CMOS VLSI Frequency Translation for Multi-Standard Wireless Communication Transceivers

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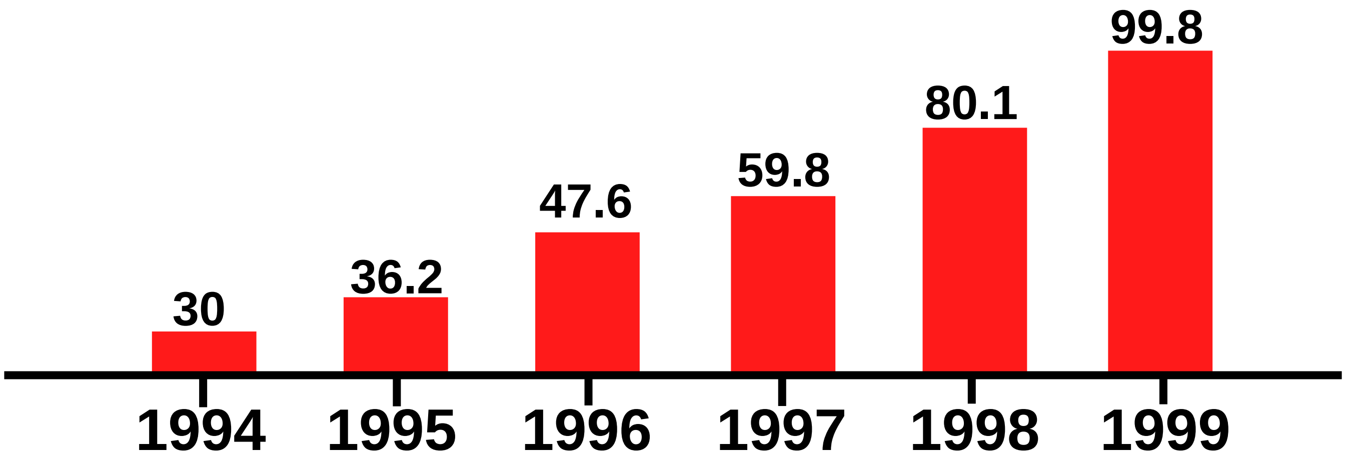
Qualifying Examination

April 8th, 1996

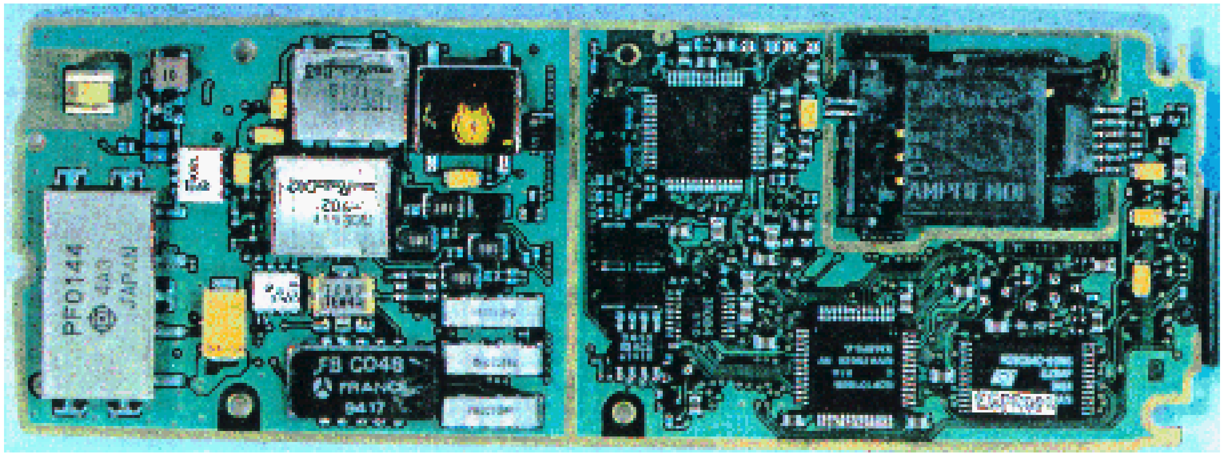
High Demand for Portable Transceivers

Projected World-Wide Cellular Phone Sales (units in millions)
(Source:Dataquest)



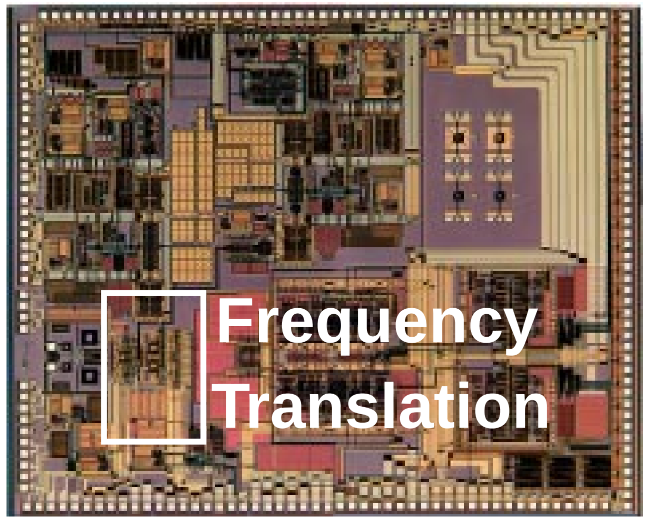
- **Variety of RF standards**
- **Cellular, Cordless, and PCS transceiver units all require:**
  - **Low Cost**
  - **Low Power**
  - **Portability**

Existing Hardware Solutions are Inefficient



- Current transceiver requires many discrete components
- Multi-components are highly power & cost inefficient
- Multi-standard capability prohibitively large

Multi-Standard CMOS Solution



- **Single Chip Solution**
- **CMOS Technology**
- **Multi-Standard Sol.**

Lower Power

Lower Cost

Increased Portability

Frequency Translation w/o Discrete Components

Research Proposal

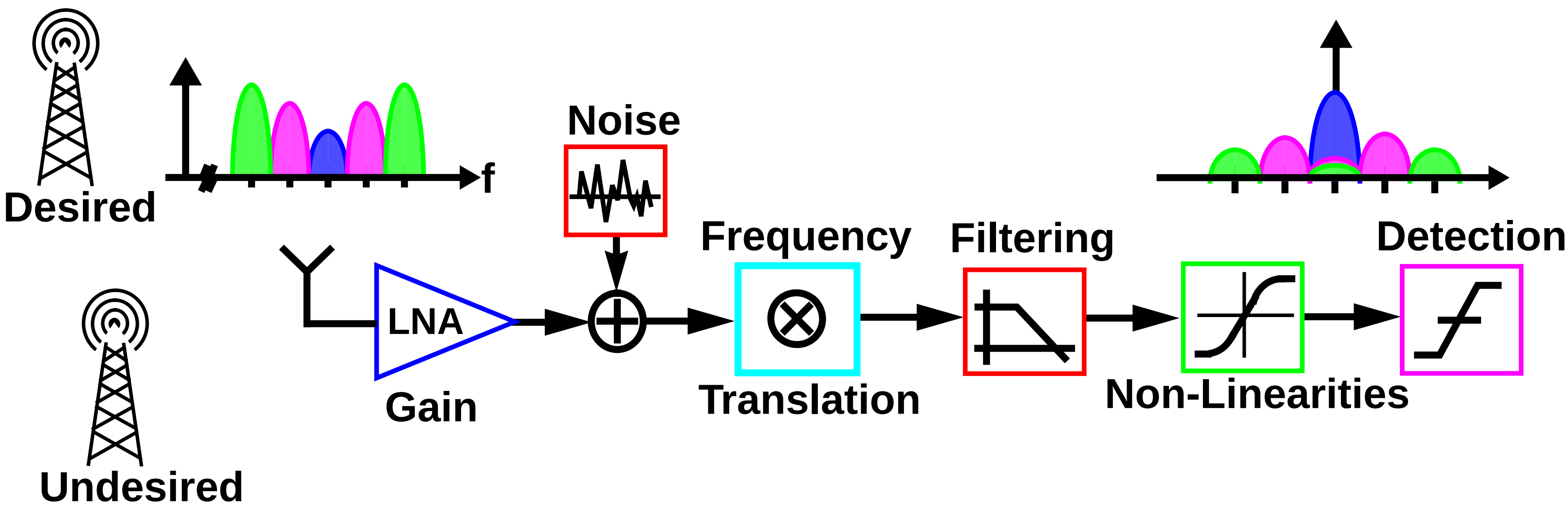
System Contribution

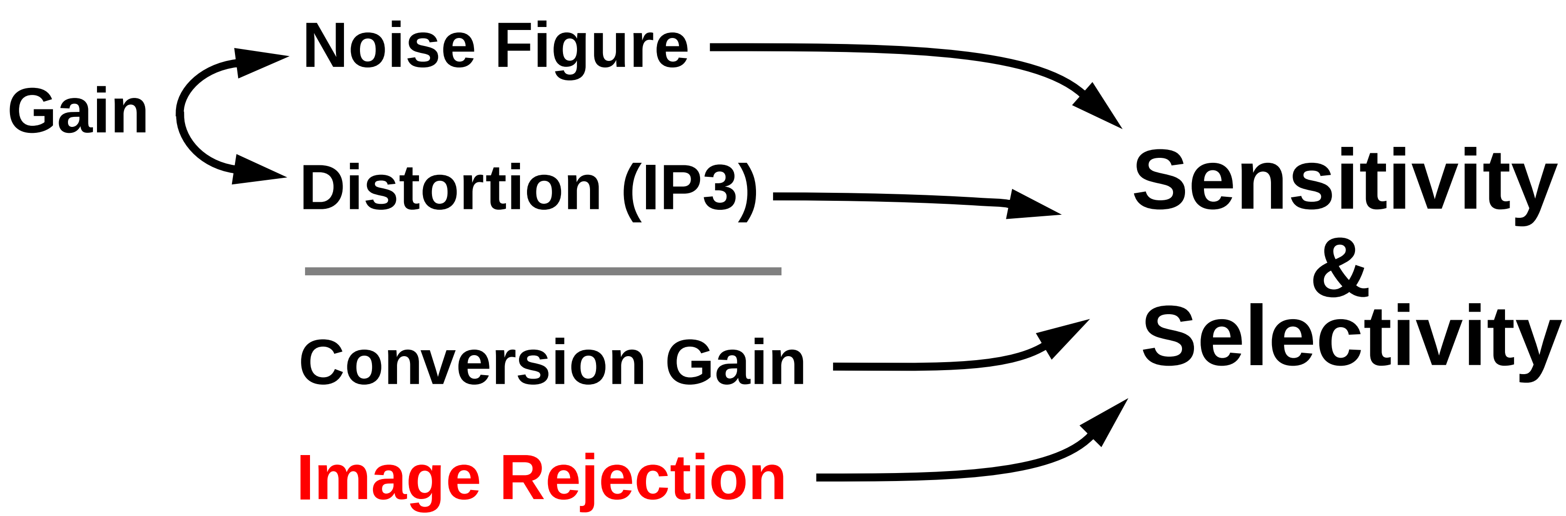
- Examine solutions to full integration of frequency translation system
- Frequency translation w/ multi-standard capability

Circuit Contribution

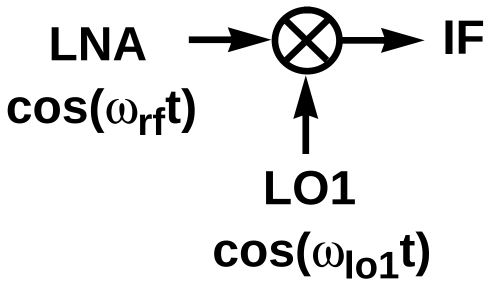
- Determine the fundamental limits of CMOS mixers in a multi-standard environment

Receiver Issues





Frequency Translation Basics



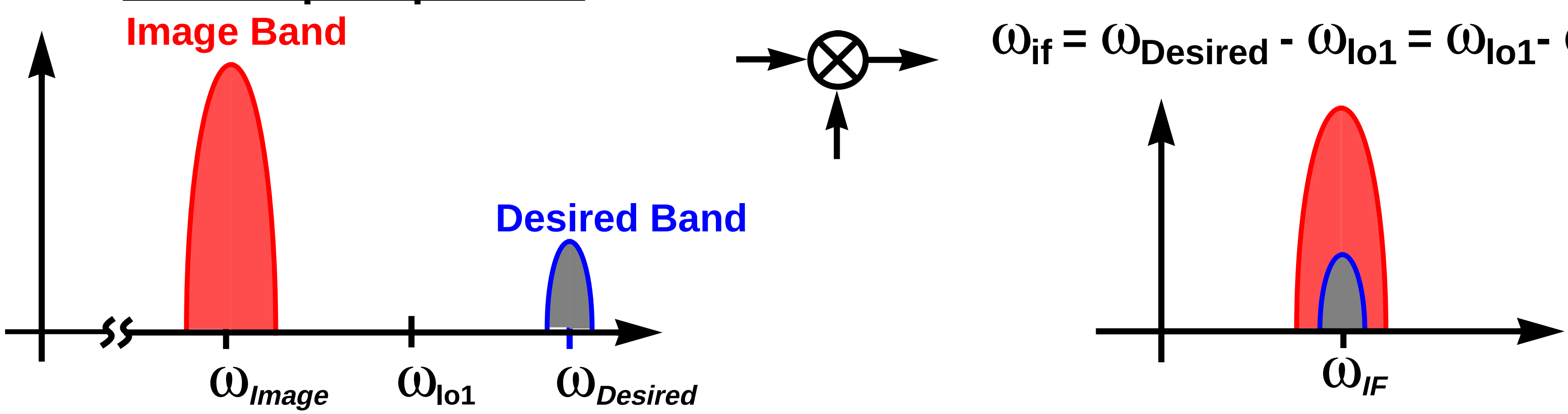
$$\cos(\omega_{rf}t) \bullet \cos(\omega_{lo1}t) =$$

$$1/2\ [\ \cos(\{\omega_{rf} - \omega_{lo1}\}t) + \cos(\{\omega_{rf} + \omega_{lo1}\}t)\ ]$$

LNA Output Spectrum

IF Output

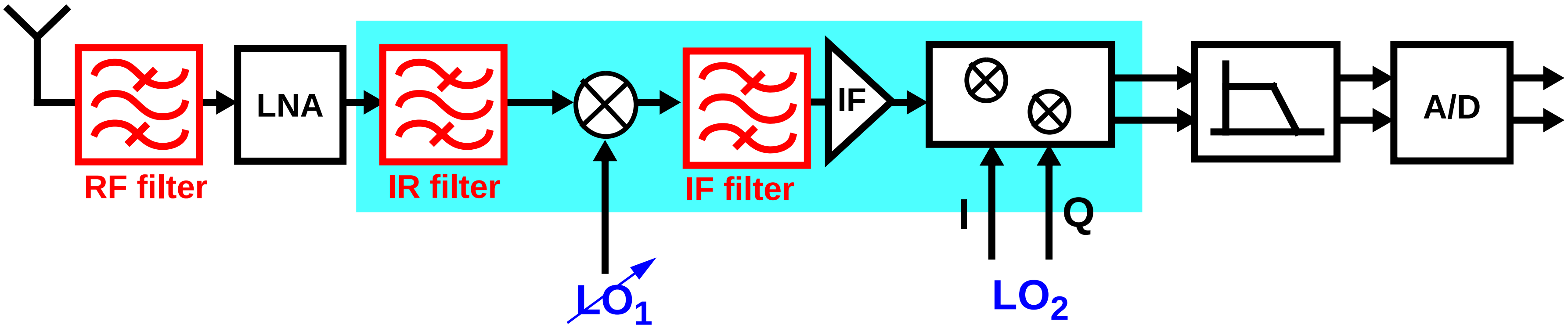
$$\omega_{if} = \omega_{Desired} - \omega_{lo1} = \omega_{lo1} - \omega_{image}$$



Standard	Image Rejection
IS54	60dB
GSM	70dB
DECT	70dB

Traditional Receiver Architecture

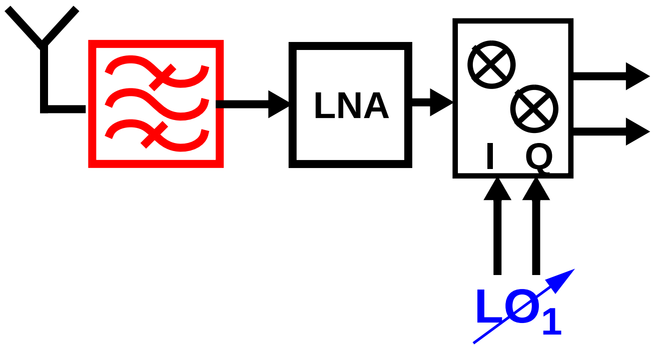
Conventional Super-Heterodyne Receiver



- IR SAW filter: image rejection & noise reduction in LO_1 mixer
- Bandpass IF filter reduces distortion

Existing Approaches to Integration

Homodyne



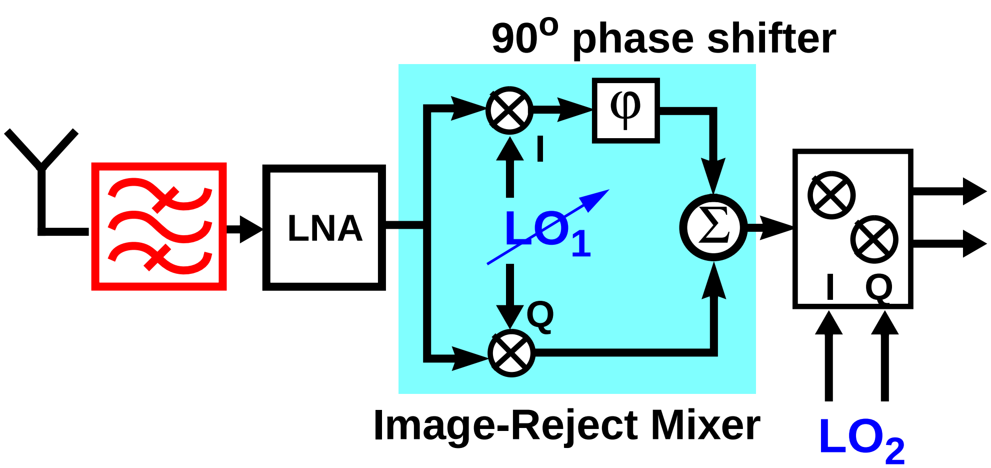
Advantage

- Zero IF, no image band present

Disadvantage

- LO leakage problem

Heterodyne w/ Image-Rejection



Advantage

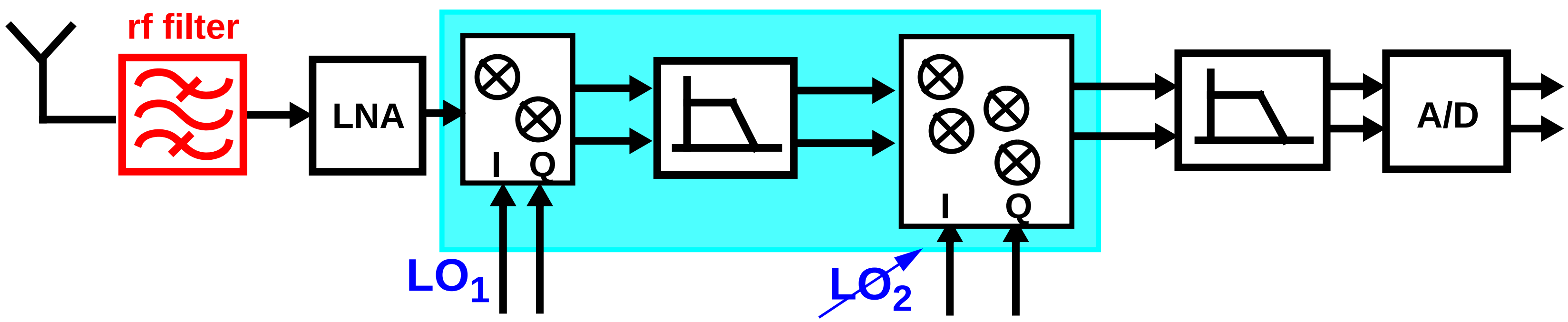
- Need for IR filter eliminated

Disadvantage

- 90^o phase shifter requires passive component tuning & matching

Multi-Standard Receiver Architecture

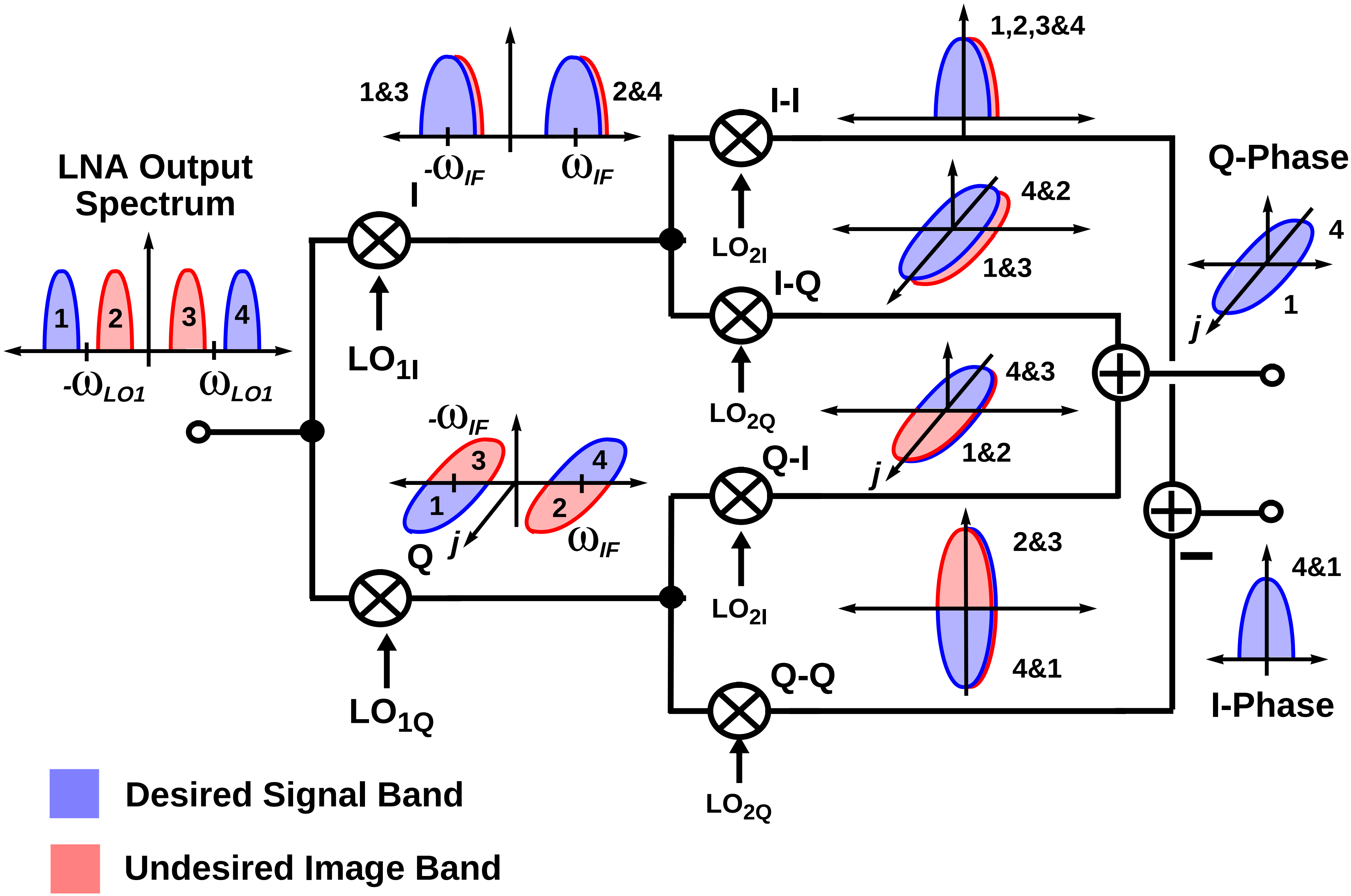
Wideband-Heterodyne w/ Double Conversion



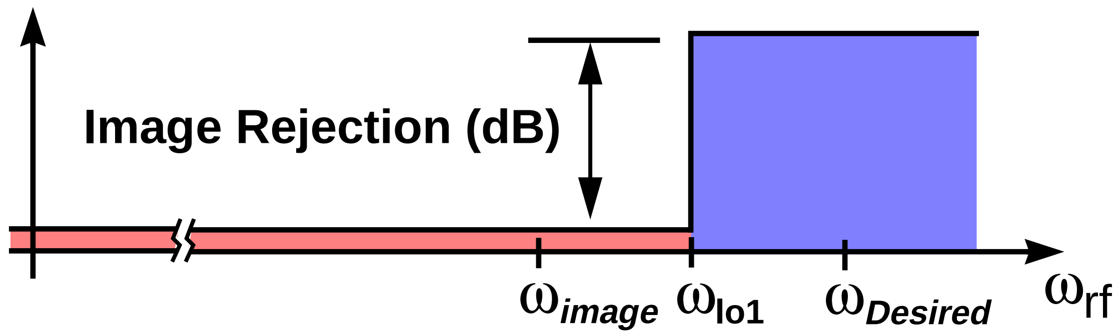
- New approach utilizes six analog continuous time active mixers
- Mixer performs image-rejection and modulation to baseband
- LO2 channel selection affects image-rejection mixer specifications

Off-chip filters replaced by active rejection

Image Cancellation Scheme



New Architecture is Multi-Standard Capable



- Image attenuation is independent of passive components; exploits the odd and even properties of sine and cosine
- Pass & stop band determined by ω_{LO1} & ω_{LO2} only
- Sharp transition between pass & stop band
- Image-rejection mixer is programmable

Image Rejection is self-aligning

Mixer Architectural Non-Idealities

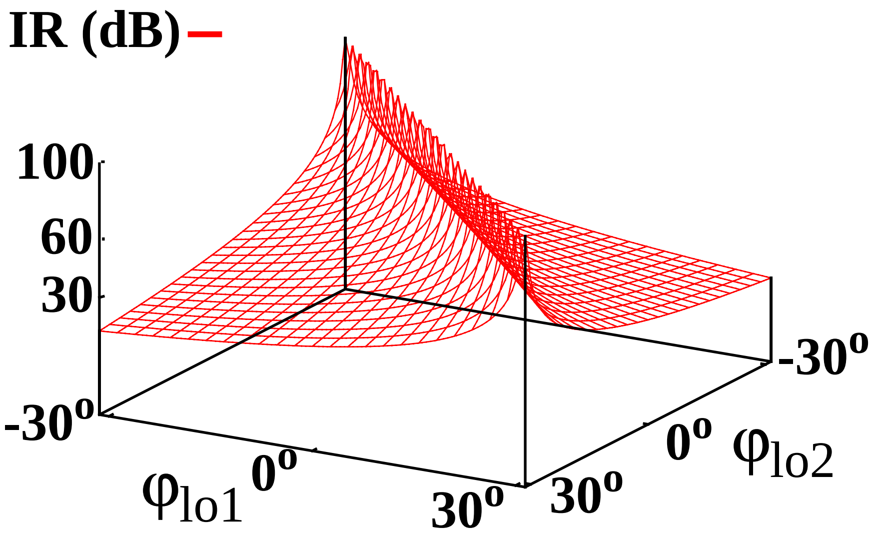


Image Attentuation vs. LO phase error

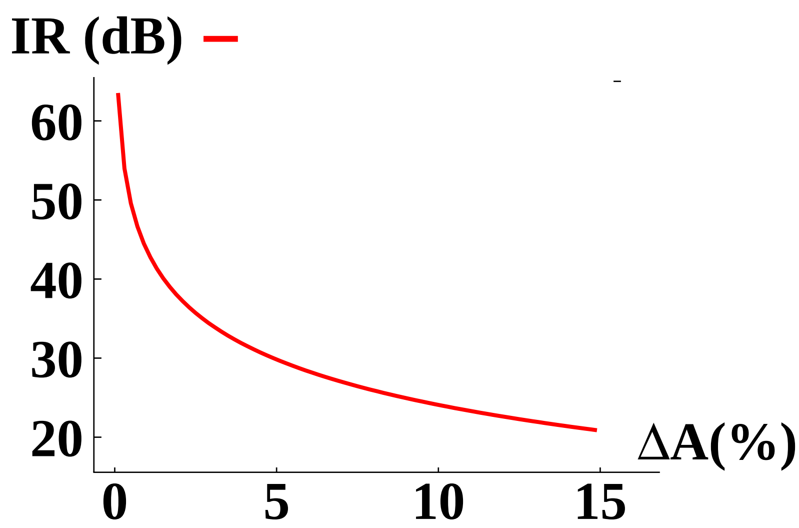
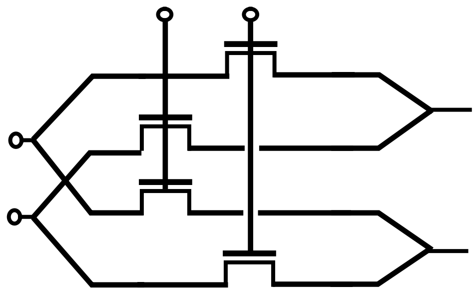


Image Attentuation vs. Gain Mismatch (%)

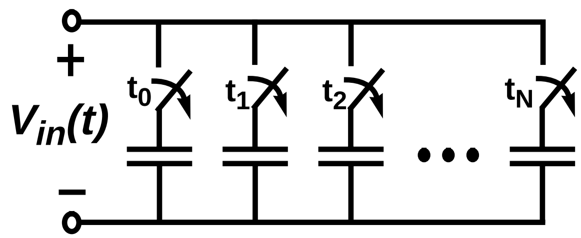
- Matching is a critical issue
    - 30dB of IR requires I/Q phase matching better than 4^{o}
    - 5% gain error for 30dB of image-rejection

Mixer Topologies

Passive Mixers



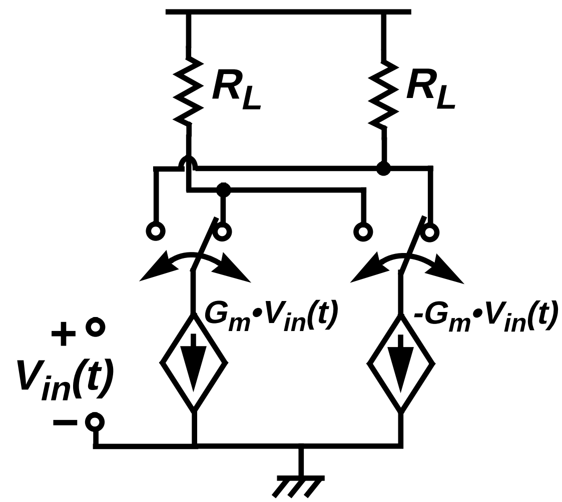
Resistive/Switching Demodulator



Sampling Demodulator

- **No static power consumption**
- **Excellent linearity**
- **Low gain - conversion loss**
- **Poor noise performance**

Active Mixers

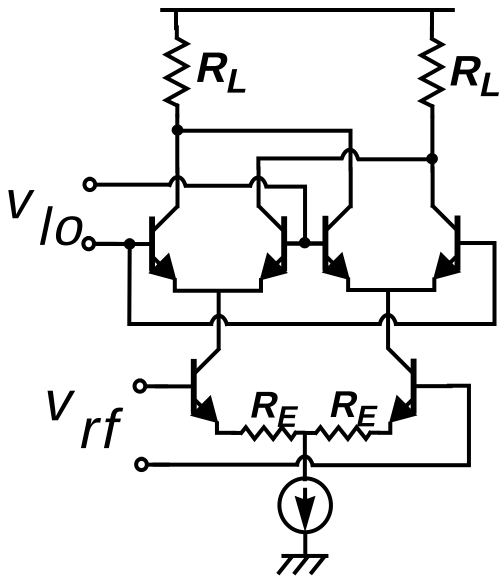


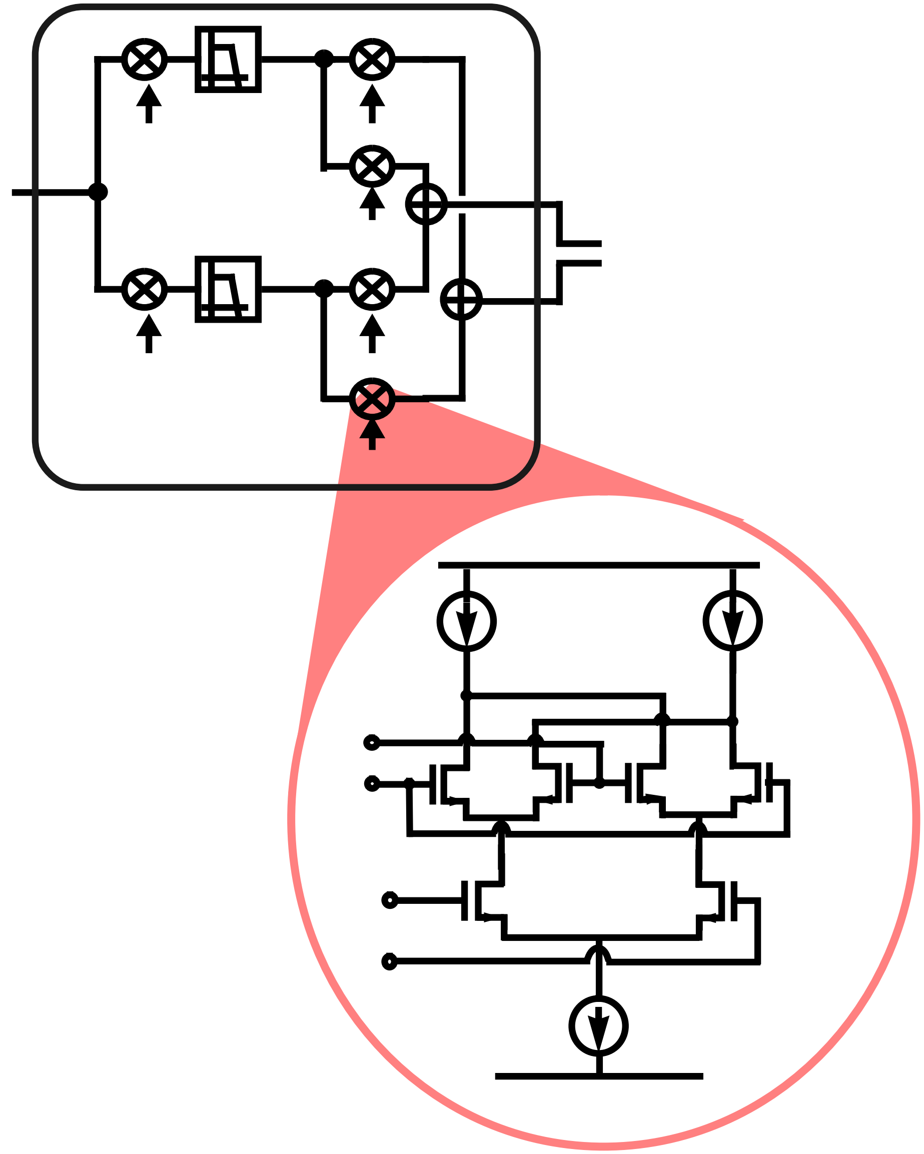
Current Modulator

- **Static power consumption**
- **Fair linearity**
- **Fair gain**
- **Clear design trade-offs**

Gilbert Cell Performs Current Modulation

(Barrie Gilbert, JSSC Dec. 1968)



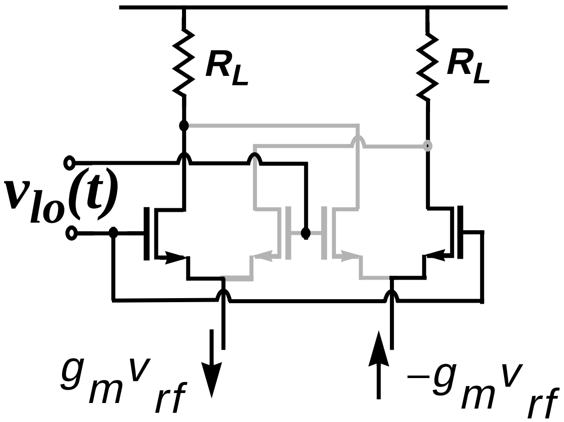


- **Input differential pair acts as gain stage**
- **Bipolar / CMOS devices driven w/ LO act as switches**

Conversion Gain of a CMOS Gilbert Cell

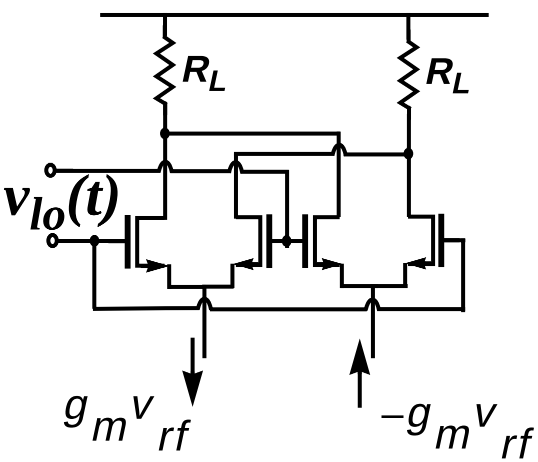
Unbalanced State

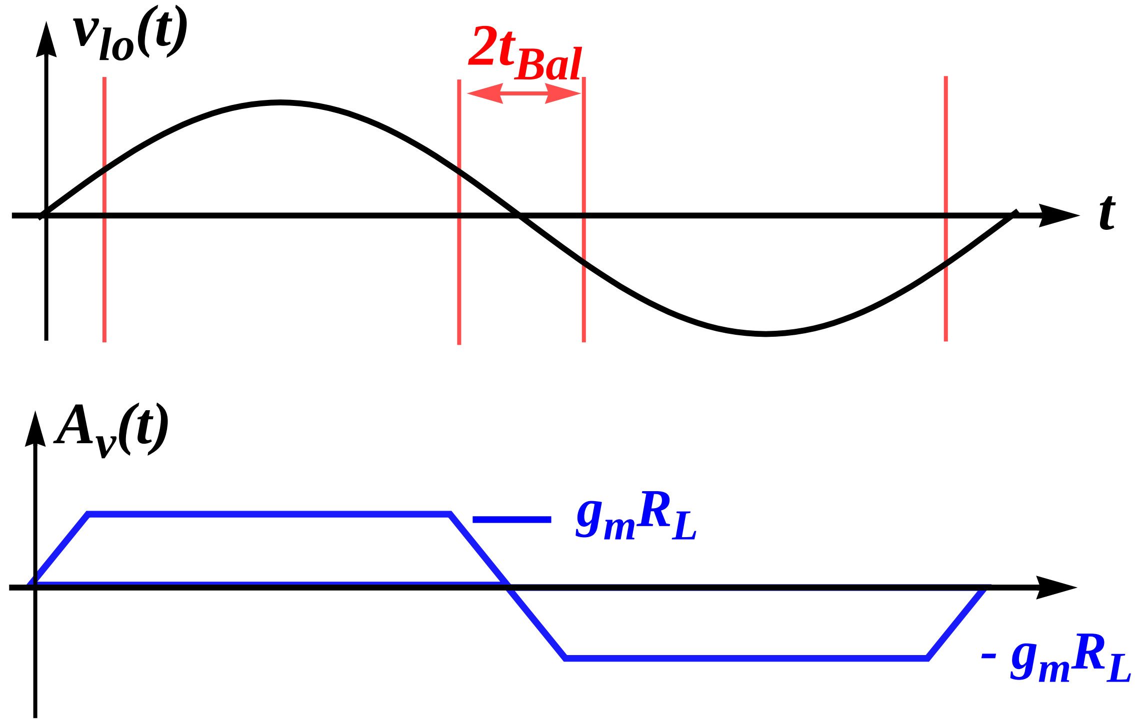
$v_{lo}(t) > \sqrt{2}\,(V_{gs}\text{-}V_t)$



Balanced State

$v_{lo}(t) < \sqrt{2}\,(V_{gs}\text{-}V_t)$





$$\text{Conversion Gain} = \left(1 - \frac{2}{\pi}\frac{\sqrt{2}\,(V_{gs} - V_t)_{sw}}{Vlo}\right)\frac{I_D}{(V_{gs}\text{-}V_t)_{input}}\,R_L \bullet \left(\frac{2}{\pi}\right)$$

Noise Performance

SSB Noise Sources

- LO1 Mixer
  - Input Devices

DSB Noise Sources

- LNA
- LO1 Mixer
  - Load Devices
  - Switches
- LO2 Mixer
  - All Devices

SSB

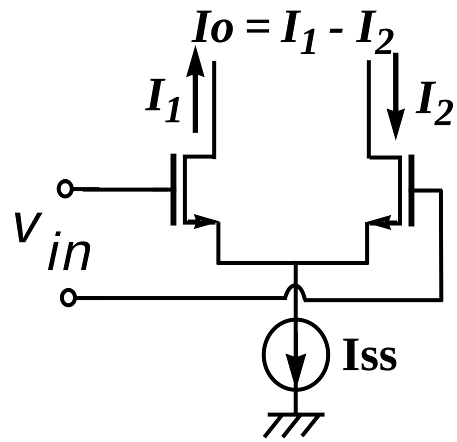
$$R_{in} = \left(\left(\frac{2}{3}\right)\frac{(V_{gs} - V_t)_{IN}}{I_D}\right) 2 \times 2 \quad \sim \quad \frac{(V_{gs} - V_t)_{IN}}{I_D}$$

$$R_{LOAD} = \frac{R_L^{\;2}}{CG^2}\left(\frac{1}{R_L} + \frac{I_D}{(V_{GS} - V_t)_{LOAD}}\right) \times 2$$

$$R_{SW} = \frac{\left(\frac{2}{3}\right)}{CG^2}\frac{f_{lo}\sqrt{I_B}}{(V_{GS} - V_t)}\int_0^{I_B}\left|\frac{[\sqrt{I_B - x}\;x + \sqrt{x}(I_B - x)]}{(I_B + 2\sqrt{I_B - x}\sqrt{x})}\right| dx \times 2$$

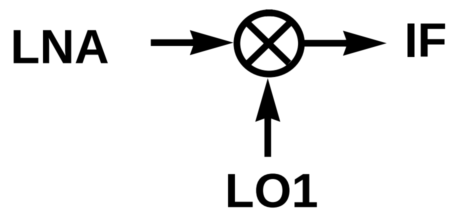
Other Performance Parameters

Distortion



$$V_{ip3} = 4\sqrt{\frac{2}{3}}(V_{gs} - V_t)$$

Power



$$P = 1.2 I_{BIAS} V_{dd}$$

DR

$$DR = 10\log\left(\frac{V^2_{out(p-p)}}{CG^2}\right) + 20(dB) - 10\log(4kTR_{eq}\Delta f)$$

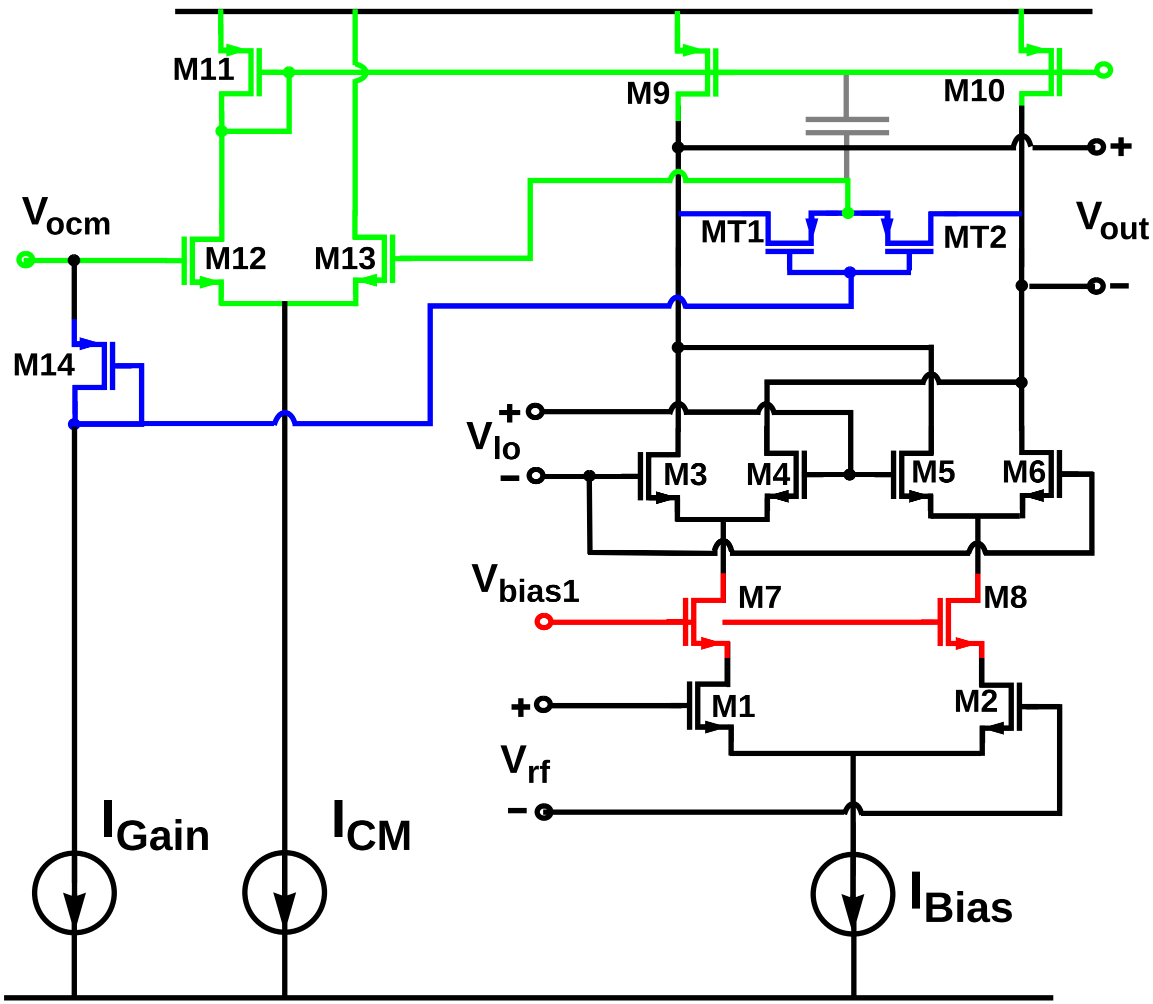
Performance Limits for Different Standards

Assumptions

- **Gain of the LNA 20 or 0(dB)**
- **LO1 Mixer CG is 1**
- **LO2 Mixer CG is 3**
- **$R_{eq}^{LNA} = 150\Omega$**
- **$R_{eq}^{BB} = 82\Omega$**

Standard	IP3	DR	NF_{total}	NF(@LNA)	Power
IS-54	25dBm	100dB	5dB	Not Possible	
GSM	-5dBm	100dB	8dB	2.2dB	55mW
DECT	0dBm	74dB	15dB	14dB	4.7mW
802.11	+3dBm	80dB	8dB	2.2dB	55mW

New Gilbert Cell with Variable Gain



<u>**New Features**</u>

Common Mode FB

Adjustable Gain

LO Shielding

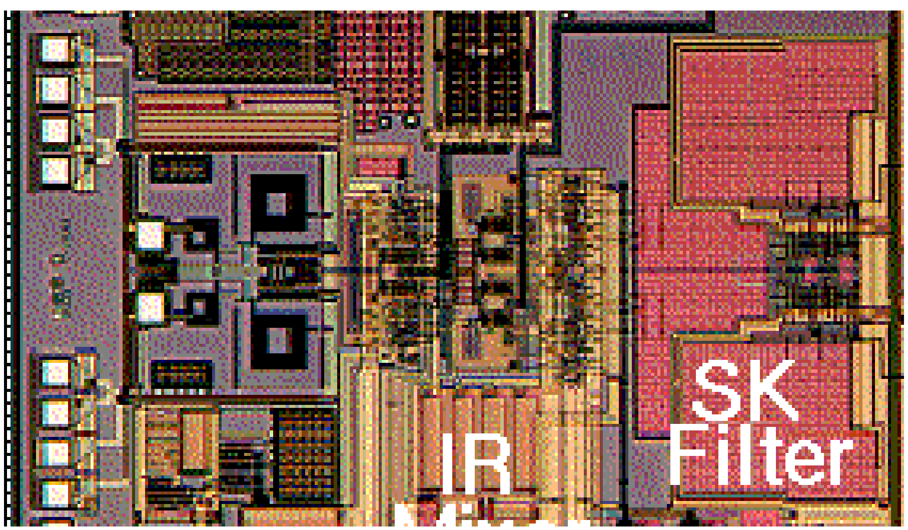
Design for the DECT Standard

LO1 Mixers Design Issues

- **LO1 & IF trade-off**
- **Gain BW product difficult to achieve**
- **AC coupling required**

LO2 Mixers Design Issues

- **High gain required**
- **DC offset due to LO leakage**
- **PMOS flicker noise**
- **Offset compensation current DAC**



	Simulated	Measured
IR	N/A	26dB
IP3	+6dBm	
CG	10dB	8dB
NF	2.0dB	
Power	55mW	55mW

Comparison to Other Work

Image-Rejection Mixers

Author, Publication	RF / IF (GHz)	IR(dB)	NF(dB)	IP3(dBm)	CG(dB)
M. MacDonald, ISSCC ‘93	1.9 / 0.110	14.1	18	-12	7
Steyart, JSSC Dec. ‘95	0.9 / ??	30	24	+28	9
D.Pache, et al., CICC ‘95	2 / 0.2	35	??	-5	10
J. Rudell & P. Gray, ...	1.9 / 0.22	26			

CMOS Gilbert Cells

Author	L(μm)	IP3(dBm)	NF(dB)	CG(dB)	RF(GHz)
D.K. Lovelace, ‘93	1.5	0	8 SSB	10.5	0.86
A. Abidi, JSSC ‘96	1.0	28	4.5 DSB	0	0.9
J. Rudell & P. Gray,..	0.6				1.8

Expected Research Contributions

- To demonstrate the feasibility of a fully integrated heterodyne mixer
- Understand issues involved in multi-standard implementations of heterodyne mixers
- Complete behavioral understanding of the CMOS Gilbert cell

Current Project Status

- **Project Status & Results**
  - **Simulated results**
    - **IP3 of the entire IR mixer is +6dBm**
    - **Entire IR mixer dissipates 55mW**
    - **10dB of conversion gain**
  - **Measured results**
    - **Prototype image-reject mixer was found fully functional w/ 26dB of image-rejection**
- **Future Work.**
    - **Develop better models for noise and distortion of CMOS Gilbert cell**
    - **Compare analytical models to measured results of individual CMOS mixer testchip**