Low Power RFICs for Transceiver Applications

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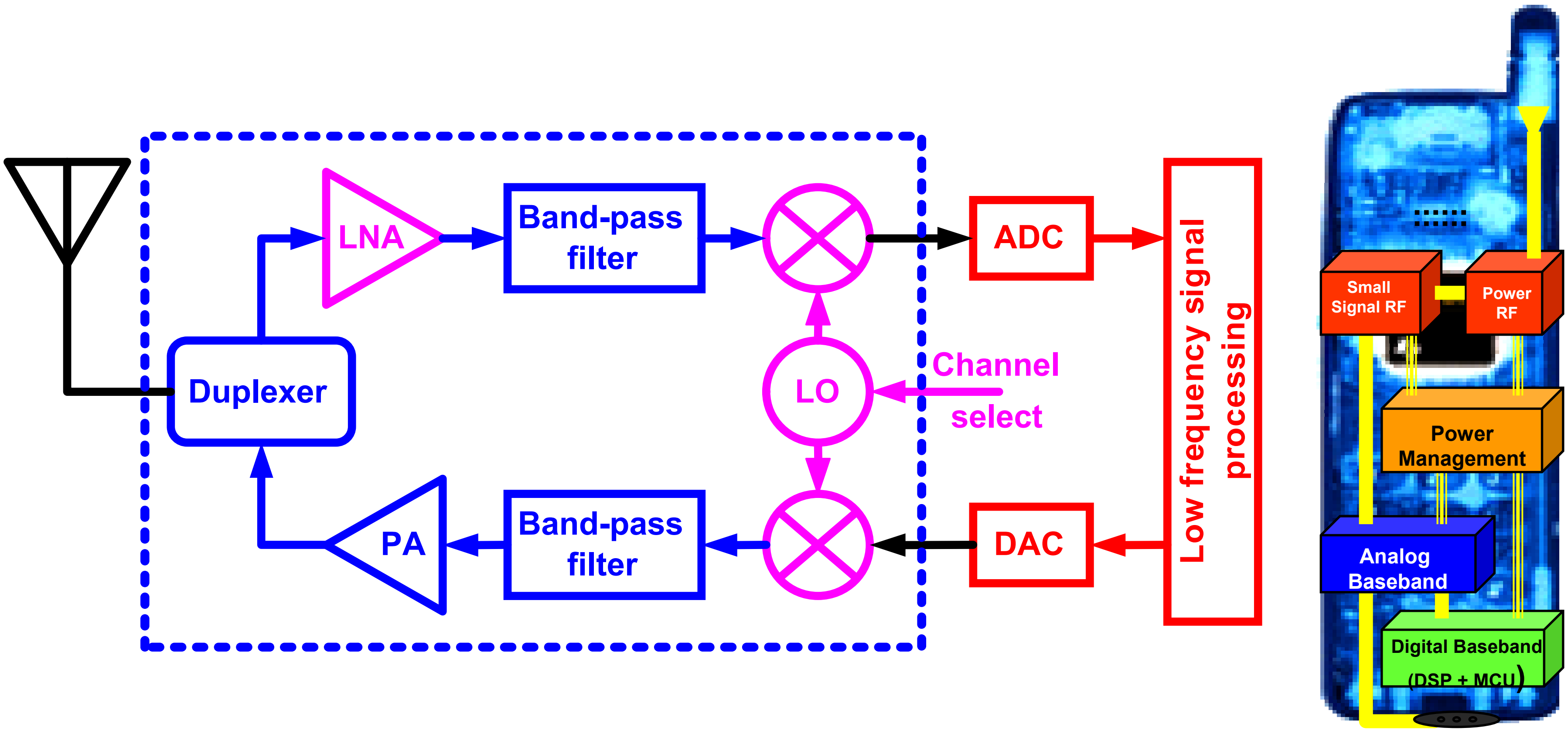
RF & Wideband Projects

- Rizwan Murji – RFICs for wireless applications
- Sasan Naseh – Reliability of RFICs
- Wai Leung Ngan – Mismatch effects on oscillators
- Nabeel Jafferali – Low-voltage, low-power mixers
- Ahmed Fakhr – Low-voltage, micro-power oscillators
- Saman Asgaran – RF noise modeling and RF LNAs
- Samar Abdelsayed – RF PA and integrated antenna
- Munir Eldesouki – RF PA and integrated filter
- Juan Ranuárez – CMOS distributed amplifiers
- Ehab El-Badry – SiGe distributed amplifiers
- Guennadi Kouzaev – Modeling of passives
- Ognian Marinov – Instrumentation ICs

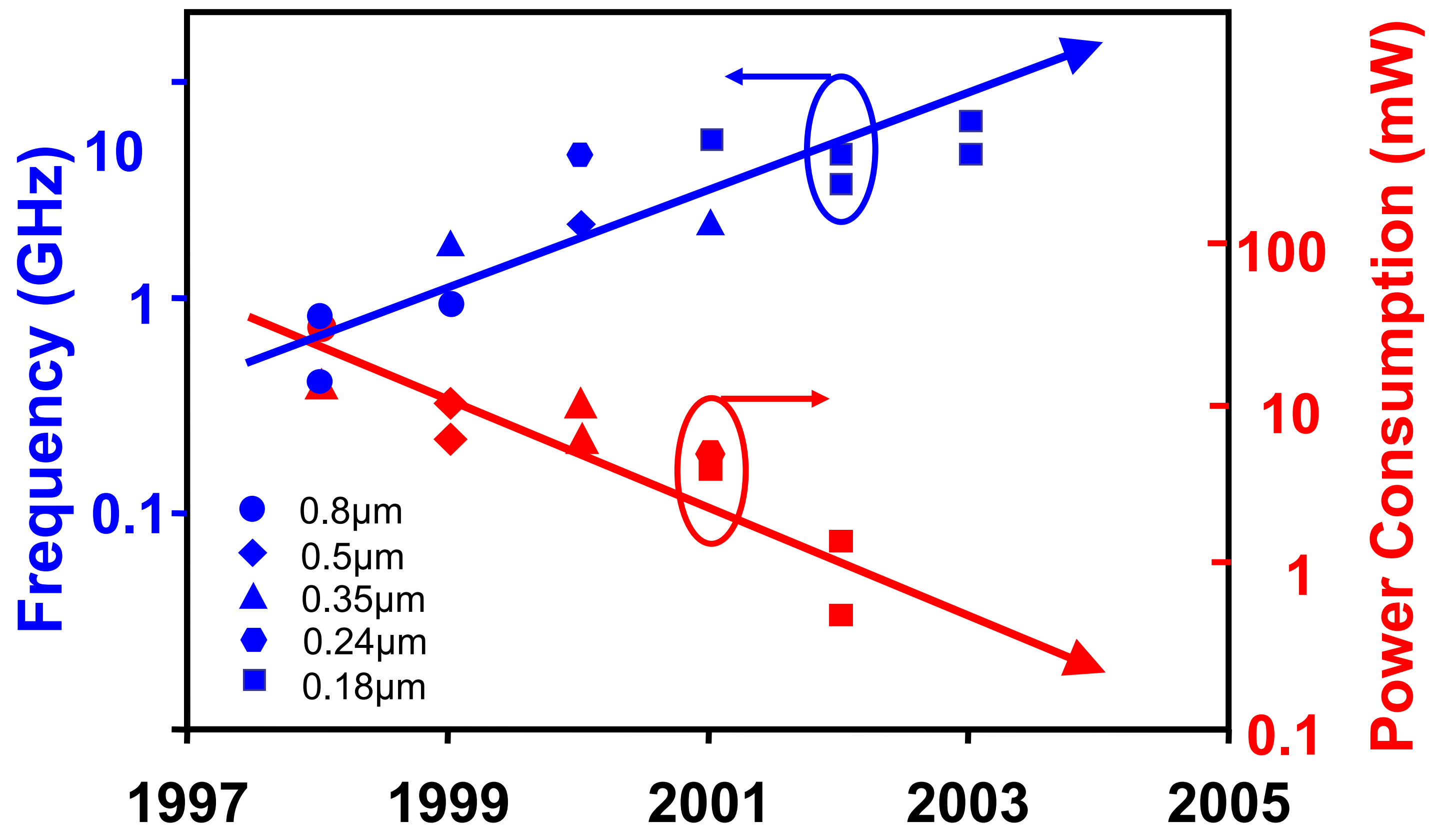
The Wireless Transceiver



Outline of Talk

- Mixers
  - Gilbert cell and body-input mixers
- Oscillators
  - VCO with AAC and micro-power VCO
- Hot-carrier effects on RFICs
- Mismatch effects
- Subthreshold operation
- Conclusions

RF CMOS Mixer Trends



- Frequency and power vs. year of published high-frequency CMOS mixer designs and expected trend

Mixer Characteristics

- **Power Consumption**

$$V_{DD} \times I_{DD}$$

- **Linearity (IIP3)**

- **Conversion Gain**

$$10\log\left(\frac{P_{out}(\omega = \omega_{IF})}{P_{in}(\omega = \omega_{RF})}\right)$$

- **Noise Figure**

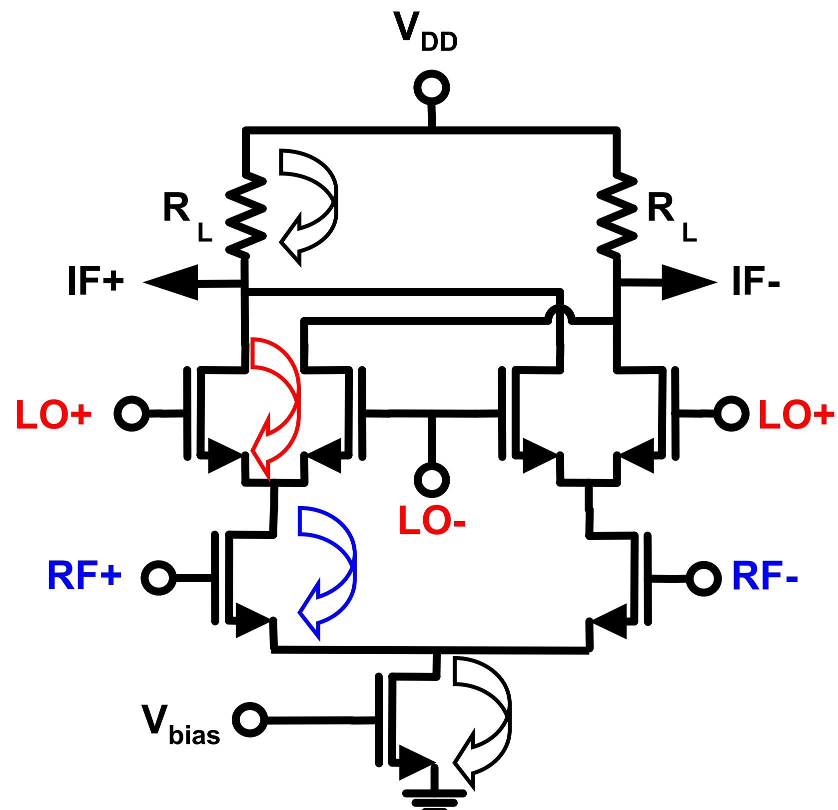
$$NF = \frac{SNR_{input}}{SNR_{output}}$$

$$FoM = 20\log(f_{RF}) + CG - NF + IIP3 - 10\log(P_C)$$

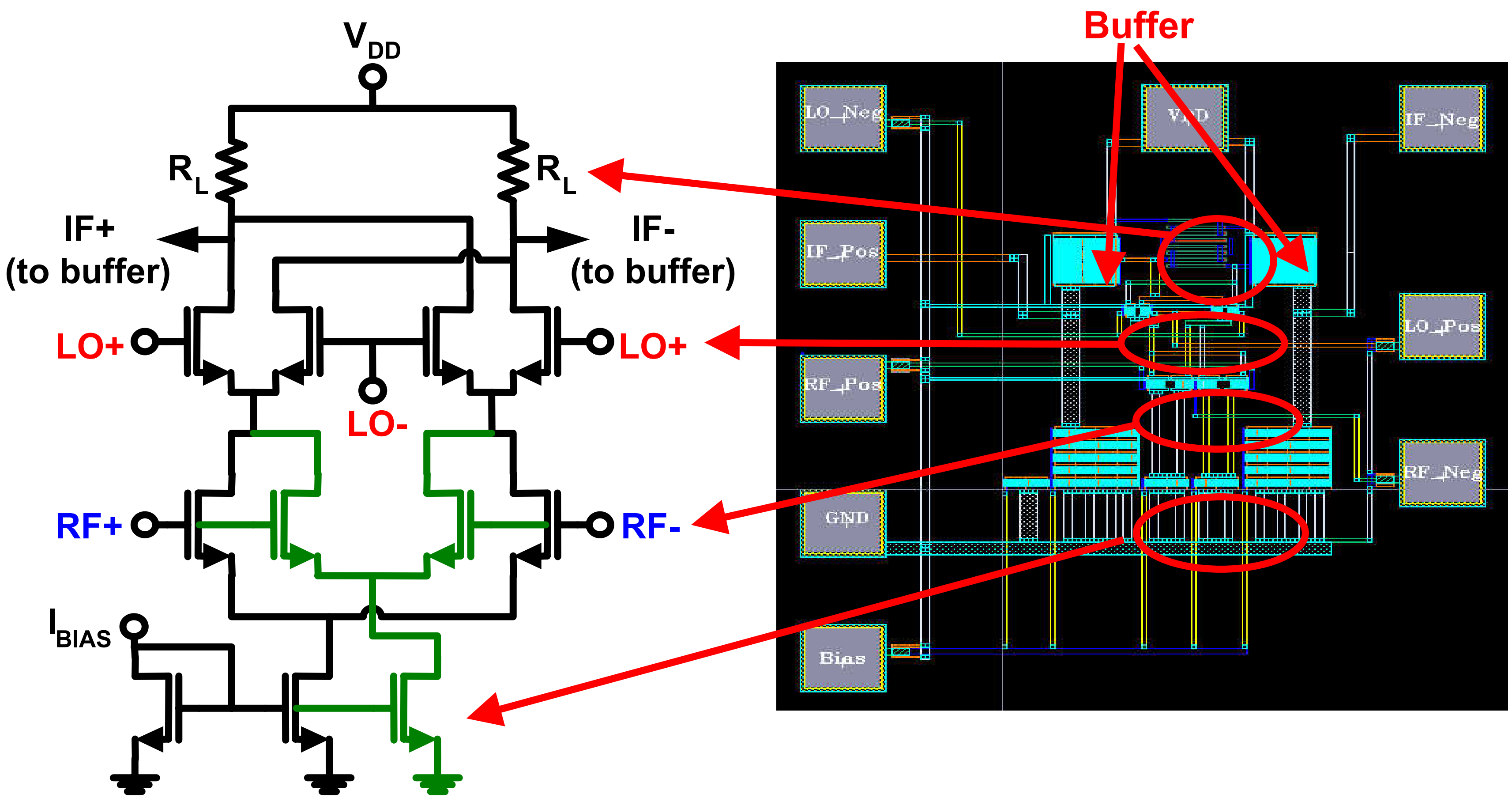
f_{RF} normalized to 1Hz, *CG* in dB, *NF* in dB, *IIP3* in dBm and P_C normalized to 1W

RF CMOS Mixer

- Gilbert-cell mixer introduced in 1968 (with BJTs)
- Most popular mixer circuit
- Low voltage operation issues
  - stacked transistors
  - degrades linearity and conversion gain



Gilbert Mixer - g_m Cell Technique

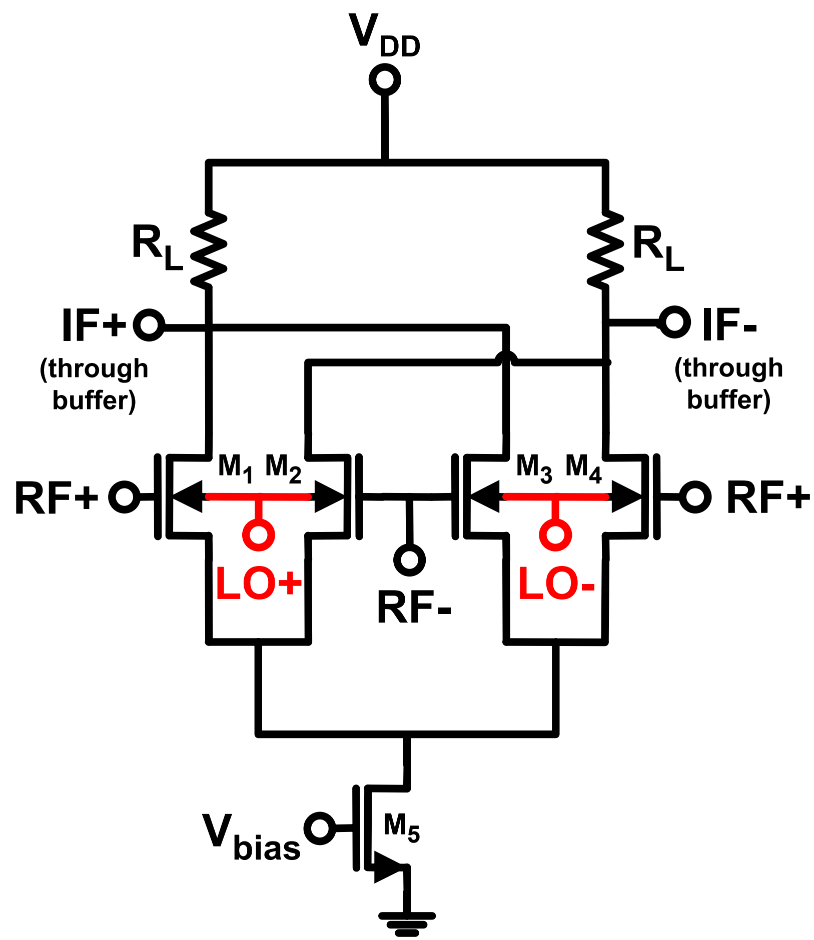


Supply voltage/Power	1.2V/3.95mW	SSB Noise Figure/IIP3	17dB/8dBm
RF Input/Conversion Gain	1.9GHz/-2dB	FoM/Technology	199dB/0.18μm

$$FoM = 20\log(f_{RF}) + CG - NF + IIP3 - 10\log(P_C)$$

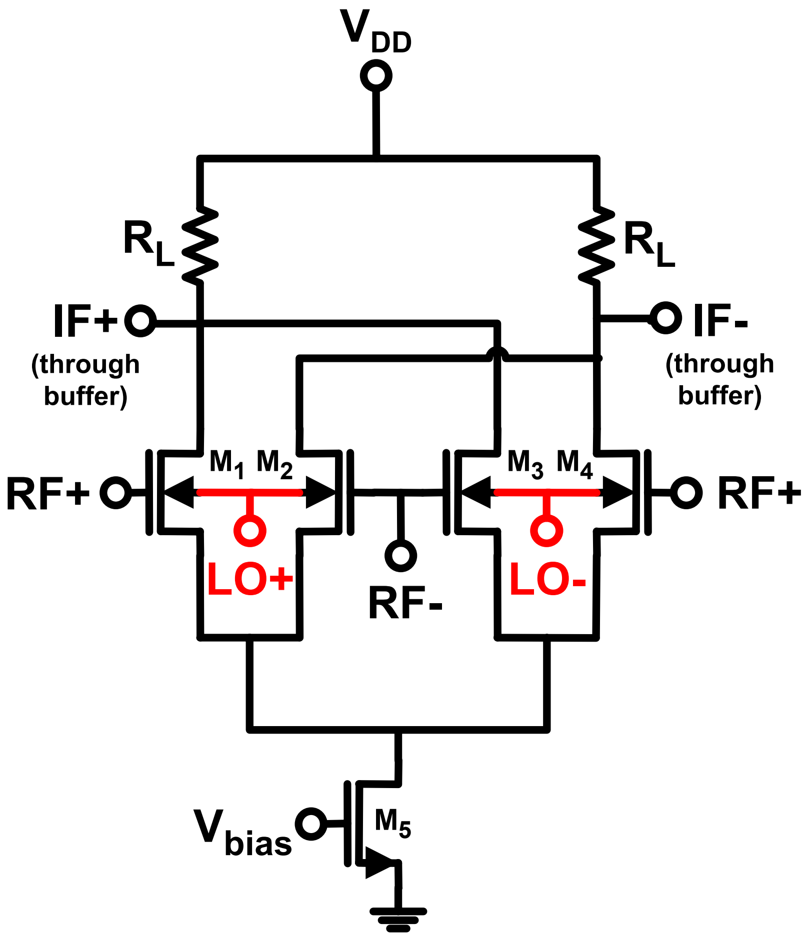
Body-Input Mixer

- True four-terminal MOSFET
  - Body used as large-signal input for LO
- Lowers minimum supply voltage
- Designed for low power consumption



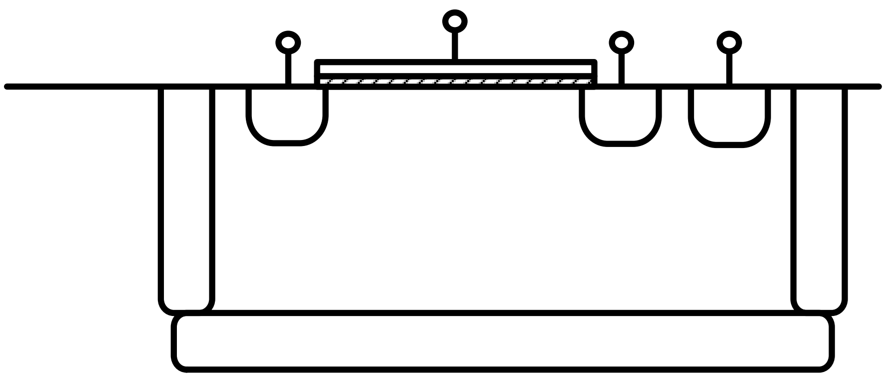
Body-Input Mixer

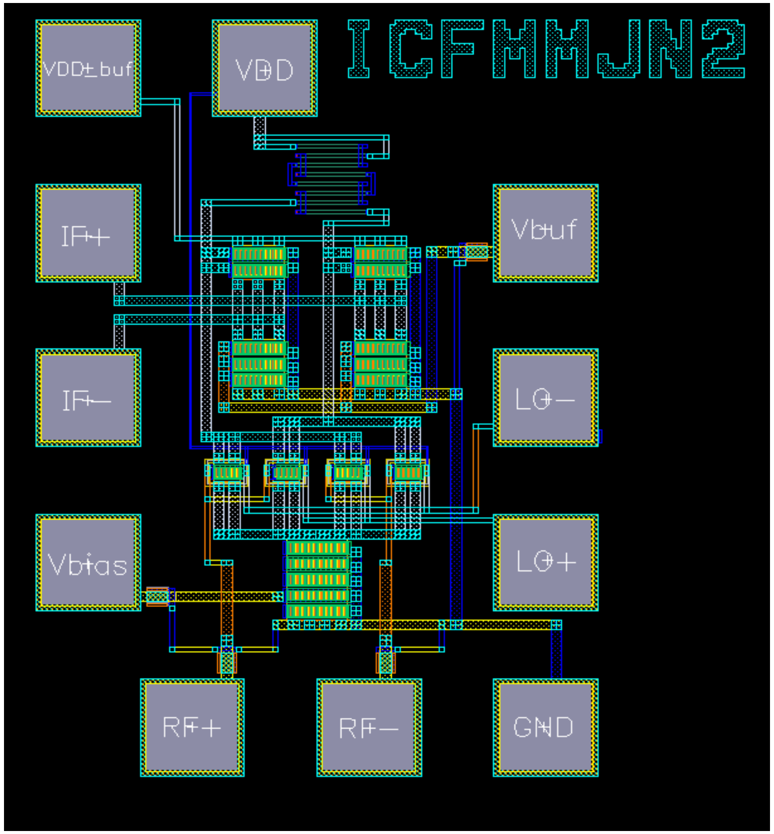
- **Advantages**
  - low-voltage, low-power operation possible
  - good CG, NF; acceptable IIP3
- **Disadvantages**
  - high LO power requirement
  - low gain compression



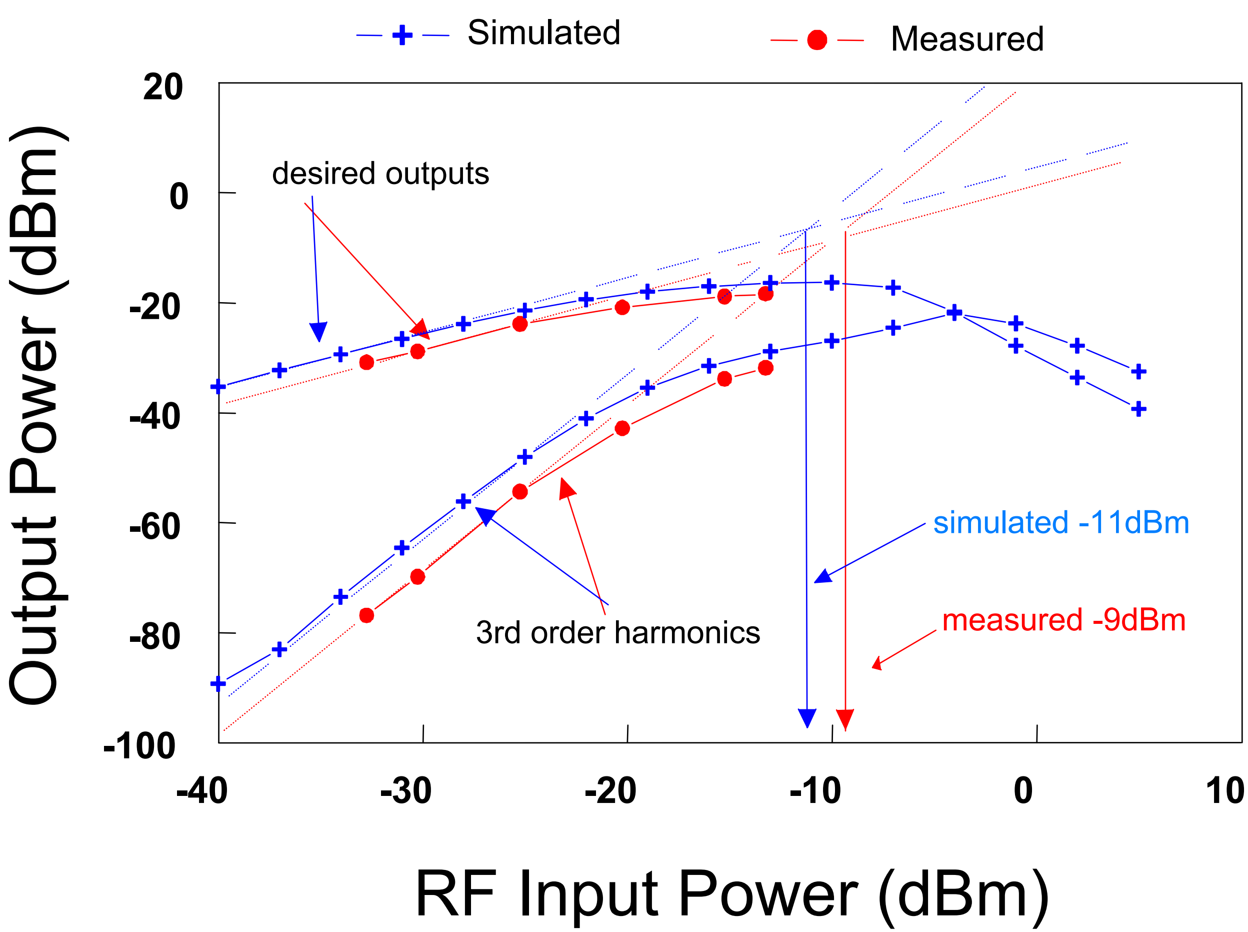
Body-Input Mixer

- Designed in TSMC's 0.18μm CMOS process
- Deep n-well required for this design, available in this process

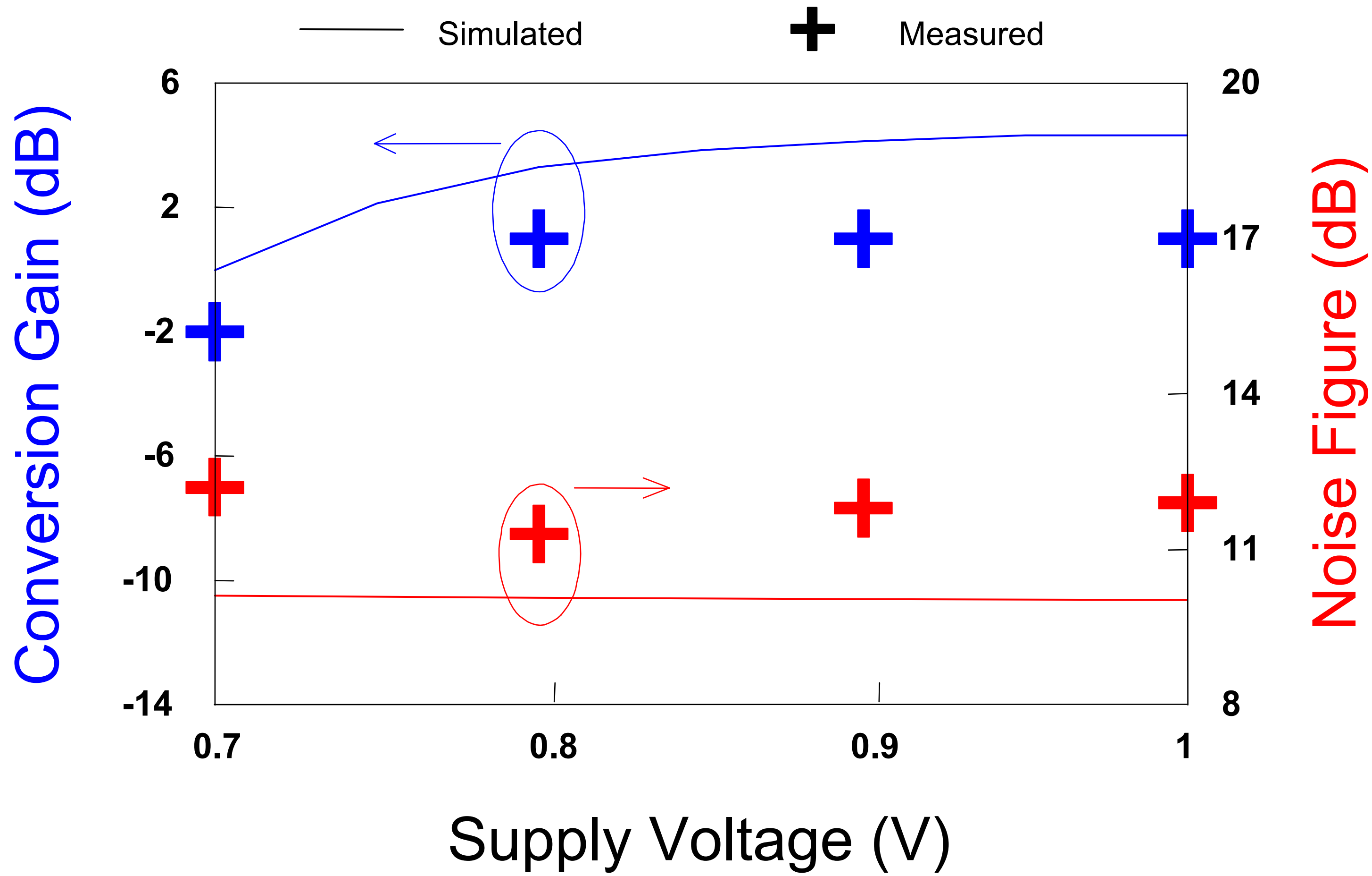




Results - Linearity



Results – Voltage Supply Effects



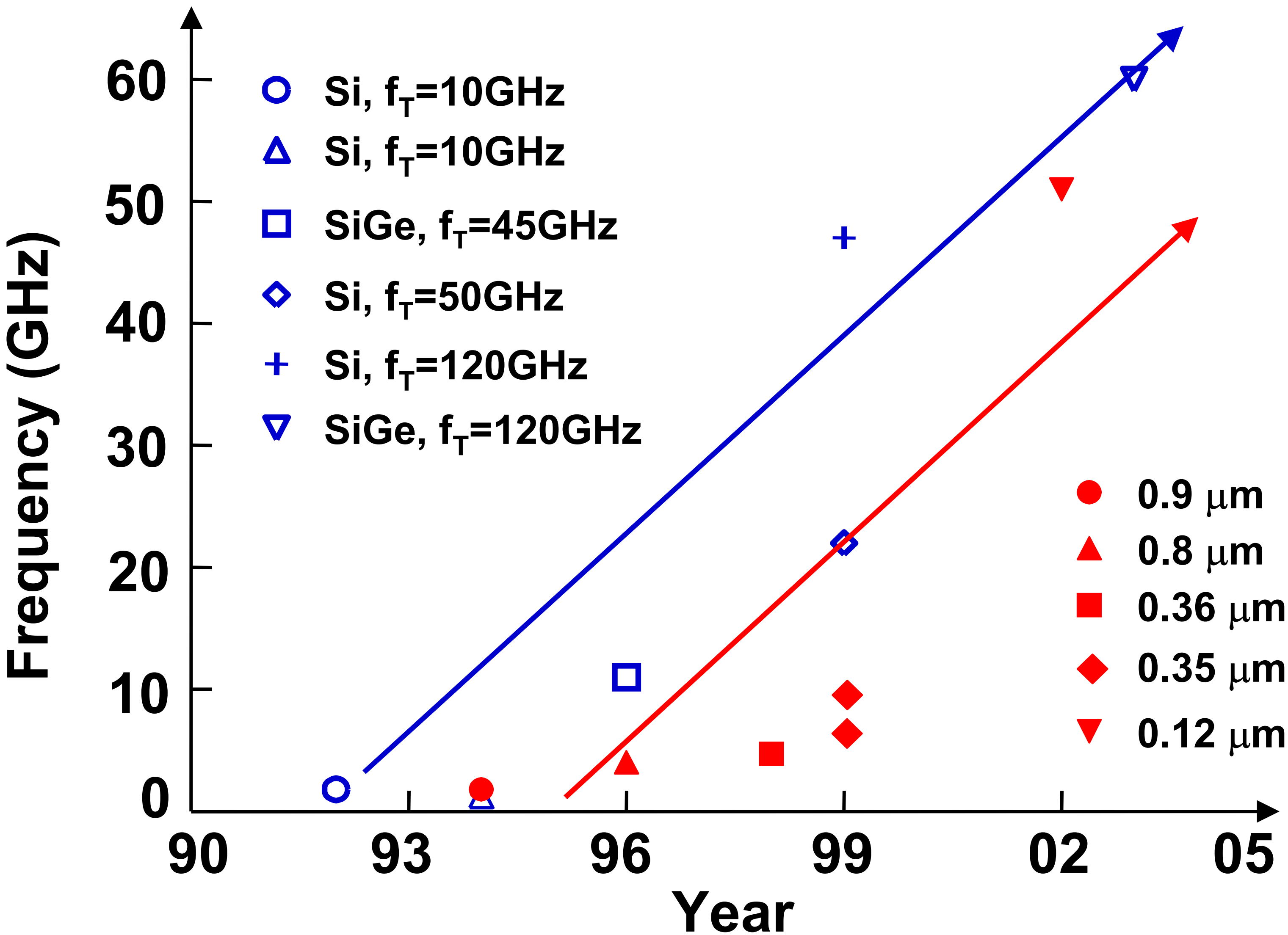
Results - Summary

Supply Voltage (V)	0.8
Current (mA)	0.5
Power Consumption (mW)	**0.4**
RF Input Frequency (GHz)	1.9
LO Input Frequency (GHz)	1.65
RF Input Power (dBm)	-25
LO Input Power (dBm)	0
IF Output Frequency (MHz)	250
Conversion Gain (dB)	**1**
SSB Noise Figure (dB)	**11**
IIP3 (dBm)	**-9**

Comparisons

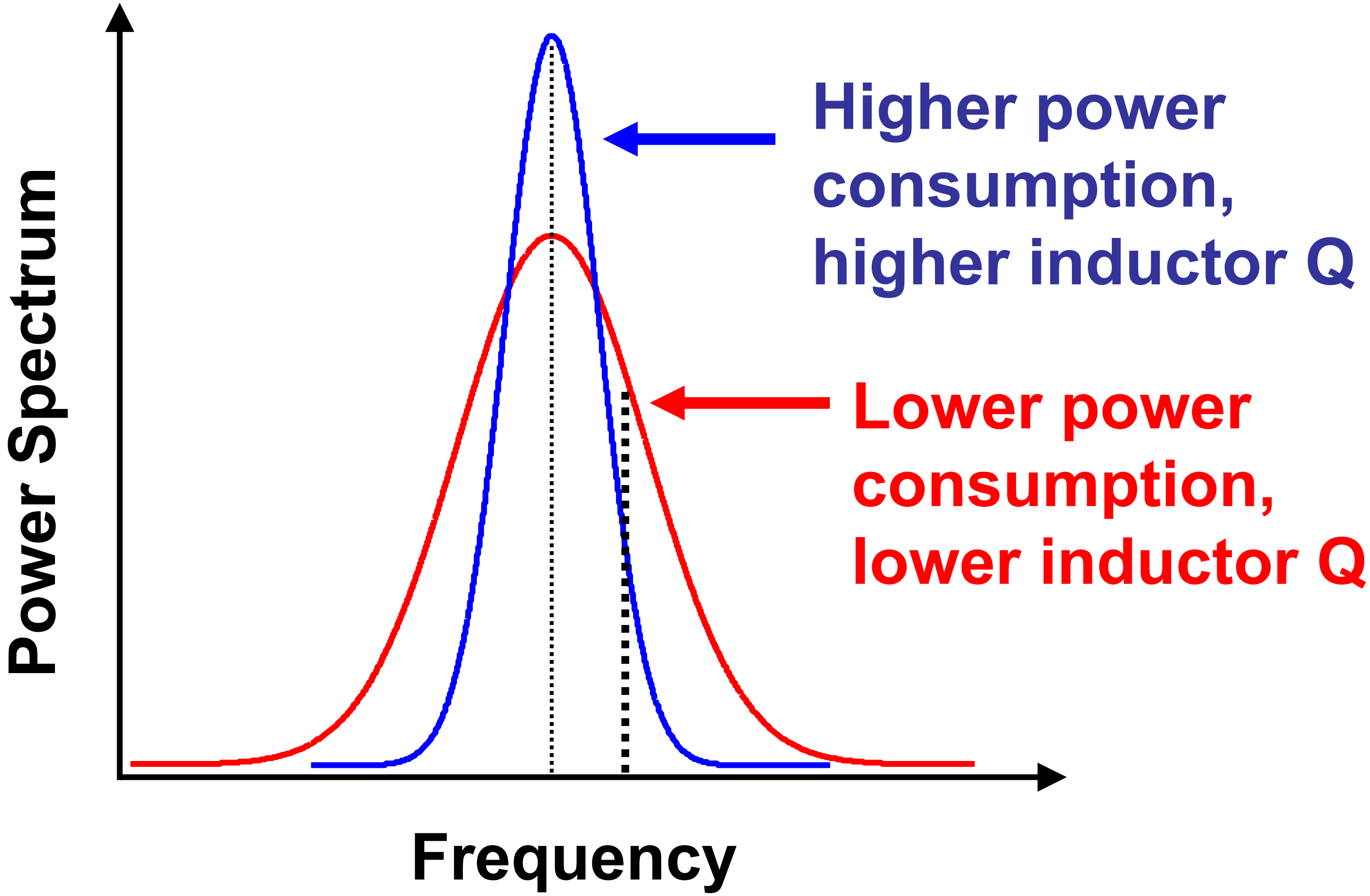
	Tech-nology	f_{RF} GHz	CG dB	NF dB	IIP3 dBm	P_C mW	FoM
Body-input	***0.18µm***	***1.9***	***1***	***11***	***-9***	***0.4***	***201***
Gilbert Cell – 2003	**0.18µm**	**1.9**	**-2**	**17**	**8**	**4**	**199**
Taris et al – 2003	0.18µm	2.4	10	14	-5	12	198
Debono et al – 2001	0.35µm	0.9	2	13.5	3.5	4.7	194
Kan et al – 2000	0.8µm	0.9	-8.4	28	25.5	1.5	196

Trends - VCO Frequency



Oscillator Phase Noise

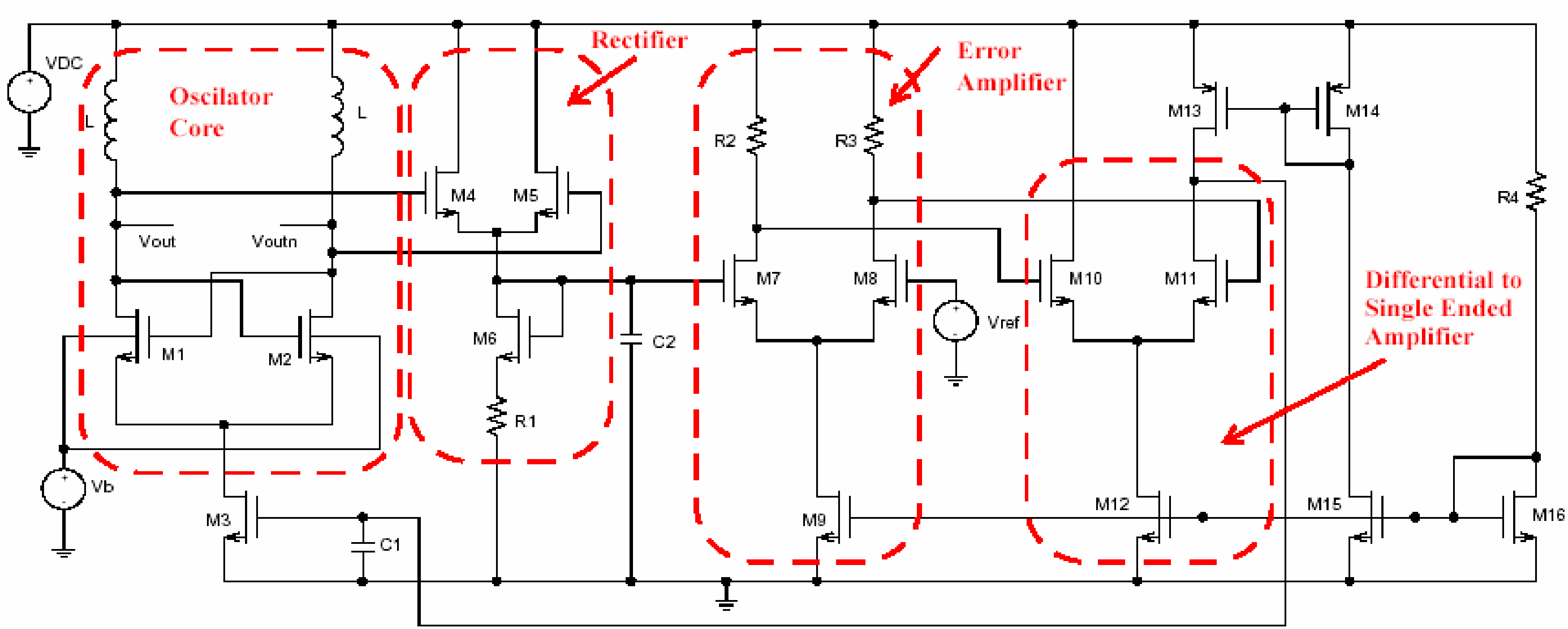
- Effect of power consumption and inductor quality on oscillator



Why a VCO with AAC?

- **VCO requirements**
  - Low phase noise implementation
  - Low power implementation
  - Large tuning range (VCO gain)
  - Additional issues of a practical implementation can be solved with an AAC circuit
- **AAC allows**
  - A fast and reliable start up
  - The oscillator to be set to its optimal bias point in terms of noise, while still biasing it with the optimal current at startup
  - A well defined level of output power
- **AAC disadvantages**
  - Larger area required for AAC
  - Slight increase in power consumption due to AAC circuitry

VCO with AAC implementation

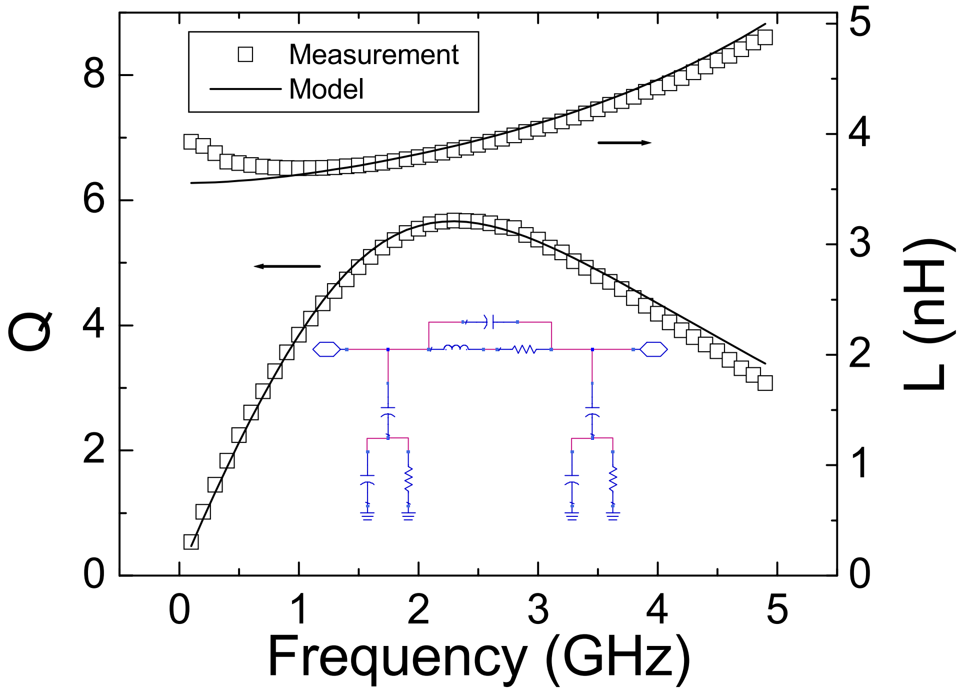


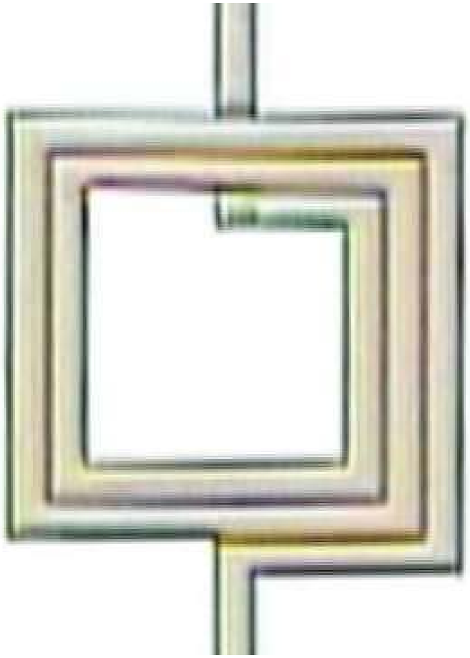
- Frequency is tuned by V_{bs} of the cross-coupled M1-M2 pair
- Output amplitude controlled by V_{ref}

$$f_o = \frac{1}{2\pi\sqrt{L \cdot C_{tk}}}$$

$$f_o = \frac{1}{2\pi\sqrt{L \cdot (C_{tk} + C_{AAC})}}$$

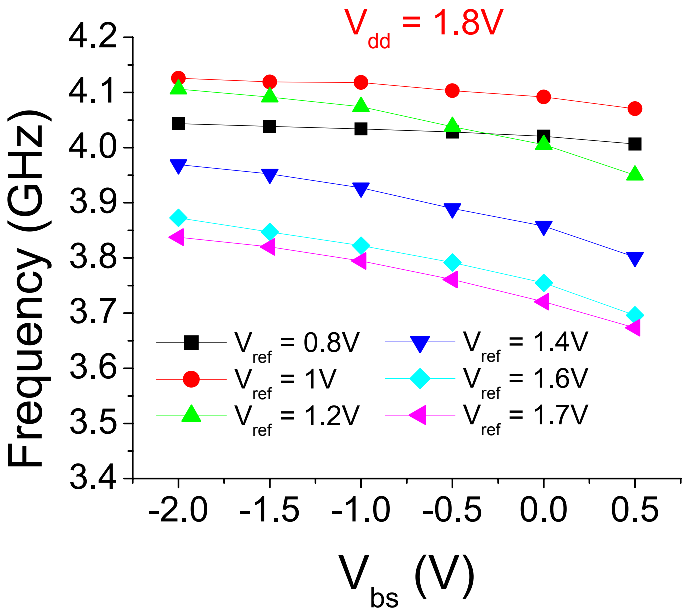
Spiral Inductor Model

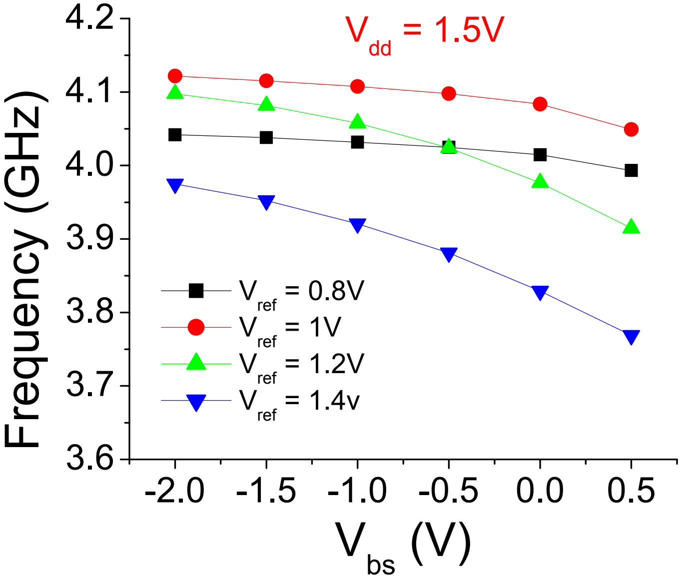




- Good equivalent circuit model at the frequency of interest (4 GHz)
- Q of ~4 at 4 GHz
- Currently investigating other types of components as inductors such as microstrip line or coplanar wave guide

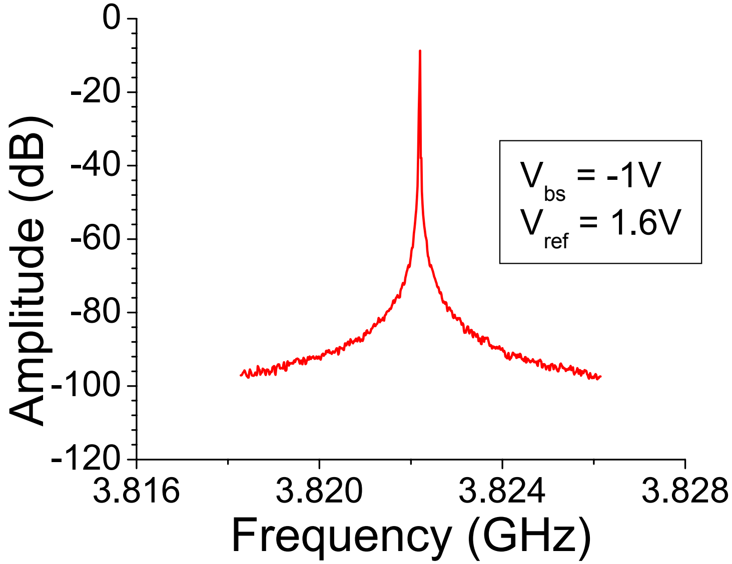
Measured Tuning Range

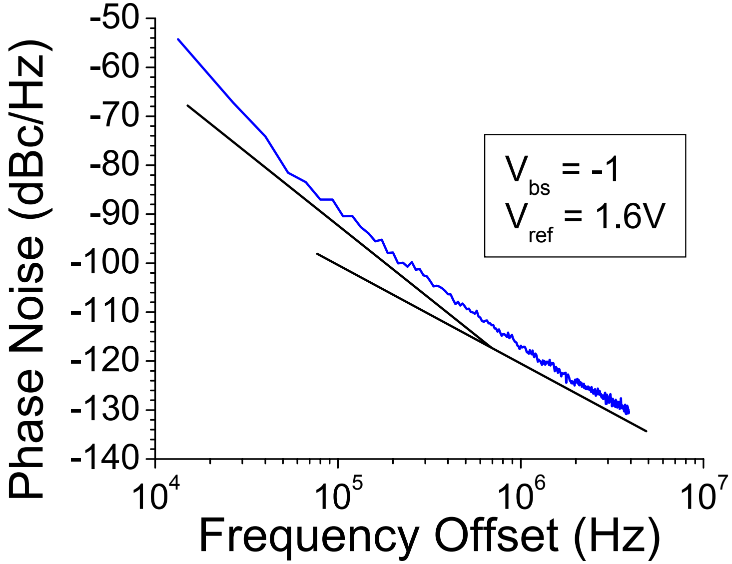




- Tuning range investigated for 2 supply voltages:
  - At **V_{dd} = 1.8 V** the tuning range is **452.4 MHz**
  - At **V_{dd} = 1.5 V** the tuning range is **353 MHz**
- As V_{bs} becomes more reversed biased, the frequency increases

Spectrum & Phase Noise at 1.8V





- Spectrum and phase noise shown for V_{bs} = -1V, V_{ref} = 1.6V and V_{dd} = 1.8V
- Peak is -8.7dBm at 3.822GHz
- PN@100kHz = -88.7dBc/Hz, PN@600kHz = -111.11dBc/Hz and PN@1MHz = -116.88dBc/Hz

Figure of Merit

$$FOM = 20\log\left(\frac{\omega_o}{\Delta\omega}\right) - \phi - 10\log P - 20\log Q$$

Ref.	Q	f_o (GHz)	ϕ (dBc/Hz)	P (mW)	FOM
[1]	16	0.8	-124@1MHz	4.32	151.6
[2]	15	2	-99@100kHz	13.2	150.3
[3]	**5.5**	**10.02**	**-102@1MHz**	**3.7**	**161.5**
[4]	8	2.56	-123@1MHz	14	161.6
This Work	**4.2**	**3.82**	**-116.9@1MHz**	**7.24@1.8V**	**167.6**
This Work	**4.2**	**3.88**	**-114.7@1MHz**	**4.47@1.5V**	**167.6**

[1] M. A. Margarit, J. L. Tham, R. G. Meyer and M. J. Deen, "A low-noise, low-power VCO with automatic amplitude control for wireless applications," IEEE J. Solid-St. Circuits, vol. 34(6), pp. 761-771, 1999.

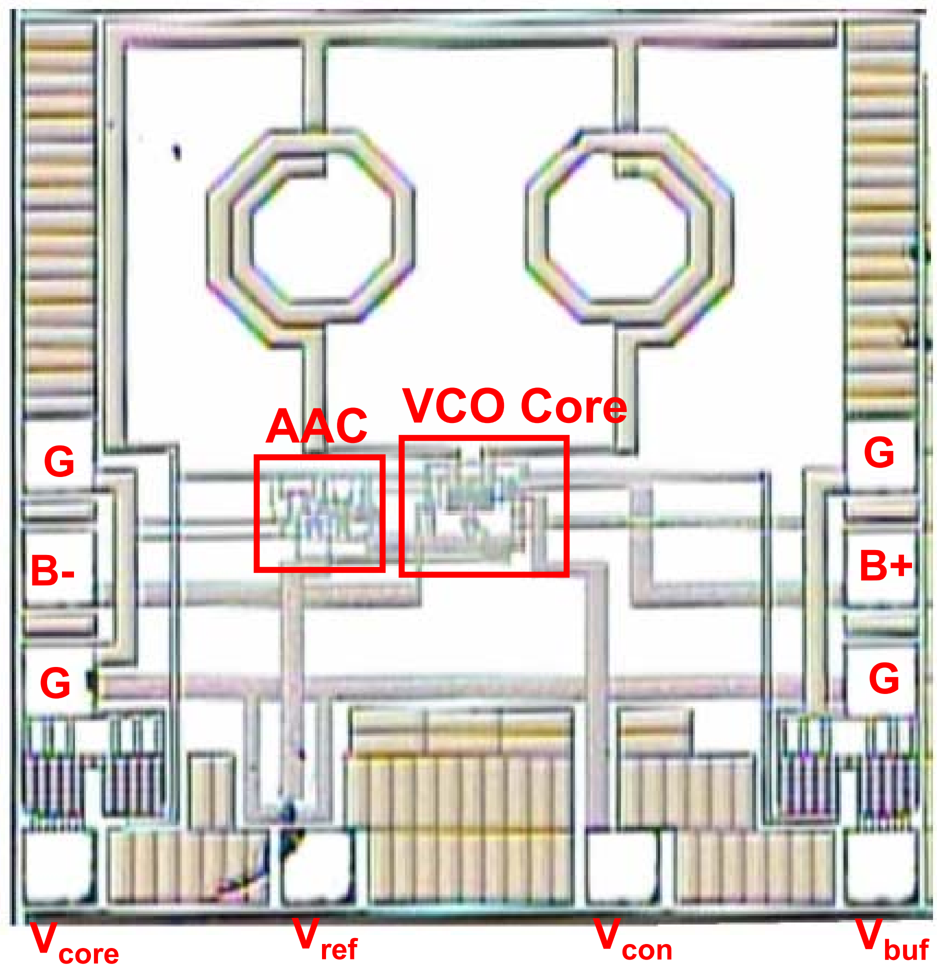
[2] A. Zanchi, C. Samori, S. Levantino and A. Lacaita, "A 2-V 2.5GHz-104-dBc/Hz at 100kHz fully integrated VCO with wide-band low-noise automatic amplitude control," IEEE J. Solid-St. Circuits, vol. 26(4), pp. 611-619, April 2001.

[3] R. Murji and J. M. Deen, "A Low-Power, 10 GHz Back-Gated Tuned Voltage Controlled Oscillator with Automatic Amplitude and Temperature Compensation," ISCAS 2004, Vancouver, BC, Canada, 4 pages, (23-26 May, 2004)

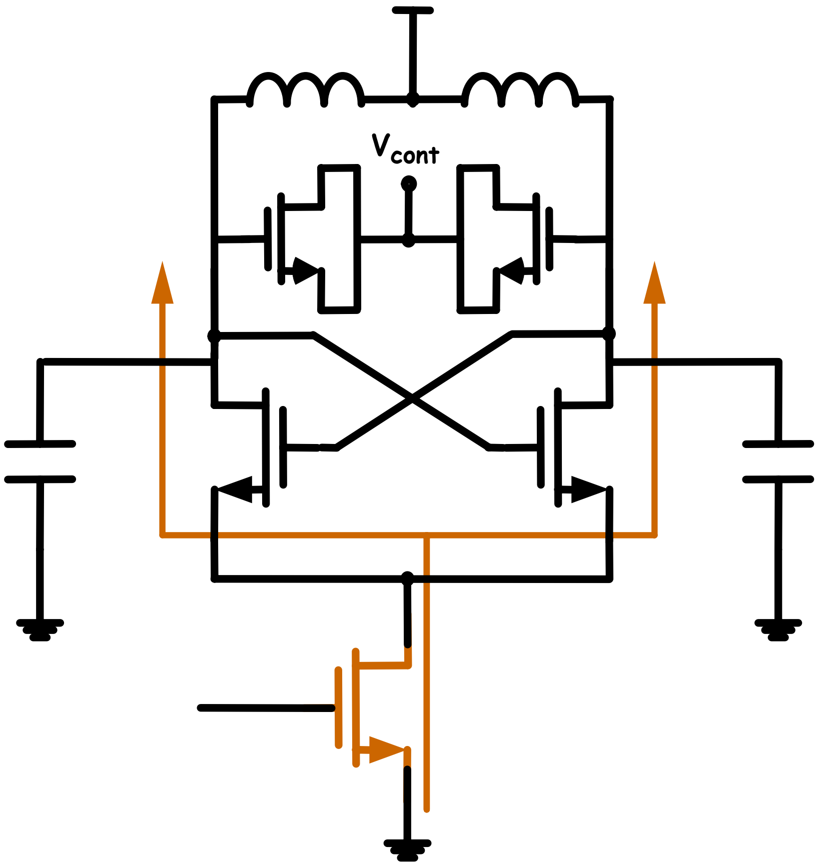
[4] J. W. M. Rogers et al, "A study of digital and analog automatic-amplitude control circuitry for voltage-controlled oscillators," IEEE J. Solid-St. Circuits, vol. 38(2), pp. 352-356, 2003.

Summary of Results and Layout

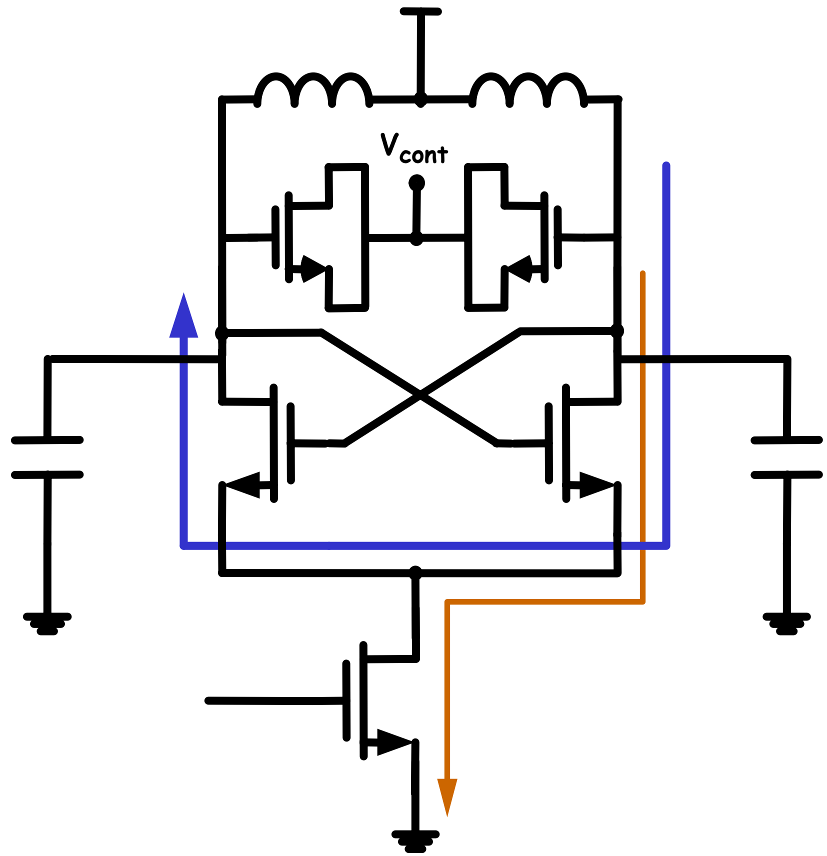
Parameter	Summary
Supply Voltage	1.8 V **1.5 V**
Current Consumption	0.520 to 4.2 mA **0.515 to 2.9 mA**
Power Consumption	0.936 to 7.56 mW **0.77 to 4.35 mW**
Best Phase-Noise @1MHZ offset (dBc/Hz)	-116.9@3.82GHz **-114.7@3.88GHz**
Maximum Operating Frequency	4.12 GHz **4.12 GHz**
Tuning Range	451MHz **353 MHz**
Area	1.18 x 1.2 mm^2
Technology	TSMC 0.18 μm



Background - Noise in VCO

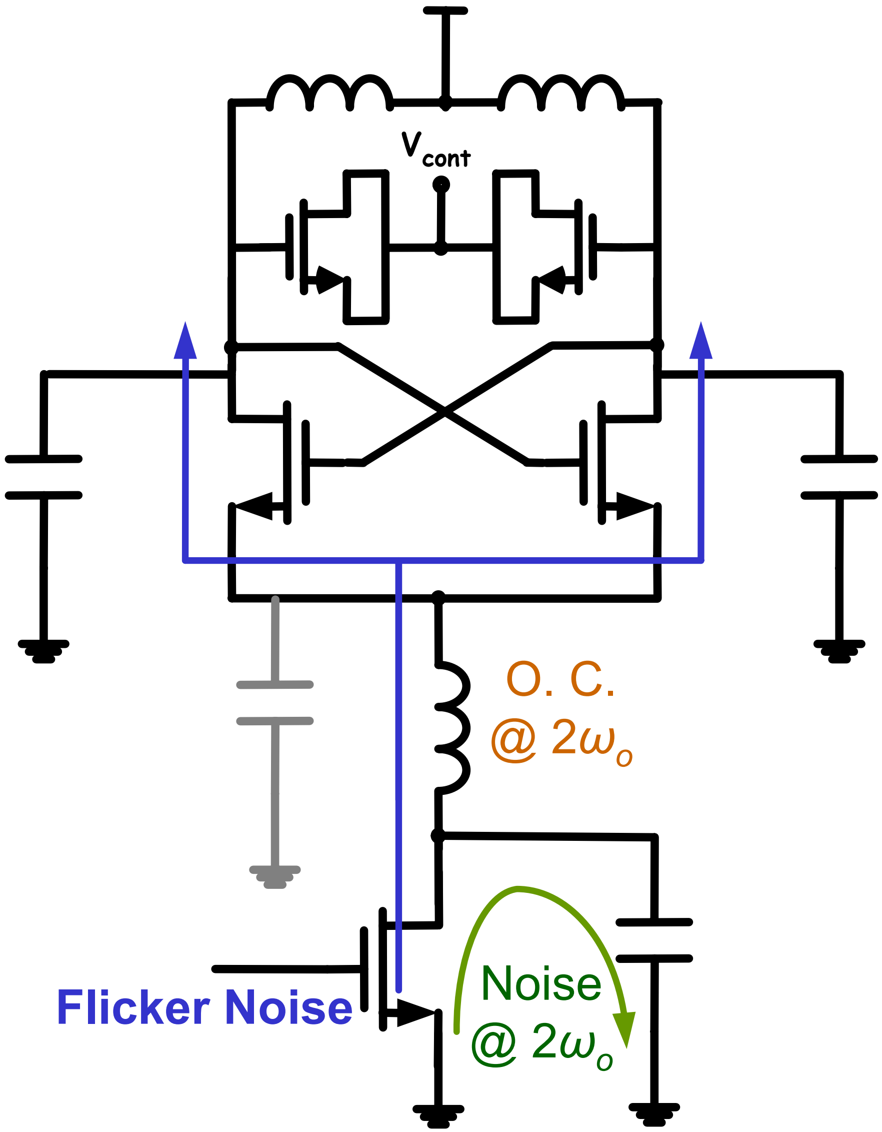


Flicker Noise and
Noise at Harmonics



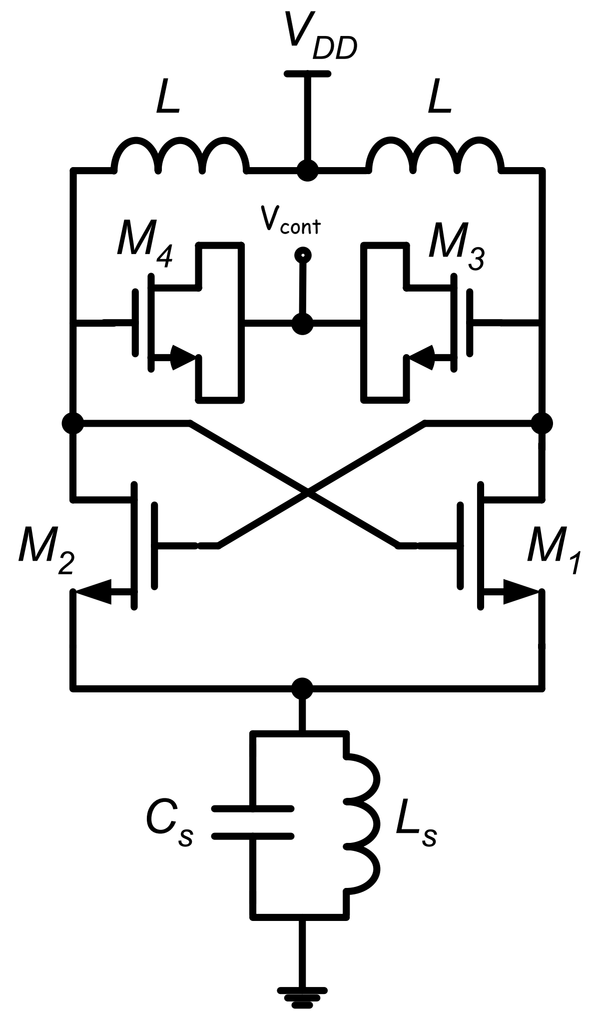
Even Harmonics
Odd Harmonics

Background - Noise Filtering



Background – Noise Filtering

- **Voltage-Biased Oscillator**
- **Advantages**
  - **Low phase noise**
  - **Low voltage applications**
- **Disadvantages**
  - **High current consumption**



Low-Voltage, Low-Power

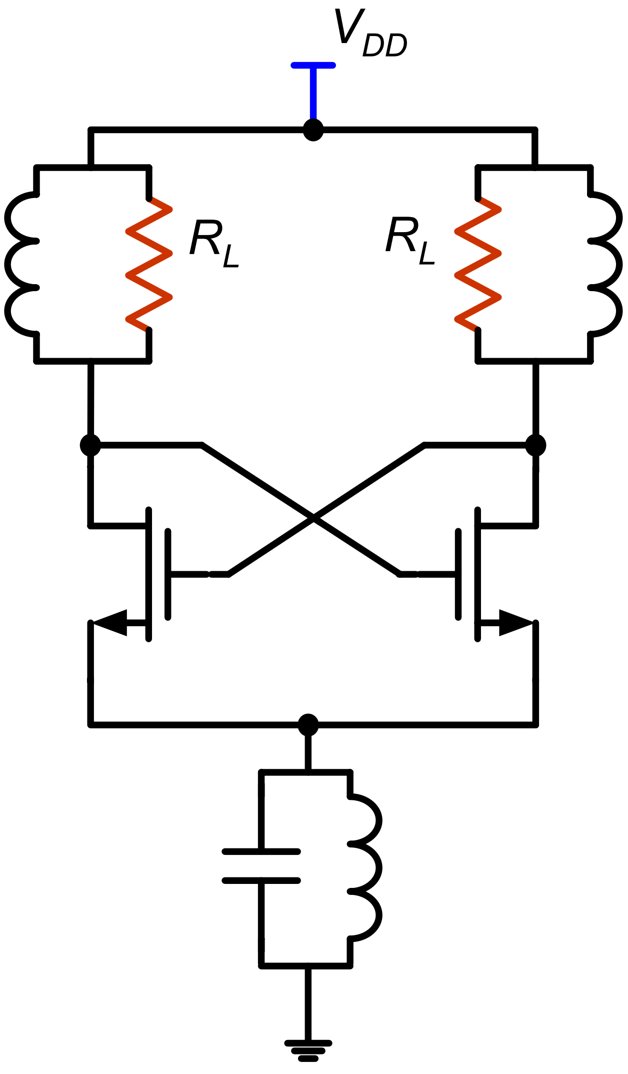
- **Power = I x V_{DD}**

▪ **Condition of oscillation**

$$g_m \cdot R_L > 1, \qquad R_L \sim Q\,(\omega L)$$

▪ **Phase noise**

$$L(\omega_m) \propto \frac{1}{V_o^2}\frac{kT}{C}\frac{\omega_o}{Q}\frac{1}{\omega_m^2}$$



Low-Voltage, Low-Power

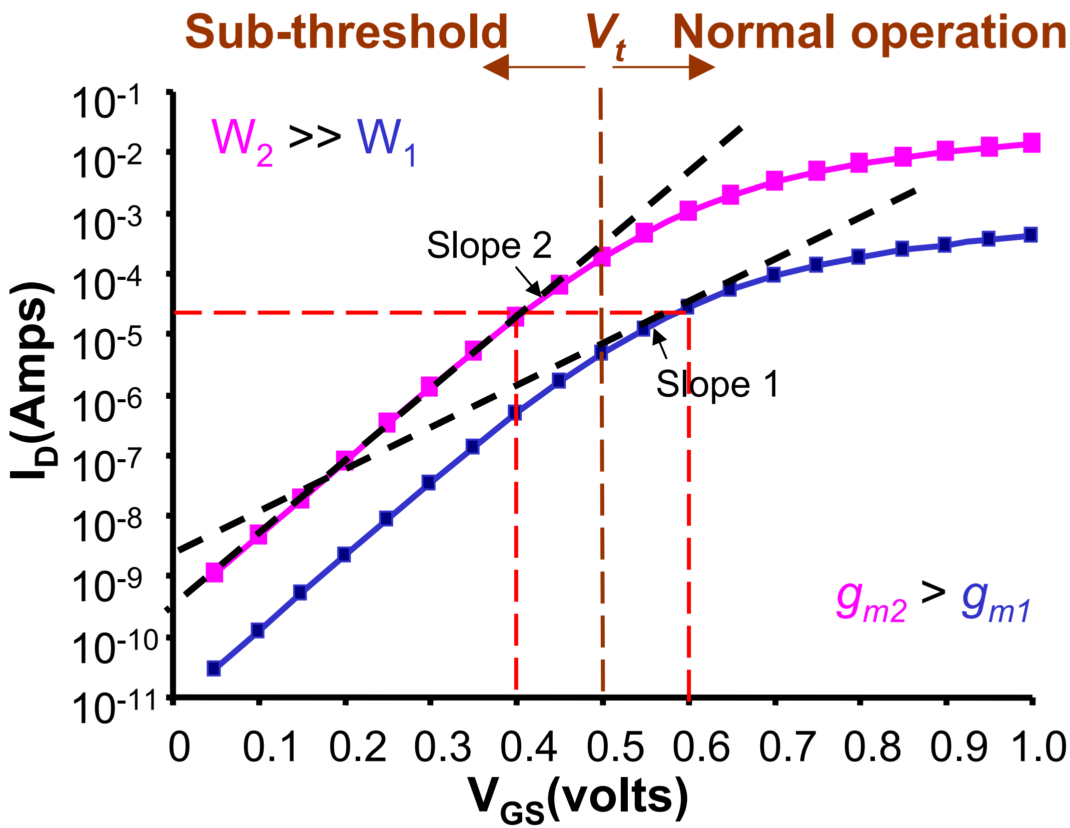
- **Minimize I_D for a given g_m**

For normal operation

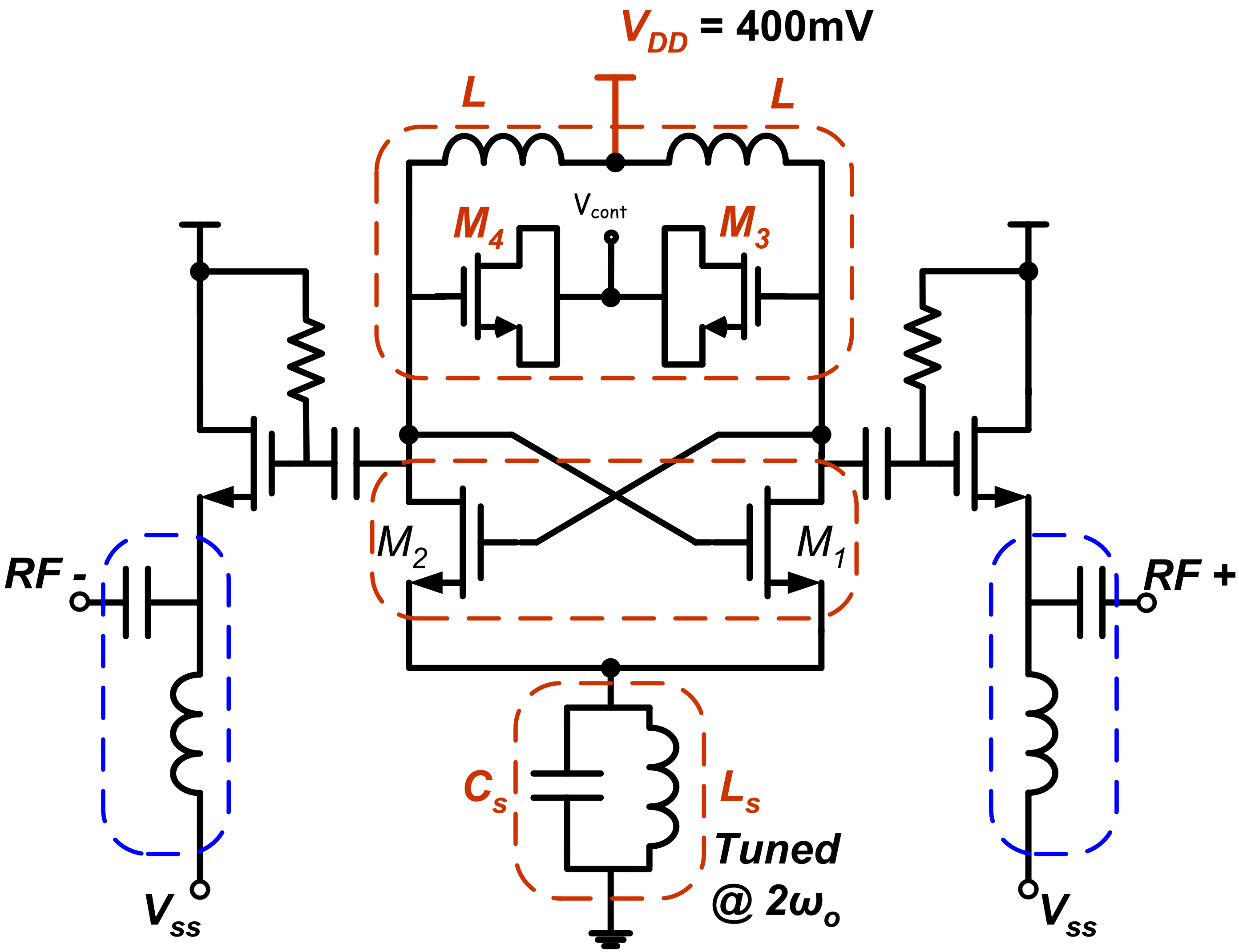
$$g_m = \sqrt{2\mu_n C_{ox}\left(\frac{W}{L}\right)I_D}$$

For sub-threshold

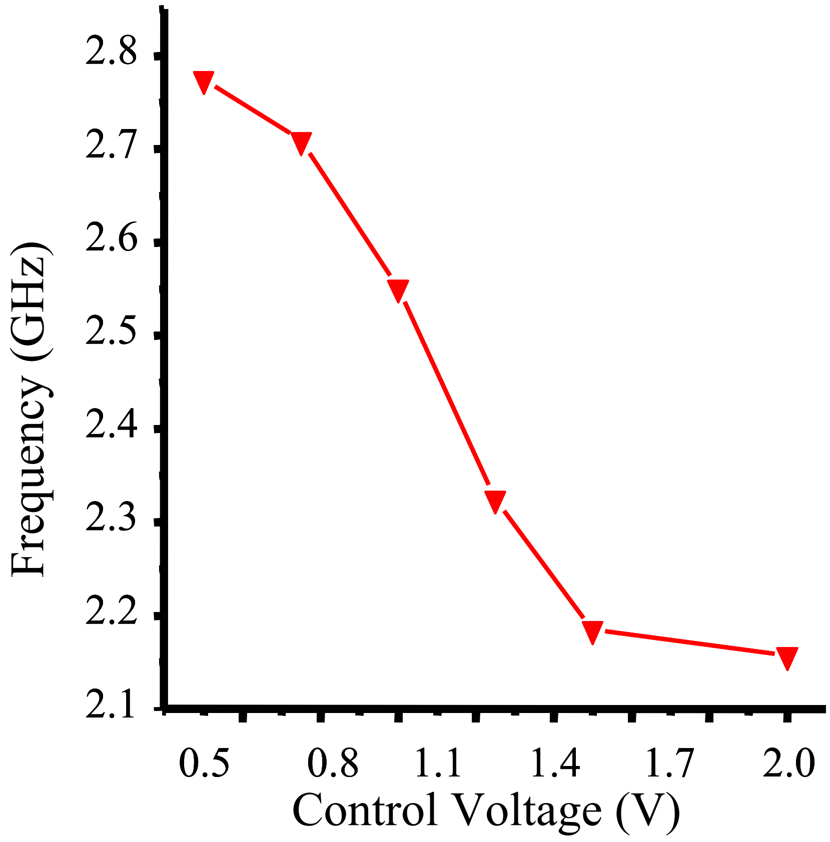
$$g_m = \frac{I_D}{n\varphi_t}$$

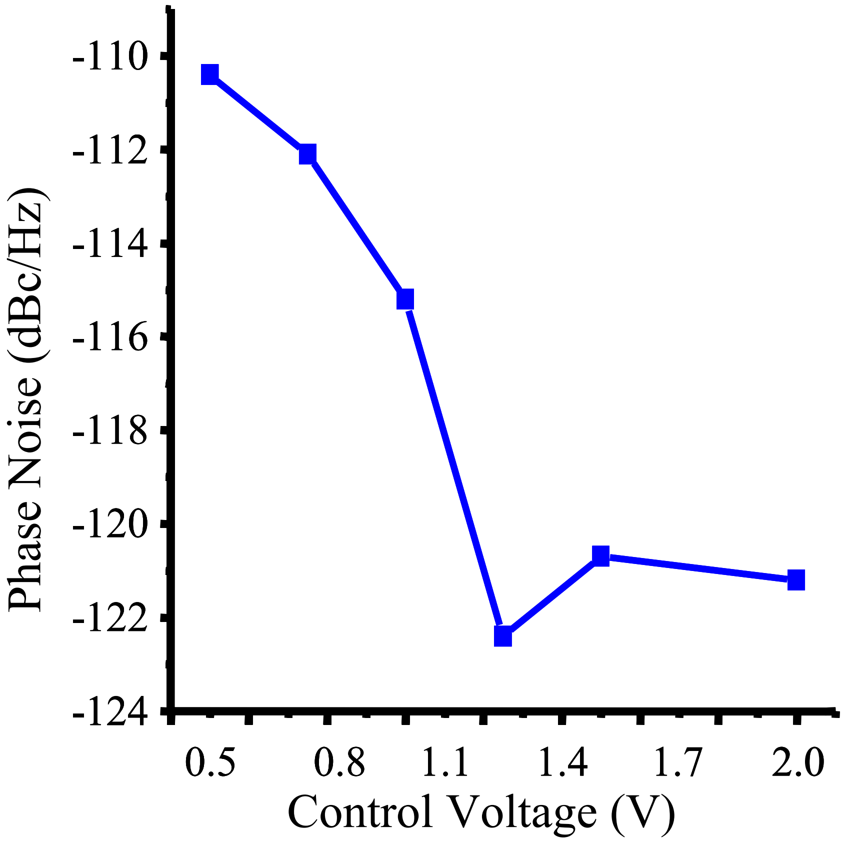


Oscillator Design



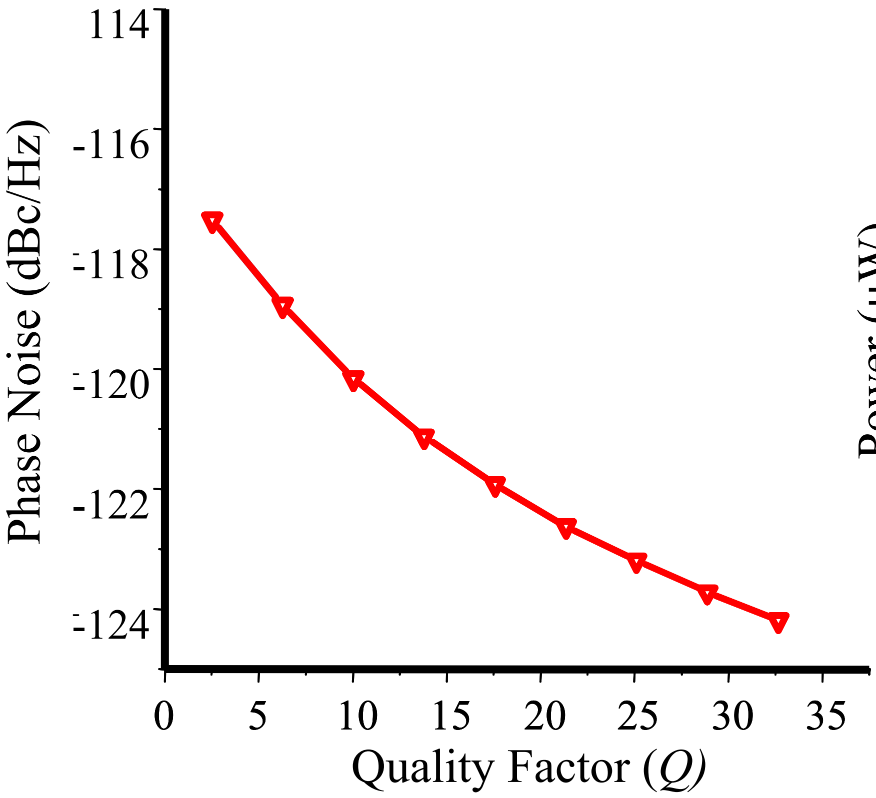
Results – Frequency and PN

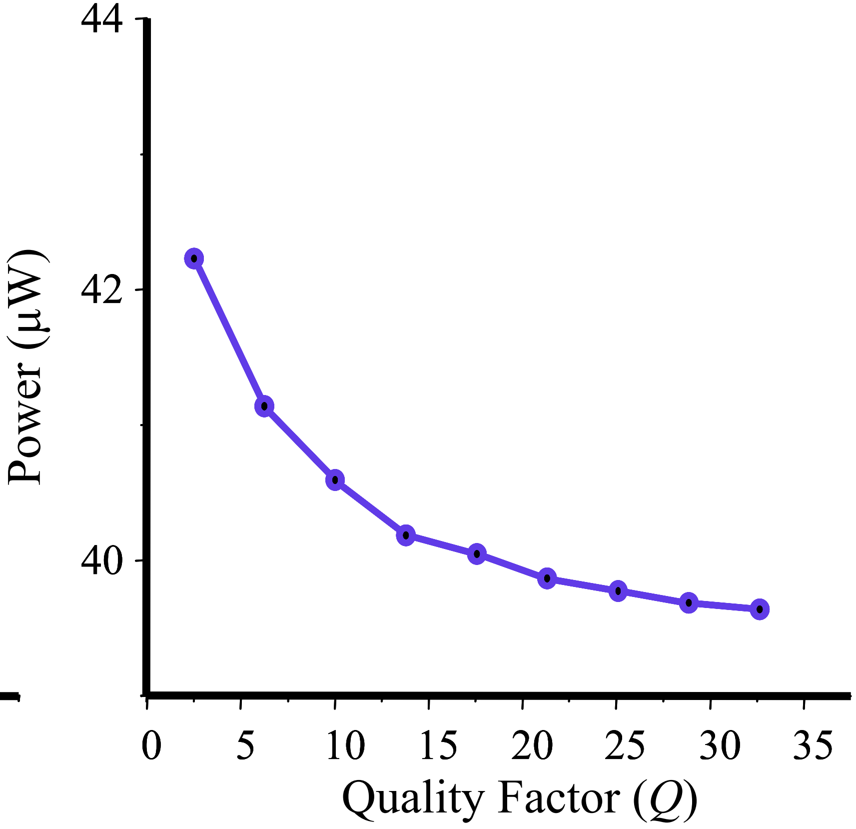




Results – PN and Power

- Effect of current-source tank circuit





Comparisons

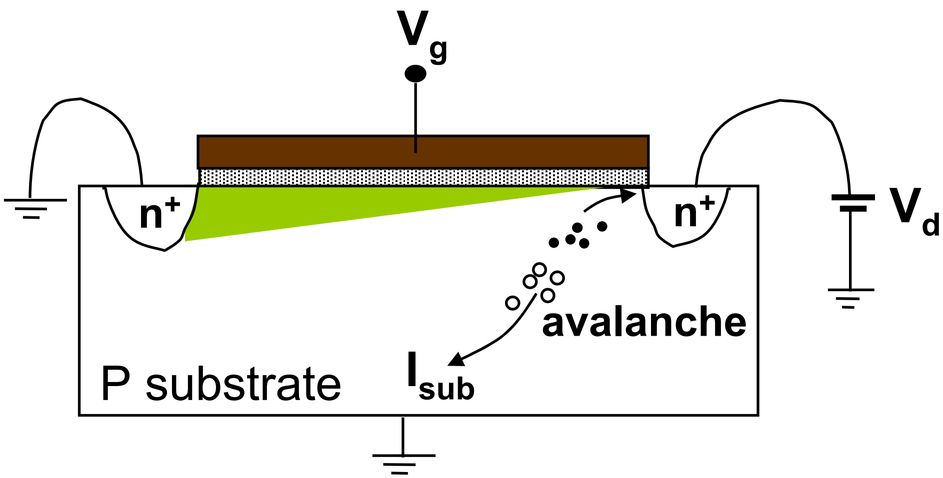
$$FoM = 20 \cdot \log\left(\frac{f_o}{f_m}\right) - PN - Power\,(dBm) - 20 \cdot \log(Q)$$

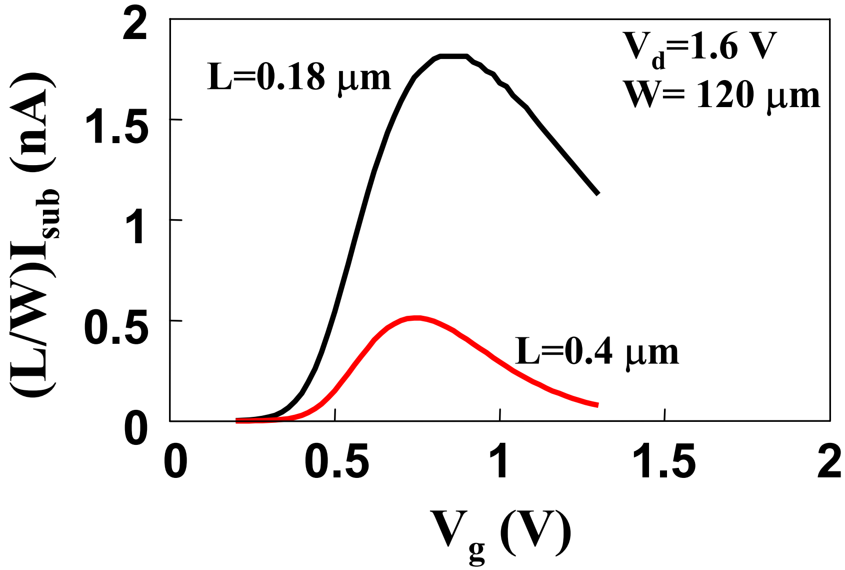
References	Q	f_o (GHz)	PN	$Power$ (mW)	FoM
This work	**60**	**2.4**	**-123@1MHz**	**0.04**	**168.5**
Troedsson, ASIC, 2002	13	2.4	-124@1MHz	5.5	161.6
Troedsson, RAWCON 2002	13.4	2.4	-130@3MHz	1.98	162.5
Mostafa, 2000	5	10	-101@100kHz	9	158.9

Hot Carrier Reliability - RF CMOS

- **Reducing the channel length of MOSFETs into deep submicron**
  - CMOS is now very attractive for RFICs
- **With channel length reduction**
  - Electric fields increase because of V_{DD} and L scaling
  - Hot carriers become an important reliability issue
- **HC damages lead to degradation of parameters of CMOS RF circuit**
  - Lower gain, higher noise figure, higher phase noise, …

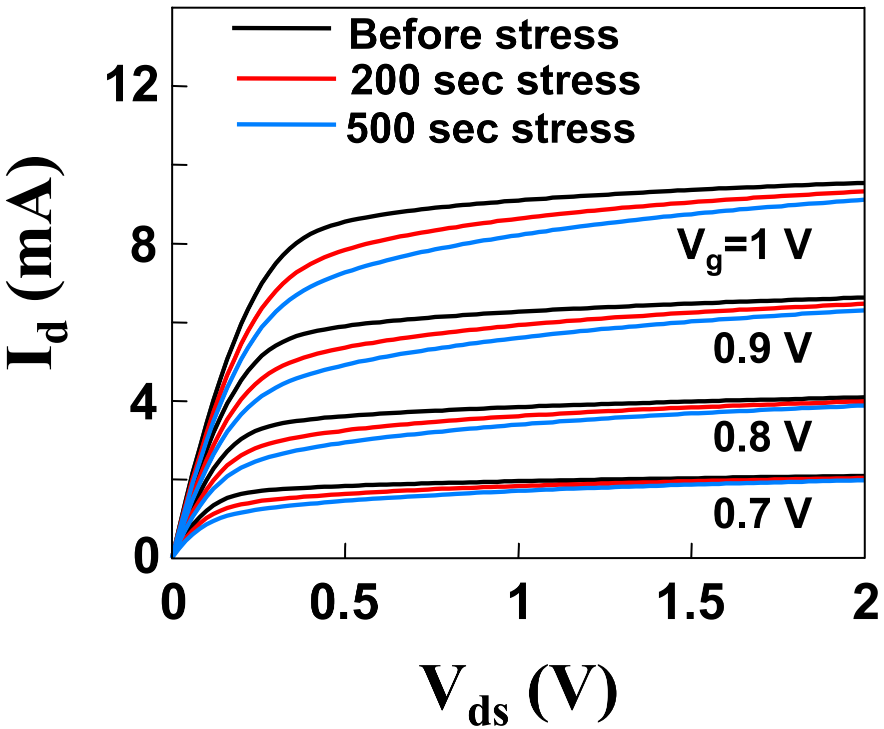
Hot Carriers in NMOSFETs

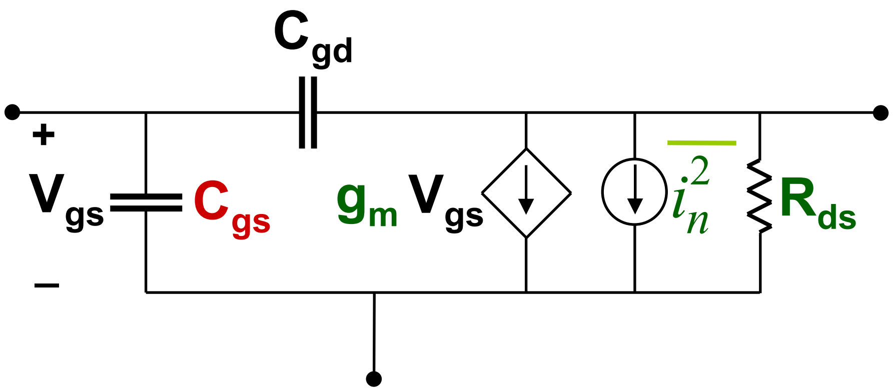




- Physical effects caused by hot carriers are interface traps and oxide trapped charges
- Substrate current can be used as a measure of stress

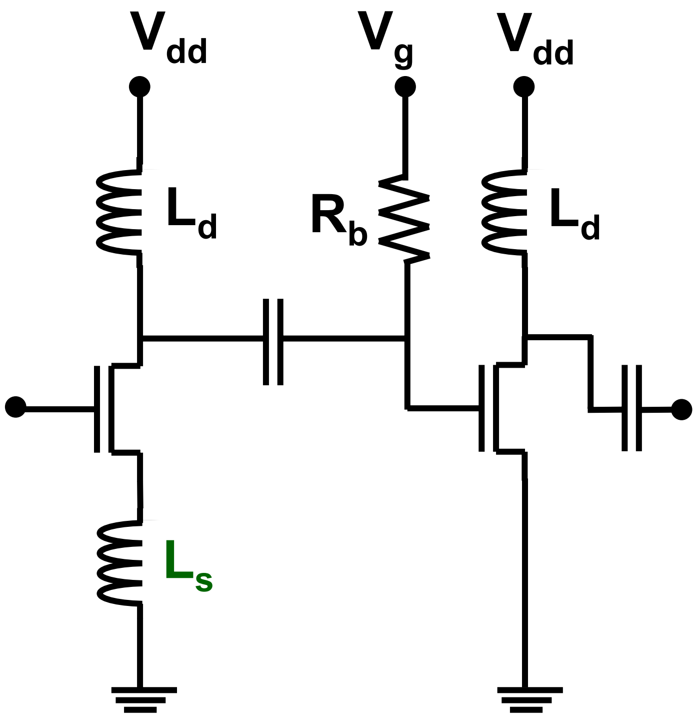
HC Effects - Device Performance

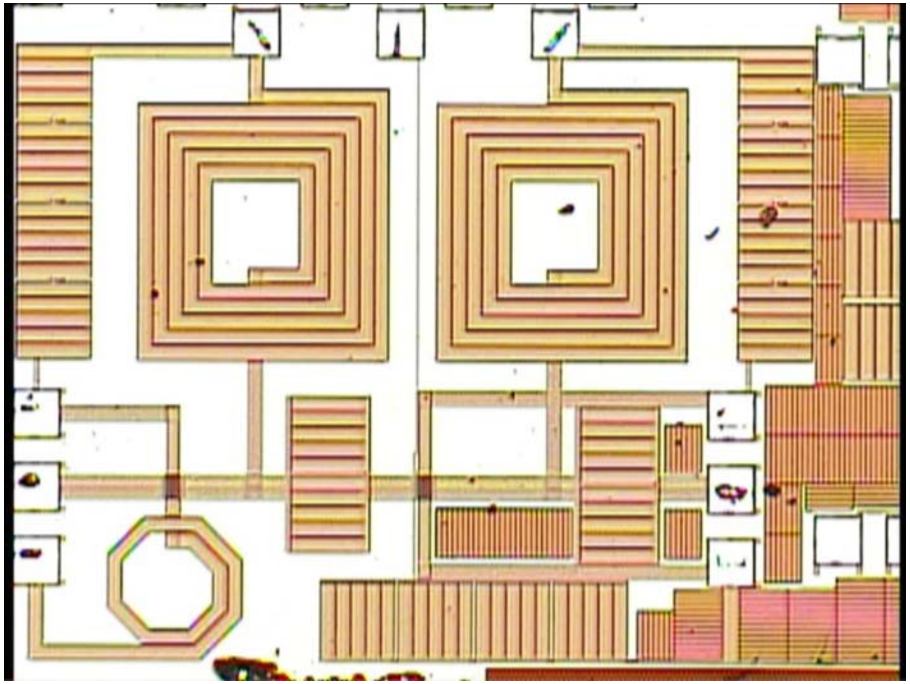




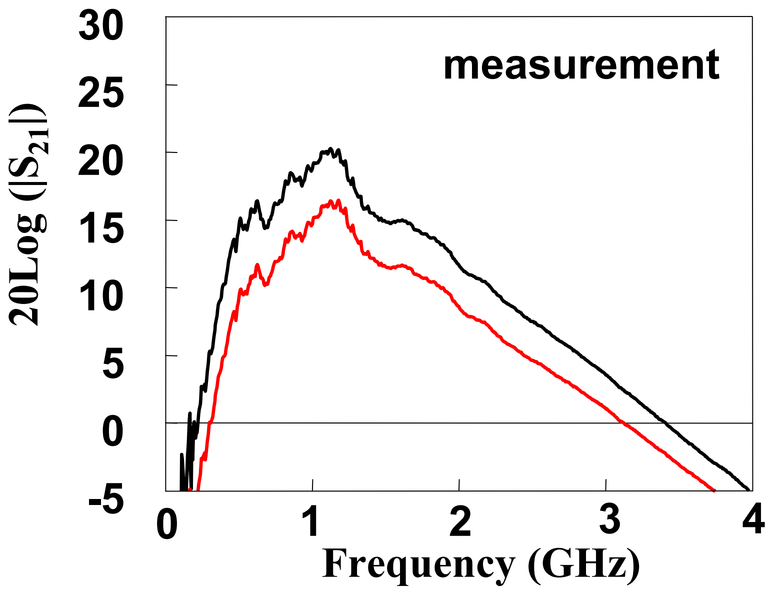
- HC deteriorate parameters such as V_{th}, g_m, g_{ds} , C_{gs}, and channel noise
- RF performance deterioration are manifested by degradation of f_T and f_{max}

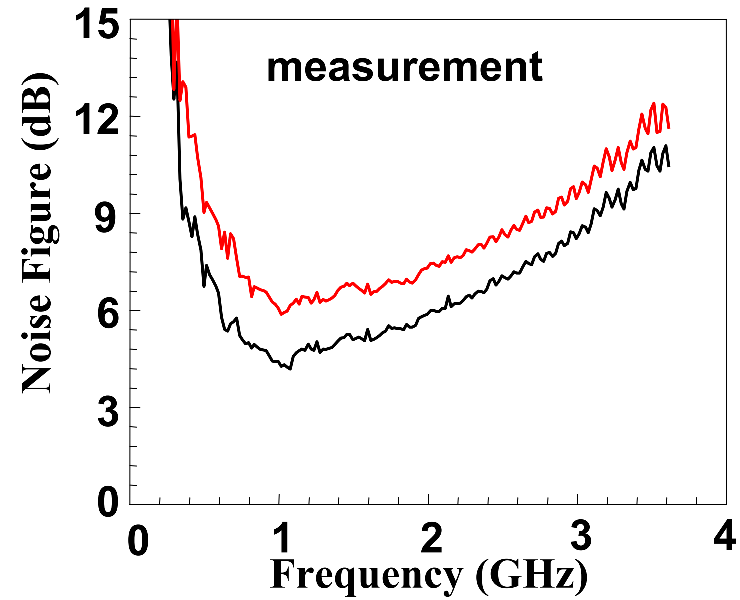
HC Effects on RF Circuits: LNA

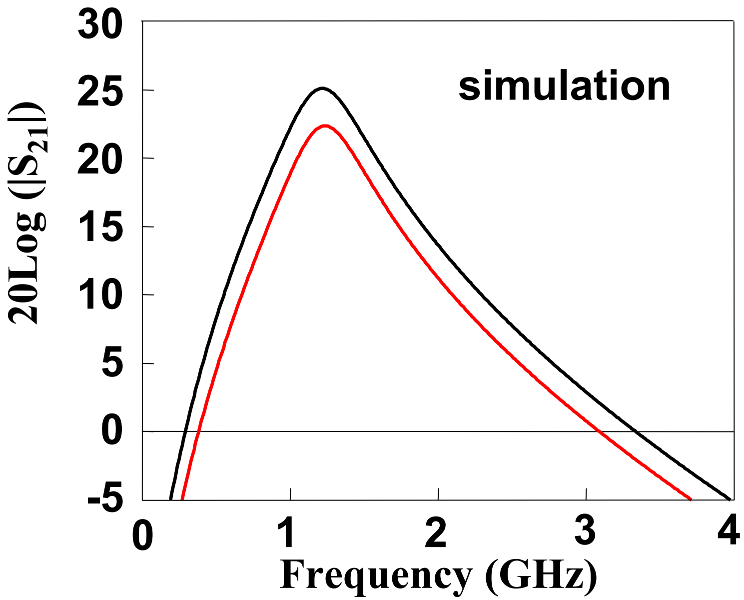


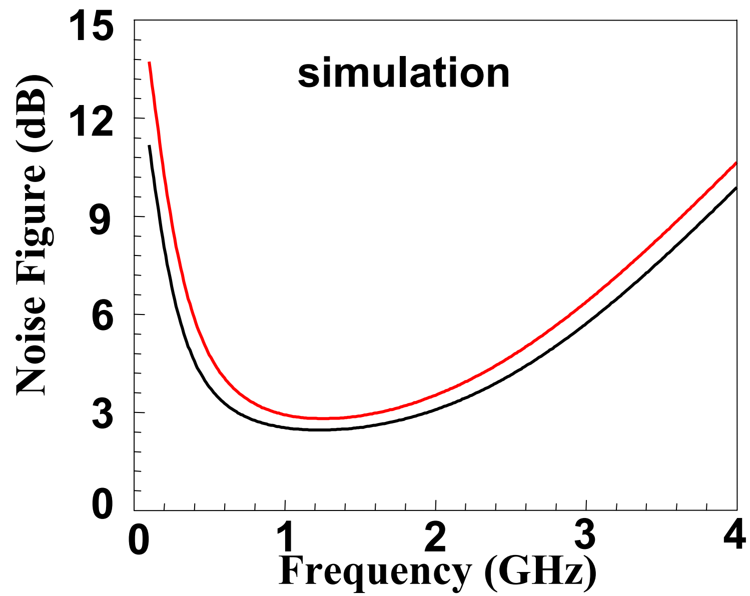


HC Effects on Gain, NF

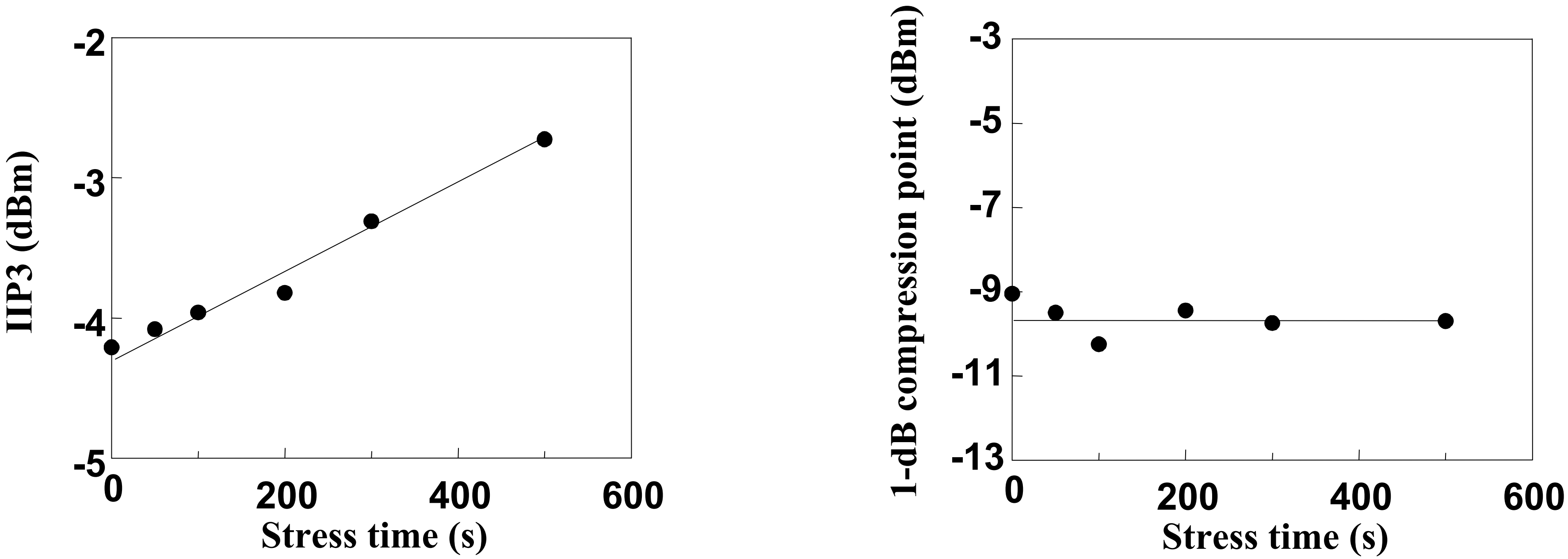








HC Effects on Linearity

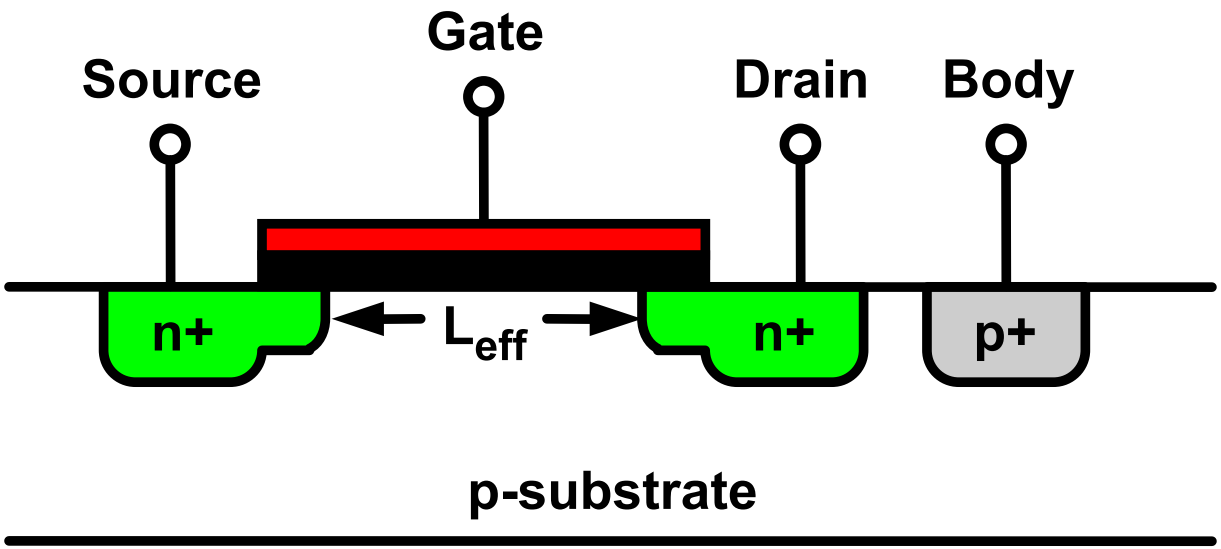


- Linearity might be affected by HC

Mismatch Issues - Oscillator

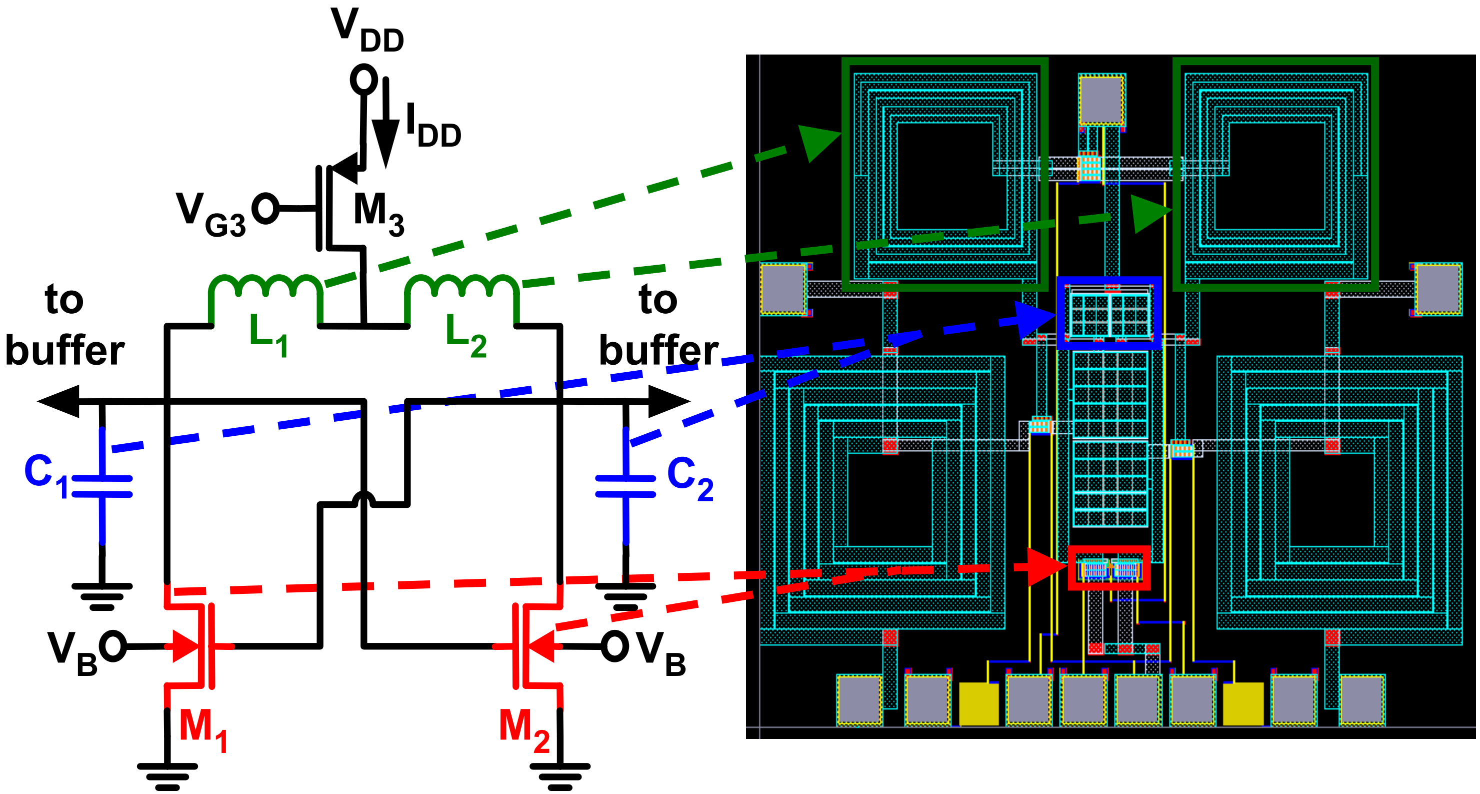
- Increasing use of CMOS for RFICs
- Process- and design-induced mismatch effects will become increasingly important
- Few publications on mismatch at high frequencies
- Many published research at lower frequencies
- Better prediction of RFICs' performance

Oscillator Mismatch Issues



- Transistor’s dimensions at design and simulation stages are different from fabrication
- Transistor’s channel length smaller than its channel width
- CLFEs are crucial on differential RFICs

Oscillator Mismatch Issues

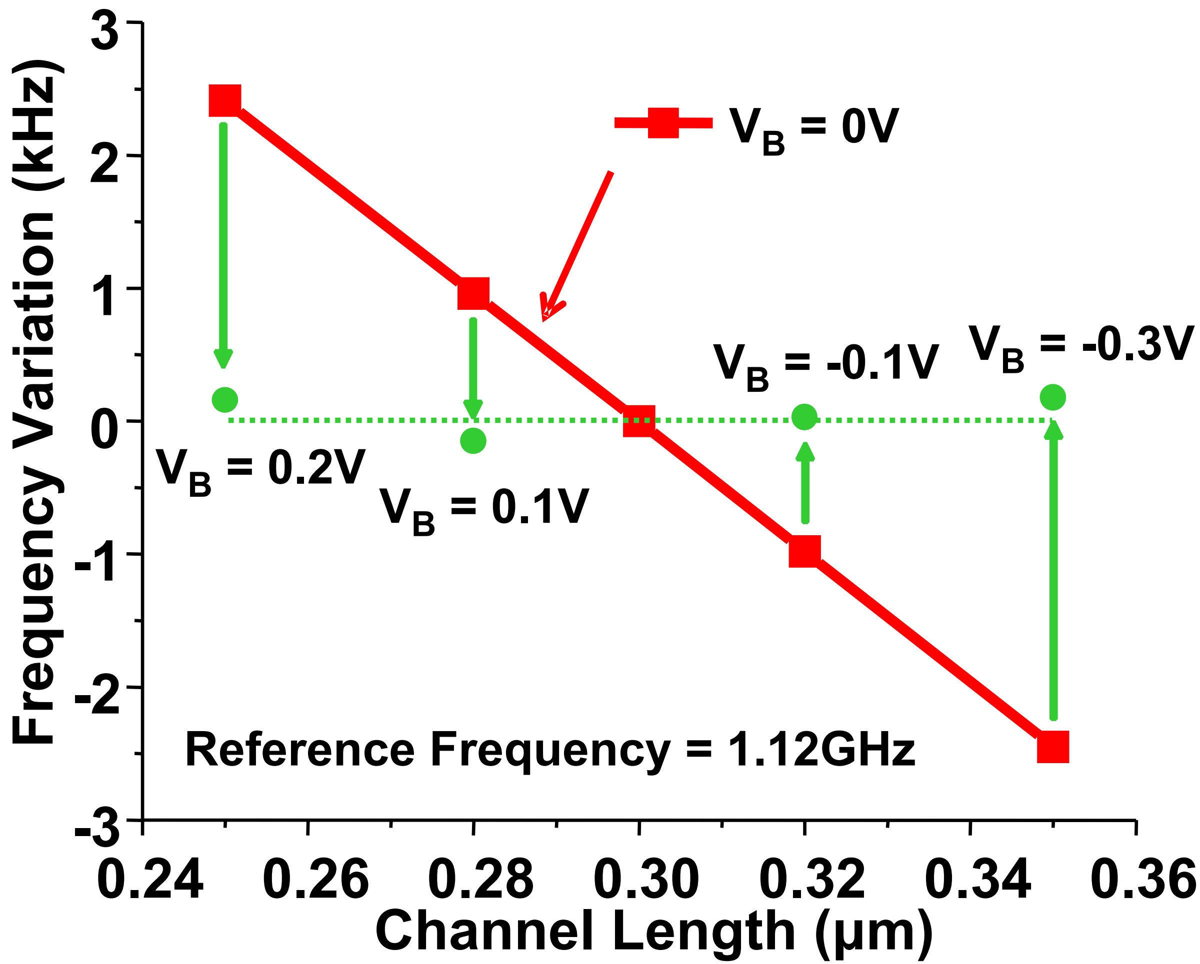


- M_1, M_2: L = 0.25µm, 0.28µm, 0.3µm (reference), 0.32µm, 0.35µm
- **Power** = 6.48mW and **Current** I_{DD} = 3.6mA are approximately constant for all channel length values

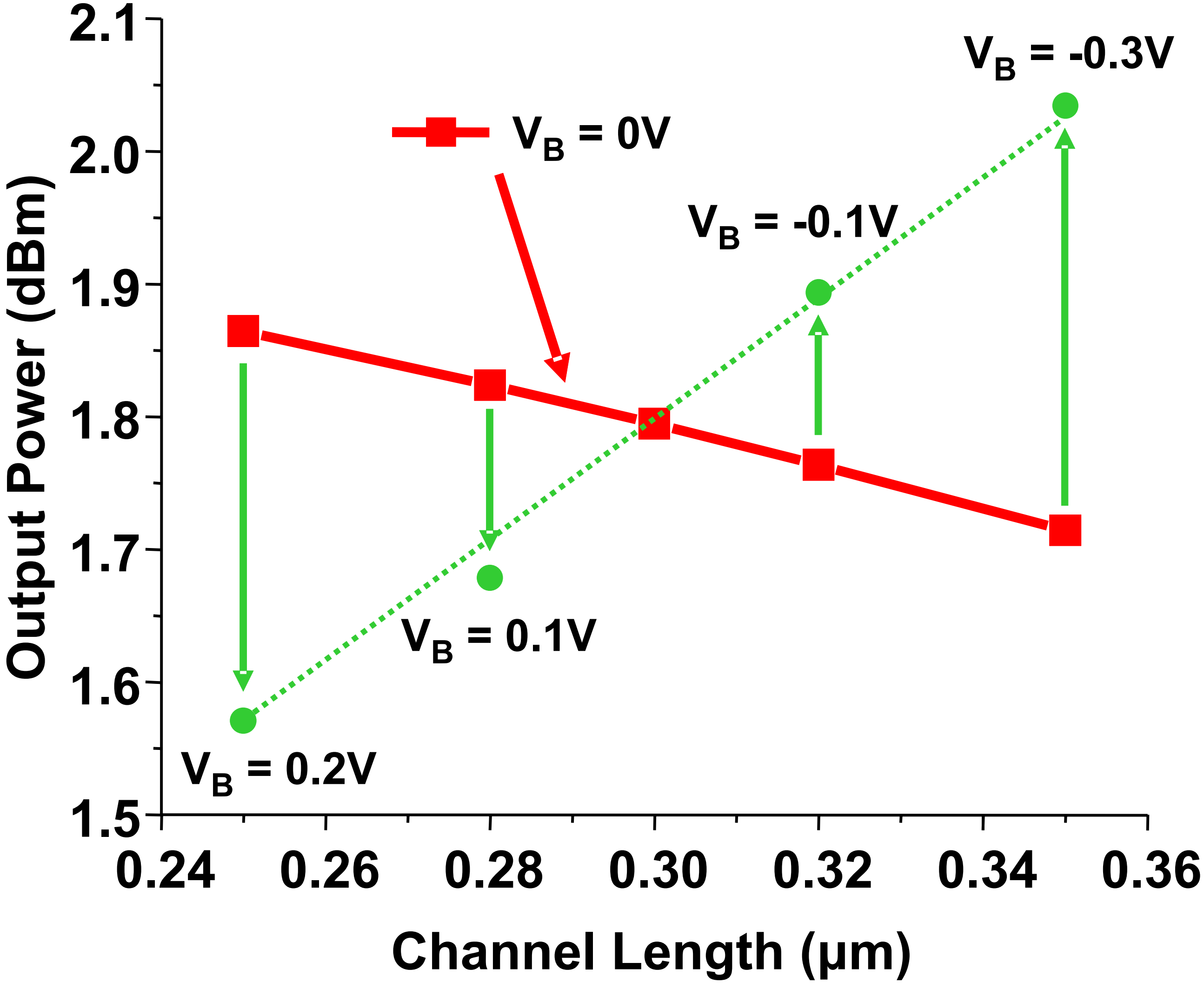
CLFEs on Oscillator Frequency

$$\Delta f_0 = \frac{1}{2\pi\sqrt{L}}\left(\frac{1}{\sqrt{2C_t + C_{gs,fab}}} - \frac{1}{\sqrt{2C_t + C_{gs,design}}}\right)$$

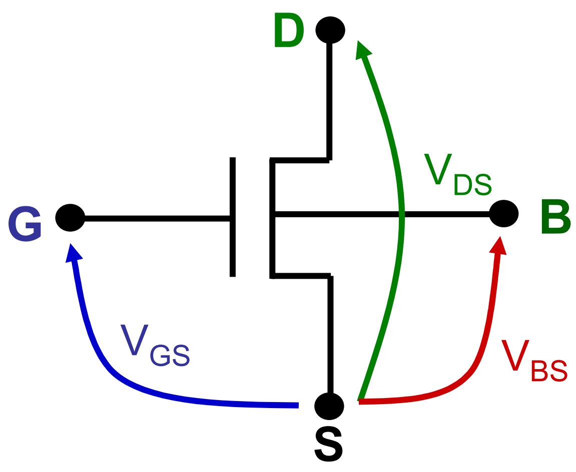
$$C_{gs,fab} = C_{gs,design}\left(\frac{L_{eff,fab}}{L_{eff,design}}\right)$$

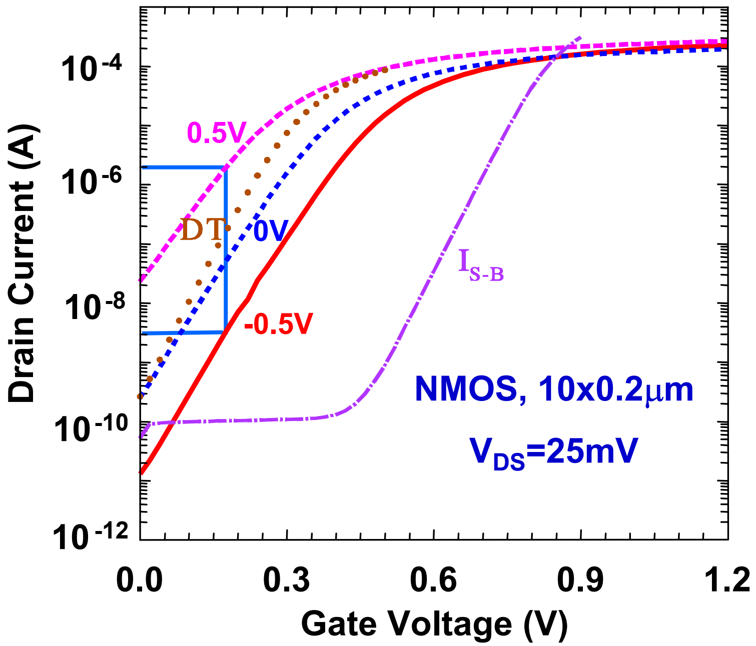


CLFEs on Output Power



Trend – New Operation Mode

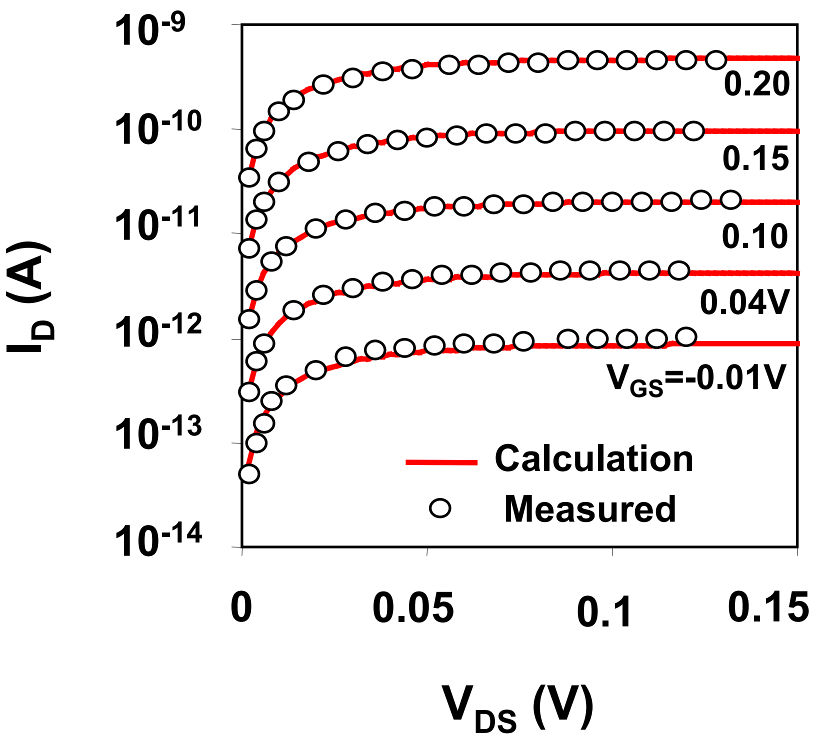




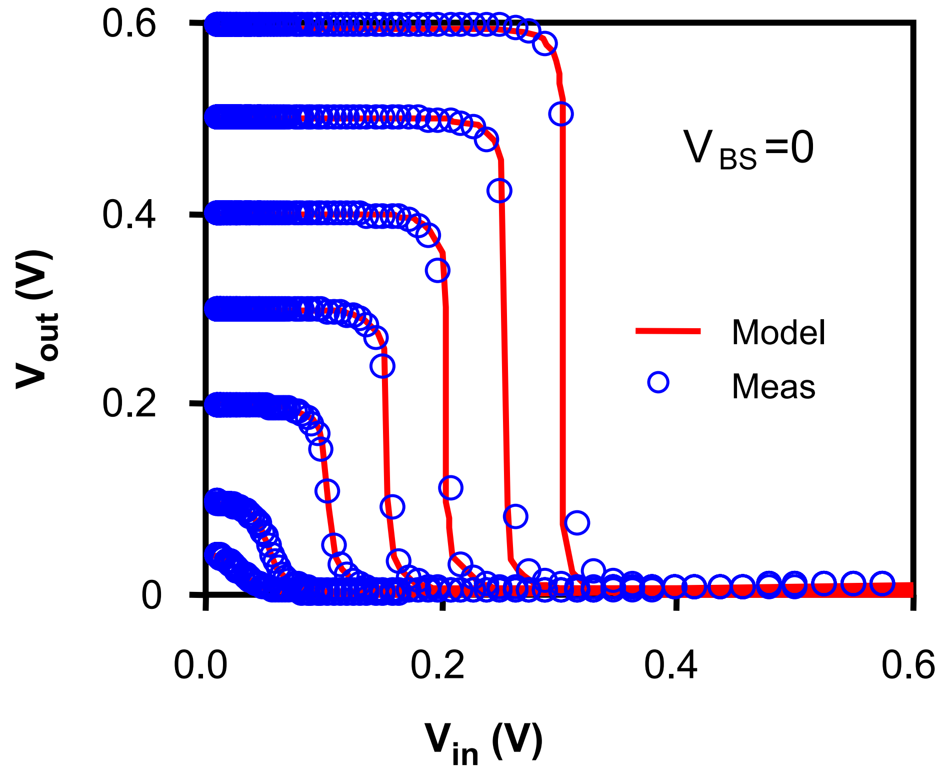
- V_{BS} improves the MOSFET performance
  - **Forward substrate** biasing (V_{BS}>0) reduces the threshold voltage V_T ➔ low voltage applications
  - **Forward substrate** biasing (V_{BS}>0) speeds - up the MOSFET ➔ RF applications
  - **Reverse substrate** biasing (V_{BS}<0) reduces the I_D ➔ low power applications

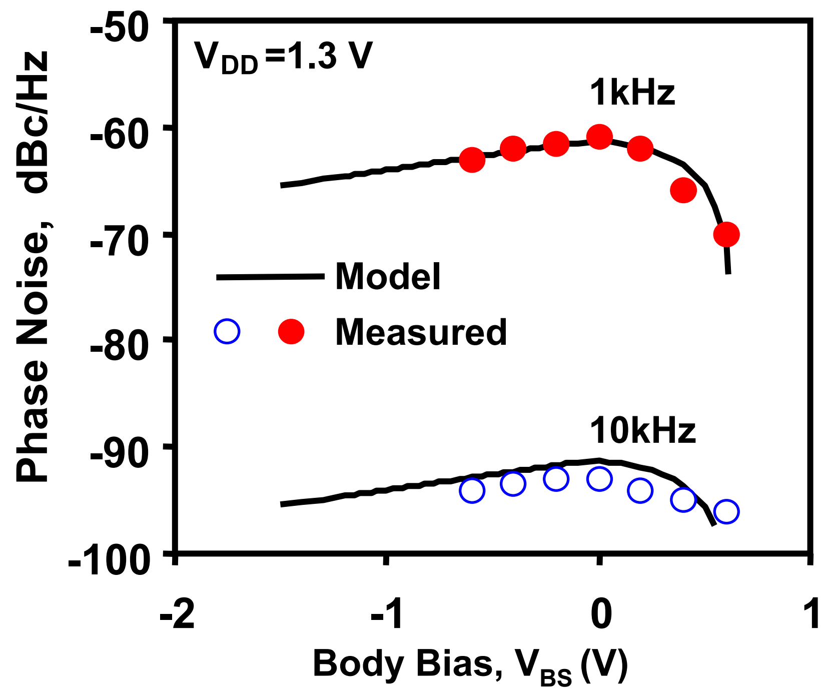
Design: Sub-Threshold

- Operate transistor in weak inversion
- Very low V_{DS} required to operate transistor
  - ➔ **low-voltage applications**
- Drain current I_D also very low
  - ➔ **low-power applications**



VTC and Phase noise





Measurement: RO VCO functional down to ~ 80 mV supply voltage.

Body voltage can affect the phase noise in ring oscillator

Conclusions

- Low voltage mixers
  - Gilbert cell and body-input mixers (0.8V, 0.4mW)
- Oscillators
  - VCO with AAC and micro-power VCO (o.4V, 40μW)
- Hot-carrier effects on LNAs
  - Reduced gain, increased noise figure
- Mismatch effects on oscillator
- Trends- deep subthreshold oscillator

Thank You!