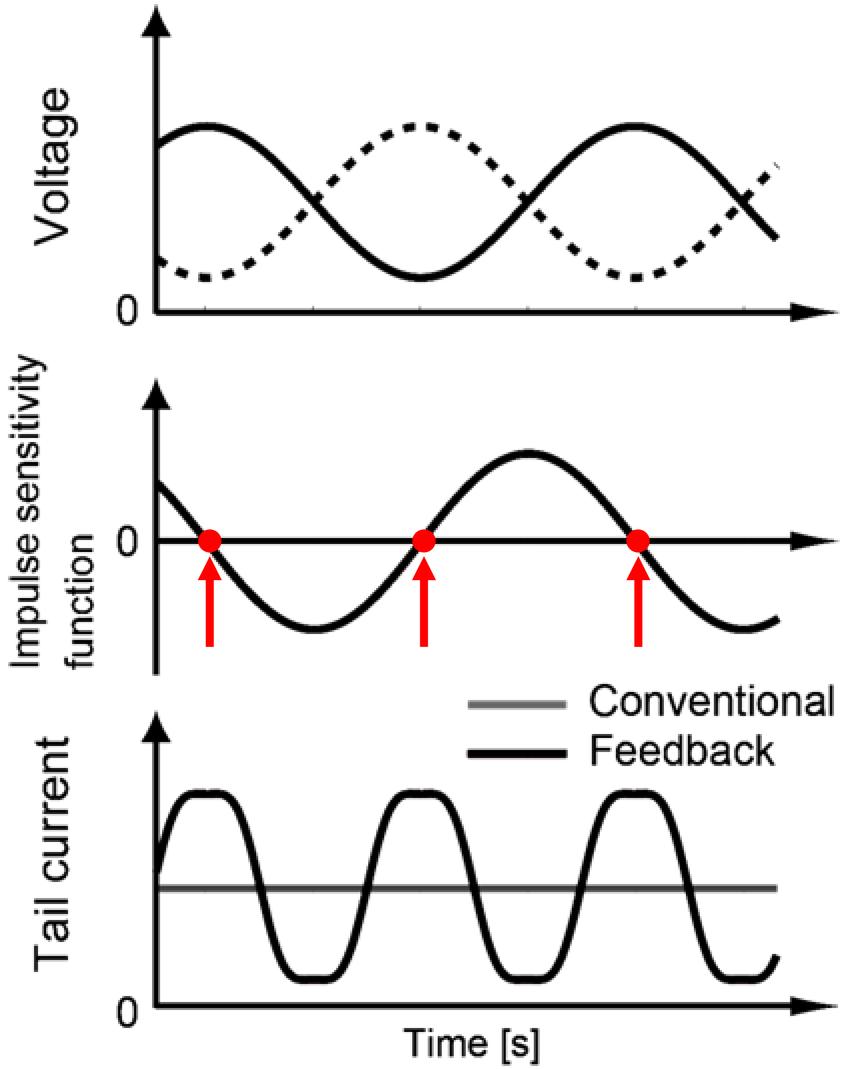


Tail-feedback VCO



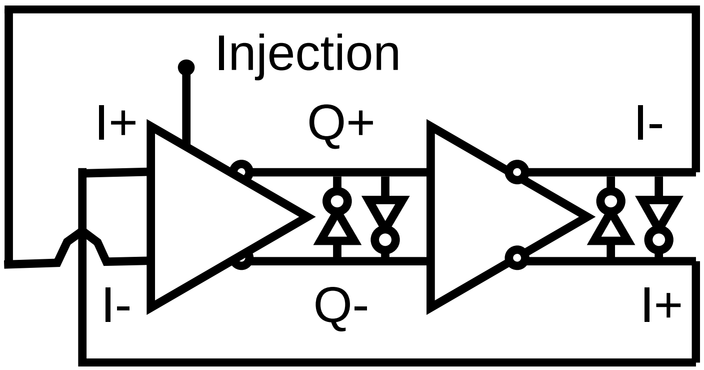


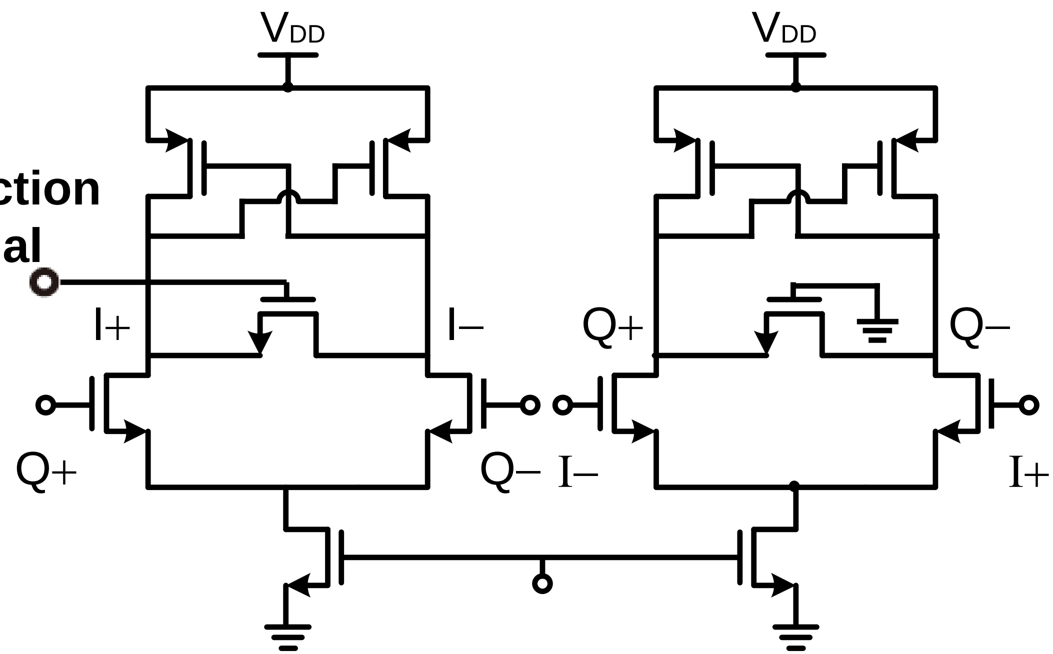
Tail feedback

3.5dB phase noise improvement

- **Tuning range : 8.0 to 12.0 GHz**

Injection Locked Frequency Divider



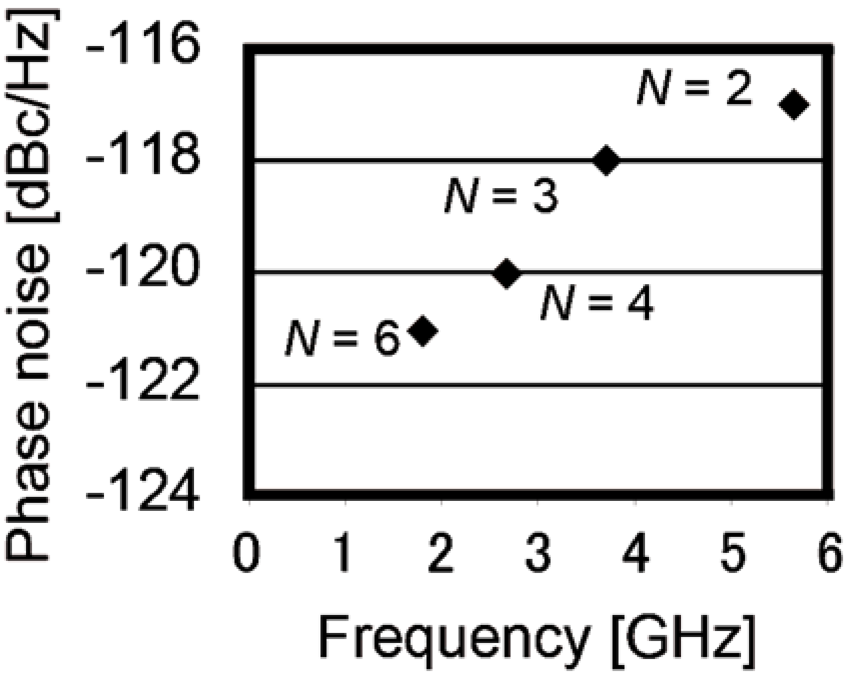


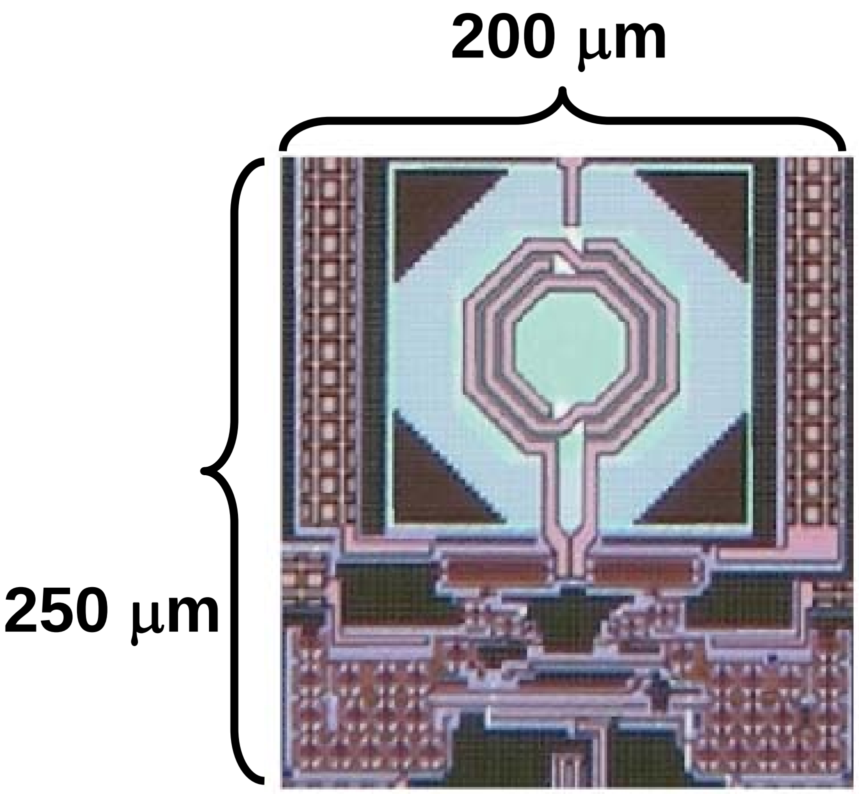
2-stage differential ILFD is utilized.

Tuning range : 1.3 to 6.0 GHz

Merit: Quadrature output, No Spur,
Wide frequency range

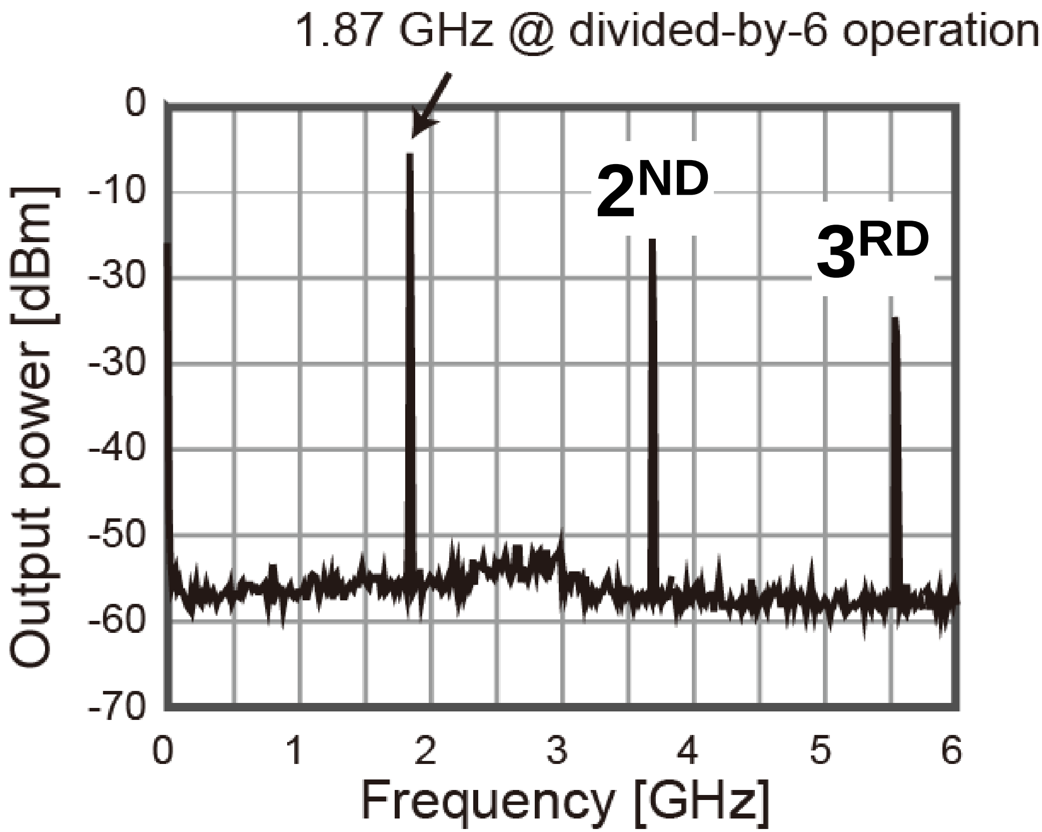
Measurement Result





Fabricated by 90 nm CMOS Process

Output spectrum



Even harmonics can be canceled by differential config.

Odd harmonics can be canceled by harmonic-rejection mixer.

VCO performance

Technology	Standard 90nm CMOS
Supply voltage	1.2 V
Power consumption of VCO core	4.8 - 10.2 mW
Power consumption of ILFD	1.0 - 1.3 mW
Power consumption of FF dividers	- 0.1 mW
Total power consumption	5.9 - 11.2 mW
Tuning range	9.3 MHz - 5.7 GHz
Chip area	250 μm x 200 μm

VCO measurement summary

	This work*	VLSI 2009**	RFIC 2009***
Architecture	VCO with ILFD	QVCO with mixer and dividers	2VCOs and dividers
Divide ratio	2,3,4,6…	2,3,4,5, 6,8,10	2,4,8,16,32…
Tuning range of core LC-VCO	±20 %	±20 %	±33.3 % (total)
Output freq.	0.009 - 5.7 GHz	1 - 10 GHz	0.1 - 5.0 GHz
Power cons.	5.9 - 11.2 mW	31 mW	19.8 mW
FoMT	-210 dBc/Hz	-194 dBc/Hz	-209 dBc/Hz
Area	0.05 mm^2	0.29 mm^2	0.22 mm^2

*S. Hara, *et al*., A-SSCC, Nov. 2009

**B. Razavi, *VLSI Circuits*, June 2009.

***P. Nuzzo, *et al*., RFIC, June 2009.

Summary and Conclusion

- **A differential LC-VCO and injection locked frequency divider are utilized instead of a QVCO and SSBMs to reduce spurious, layout area, and power consumption.**
- **The proposed wideband VCO can achieve wide tuning range with the best FoM_T.**

FTR=199% (9.3MH-5.7GHz)

FOM_T=-210dBc/Hz

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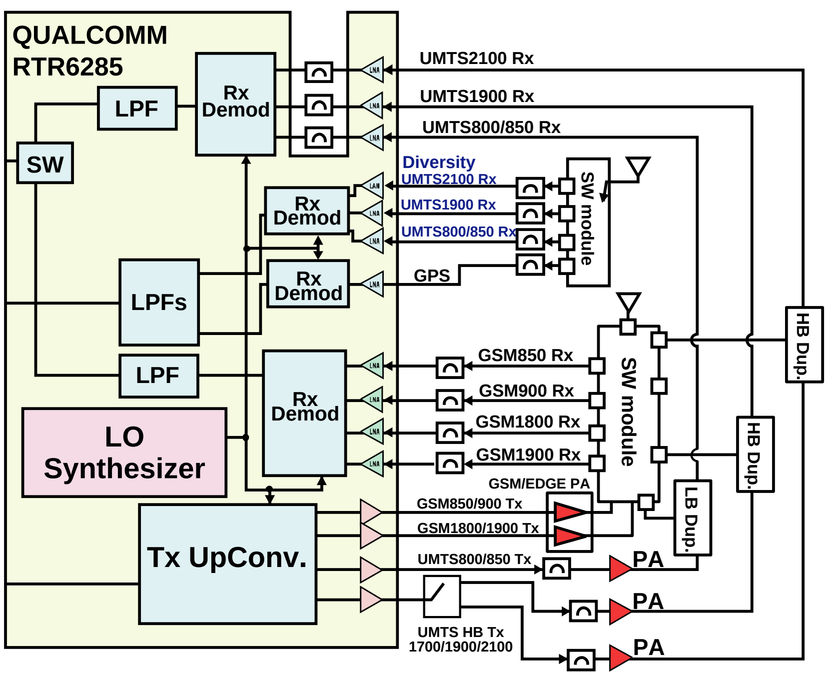
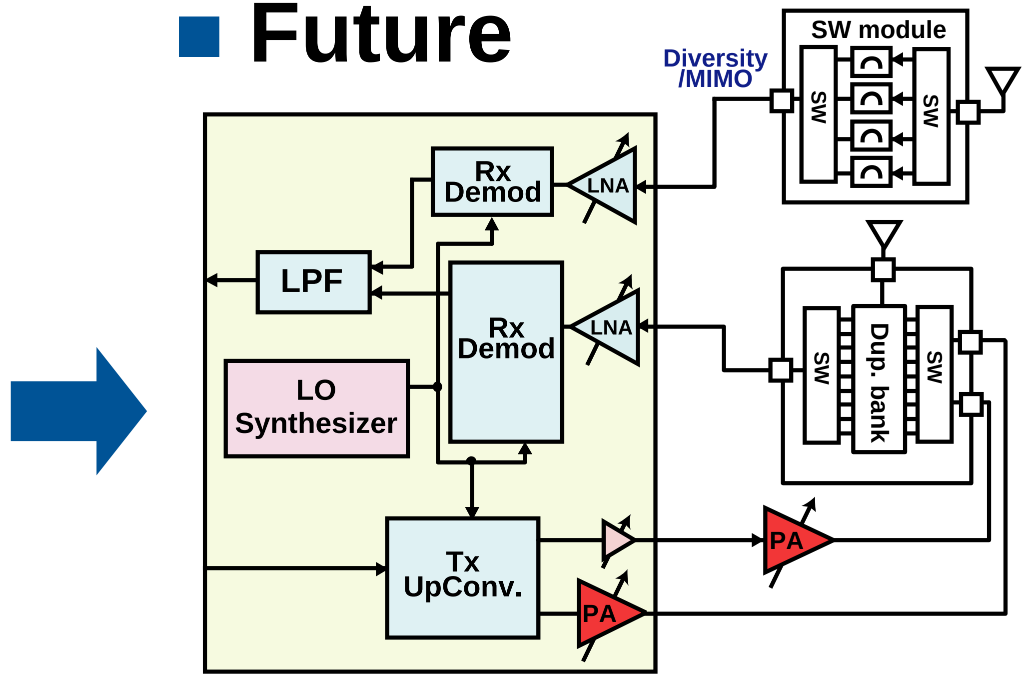
Tx requirements

- On/off-chip tunable/switchable multi-standard PA
- Must keep the same Pout/PAE with smaller total footprint size and less number of components

■ Present



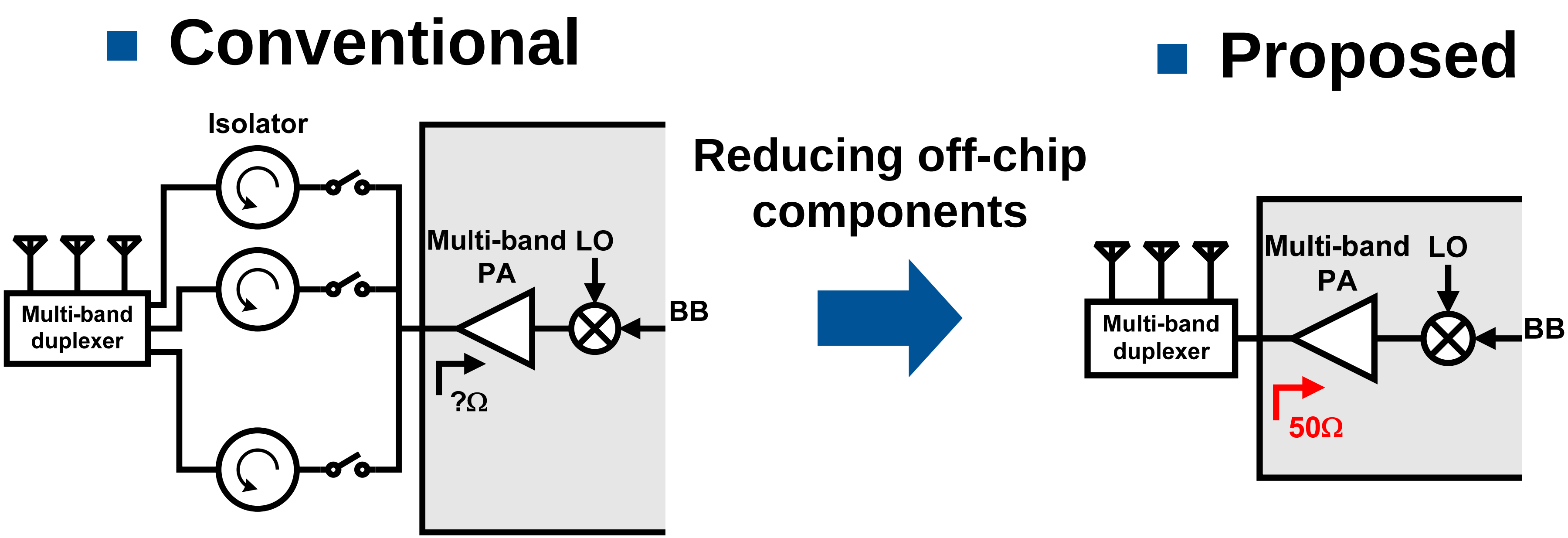
■ Future



tunable/switchable

Challenge of tunable CMOS PA

- Tunable CMOS PA with tunable impedance matching to reduce external components
  - isolators
    - -Reduce reflection due to impedance mismatch
    - -Protect PAs from reflected wave



Output impedance tuning 1

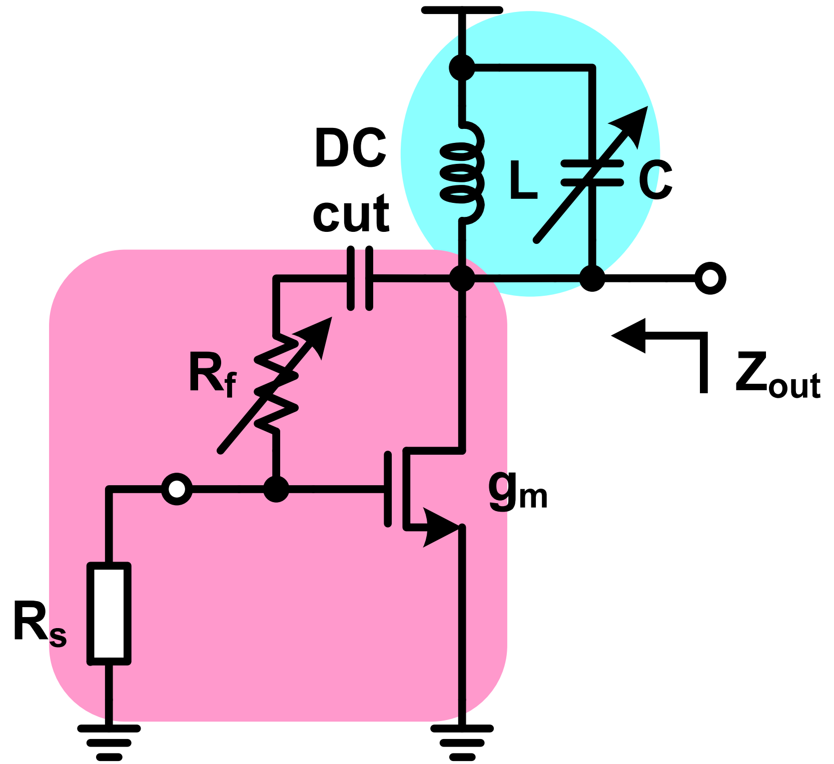
If $r_{ds}=\infty$,

$$Z_{out}=\frac{R_f+R_s}{g_mR_s+1}//\frac{1}{j\omega C}//(R_L+j\omega L)$$

When $f=\frac{1}{2\pi\sqrt{LC}}$

(Resonance frequency)

$$Z_{out}=\frac{R_f+R_s}{g_mR_s+1}//\frac{L}{CR_L}$$



R_s : source impedance (50Ω)

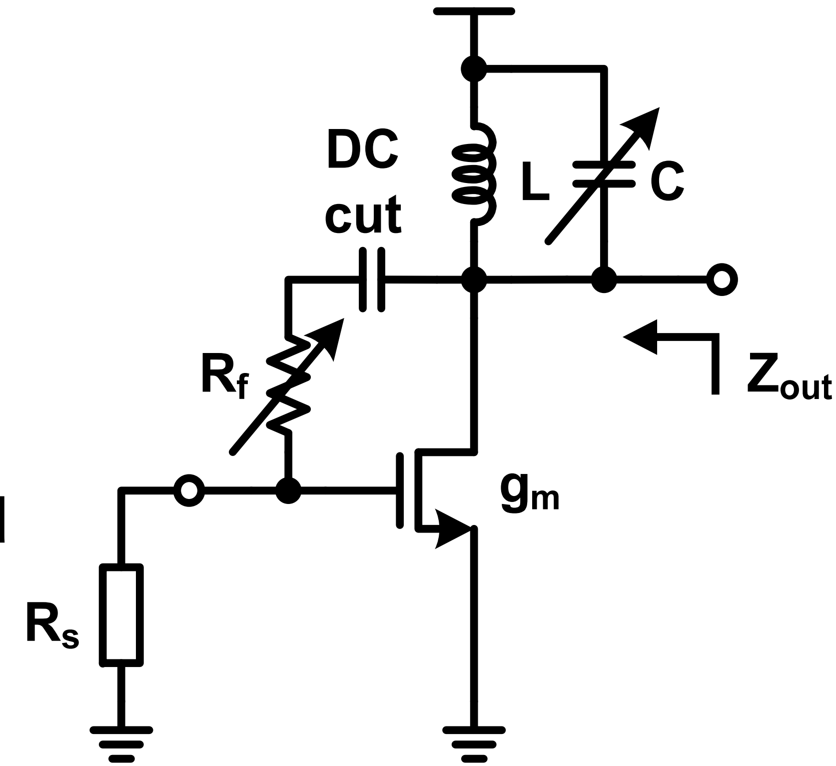
R_L : inductor parasitic resistance

Tune C to cancel imaginary part of Z_{out} at arbitrary frequency

Output impedance tuning 2

$$Z_{out} = \frac{R_f + R_s}{g_m R_s + 1} \,//\, \frac{L}{CR_L}$$

- **Tune R_f to match Z_{out} to 50Ω**
- **Z_{out} depends on the value of C, so R_f needs to be adjusted according to the matching frequency**

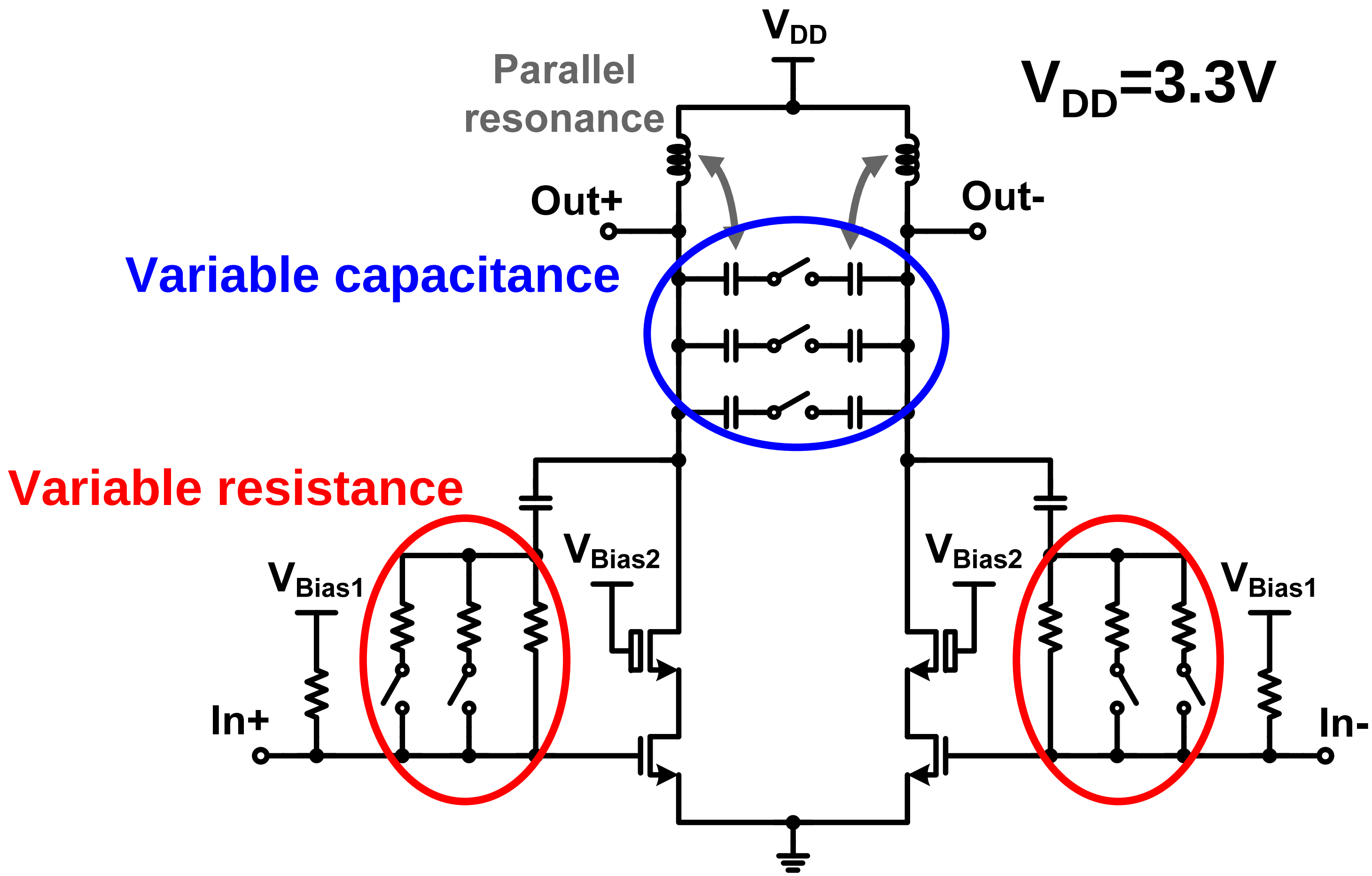


R_s : source impedance (50Ω)

R_L : inductor parasitic resistance

Cascoded thick-oxide transistors are utilized because of larger r_{ds} and voltage-stress robustness.

Schematic of the proposed PA

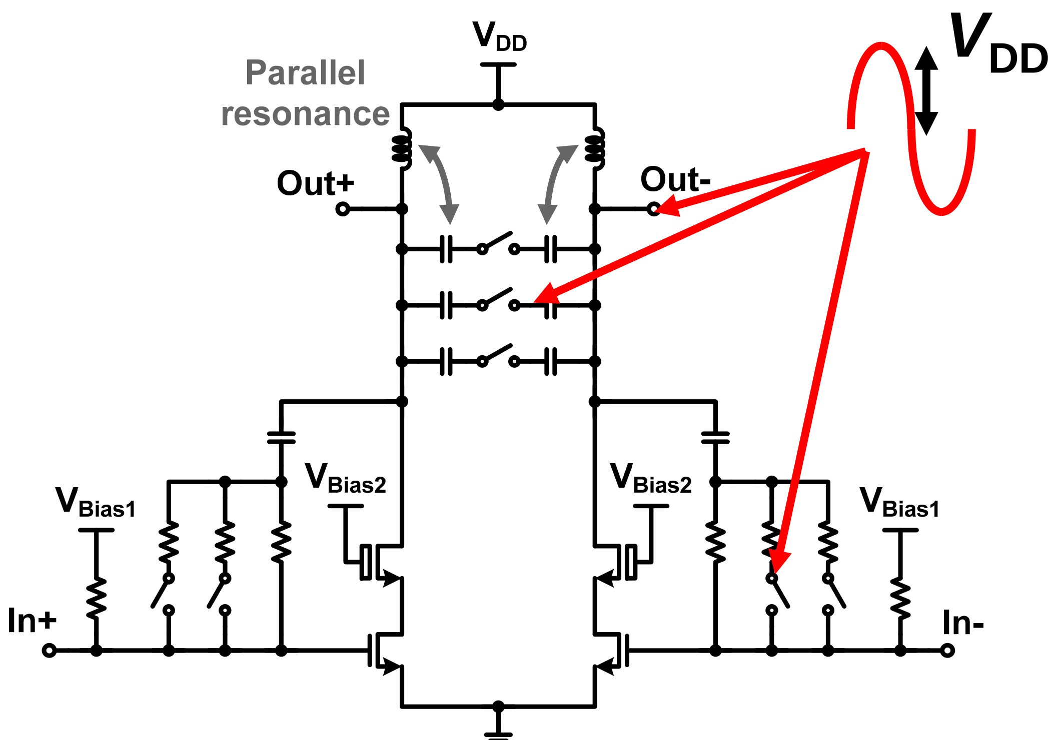


- Change output matching band by switching C and R
- Differential topology for 3dB larger P_{sat}

Voltage stress of switches

- Maximum voltage swing at output node is about V_{DD}=3.3V
- The same voltage is applied to switches when they are off

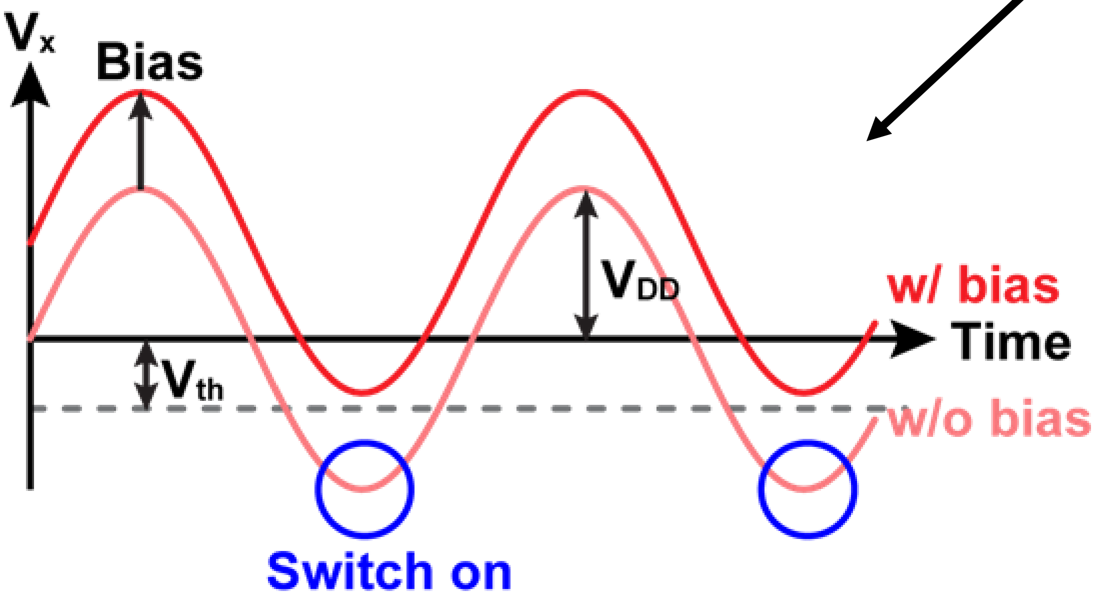
➡ **Thick oxide nMOS is applied as a switch**

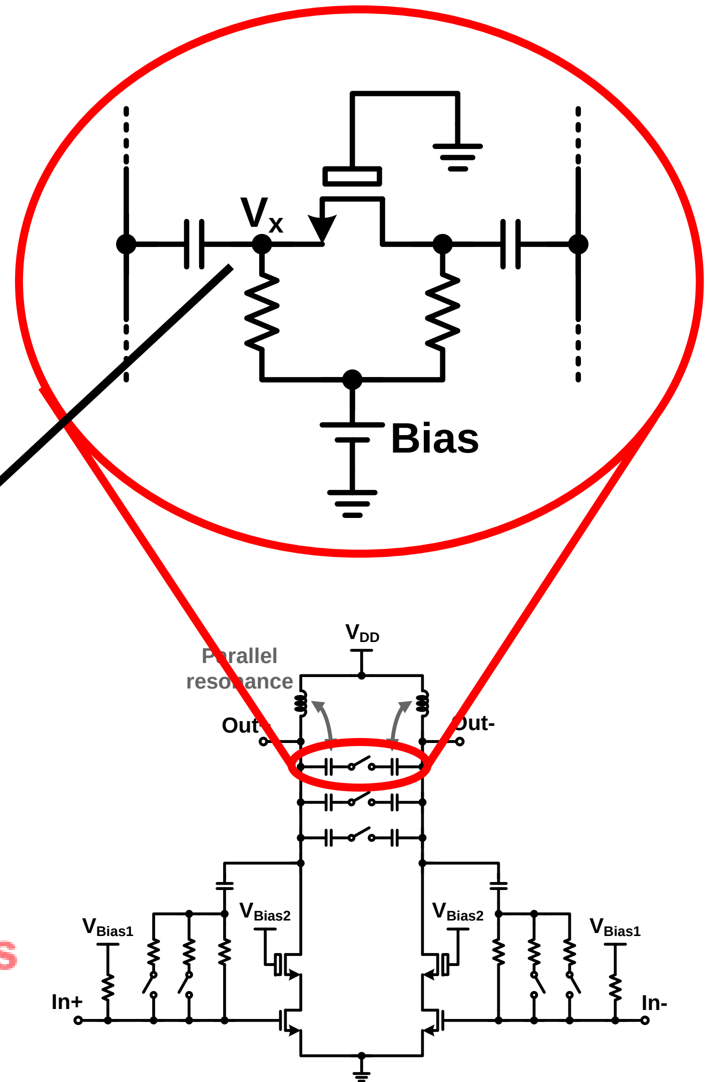


Switch biasing

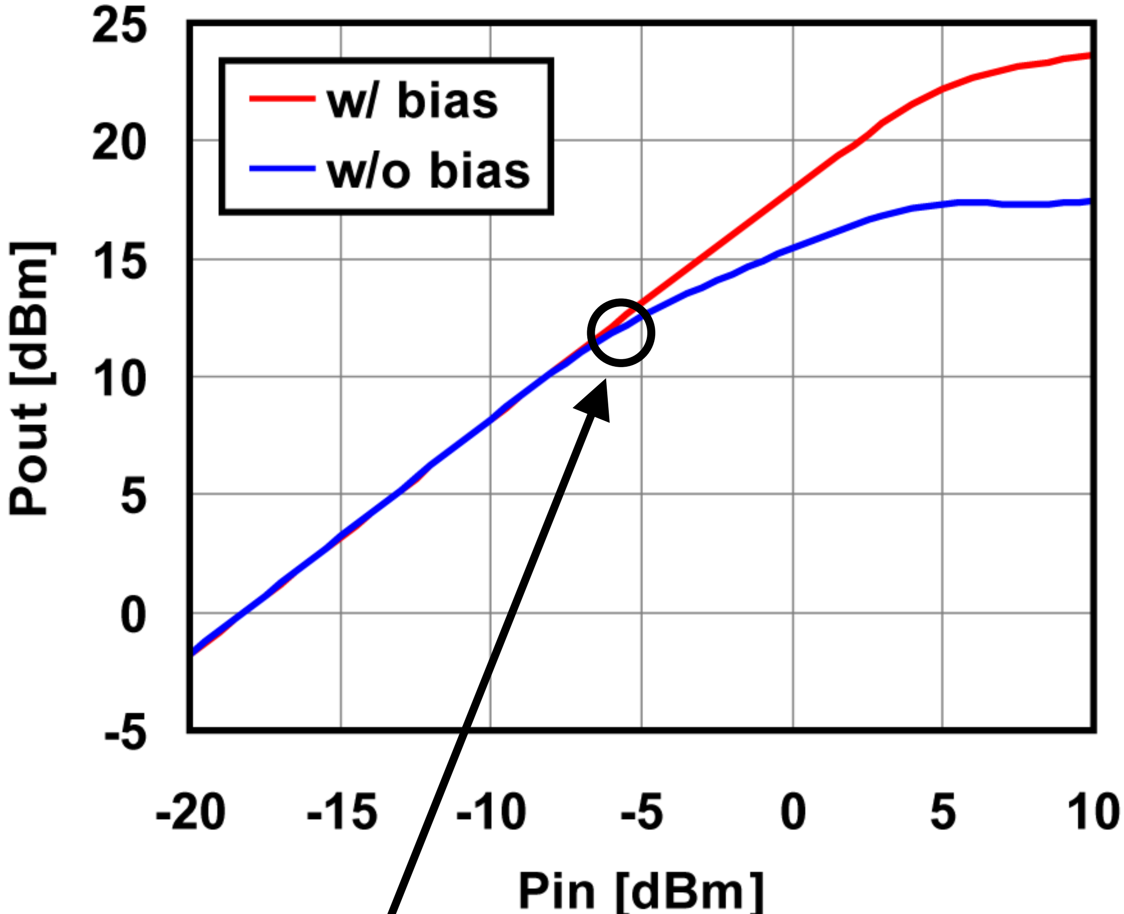
- **Large voltage swing makes an off-state switch turned on for a moment**
- **Degrade large signal characteristics such as P_{1dB}**

Bias to source and drain of off-state switches





Simulation of switch biasing effect



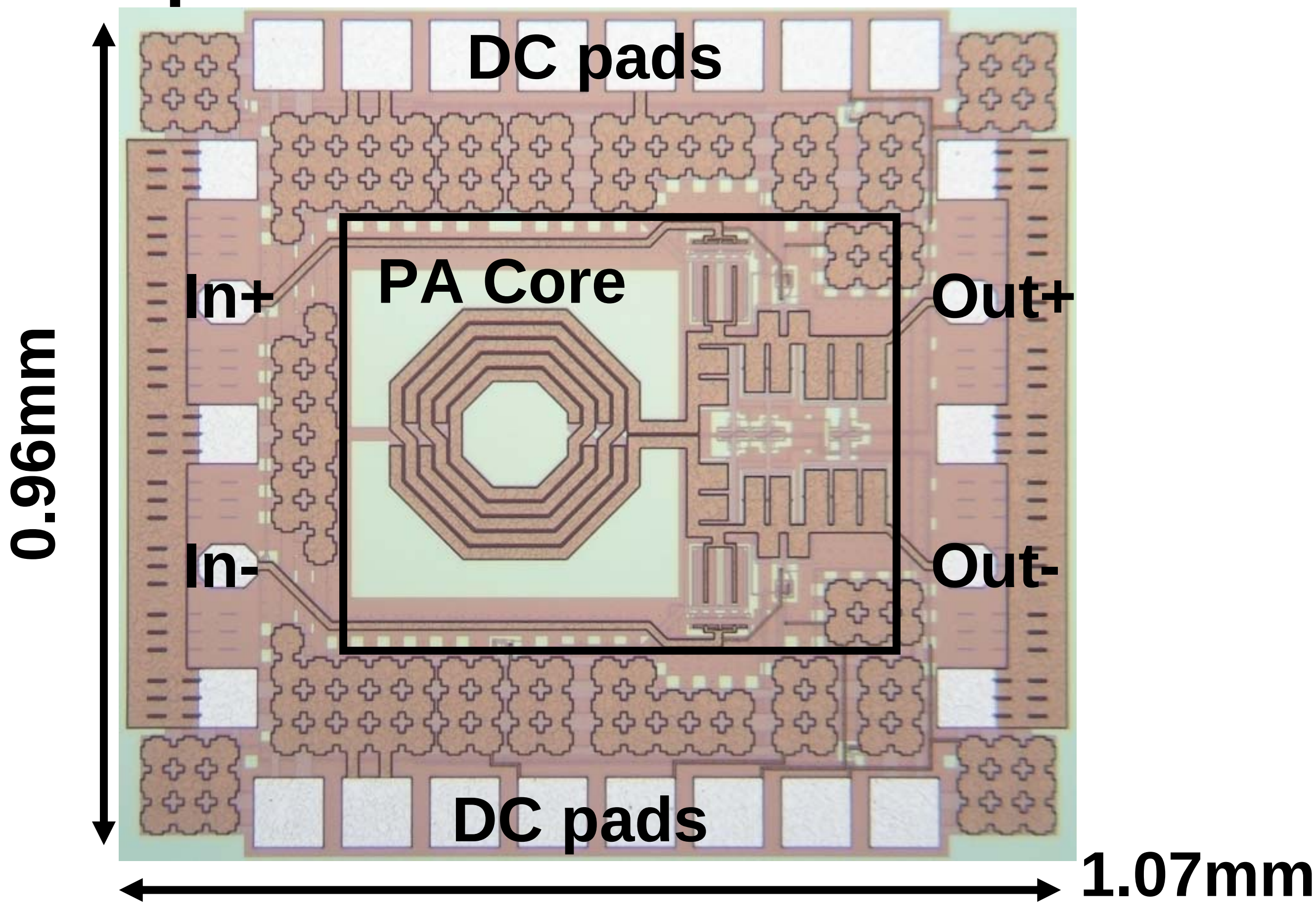
P1dB=22dBm

P1dB=13dBm

Off-state switches start to be turned on

Chip micrograph[7]

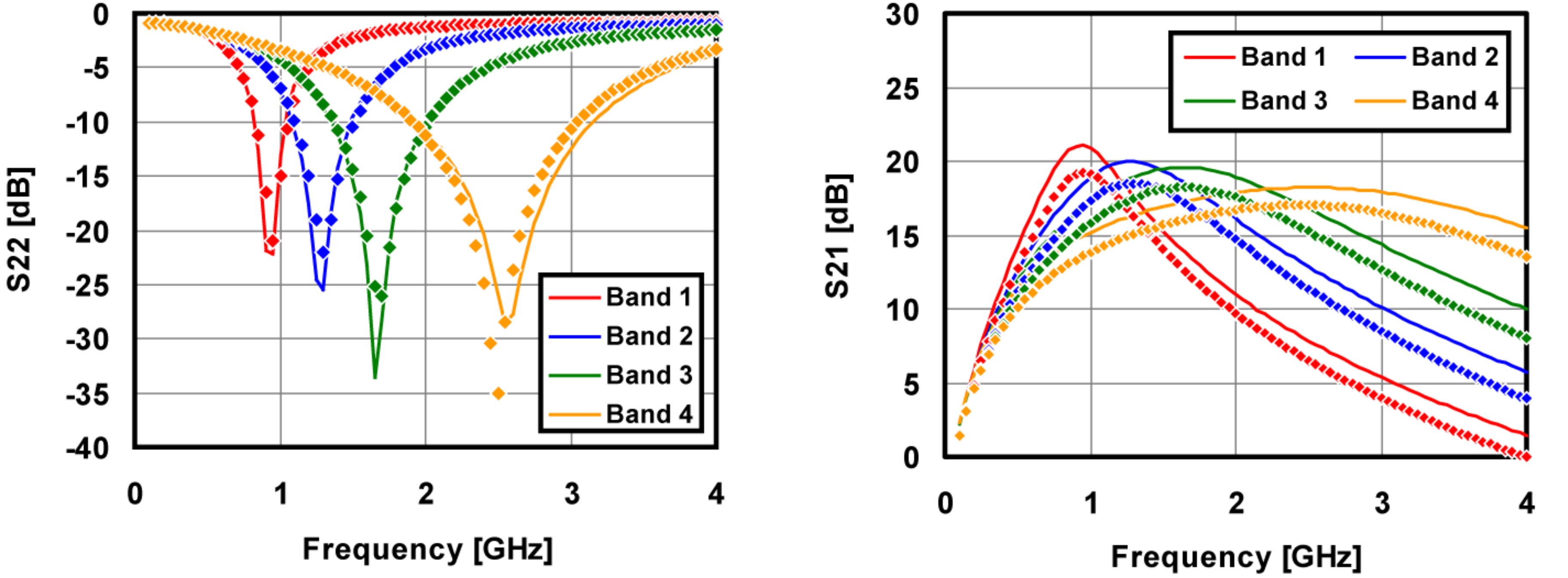
- 0.18μm CMOS
- Chip was measured using probes and external DC block capacitors



Small signal S-parameters

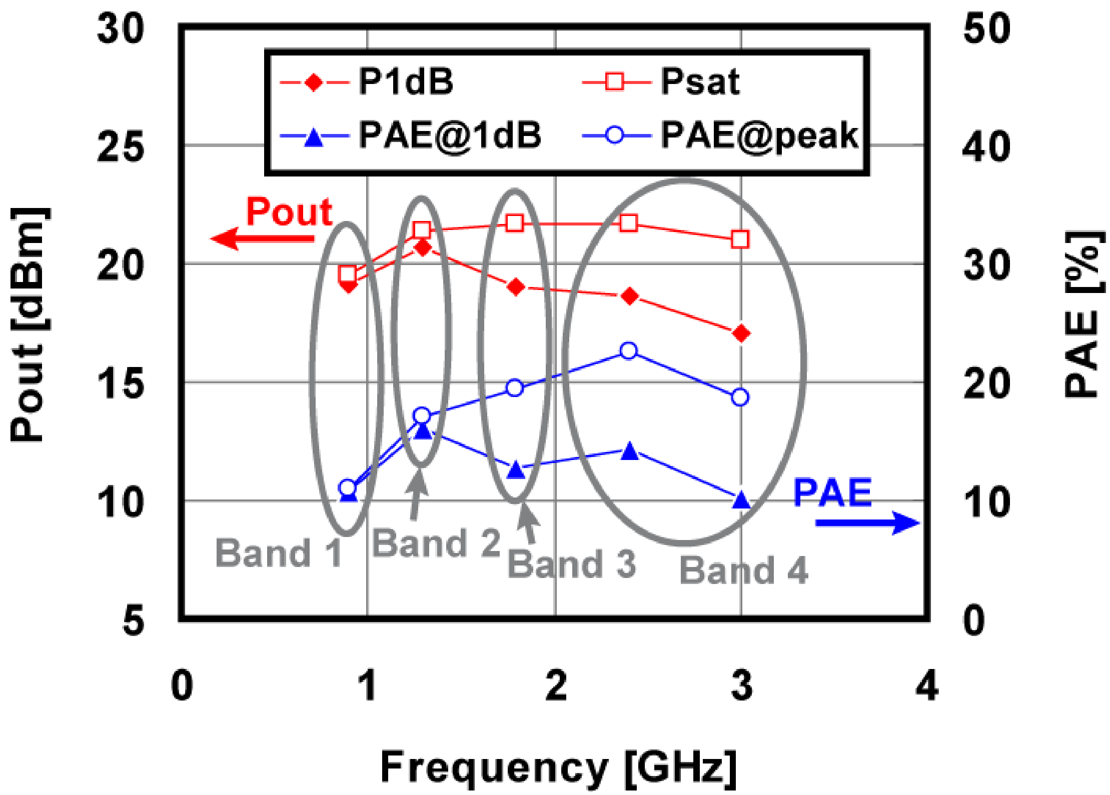
- **Differential mode S-parameter calculated from 4-port S-parameter**

Solid line : Simulation
Marker : Measurement



0.9~3.0GHz, S22 < -10dB, S21 > 16dB

P_{out}, PAE v.s. Frequency



- **Measured large signal performance in each band and each signal frequency**
- **P_{sat} is larger than 19dBm, and PAE@peak is larger than 11% at the entire frequency range**

Comparison of CMOS PAs

	Tech.	V_{DD} [V]	Freq. [GHz]	P_{sat} [dBm]	PAE@peak [%]	Area [mm^2]	Output matching
RFIC ’04 [3]	0.13μm CMOS	2.0	2.0 ~ 8.0	7 ~ 10	2 (@1dB)	—	Wideband
ISSCC ’09 [4]	0.13μm CMOS	1.5	0.5 ~ 5.0	14 ~ 21	3 ~ 16 (drain eff.)	3.6	Wideband
T-MTT ’07 [5]	0.18μm CMOS	2.8	3.7 ~ 8.8	16 ~ 19	8 ~ 25	2.8	Wideband
ISSCC ‘09 [6]	0.13μm CMOS	3.0	1.0 ~ 2.5	28 ~ 31	18 ~ 43	2.56*	Wideband
This work [7]	0.18μm CMOS	3.3	0.9 ~ 3.0	20 ~ 22	11 ~ 23	1.03	Tunable

*With distributor

Summary & Conclusion

- The first tunable CMOS PA utilizing a feedback technique
- 0.9-3.0 GHz output matching
- At the entire frequency range, over 19dBm output power and over 11% PAE is achieved

Outline

- Roadmap for multi-standard RFIC
- Rx requirements
  - Linearity & NF
- LO requirements
  - Q and V_{DD}
  - Frequency tuning range
  - Multi-band VCO results
- Tx requirements
  - Tunable PA results
- **Conclusion**

Conclusion

Rx

- **NF and linearity trade-off is very tough for realizing a full-SDR/CR. A new idea is still required.**
- **Some kind of reconfiguration is required to satisfy various requirements for every wireless standards.**
  - Linearity, Noise, Power consumption, etc
- **We should also pay attention to the research trend of external components, *e.g.*, duplexer, antenna, SW, etc.**

Tx

- **Tunablity is required.**

LO

- **There are some ways, but it is still challenging.**

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VCO

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Appendix

3GPP standard (GSM/UMTS/LTE)

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode	Tx-Rx separation	Band width	
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD	190 MHz	60 MHz	UMTS2100 (Japan)
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD	80 MHz	60 MHz	PCS/DCS1900(region2 North America)
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD	95 MHz	75 MHz	DCS/GSM1800 (EU, China, etc)
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD	400 MHz	45 MHz	UMTS1.7/2.1 (AWS, region 2)
5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD	45 MHz	25 MHz	UMTS850 (GSM850, region 2)
6	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD	45 MHz	10 MHz	UMTS800 (Japan)
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD	120 MHz	70 MHz	UMTS2600 (North America)
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD	45 MHz	35 MHz	UMTS900 (E-GSM900) (EU, China, etc)
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD	95 MHz	35 MHz	UMTS1700 (Japan)
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD	400 MHz	60 MHz	Extended UMTS1.7/2.1 (region 2)
11	1427.9 MHz – 1452.9 MHz	1475.9 MHz – 1500.9 MHz	FDD	48 MHz	25 MHz	UMTS1500 (Japan, PDC1500)
12	698 MHz – 716 MHz	728 MHz – 746 MHz	FDD	30 MHz	18 MHz	TBD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD	-31 MHz	10 MHz	TBD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD	-30 MHz	10 MHz	TBD
…						
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD	30 MHz	12 MHz	TBD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD	45 MHz	15 MHz	TBD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD	45 MHz	15 MHz	TBD
...						
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD		20 MHz	
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD		15 MHz	
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD		60 MHz	
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD		60 MHz	
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD		20 MHz	
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD		50 MHz	
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD		40 MHz	
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD		100 MHz	

3GPP TS 36.101, v9.1.0, 2009-09

+ GPS, DTV, WLAN, Bluetooth

Theoretical limit of phase noise

	NMOS VCO	CMOS VCO	Class-C VCO
$v_{\mathrm{out}+}, v_{\mathrm{out}-}$	$0 \sim 2V_{\mathrm{DD}}$	$0 \sim V_{\mathrm{DD}}$	$V_{\mathrm{DD}} \pm \frac{V_{\mathrm{DD}}+V_{\mathrm{od}}}{1+k}$
v_{sig}	$R_{\mathrm{p}} i_{\mathrm{sig}}$	$R_{\mathrm{p}} i_{\mathrm{sig}}$	$R_{\mathrm{p}} i_{\mathrm{sig}}$
i_{sig}	$\frac{2}{\pi} I_{\mathrm{bias}} \sin \omega t$	$\frac{4}{\pi} I_{\mathrm{bias}} \sin \omega t$	$I_{\mathrm{bias}} \sin \omega t$
I-limit	$I_{\mathrm{bias}} < \frac{\pi V_{\mathrm{DD}}}{R_{\mathrm{p}}}$	$I_{\mathrm{bias}} < \frac{\pi V_{\mathrm{DD}}}{4R_{\mathrm{p}}}$	$\frac{V_{\mathrm{od}}}{kR_{\mathrm{p}}} < I_{\mathrm{bias}} < \frac{V_{\mathrm{DD}}+V_{\mathrm{od}}}{(1+k)R_{\mathrm{p}}}$
$P_{\mathrm{sig(I\ region)}}$	$\frac{2R_{\mathrm{p}} I_{\mathrm{bias}}^2}{\pi^2}$	$\frac{8R_{\mathrm{p}} I_{\mathrm{bias}}^2}{\pi^2}$	$\frac{R_{\mathrm{p}} I_{\mathrm{bias}}^2}{2}$
$P_{\mathrm{sig(V\ region)}}$	$\frac{2V_{\mathrm{DD}}^2}{R_{\mathrm{p}}}$	$\frac{V_{\mathrm{DD}}^2}{2R_{\mathrm{p}}}$	—
$P_{\mathrm{sig(max)}}$	$\frac{2V_{\mathrm{DD}}^2}{R_{\mathrm{p}}}$	$\frac{V_{\mathrm{DD}}^2}{2R_{\mathrm{p}}}$	$\frac{1}{2R_{\mathrm{p}}} \left(\frac{V_{\mathrm{DD}}+V_{\mathrm{od}}}{1+k}\right)^2$
$PN_{\mathrm{(I\ region)}}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{\pi^2(1+\gamma_{\mathrm{N}})}{4R_{\mathrm{p}} I_{\mathrm{bias}}^2}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{\pi^2(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})}{16R_{\mathrm{p}} I_{\mathrm{bias}}^2}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}}{k})}{2R_{\mathrm{p}} I_{\mathrm{bias}}^2}$
$PN_{\mathrm{(V\ region)}}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\gamma_{\mathrm{N}})R_{\mathrm{p}}}{4V_{\mathrm{DD}}^2}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})R_{\mathrm{p}}}{V_{\mathrm{DD}}^2}$	—
$PN_{\mathrm{(min)}}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\gamma_{\mathrm{N}})R_{\mathrm{p}}}{4V_{\mathrm{DD}}^2}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})R_{\mathrm{p}}}{V_{\mathrm{DD}}^2}$	$\frac{f_0^2}{\Delta f^2} \frac{k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}}{k})R_{\mathrm{p}}(1+k)^2}{2(V_{\mathrm{DD}}+V_{\mathrm{od}})^2}$
$FoM_{\mathrm{(I\ region)}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{\pi^2(1+\gamma_{\mathrm{N}})V_{\mathrm{DD}}}{4R_{\mathrm{p}} I_{\mathrm{bias}}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{\pi^2(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})V_{\mathrm{DD}}}{16R_{\mathrm{p}} I_{\mathrm{bias}}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}}{k})V_{\mathrm{DD}}}{2R_{\mathrm{p}} I_{\mathrm{bias}}}$
$FoM_{\mathrm{(V\ region)}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{(1+\gamma_{\mathrm{N}})R_{\mathrm{p}} I_{\mathrm{bias}}}{4V_{\mathrm{DD}}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})R_{\mathrm{p}} I_{\mathrm{bias}}}{V_{\mathrm{DD}}}$	—
$FoM_{\mathrm{(min)}}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{\pi(1+\gamma_{\mathrm{N}})}{4}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{\pi(1+\frac{\gamma_{\mathrm{N}}+\gamma_{\mathrm{P}}}{2})}{4}$	$\frac{10^3 k_{\mathrm{B}}T}{Q^2} \frac{(1+\frac{\gamma_{\mathrm{N}}}{k})(1+k)V_{\mathrm{DD}}}{2(V_{\mathrm{DD}}+V_{\mathrm{od}})}$